NDC ASPECTS

NDC ASPECTS - Contribution of international bunker fuels to the Paris Agreement goals (D2.1)

WP2 – Global Conditions and Benchmarks

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Ioannis Tsiropoulos, Panagiotis Fragkos, Tamara Apostolou, Charalampidis Ioannis, Nikos Tsanakas, Panagiotis Karkatsoulis, Vassiliki Sourtzi, Eleftheria Zisarou

E3-Modelling

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www.ndc-aspects.eu

Panagiotis Fragkos	E3-Modelling
fragkos@e3modelling.com	https://e3modelling.com/
	Athens/Greece

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Responsible Author:	Tsiropoulos Ioannis (E3-Modelling), Panagiotis Fragkos (E3-Modelling)
Contributors:	Apostolou Tamara (E3-Modelling) Charalampidis Ioannis (E3-Modelling) Tsanakas Nikolaos (E3-Modelling) Karkatsoulis Panagiotis (E3-Modelling) Sourtzi Vassiliki Marianna (E3-Modelling) Eleftheria Zisarou (E3-Modelling)
7Internal Reviewers:	Jon Sampedro (BC3), Yann Briand (IDDRI)

Preface

The NDC ASPECTS project will provide inputs to the Global Stocktake under the Paris Agreement (PA) and support the potential revision of existing Nationally Determined Contributions (NDCs) of the PA's parties, as well as development of new NDCs for the post 2030 period. The project will focus on four sectoral systems that are highly relevant in terms of the greenhouse gas emissions they produce yet have thus far made only limited progress in decarbonization. To advance these transformations will require to understand and leverage the internal logic of those systems and take into account specific transformation challenges. These sectors are transport & mobility (land-based transport and international aviation & shipping), emission intensive industries, buildings, and agriculture, forestry & land-use, including their supply by and interaction with the energy conversion sector.

1. Changes with respect to the DoA

No change with respect to the DoA

2. Dissemination and uptake

Researchers, modellers, policy makers, and sector-specific experts.

3. Short Summary of results

The Paris Agreement goals require global efforts to reduce GHG emissions to limit global temperature rise to 2°C before pre-industrial levels, while pursuing efforts to limit the increase even further to 1.5°C. To achieve such goals, mitigation measures should be implemented across sectors. The international maritime and aviation sectors, commonly referred to as international bunker fuel sectors, compared to other transport sectors, account for about 2-3% of global CO_2 emissions. However, owing to drivers such as global population and economic growth and rising standards of living their contribution to global emissions is expected to increase to more than 10% if no emission reduction measures are taken up. Moreover, the uptake of mitigation measures in these sectors is challenged by the high costs of zero- and low-carbon fuel production technologies (e.g., biofuels, synthetic fuels), the long lifetime of aircraft and vessel assets, the limited electrification potential, and the international dimension of the sectors.

This report presents the development of two international bunker fuel models, for maritime and aviation that can assess the potential contribution of the sectors to meet deep decarbonization goals such as those of the Paris Agreement objectives. The models are calibrated to latest available information. In the short-term both models take into account the impact of the COVID-19 pandemic, and include mechanisms that can account for different policies, technologies, and prices. We quantify global and regional scenarios as well as regional case studies to demonstrate the potential contribution of international bunker fuels to GHG mitigation efforts. Then, the report discusses how the modelling of international transport (aviation and shipping) is improved in the global energy model PROMETHEUS, with endogenization of the emission reduction options (e.g., accelerated efficiency and operational improvements, advanced biofuels, clean synthetic fuels, hydrogen). Finally, the enhanced global modelling framework was used to investigate deep decarbonisation pathways and strategies for the international shipping and aviation sectors highlighting feasible policy measures and actions in the relatively short-term and possible enhancements in the longer-term, as well as the synergies of domestic climate action with the decarbonisation of bunker fuels.

4. Evidence of accomplishment

The present report that is compiled by E3-Modelling. Ioannis Tsiropoulos has contributed to the coordination of sections 2-3 and the development of the case studies (in section 3). Tamara Apostolou and Nikolaos Tsanakas developed the section on international maritime (section 2.1 and global maritime results with the bottom-up model in section 3.1). Ioannis Charalampidis and Ioannis Tsiropoulos developed the section on international aviation (section 2.2 and 3.2). Panagiotis Karkatsoulis contributed to the methodology of international maritime and aviation (section 2). Vasiliki Marianna Sourtzi contributed to the literature review. The top-down analysis with the PROMETHEUS global energy system models (section 4) was prepared by Panagiotis Fragkos and it is included as a manuscript, as it has already been submitted and is currently under review in a scientific journal. Eleftheria Zisarou contributed to the conclusions of the study.

LIST OF PARTICIPANTS

	Participant Name	Short Name	Country	Logo
1	Wuppertal Institut Fuer Klima, Umwelt, Energie gGmbH	WI	Germany	
2	Vrije Universiteit Brussel	VUB	Belgium	
3	Institut du Développement Durable et des Relations Internationales	IDDRI	France	
4	Deutsches Zentrum für Luft- und Raumfahrt e.V.	DLR	Germany	
5	E3-MODELLING S.A.	E3M	Greece	
6	Asociación BC3 Basque Centre for Climate Change – Klima Aldaketa Ikergai	BC3	Spain	
7	Ita-Suomen Yliopisto	UEF	Finland	
8	Indian Institute of Management	IIMA	India	
9	University of Cape Town	UCT	South Africa	
10	Tsinghua University	TU	China	
11	Institut Pertanian Bogor	IPB	Indonesia	
12	University System of Maryland	UMD	USA	
13	HOLISTIC P.C.	HOLISTIC	Greece	

Executive Summary

The international maritime and aviation sectors while having a comparably small share in global GHG emissions (around 3% in global GHG emissions in 2018, and 2% in global CO_2 emissions in 2019, from international maritime and aviation, respectively) pose a great challenge to global decarbonisation efforts. Despite scientific warnings and without specific actions and ambitious policies to change the production, consumption and trading organisation, the activity and resulting emissions of maritime and aviation industries is expected to grow vigorously. Owing to drivers such as global population increase, trade expansion, and economic growth the contribution of these sectors is expected to reach even 40% of global CO_2 emissions by 2050 if no emission reduction measures are taken by these sectors, thus undermining the Paris Agreement objectives. Key decarbonization options for the sectors relate with the uptake of alternative fuels (e.g., zero- and low-carbon fuels), new technologies (e.g., fuel-cell vessels, electric aircrafts), operational and performance standards (e.g., reduction in Carbon Intensity Indicator, Energy Efficiency Existing Shipping Index (EEXI)), as well as optimization of logistics and other operations. However, it is worth noting that reaching the Paris Agreement goals and carbon neutrality will require structural organisational changes alongside technological changes, in all economic systems including the production, consumption and trading systems, as there is no silver bullet whether from the supply or the demand side.

The report at hand presents: (a) a bottom-up sectoral assessment by detailing the development of two bottom-up sectoral international bunker fuel models for maritime (PRIMES-International Maritime) and aviation (Global Aviation Model), and (b) the consistent integration of data and insights from the bottom-up tools in the compressive global energy system model PROMETHEUS to improve the representation of international aviation and shipping and assess their contribution to achieve Paris goals capturing also the systemic impacts to other sectors, fuels and transition pathways. The assessment based on both bottom-up sectorally detailed tools and on comprehensive global energy system modelling enables the rigorous analysis of decarbonisation strategies in international transport sectors.

Bottom-up assessment using sectoral models

The bottom-up models aim at assessing the potential contribution of the international shipping and aviation sectors to achieve deep emission reduction in line with Paris Agreement goals. In the short-term the models consider the impact and recovery from the COVID-19 pandemic, and include mechanisms that can incorporate different fuel prices, policies, and technologies. The bottom-up models are validated with latest statistical data and information from various organizations. The two models developed and presented in this report are:

- The PRIMES-International Maritime model, that assesses current and future policies that impact the maritime sector by projecting international maritime activity, fleet composition, bunker fuel consumption by type of fuel and the derived GHG and other pollutant emissions until 2050. It covers the global maritime sector split by various shipping segments (dry bulk, tankers, containers, general cargo). The model, while regional in its disaggregation, includes more than 40 countries explicitly as key trading countries. On the supply module, the model includes a detailed representation of technologies and fuels.

- The Global Aviation Model (GAM), with the aim to perform long-term fuel consumption and emission projections for international passenger aviation under scenario assumptions. The GAM model has a global scope, covering in detail passenger trips per origin and destination between 105 countries, representing approximately 97-98% of passenger air transport demand in 2019. The trips are distinguished in different distance bands, the demand of the different distance classes is met by aircrafts of two different sizes. The supply module includes explicitly different aircraft technologies, different propulsion systems and different fuel types (i.e., conventional kerosene, alternative low-emission jet fuels, hydrogen and electricity).

Further to the model development and in order to address the implications of decarbonization of international maritime and aviation, the following **scenarios**[1] were quantified:

- The PRIMES-International Maritime model is used to quantify a baseline scenario on the projected growth of the sector by sub-sector globally (*Base*). The Base scenario is developed in a context of moderate climate and energy policies.
- The Global Aviation Model is used to quantify three global scenarios, namely a Reference (*Ref*) scenario in which no major decarbonization action is taken up by the sector, the *C-price* scenario that assumes a gradually increasing carbon price on fossil kerosene, and the *Mandates* scenario that in addition to carbon price it assumes quotas on alternative jet fuels.

The results of PRIMES-International Maritime show total maritime trade activity for major shipping segments to grow by almost 90% in 2050 compared to 2018 under business-as-usual considerations. This outcome is comparable to IRENA's (2021) BES scenario that also projects global activity growth of 90% in 2050. With respect to global aviation, the modelling shows a vast growth of the sector to almost 19 Gpkm in 2050 under baseline scenario considerations. Such projections are within the range of ICAO (2022) and ICCT (2022) estimates. Such outcomes signify the importance to decarbonize the sectors as future projections corroborate its vast potential growth, in line with other research findings. The Global Aviation Model results also points to lower energy use in decarbonization scenarios by 8-13% in 2050 (compared to *Ref*), partly due to less activity due to price effects induced by more expensive fuels (whether due to the carbon price or due to the mandate). Regarding the fuel mix the C-price scenario shows a notable uptake of hydrogen in 2050. In contrast, in the Mandates scenario owing to the alternative jet fuel quotas, their uptake is significant (i.e., more than 50% of fuel consumption in aviation, while retaining an 86% share in the pool of liquid jet fuels). The analysis shows that price signals alone may not be adequate to achieve the emission reduction required for the ambitious Paris Agreement emissions reduction trajectories. To that end, alternative jet fuel mandates may be necessary to achieve further emission reduction from the sector.

In addition to the global scenarios, a **regional case study** (see footnote 1) was developed for maritime and aviation for Europe. In particular, the case-study scenarios are:

- For European maritime: (a) the *Allmar* scenario provides a carbon price signal to the European maritime sector on the emissions from maritime transport activity in intra-European and extra-European routes, and (b) the *OperStand* scenario that assumes, in addition to Allmar, operational standards to apply early in the time horizon.

[1] The global and regional case-study scenarios of the sectoral bottom-up models for international maritime and international aviation are developed separately and are not identical (e.g., Baseline and Reference, or carbon price level, or emission reduction level in 2050), and therefore they are not directly comparable (e.g., to draw cross-sectoral conclusions). The main premise of the baseline scenarios, however, is that of a continuation of existing policies and the absence of deep decarbonization drivers. Moreover, all scenarios consider the same macro-economic and demographic drivers.

- For European aviation: (a) the *TickTax* scenario that assumes an additional fixed cost on the ticket price that increases gradually to about 180 Eur/ticket in 2050. This ticket price is considered sufficient to induce modal shifts to fast rail, (b) the *NeutralMand* scenario that considers mandates on alternative jet fuels apply, being technology agnostic (i.e., not prescribed on a specific fuel).

In line with the global *Base* scenario, the European maritime sector demand is projected to grow between 2030 and 2050, with minor yet present differences in activity growth. Moreover, results of the case study show that energy consumption per transport unit improves significantly from 2020 to 2050. The impact in the energy intensity improvements is notable, as in the *Allmar* scenario the energy use per tkm is lower by 16% in 2050 compared to 2020. Operational standards are shown to further lead to improvements in energy consumption per transport work, particularly early in the time horizon. Bunker fuel consumption is lower by about 7% and 9% in *Allmar* and *OperStand* compared to Base, respectively in 2030, and about 15% and 16% in 2050. Owing to the GHG intensity target assumed in EU maritime, the penetration of zero emission fuels to about 90% in 2050 in both scenarios. Biofuels are the main alternative maritime fuel used in the shipping sector in both decarbonization scenarios (*Allmar*, *OperStand*). The main driver for the higher relative uptake of biofuels compared to synthetic fuels is their price differential; biofuels are assumed to cost about 25% less than e-liquids. From the case study projections, a finding is that while the penetration of gaseous fuels (LNG) increases towards 2050, the ambition to reduce emissions by means of a carbon price and additional operational standards requires notably higher shares of gaseous fuels in maritime (*AllMar* and *OperStand*).

The results of the European aviation case study show that ticket taxation would increase substantially the ticket price to induce the necessary modal shifts to less carbon intensive modes so that it can lead to the necessary emissions reduction. Moreover, the *TickTax* scenario also leads to lower air transport activity as transport by air becomes more expensive for households and in this scenario the sector contracts substantially, especially when compared to the *NeutralMand* scenario. Another finding of the regional case study on aviation is that the in the *TickTax* scenario the carbon intensity of air travel is notably higher than that of the Mandates scenario. As such, despite that the sector has stimuli for efficiency improvements to avoid contraction, it underperforms compared to the *NeutralMand* scenario.

The validity of such findings can be further explored by means of sensitivity analysis, for example on fuel prices as these are a key driver for the uptake of different alternative fuels. Important work is required to improve the models and explore the contribution of international bunker fuels to the Paris Agreement goals. Both global international maritime and aviation models could benefit by improving data alignment across activity, energy and emissions on a regional basis, regional differentiation of fuel prices, higher technology representation. The findings of the present work point towards the importance of supply-side measures (e.g., deployment of alternative fuels). However, as discussed, demand-side measures may also prove important contributor to the decarbonization of the sectors. As such the models, could be improved to enable the quantification of feedbacks from the demand side.

Full-scale global Energy systems assessment using PROMETHEUS

The sectoral bottom-up tools provide detailed analysis of decarbonisation strategies for the international shipping and aviation sectors. However, the implications for the entire energy system, the systemic feedbacks and the interplay with domestic climate policies are not captured by sectoral models and require the use of a comprehensive global energy system model. In the current study, we use and further expand the PROMETHEUS model with an improved representation of international transport sectors, informed by data and insights from the bottom-up sectoral tools. The modelling enhancements capture the short-term impacts of the COVID-19 pandemic and are validated with the latest statistical data and information, while integrating detailed techno-economic assumptions for various emission reduction options, both on the demand side and on the supply side, using alternative low-emission fuels, including biofuels, synthetic e-fuels, electricity, and hydrogen.

Under current climate policy and technology trends, emissions from international transport are projected to massively increase until 2050 driven by strong activity growth and the continued dominance of oil-based products. This increasing emissions trajectory is not compatible with the Paris Agreement goals, which require rapid emission reductions towards carbon neutrality by mid-century through a large-scale transformation of the global energy and transport systems. The model-based analysis shows that the international shipping and aviation industries should also be massively transformed to ensure compatibility with the Paris goals, based on accelerated energy efficiency improvements, moderation of activity growth (through lifestyle changes and shortened supply chains) and large uptake of low-carbon fuels, especially advanced biofuels, hydrogen, ammonia, and synthetic kerosene. Advanced biofuels play a key role for the transformation of international shipping and aviation sectors, contributing more than half of their energy requirements by 2050 in scenarios compatible with the 1.5^{o}C Paris goal. The study shows that the combination of technical and operational measures along with a significant uptake of alternative low-carbon fuels is critical to ensure large emissions reductions in these sectors, with limited cost increases.

The decarbonisation of transport requires both demand and supply-side mitigation options as no single solution is sufficient for decarbonisation. This is particularly the case for international aviation and shipping, where technical solutions are limited and face high costs and large uptake and commercialization barriers, increasing the challenges to decarbonise these sectors. In this context, the transition to climate neutrality requires large economic and trade re-organisation, as the uptake of low-emission sustainable fuels should be articulated with systemic changes to curb demand growth, like changes in supply chain organisation and management for shipping or in the models of tourism and business trips for aviation.

The emissions reductions achieved in international transport in the 1.5^{o}C-compatible scenarios range between 65% and 85% relative to 2015 levels, indicating that the sectoral goals of IMO and ICAO for 2050 are over-achieved in these scenarios. More ambitious emission reduction goals should be established for international transport to ensure that the sectoral transition is compatible with the 1.5^{o}C Paris goal, as declared by several countries in COP26 towards net zero shipping. The combination of ambitious decarbonization effort with activity growth moderation (due to lifestyle changes and shortened supply chains) achieves even larger emission reductions by 2050, and with reduced mitigation costs while reducing the stresses in the entire energy system due to the lower use of expensive low-carbon fuels. The decarbonization in international shipping and aviation should be driven by a combination of market-based policy mechanisms (carbon pricing) with regulatory instruments (e.g., blending mandates, technology, or efficiency standards).

The decarbonisation of the international maritime and aviation sectors requires accelerated transformational dynamics even in this decade to pave the way for decarbonisation by 2050 given the slow stock turnover in these sectors. Large amounts of direct and indirect investment are needed related to the production, transport infrastructure, trade, and use of sustainable, low-emission fuels and associated technologies. The uptake of low-carbon fuels would also imply large changes in the entire energy system via complex interlinkages, which are captured through the global system-wide modelling framework. The decarbonisation of international transport may generate synergies and trade-offs with the low-carbon transition in other sectors, by increasing the competition for the limited biomass resources or creating stresses in the renewable energy potentials needed to produce green hydrogen and e-fuels. On the other hand, domestic climate policy results in a lower demand for international shipping due to reduced fossil energy trade, indicating a positive feedback and synergies of the energy transition with the decarbonisation of the shipping sector.

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1 Introduction

The UNFCCC Paris Agreement introduced goals to reduce global GHG emissions by limiting global temperature rise to 2°C before pre-industrial levels, while pursuing efforts to limit the increase even further to 1.5°C. Substantial mitigation measures should be implemented in order to meet such goals. The transport sector is a major CO_2 emissions source accounting for about 7.7 $GtCO_2$ in 2022 as mobility demand rebounded from the impacts of the COVID pandemic (IEA, 2022). While estimations regarding the contribution of the aviation and maritime sector in global CO_2 emissions vary, they both account for a small share in global GHG emissions. Aviation is estimated to account for 2.1% of global CO_2 emissions and 12% of CO_2 emissions related to transport (ATAG, 2022). Total maritime is estimated to contribute between 2% and 3% to global GHG emissions, with 2018 figures pointing towards about 2.9% contribution of the sector in total emissions, i.e., 1.08 $GtCO_{2eq}$ including international, domestic and fishing (IMO 2020, EC 2018).

Owing to drivers such as global population increase, and economic growth the contribution of these sectors is expected to reach even 40% of global CO_2 emissions by 2050 if no emission reduction measures are taken by these sectors, thus undermining the Paris Agreement objectives (EEA, 2019). Specifically, shipping plays a critical role to economic development and trade around the world. According to IMO 2022 (SBSTA 57) more than 80% of the global trade is carried by sea. Growing demand for goods will result to an increase of world fleet activity and consequently to higher global emissions from seaborne transportation (Nwaoha, Ombor, and Okwu, 2016). A similar pattern is also observed for air transport, as international aviation is causally linked to world economy with economic growth leading to higher demand for airborne transportation (Zhang and Graham, 2020). Notably, these megatrends and the sectoral growth is expected to remain despite the influence that continuous lockdowns and prolonged protective measures against COVID-19 had on the sectors[2].

Key decarbonization options for the sectors relate with the uptake of alternative fuels (e.g., zero- and low-carbon fuels), new technologies (e.g., fuel-cell vessels, electric aircrafts), operational and performance standards (e.g., Carbon Intensity Indicator, Energy Efficiency Existing Shipping Index (EEXI)), as well as optimization of logistics and other operations. However, it is worth noting that reaching the Paris Agreement and carbon neutrality will require structural organisational changes alongside technological changes, in all systems including the production, consumption and trading systems. While technological changes such as shifting fuels are necessary, this should not be considered as a silver bullet and should be articulated with « systemic changes » highlighted by the latest WGIII IPCC report, like changes in supply chain organisation and management for shipping or in the models of tourism for aviation (IPCC, Transport Chapter, 2022). Moreover, activity shifts from aviation towards land modes (e.g., speed rail) is another possible option of mitigating the impact that the sector may have, though with limited potential as there are, among others, regional barriers (see e.g., T&E 2020). Despite scientific warnings and without specific actions to change the production, consumption, and trading organisation, maritime and aviation are two industries with expected growth in activity and resulting emissions. Nonetheless the emissions of maritime and aviation are hard to abate and the challenges these sectors face are great owing to high costs of zero- and low-carbon fuel production technologies such as biofuels and synthetic hydrocarbon fuels, the long lifetime of aircraft and vessel assets and the international dimension of the sectors. For instance, in 2019 sustainable fuels used in global aviation

[2] In 2021, CO_2 emissions in global aviation reached 60% of the pre-pandemic levels owing to activity reduction (IEA, 2021). On the contrary, emissions in shipping increased by 4.9% compared to 2020 surpassing also 2019, denoting that the increased demand for consumer goods in conjunction with longer ton -mile trade, higher speeds and port congestion led ton increases shipping activity (SSY, 2022).

accounted for less than 1% of jet fuel demand. Sharmina et al. (2020) identify aviation and maritime among the critical sectors owing to their difficulty to decarbonize so as to limit temperature to 1.5-2 °C by 2100.

International organizations such as the International Civil Aviation Organization (ICAO) and the International Air Transport Association (IATA) promote the production and use of alternative fuels in aviation (sustainable advanced fuels). IATA introduces initiatives to achieve net zero in their members' CO_2 emissions by 2050 that will mainly result from the use of alternative fuels, new technologies, efficiency improvements but also offsetting programmes. Offsetting emissions is a principal mechanism proposed by ICAO as means to contribute to the sectors mitigation efforts. For the maritime sector, international, regional as well as national policies and initiatives aim at reducing the sector's GHG footprint. The International Maritime Organization (IMO) issued in 2018 an initial GHG emissions reduction strategy foreseeing the reduction in total GHG emissions, by at least 50% by 2050 compared to 2008, and the vision to phase out emissions from international shipping as soon as possible to align with the Paris Agreement. The strategy currently mandates carbon intensity reduction targets i.e., reduction of CO_2 emissions (per transport work) by at least 40% by 2030, pursuing efforts towards 70% by 2050, from 2008 levels[3]. This ambition level is expected to be raised by IMO member states by June 2023. At the regional level, for example, the European Commission (EC) through its "Fit For 55" policy package proposal promotes the usage of alternative fuels (renewable or low-carbon fuels) in both aviation and maritime vessels so that the sectors contribute to the region's broader targets of 55% reduction in CO_2 emissions by 2030 compared to 1990 and carbon neutrality in 2050 (European Parliament, 2022).

It should also be mentioned that decarbonisation pathways through the deployment of cleaner fuels and/or technologies may mitigate over time other environmental impacts such as air pollutants (e.g., SO_2, also on a lifecycle basis; Stathatou et al. 2022), noise levels (e.g., electric airplanes). Such impacts and in particular the interplay and potential tradeoffs of decarbonisation options on impact categories other than climate change is not examined in this report.

Against this background, this report addresses the potential contribution of international aviation and maritime bunker fuels to the Paris Agreement goals on climate change mitigation. To do so, we develop, extend and use sectoral international aviation and maritime models and develop scenarios that quantify the emission reduction trajectories of these sectors. In support of these goals, specific regional case studies with a regional (Europe) focus are also developed and examined further. In addition, drawing on the data and insights from the sectoral models and case studies, we further extend and improve the global PROMETHEUS energy system model with an enhanced representation of international shipping and aviation sectors. Various emission reduction options are introduced in the modelling framework, including advanced biofuels, synthetic fuels, hydrogen, energy efficiency improvements, and re-organisation of logistics and international value chains to reduce activity, enabling the investigation of their systemic impacts in the context of meeting Paris goals. The potential transformation of the sectors to achieve ambitious deep decarbonisation targets by 2050 and the interplay between national climate action and international transport are explored (e.g., reduced trade of fossil fuels, thus reducing emissions from bunker fuels).

[3] The strategy will be revised in 2023, with discussions for more ambitious goals that would potentially take Well-to-Wake emissions into consideration having intensified. For the time being, intermediate mandatory carbon intensity reduction targets have already been scheduled to be adopted (MEPC 76) in support of the achievement of the longer term carbon intensity reduction targets. More specifically, the Carbon Intensity Indicator (CII) is an operational efficiency measure to be implemented starting January 1st 2023 that foresees the drop in CO_2 intensity from maritime fuel combustion in tons CO_2 per deadweight nautical mile transported by a cumulative -11% by 2026 from 2019 levels (or a 1% annual improvement in carbon intensity between 2019-2022 and 2% annual improvement from 2023 to 2026)

This report is structured as follows: in section 2 we present the methodological approach that includes the bottom-up model description, data description and scenario development for international maritime and aviation. In section 3 we present results for decarbonization scenarios for international maritime and aviation to 2050, with case studies for the EU region. In section 4 we present results based on the global energy system model PROMETHEUS that explores transformation pathways of international shipping and aviation sectors in well-below 2 ^{o}C and 1.5 ^{o}C Paris-compatible scenarios. Finally, section 5 draws the conclusions from the presented work.

2 Methodology, data, and scenarios

2.1 International maritime

The international maritime sector has been estimated to account for 2% of global CO_2 emissions, which amounted to 740 million tons of CO_2 in 2018 under a voyage-based approach, while under a vessel-based approach emissions are calculated at 919 million tons (IMO 2020). This represents 90% of the maritime sector's emissions in 2008, which can rise to between 90% and 130% of 2008 emissions by 2050, if no measures are taken, based on a range of plausible and energy scenarios (IMO 2020). Other literature suggests that maritime emissions could grow between 50% and 250% by 2050, which could increase the sector's contribution up to 17% (Cames et. al 2015).

Despite an overall increase in emissions from maritime over time, the average carbon intensity of the sector is estimated to have improved in 2018 compared to 2008[4]. Efficiency improvements leading to fuel consumption savings have partly contributed to this reduction and were driven mainly by the IMO's mandated energy efficiency requirements[5] (IRENA 2021, IMO 2020).

In support of the achievement of the carbon intensity reduction in the long term and GHG mitigation targets, intermediate mandatory carbon intensity reduction targets have already been adopted (MEPC 76). More specifically, the Carbon Intensity Indicator (CII) is an operational efficiency measure targeting to reduce CO_2 intensity of fuels used in maritime[6]. Technical measures have also been introduced by the IMO to contribute to GHG emissions reduction. Specifically, the Energy Efficiency Existing Ships Index (EEXI) addresses the technical design of a ship and is based on a required reduction factor calculated as a percentage relative to a baseline[7]. Regional policies are also being proposed (see example for the EU in Box 1).

Box 1 Snapshot of policy landscape in the EU

The "Fit For 55" policy package proposal of the EC aims to support its targets on 55% reduction in GHG emissions by 2030 compared to 1990 levels and carbon neutrality in 2050. In this direction, the FuelEU Maritime initiative supports the uptake of sustainable maritime fuels via targets that limit the GHG intensity of fuel use in the sector. Furthermore, the EC proposal on the Revision of the EU Emissions Trading System (ETS) includes its extension to maritime by phasing it in over 2023-2026.

There are several options to comply with the above policies and maritime stakeholders have already started to look into and adopt compliance measures, including technical and operational efficiency

4 Benchmark year against which IMO has set its GHG emissions and carbon intensity reduction targets.

5 MARPOL Annex VI, Chapter 4; EEDI (Energy Efficiency Design Index for newly built vessels), EEOI (Energy Efficiency Operational Indica-tor for new and existing vessels) and the SEEMP (Ship Energy Efficiency Management Plan).

6 Implemented from January 2023: 1% annual improvement in carbon intensity between 2019-2022 and 2% annual improvement from 2023 to 2026.

7 While EEXI approval has to be attained once and at latest by the first periodical survey in 2023 (IMO, 2021).

measures (e.g., emissions saving devices and eco-electronic engines, slow steaming, voyage optimization), blending biofuels, as well new propulsion technologies[8]. Research suggests that technical and operational measures will not be sufficient to achieve deep decarbonization in the sector, as the growth of trade and fleet under a business-as-usual scenario is projected to overtake any improvements in energy efficiency, while zero carbon fuels will need to make a significant contribution to the sector's decarbonization (Cullinane and Yang, 2022). On the other hand, Lindstad et al. (2021) suggest that although zero carbon fuels (e.g., fuels made from renewable sources) are considered by many as the most promising option to achieve longer term GHG reduction targets, their GHG reduction potential (focusing on e-fuels) depends entirely on the availability of renewable electricity and comes with additional costs. Recent literature also suggests that SO_2 emissions from biofuels may result to lower SO_2 emissions (Stathatou et al. 2022) though they may still remain a key problem over the lifecycle (dos Santos et al. 2022), while other alternatives (e.g., LNG) are free from SO_x emissions. The trade-offs of decarbonization options with non-CO_2 emissions are not a subject of the present analysis.

Lindstad et al. (2021) concluded that dual fuel engines offer flexibility in the transition. Zhao et. al (2022) conclude that hydrogen, ammonia, and nuclear energy present advantages in environmental performance, while LNG and biofuels amongst others are economically more beneficial taking calorific value and fuel prices into consideration, as well as safety issues. Other literature raises concerns regarding ammonia and the potential disruptions that it may induce in the nitrogen cycle, a subject that needs further exploration (Wolfram et al. 2022).

Despite the fact that low and zero carbon fuels are deemed necessary for the GHG mitigation of international maritime to align with the Paris Agreement targets, there are many uncertainties related to the deployment of zero emissions propulsion technologies and fuels. These uncertainties are linked to the real lifecycle impact from Well-to-Wake, the technical and industrial maturity of solutions, the availability of fuel supply and bunkering infrastructure, as well as safety challenges, amongst others. The risk of market players being left with stranded assets expensive to operate (e.g., the risk premium of implementing innovative technologies too early – high upfront investment – and CAPEX recovery), as well as the diverse profile of the current fleet structure per shipping sector in terms of age, technology and trade (i.e., cost-effectiveness of abatement options varies substantially) are putting the sector far behind from a massive fleet renewal that will be required to fully decarbonize the sector.

2.1.1 Maritime: modelling approach and data

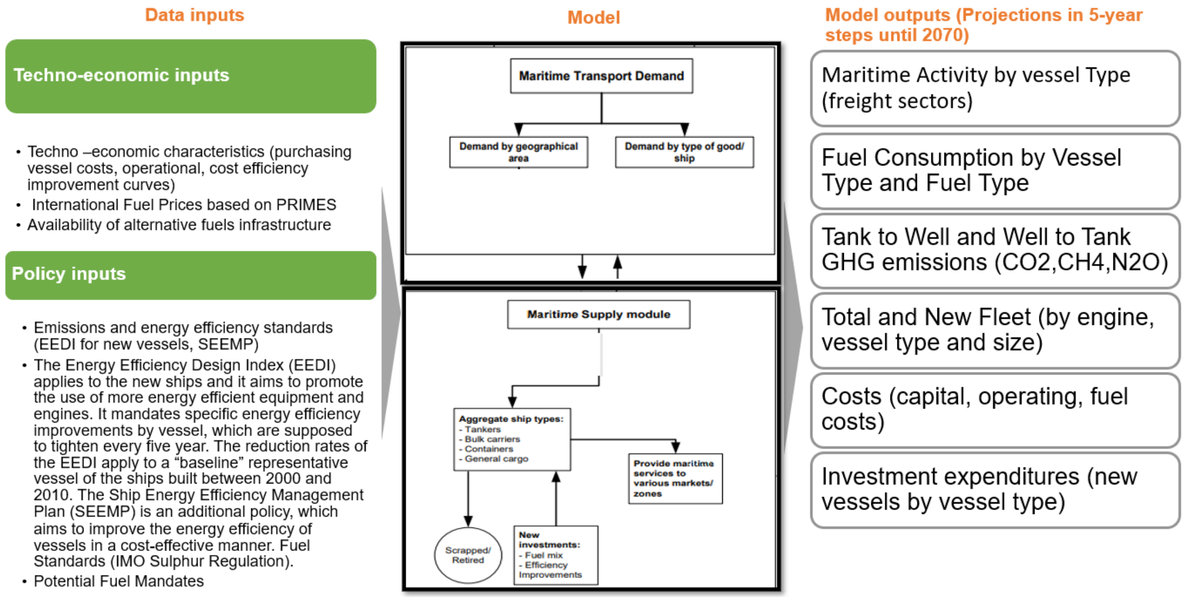
Model description

The PRIMES-International Maritime model assesses current and future policies that impact the maritime sector by projecting international maritime activity, fleet composition, bunker fuel consumption by type of fuel and the derived GHG and other pollutant emissions until 2050. The model covers the global maritime sector split by various shipping segments, namely dry bulk, tankers, containers, and general carriers. The model, while regional in its disaggregation, includes more than 40 countries explicitly as key trading countries. In the sections that follow, we describe the modelling approach for international maritime, the main data and sources used, and the scenarios developed to quantify the development of the sector in a Baseline scenario context. The contribution of the sector to the Paris

8 For example, 49% of the orderbook excl. LNG carriers is with new propulsion technologies – mostly LNG dual fueled with increasing focus on methanol and ammonia ready options according to Clarksons (2022).

Agreement goals is illustrated by the development of a regional case study. A schematic overview of the PRIMES-International Maritime model is presented in Figure 1.

Figure 1 Schematic overview of the PRIMES-International Maritime model



The model consists of a modular structure encompassing demand and supply.

(a) Demand

The PRIMES-International Maritime model projects maritime activity to 2050 per shipping sector adjusting the geographical resolution of the GEM-E3 model to major trade routes related to dry bulk (including general cargo), tankers and containers. The provision of bilateral trade flows is initially based on the GEM-E3 model that explicitly models 46 countries/regions and 60 economic activities (E3-Modelling 2017)[9]. For GDP projections the main sources used by the GEM-E3 model are DG ECFIN's Ageing Report 2021 (EC 2021) for the EU, and IEA's WEO 2020 (for short-term projections until 2025; IEA 2020), and OECD (2018) for long-term projections for non-EU countries/regions.

A critical aspect in this process is the conversion of monetary flows to physical units (i.e., ton-miles) that are used by the PRIMES-International Maritime model. This is based on a two-stage-error-correction model, which correlates total maritime activity per shipping sector with GDP, bunker prices and trade per relevant to each shipping segment cargo type (imports and exports in volumes) (see Equation 1). The co-efficient of determination (R^2) of the regressions performed for each shipping sector indicated an almost perfect fit of the model, particularly for dry bulk (R^2=0.99), followed by tankers (R^2=0.98) and containers (R^2=0.95). This means that the variance of the dependent variable (ton-miles per sector) is almost completely explained by movements in the independent variables selected. Detailed diagnostic and specification tests were not performed.

[9] The bilateral trade flows are derived endogenously in GEM-E3 as economic flows by economic activity and transport mode (air, water, land) and purpose (passenger, freight).

The historical data used are based on time series between 1990 and 2022 provided by Clarksons SIN (i.e., trade in volumes per cargo type and global bunker prices; Clarksons (2022)) and IMF (2022) (i.e., GDP).

Equation 1

$$Log\ (MA_i) = a_0 + \sum_{i=1}^{t} a_i \, log(X_i) + u_i$$

i : independent variables (GDP, bunker price, trade volumes per cargo type)

$MA_{i,t}$: Maritime Activity

The derived elasticities from Equation 1 are then applied on bilateral trade projections of GEM-E3, aggregated per cargo type relevant to each sector (Table 1).

Table 1 Aggregation of transported cargoes per different vessel types

Vessel type	Cargo transported
Bulk Carriers	• Ferrous metals (e.g., iron ore) • Coal • Grains • Minor bulks and minerals (including steel and non-ferrous metals)
Tankers	• Crude oil and products • Chemicals
Containers	• Final goods
General cargo	• General (assumed as a % of dry bulk)

The derived ton-miles per country pair indicated by the disaggregation of GEM-E3 were adjusted with the use of calibration factors to match historical ton-miles shares of major country origins in total ton-miles for each shipping segment for 2018 (historical ton-miles shares based on Clarksons (2022). The disaggregation of maritime trade into tons followed a top-down approach, where indicative distances in nautical miles per country pair were selected to derive bilateral tons from ton-miles. Distances are based on www.sea-distances.org, from which the shortest calculated distance between two representative ports for each country pair was selected. Distances were then calibrated so that trade volumes in 2018 were aligned with the Clarksons (2022) estimated trade volumes for 2018 per shipping segment. This resulted in a range of 1.1% to 3.5% higher average distances than the originally selected for each shipping sector, reflecting the multiple ports involved in the trade of each country pair and potentially different trade routes that ultimately differentiate trade distances between countries.

The demand module further considers bilateral trade transactions between Origin and Destination countries or regions by types of cargo that are aggregated and assigned to different shipping sectors, namely dry bulk, tankers, containers, and general cargo. The regional and cargo disaggregation is initially based on the granularity of the GEM-E3 model, which is calibrated to Clarksons historical volumes and ton-miles data per shipping sector for the years 2015, 2018 and 2020. At the same time the EU27 calibration is in line with the Eurostat activity data in ton-miles and in-line with the coverage of the PRIMES-Maritime (EU model; EU27). The total maritime activity projection is based on econometric functions that relate trade activity in ton-miles with GDP, trade volumes for commodities (ferrous, non-ferrous metals, coal, grains, crude oil, oil and chemical products, final goods), as well as global average bunker prices. The long-term elasticities are found via a double log econometric model (Equation 2). Following the econometric projections of total ton-miles per shipping sector, the demand module assigns the ton-miles activity to each country or region following the calibration of the base year on ton-miles per major trading origin (e.g., Brazil, Australia, China, SE Asia (ex. China), Saudi Arabia, EU27) and derives the volumes traded from projected ton-miles using indicative distances per country pair.

Equation 2

$$ACT_{s,t} = ACT_{s,t-1} \cdot exp\left(\varepsilon 2_s \cdot ln\left(\frac{BP_{s,t}}{BP_{s,t-1}}\right) + \sum_{b_s} \varepsilon 1_{s,b_s} \cdot ln\left(\frac{VOL_{s,b_s,t}}{VOL_{s,b_s,t-1}}\right) + \varepsilon 3_s \cdot ln\left(\frac{GDP_{s,t}}{GDP_{s,t-1}}\right)\right)$$

$ACT_{s,t}$: Annual international maritime activity projections per shipping sector, s, where $s \in \mathcal{S}, \mathcal{S} = \{\text{dry bulk, oil and product tankers, container, general carriers}\}$, and product b_s, where $b_{dry\ bulk} \in \{Iron\ Ore, Coal, Grains, Minor\ bulk\}$, $b_{tanker} \in \{Crude\ oil, Oil\ Products\}$, $b_{container} \in \{Container\}$ and $b_{general\ carriers}$ is assumed as a share of $other\ dry$.

$ACT_{s,t-1}$: Annual international maritime activity projection per shipping sector for forecast year 2022 from Clarksons in ton-miles

$BP_{s,t}$: Estimated global average bunker prices of major bunkering ports for sector s and year t

$VOL_{s,b_s,t}$: Traded volume in million tons for sector s, product b_s and year t

$VOL_{s,b_s,t-1}$: Traded volume in million tons for sector s, product b_s and year $t-1$

$GDP_{s,,t}$: Global GDP for sector s (container only) and year t

$GDP_{s,,t-1}$: Global GDP for sector s (container only) and year $t-1$.

$\varepsilon 1_s$: elasticity of ton-mile demand with respect to traded volumes - positive

$\varepsilon 2_s$: elasticity of ton-mile demand with respect to bunker prices - negative

$\varepsilon 3_s$: elasticity of ton-mile demand with respect to global GDP (for s=container only) – positive

In addition, the model endogenously derives the distribution of ton-miles activity per vessel size, age and fuel type in each trade route (Equation 3).

Equation 3

$$\sum_{s} ACT_{s,t} = \sum_{s,z,o,d,e} [trip\_share_{o,d,s,z,e} \cdot load\_factor_{s,z} \cdot stock_{s,z,a,e} \cdot distance_{o,d}]$$

$trip\_share_{o,d,s,z,e,f}$: endogenous split of vessel stock by origin, destination, vessel type, size and engine

$load\_factor_{s,z}$: load factor determined as a % of available deadweight capacity

$stock_{s,z,a,e}$:Number of vessels per shipping type,size,age and engine type

$distance_{o,d}$:nautical miles between origin and destination

(b) Supply

The supply module simulates the global fleet requirements necessary to perform the projected maritime activity. It simulates the global maritime fleet by shipping sector and sizes deployed to perform the maritime transport work. Vessel sizes are distributed to maritime transport work per trade route using Gompertz probability distribution functions[10]. Vessels are allocated to maritime activity in markets where different regulatory regimes may apply (e.g., SECA/ECA zones) using the mandated fuels for these areas (i.e., <0.1% sulphur marine fuel).

The vessels are purposely designed to transport specific types of cargoes and thus the PRIMES-International Maritime model is developed on this basis, considering global general cargo activity as a share of dry bulk activity (and not considering potential trade substitution between vessel types (e.g., between bulkers and containers). Moreover, the quantity of cargo that a vessel can transport is provided by its designed characteristics such as the load factor and the Deadweight Tonnage (DWT). The vessel types used in PRIMES-International Maritime are categorized based on their size by DWT (Table 2) while their cargo carrying capacity within a year varies between vessel types due to different utilization rates (i.e., percentage of fleet loaded within a year).

Table 2 Vessel types and sizes in PRIMES-International Maritime

Vessel types	Vessel sizes	Unit
Containers	< 999	TEU[a]
	1000-1999	
	2000-2999	
	3000-4999	
	5000-7999	
	8000-11999	
	> 12000	

[10] Gompertz functions are used to represent that from a certain distance onwards the economies of scale for larger vessels widen relative to smaller ones, because of the drop in per unit costs of larger vessels (i.e., cost per tonkm for larger vessels declines substantially from a certain distance onwards and thus the share of larger sizes increases and remains stable at high levels from a certain distance onwards, while the share of smaller ones from a certain distance onwards remains unchanged at low levels)

Vessel types	Vessel sizes	Unit
Dry bulk carriers	Handysize	‘000 DWT[a]
	Supramax/Ultra	
	Panamax/Kamsarmax	
	Post Panamax	
	Capesize	
Liquid tankers (oil and products, chemicals)	10-69	‘000 DWT[a]
	70-119	
	120-199	
General Cargo	One size	‘000 DWT[a]

[a] TEU: Twenty-foot Equivalent Unit, DWT: DeadWeight Tonnage

Bunker fuel consumption projections and investment decisions are estimated in the supply module; The model solves for a balance between supply and demand in each consecutive period, considering vessels’ utilization, vintages, and fleet renewal requirements with a stock-flow relationship (Equation 4). The investment decisions are made by vessel type, size, and engine. Different survival probability functions apply by sector and size, considering the sectoral characteristics (e.g., historical demolition age for each vessel type), via Gumbel distribution factors.

Equation 4

The survival probability (Pr) of each vessel is given as a function of age, by the Gumbel distribution:

$$\underset{s,z}{Pr}\left(a;\mu_{s,z},\beta_{s,z}\right) = 1 - e^{-e^{-(a-\mu_{s,z})/\beta_{s,z}}}$$

a is the age of the vessel

s is the type and z the size of vessel

$\mu_{s,z}$ is the location

$\beta_{s,z}$ the scale parameter of Gumbel distribution

The pace of fuel substitution is influenced by capital turnover in the model. The projected bunker consumption is endogenously split by fuel type. The choice of the fuel mix and technologies for new vessels is based on discrete choice modelling (Equation 5).

Equation 5

$$fuel\_share_{o,d,s,z,e,f} = \frac{m_{o,s,z,e,f} \cdot cost\_fuel_{o,d,s,z,e,f}^{-\gamma}}{\sum_{f \in \mathcal{F}_e} \left[m_{o,s,z,e,f} \cdot cost\_fuel_{o,d,s,z,e,f}^{-\gamma} \right]}$$

$m_{o,s,z,e,f}$ is the maturity of fuel (a factor that assigns a weight that describes the preference and/or availability of the fuel based on technical and/or commercial considerations; 1 means that the choice is fully competitive)

$fuel\_share_{o,d,s,z,e,f}$: % of fuel consumed per origin, shipping sector, size, engine, e, and fuel type, $f \in \mathcal{F}_e$

f for vessel type s and vessel size z in origin o

$cost\_fuel_{o,d,s,z,e,f}$ is the total cost of fuel f in Euro/hundred ton-mile

$\mathcal{F}_e$ is the set of fuels used by engine e

PRIMES-International Maritime considers exogenous policy variables such as fuel standards, potential fuel mandates, efficiency regulations (EEDI, ECA zones, IMO Sulphur Cap etc.), air pollution policies. Fuel consumption on board each vessel is derived by specific fuel consumption functions per ton-mile, using cost-efficiency curves that provide efficiency improvement possibilities at a cost. The fuels covered in the model are: Residual Fuel Oil (RFO; combined very low sulphur fuel oil and heavy fuel oil burnt by vessels with exhaust gas cleaning systems), Marine Gas Oil (MGO), LNG, alternative fuels namely biofuels (incl. biomethane), synthetic fuels (including synthetic gas), hydrogen and electricity. The total bunker fuel consumption is provided by Equation 6.

Equation 6

$$Total\_fuel\_cons = \sum_{o,d,s,e,a,f} [\, trip\_share_{o,d,s,z,e} \cdot load\_factor_{s,z} \cdot stock_{s,z,a,e} \cdot distance_{o,d} \cdot fuel\_share_{o,d,s,z,e,f} \cdot spec\_fuel\_cons_{s,z,f,a}]$$

$spec\_fuel\_cons_{s,z,f,a}$: specific fuel consumption per shipping sector, size, fuel and age of vessels in tons per million ton-mile

Combining all the above, the model solves for a market equilibrium problem, where maritime activity and fleet supply interact dynamically in each consecutive period (stepwise in 5-year periods). More precisely, the model solves for minimizing costs for the trading between Origin-Destinations. The objective function that minimizes total costs for the sector factors in fuel costs (i.e., voyage expenses), operating expenses and perceived costs related to the availability of bunkering infrastructure. Furthermore, congestion costs, ETS costs for trades related to the EU, penalties for not satisfying ECA zone requirements are also included. Equation 7 presents the optimization problem.

Equation 7

$$trip\_share_{o,d,s,z,e} = argmin\ (Total\ cost)$$

$$Total\ cost = \ congestion\ cost + fuel\ expeditures + operational\ cost + congention\ in\ ports\ cost + penalty\ for\ certain\ fuels\ in\ ECA\ zones$$

$$congestion\ cost = \sum_{o,d,s,z,e} quant_{o,d,s} \cdot variab\_cost_{o,d} \cdot cong\_cost_{s,z}\left(trip\_share_{o,d,s,z,e}\right)^2$$

$$fuel\ expeditures = \sum_{o,d,s,z,a,f} fuel\_cons_{o,d,s,z,a,f} \cdot fuel\_price_f$$

$$operational\ cost = \sum_{o,d,s,z,a} trip\_share_{o,d,s,z,e} \cdot stock_{s,z,a,e} \cdot oper\_cost\_day_{s,z,a} \cdot days\_at\_sea_{s,z,a}$$

$$congention\ in\ ports\ cost = \sum_{o,d,s,z,a} \left(trip\_share_{o,d,t,s,e}\right)^2 \cdot stock_{s,z,a,e} \cdot oper\_cost\_day_{s,z,a} \cdot days\_at\_ports_{s,z,a}$$

$$penalty\ for\ certain\ fuels\ in\ ECA\ zones = \sum_{o,d,s,z,a,f} \left(fuel\_cons_{o,d,s,z,a,f}\right)^2 \cdot ECA\_penalty_o$$

Subject to:

$$\sum_{z,a,e} trip\_share_{o,d,s,z,e} \cdot load\_factor_{t,s} \cdot stock_{s,z,a,e} = quant_{o,d,s}$$

$$trip_{share_{o,d,s,z,e}} \cdot load\_factor_{t,s} \cdot stock_{s,z,a,e} \cdot distance_{o,d} \cdot fuel\_share_{o,d,s,z,e,f} = activity_{o,d,s,z,a,f}$$

$$fuel\_cons_{o,d,s,z,a,f} = activity_{o,d,s,z,a,f} \cdot spec\_fuel\_cons_{s,z,f,a}$$

$quant_{o,d,s}$: trade in thousand tones between origin, o, and destination, d.

o: origin, d: destination, s: vessel type, z: vessel size, e: engine type, a: vessel age, f: fuel type

Finally, the emissions are derived from the projected bunker consumption mix using emission factors. GHG emissions are divided into Well-to-Tank (WtT) and Tank-to-Wake (TtW) also incorporating methane slippage emissions from combustion, as well as other pollutants (NOx, CO, NMVOC, PM10, SOx).

Inputs and Data

The key model inputs that are used in the model are: (a) maritime activity in the base year and total activity projections, (b) fleet supply in the base year, (c) fuel consumption per vessel type, size and region in the base year, (d) techno-economic characteristics of different vessel types and sizes and vessels' operating expenses, (e) bunker prices. The calibration of input data is based on a variety of sources (e.g., Clarksons SIN database, PRIMES-Maritime/ Eurostat, GEM-E3, IMO 4th GHG study, IEA energy balances, technical studies and other literature for techno economics). An overview of the input data sources is provided in Table 3, and are discussed in further detail below.

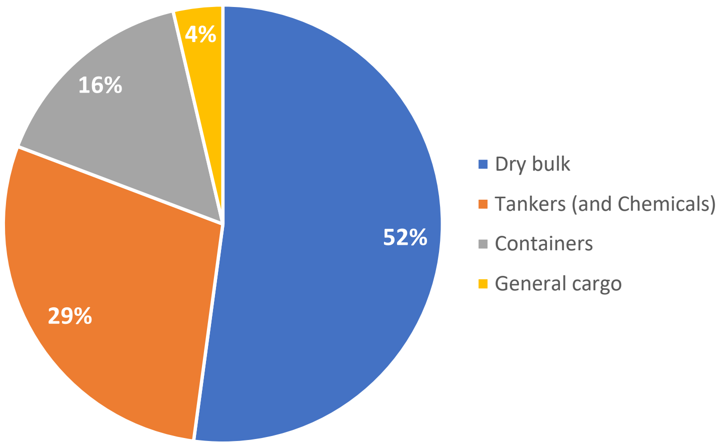
Table 3 Overview of main data sources used in the PRIMES-International Maritime model

Main data input	Source
Global GDP projections used in GEM-E3 (used for elasticity projections of containers)	EU: DG ECFIN, Ageing report 2021 Non-EU: IEA WEO 2020 for short term projection (until 2025) and OECD 2018 for long term projection
Maritime activity by shipping sector in ton-miles	Clarksons SIN – Seaborne Trade and Ton-Miles Tables (2022)
Maritime Activity Projections in Ton-Miles	E3-Modelling - Elasticities Derived from Historical Trade Volumes Data by Cargo Type (provided by Clarksons SIN), IMF Historical Global GDP data, Global Average Bunker Prices (averaged by indicative global ports prices timeseries in Clarksons (2022) for heavy sulphur fuel oil), GEM-E3 Global Bilateral Trade Flows Projections aggregated for cargo types relevant to each shipping sector
Distances	www.sea-distances.org
Maritime Fleet Data (fleet development, age)	IMO 4th GHG study fleet composition per vessel type and size adjusted for Clarksons SIN fleet age distribution (IMO 2020)
Techno-economic data	Clarksons SIN, IMO EEDI tool (for efficiency curves), SEA LNG and DNV GL studies for LNG CAPEX structure
Bunker Fuel Consumption and Specific Fuel Consumption per ton-mile	IEA Energy Balances - International Marine Bunkers per country and IMO 4th GHG study respectively for 2018 consumption data (calibrated to 2018 maritime activity per region for the sectors represented in the model)
World bunker fuel prices	PRIMES-Maritime for EU27 with regional differentiation for the rest of the world taking into consideration historical price differential between major bunkering hubs as provided by Clarksons SIN bunker price timeseries

(a) Maritime activity in the base year and total activity projections

All the necessary data used to populate the model's database for global maritime activity by shipping sector is based on Clarksons SIN database (Clarksons (2022)) and PRIMES-Maritime for the EU27, the latter being calibrated on Eurostat bilateral trade data. For the econometric projection of maritime activity, historical data on trade volumes per cargo type and ton-miles per sector, as well as global bunker prices were used from Clarksons timeseries (1999-2021). Historical global GDP timeseries were taken from IMF (IMF 2022). The model covers international maritime activity related to major commercial shipping sectors which are responsible for approximately 91% of global commercial maritime activity that is covered by Clarksons seaborne trade tables (i.e., dry bulk, tankers, containers, general cargo)[11]. Bunker fuel consumption of the above sectors represents about 80% of global bunker fuel consumption (based on GISIS (2022). The shares of international maritime activity by cargo type in the base year (2018) are show in Figure 2.

Figure 2 Shares of international maritime activity by cargo type in the base year (2018)



Note: In base year (2018) total activity reached about 52.8 trillion ton-miles. Based on data adjusted from Clarksons SIN

For the disaggregation of trade flows in ton-miles between origin and destination country or regions pairs (Table 4), we calibrated GEM-E3 trade flow disaggregation on total ton-miles using Clarksons (2022) Seaborne ton-miles and tons trade tables for 2018 (Clarksons 2022). Calibration factors were deployed to adjust the distribution of ton-miles to the GEM-E3 country pairs disaggregation. The factors were selected using as benchmark the derived average trade distances from major export countries/regions from the above-mentioned tables per cargo type (i.e., iron ore, coal, grains, minor bulks, crude oil and products, containers). The cargoes were aggregated to their relevant shipping sector to derive trading distances from major country origin per shipping sector. Trade volumes in tons were derived from ton-miles with the use of geographical distances per country or region pair from sea-distances.org.

Table 4 Export and import countries

From/To
USA
Canada
Brazil

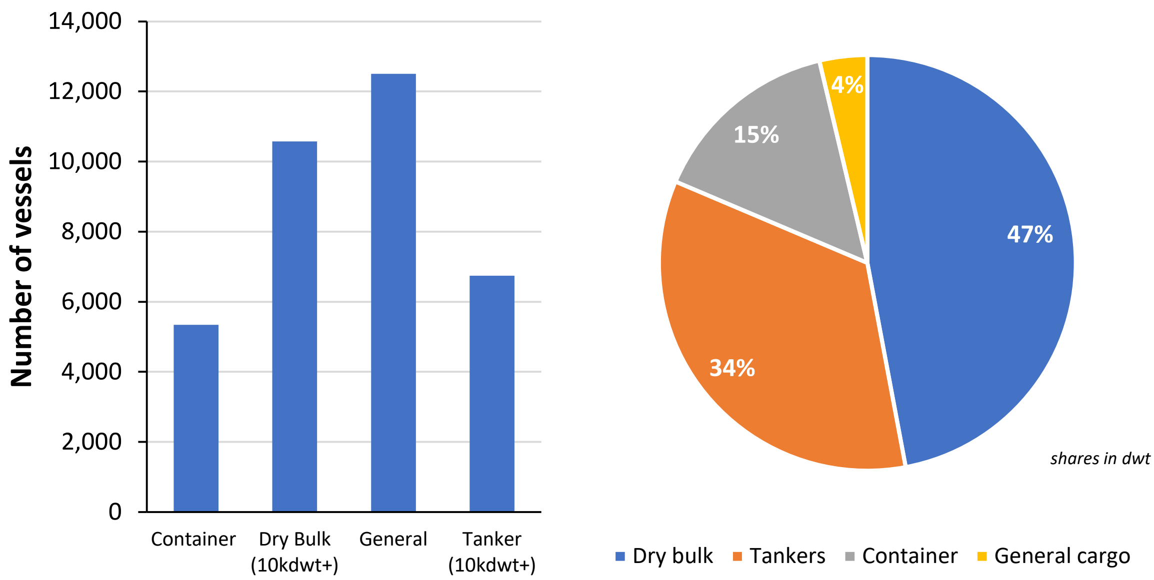
[11] General cargo activity was assumed for modelling purposes as a share of dry bulk cargo (about 7%) to align with IMO's 4th GHG study derived transport work activity for this sector.

From/To
Mexico
Argentina
China
Japan
India
South Korea
Indonesia
Turkey
Saudi Arabia
South Africa
Oceania
Russian Federation
Rest of energy producing countries
EU27+UK
Rest of Europe
Rest of the World

(b) Global maritime fleet

The global maritime fleet per sector is based on the IMO 4th GHG study (IMO (2020)) and validated with Clarksons (2022). In 2018, the combined fleet of dry bulk, tankers, containers and general carriers is estimated at 35,160 vessels (Figure 3 left). In dwt terms, 47% of which is dry bulk, followed by tankers (34%), containers (15%) and general carriers (4%) (Figure 3 left).

Figure 3 Global maritime fleet in the base year



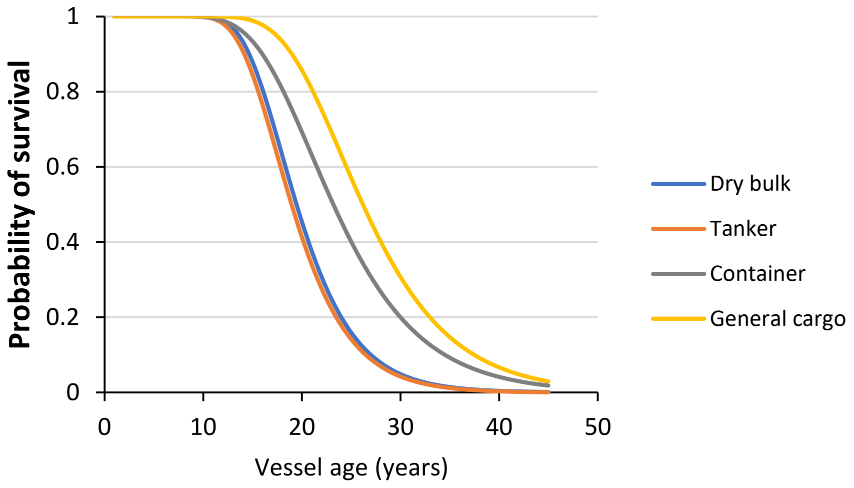
The age distribution of the global maritime fleet is based on calculations from the fleet and age distribution in Clarksons (2022). Table 5 presents the age distribution of the different vessel types.

Table 5 Age distribution of the global maritime fleet per type in 2018

Vessels	0-5 years	5-10 years	10-15 years	15-20 years	> 20 years
Dry Bulk	32.3%	40.3%	13.6%	7.3%	6.5%
Tankers	35.1%	24.1%	25.7%	10.4%	4.7%
Containers	25.5%	20.6%	29.1%	12.3%	12.5%
General	9.2%	12.1%	13.6%	4.0%	61.2%
Total fleet	**25.1%**	**25.4%**	**18.6%**	**7.7%**	**23.2%**

The stock-flow relationship in the supply module projects the evolution of the fleet into the future taking into consideration the current and future age distribution via survival probability curves for each sector (Figure 4). The anticipated supply based on the current orderbook is taken into consideration in the modelling exercise.

Figure 4 Survival probability curves of vessels by sector and years in operation



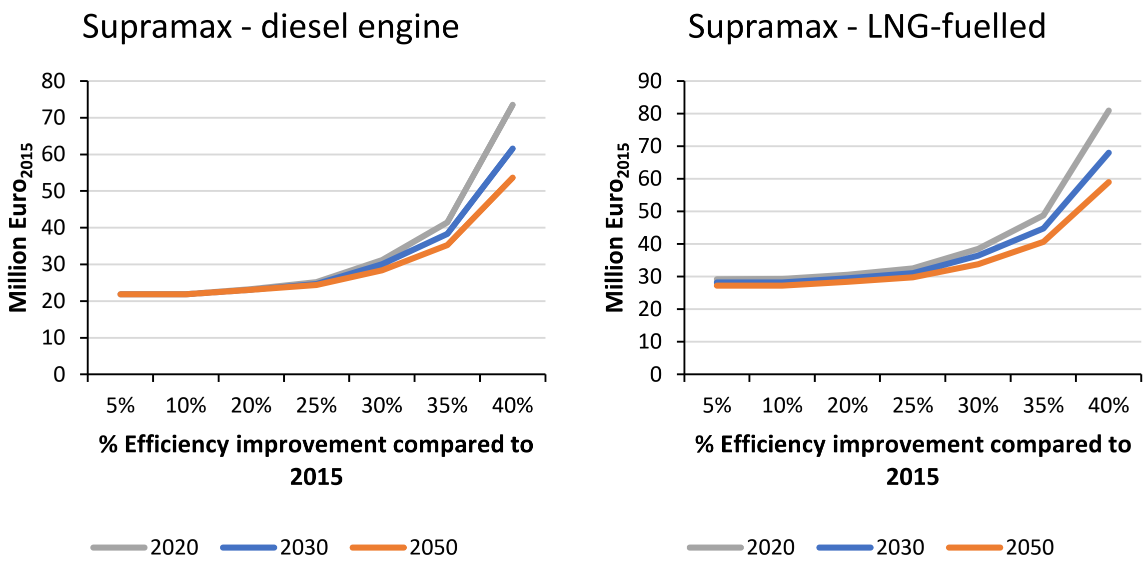
(c) Techno-economic characteristics of different vessel types and sizes

The primary source for capital expenditures (CAPEX) and operational expenditures (OPEX) costs by vessel type and sizes is Clarksons SIN database. The base data for average annual newbuilding (NB) prices on which the different costs for vessel types and sizes are based on, are derived from Clarksons SIN linked to 1st-tier shipyards valuations (i.e., NB values provided in the timeseries are on the high side- related to top quality shipyards) and are adjusted to reflect the size granularity in the PRIMES-International Maritime model. This is done so by using the weighted average prices according to the fleet deliveries composition within the model's dwt size range post-2015.

The LNG-fuelled NB prices build on the conventionally fuelled CAPEX for all vessel types and sizes. The LNG CAPEX structure and relevant premiums were taken from literature (e.g., SEA LNG and DNV GL) differentiating assumptions for smaller vessels (e.g., on relatively smaller storage requirements). When LNG-fuelled NB vessel market deals have taken place, the actual market premium was reflected on top of the diesel engine vessels. The market premium was derived by comparing contracting prices of conventionally fuelled and LNG ready and/or LNG-fuelled vessels provided primarily by Clarksons.

Efficiency curves were built according to CAPEX of various measures/devices and the fuel savings they offer to reflect the IMO EEDI efficiency tool provided for different vessel types and sizes. Higher efficiency gains are associated with higher capital costs. The LNG premium over conventionally fuelled vessels was assumed to decline over time as the LNG engine cost is likely to converge to diesel engine costs on technology maturity and scale through time- assuming LNG will become the benchmark vessel post 2025 considering that 30% of the orderbook across the major shipping sectors (i.e., dry bulk, tankers, containers) is LNG ready or LNG dual-fuelled. A premium is still assumed to hold, as increased storage requirements are considered structural. Fuel cell vessel costs are based on fuel cell techno-economics reflecting a premium over LNG partly due higher cryogenic storage requirements and higher cost for premium materials required among others for tanks and pipes. Figure 5 presents the cost-efficiency curve for a dry bulk vessel (Supramax size) with different engine types, also demonstrating the cost efficiency improvement over time.

Figure 5 Cost-efficiency curves for a Dry bulk Supramax diesel and a Supramax LNG-fuelled vessel



(d) Fuel consumption per vessel type, size and region in the base year

Bunker fuel consumption data per vessel type and size, as well as specific fuel consumption per transport work are derived from IMO (2020)[12]. Fuel consumption is calibrated in order to adjust for the different maritime activity per sector in the model in the base year (2018). We note that the activity of container ships in IMO (2020) is significantly higher than that of Clarksons (2022). As we calibrate the model based on the latter, we adjust the consumption of container ships accordingly using the specific fuel consumption per tkm for the sector from the IMO 4th GHG study. Specifically, for containers activity a +72.1% deviation in ton-miles is observed between the IMO 4th GHG Study and Clarksons data. In this respect, total fuel consumption from the above sectors for 2018 has been adjusted downwards by -19.0% (i.e., from about 222.0 million tons in IMO's 4th GHG Study to about 180.0 million tons in PRIMES-International Maritime) to adjust for the deviation in containers activity. Nevertheless, the model's derived containers' consumption for the calibration year given the lower activity levels used as input is relatively closer to actual reported fuel consumption statistics for the sector for later years (i.e., 2019 and 2020 - IMO's first reported data of global fleet consumption referring for all vessels over 5000gt engaged in international trade). A discrepancy of approx. -19.0% is observed for containers bunker consumptions to these statistics compared to a differential of -38% from IMO's implied consumption from the sector in 2018. As the fuel consumption estimation approach is an activity based one in the model, potential substitution of activity that might be taking place between dry bulk and containers, could also explain to a certain extent the difference in fuel consumption estimation between these two sectors vs reported data.

Looking at the shares of activity and fuel consumption by sector in the combined dry bulk, tankers, containers, and general cargo segments, indicates that the relative difference between the model and IMO (2020) is small (Table 6).

[12] Table 35, Bottom-Up method.

Table 6 Bunker fuel consumption per shipping sector in PRIMES-International Maritime compared to the IMO's 4th GHG study

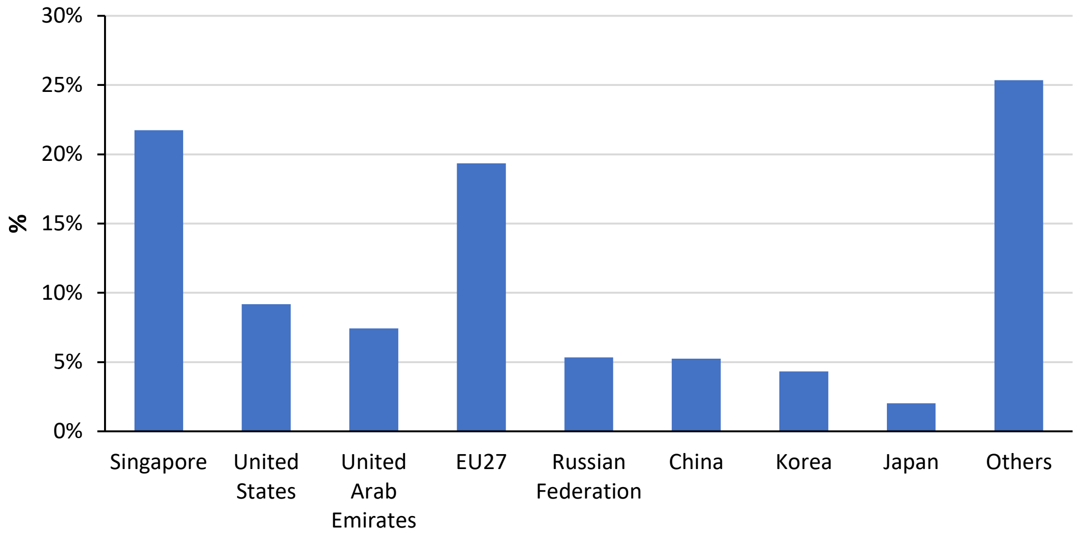
IMO 4th GHG Study (IMO 2020)		
Sectors	**Activity %**	**Fuel consumption %**
Dry Bulk	44.6%	27.7%
Tankers (and Chemicals)	28.7%	31.6%
Containers	23.7%	33.5%
General cargo	3.0%	7.2%
PRIMES-International Maritime		
Sectors	**Activity %**	**Fuel consumption %**
Dry Bulk	52.1%	35.0%
Tankers (and Chemicals)	28.6%	31.0%
Containers	15.6%	25.9%
General cargo	3.6%	8.2%

Last but not least, bunker fuel consumption per country is based on IEA's energy balances (IEA 2018) and it is aggregated by region to align with maritime activity per region, as well as it is adjusted to account for the sectors represented in the model[13] (Figure 6). The reason is that some countries such as Singapore are major bunkering hubs but are not major maritime activity contributors and vice-versa China represents a minor share of compared to its import volume[14].

[13] Sectors represented in the model account for about 80% on global maritime fuel consumption. The remaining 20% is consumed by LNG/LPG carriers, cruise ships, Ro/Ro cargo and vehicles carriers, as well as Ro/Ro passenger vessels.

[14] Singapore represents 22% of global bunkering but has a minor import/export activity. China represents 5.3% of bunker fuel sales but is responsible for more than 30% of the total ton-miles imported (IEA 2018).

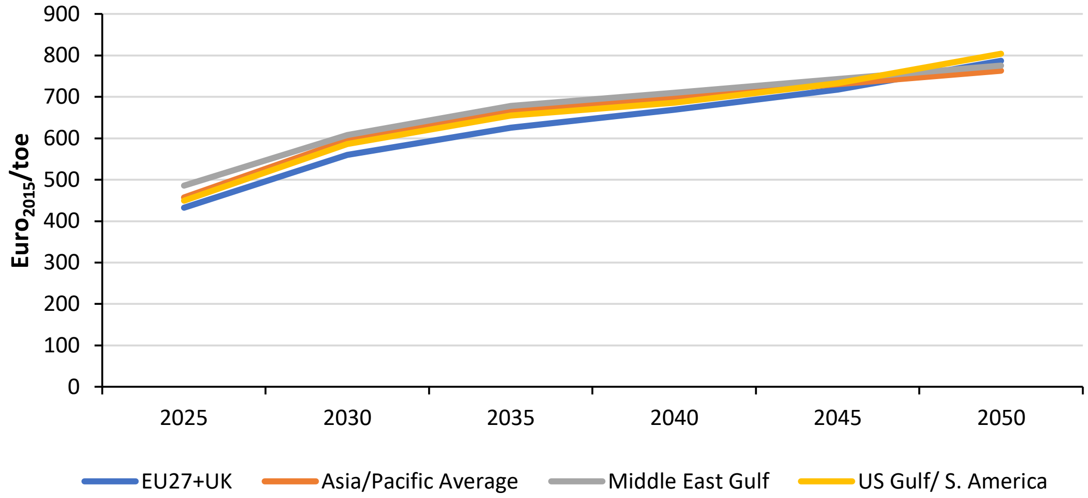
Figure 6 Shares of bunkering countries in total maritime fuel bunkering consumption in 2018



(e) Bunker fuel prices

The international bunker fuel prices are in line with the price assumptions used by PRIMES-Maritime (EU27). In particular, these were used as benchmark prices and differentiated by region according to the historical relationship of bunker price levels between regions. The bunker fuel price per region is derived from averages calculated from Clarksons timeseries for major bunkering ports. The major bunkering ports are as follows: for the Asia-Pacific region the average bunker prices were calculated including Singapore, Shanghai, Hong Kong, Tokyo, Busan. For the US and S. America, the average bunker prices of Houston, Philadelphia, Los Angeles, Panama, Santos-Brazil. For Middle East Fujairah was used. The projections follow the EU Reference Scenario 2020 projections of PRIMES-Maritime in line with oil trajectories based on the global model JRC-POLES. Relative adjustments between regions are made according to the historical crack spread between oil prices (an international oil price trajectory from the global model PROMETHEUS was used). The price difference between regions for RFO is shown in Figure 7 (as mix of VLSFO and HSFO).

Figure 7 Conventional bunker fuel price trajectory used in the modelling differentiated by region



Regarding alternative fuel prices, these are derived by the PRIMES-Maritime. Biofuels and synthetic fuel prices are assumed to peak around 2030 and decline from there onwards reflecting technology progress and economies of scale. In policy scenarios competition for biomass feedstock from other energy and transport sectors is assumed to push biofuel prices upwards until 2030, while the price signal will in turn create production at scale and lead to a deceleration of prices from that point onwards. The price gap between conventional fuels and biofuels and synthetic fuels also narrows down from 2030 to 2050. Biofuel blend prices are weighted based on the relative shares of the biofuel quantities in the RFO fuel mix depending on the quantified scenario. Synthetic fuels and clean gas prices drop significantly by 2050 owing also to the push from climate and energy policies focused on decarbonization as increased use of synthetic fuels throughout the energy system (not only in maritime) and economies of scale are assumed to occur and improve the economics of hydrogen production.

Outputs

The main model outputs are summarized in the following: (a) fleet supply (b) fuel consumption per type of fuel and engine, vessel type and size, (c) Well-To-Wake GHG emissions.

2.1.2 Maritime: scenario description

A global Base scenario is developed that cuts-off related maritime policy as of the end of 2019, representing limited ambition for the sector's GHG mitigation. The scenario includes the initial IMO's GHG strategy for a 50% GHG reduction by 2050 compared to 2008 without the mandatory intermediate carbon reduction targets adopted in 2021. The Base scenario (for EU) includes policies adopted by the EU countries before the end of 2019 and includes the impact of the COVID-19 pandemic on transport activity. The Base scenario does not include more recent regional policy initiatives launched in 2021 such as the FuelEU Maritime and the EU ETS are not included.

Next to the Base scenario that is developed and quantified with PRIMES-International Maritime, we develop and quantify two additional scenarios that are applied at the regional level (i.e., EU) as a case study (Box 2).

- The **Allmar** scenario provides a carbon price signal to the European maritime sector (stemming from an extension of e.g., the EU ETS) on the emissions from maritime transport activity in intra-European and extra-European routes.
- The **OperStand** scenario assumes, in addition to Allmar, operational standards to apply early in the time horizon, obliging vessels to reach a certain amount of emissions per transport work, without prescribing how this can be achieved.

The Allmar and OperStand scenarios that are quantified for Europe are in line with the contribution required by the sector so that region achieves its ambition to climate neutrality in 2050. Both scenarios implement the same ambition for carbon intensity improvement of the fuel use in maritime. It should be noted that no differentiation on the carbon intensity target is made between the fuel use in intra-EU and extra-EU voyages.

2.2 International aviation

The aviation sector has limited options to reduce its emissions due to the lack of commercially available zero-emission technologies, the long lifetime of committed infrastructure, the significant investments in new equipment, technologies and infrastructure, and international competition (Sharmina et al. 2021, Davis et al. 2018, EC 2020). Research focusing on alternative jet fuel supply also highlights high production costs, limited sustainable feedstock availability and capacity constraints (e.g., in regions such as Europe) as additional challenges particularly related with biofuels used in aviation (Prussi et al. 2018, Kousoulidou et al. 2016, de Jong et al. 2015, Deane et al. 2018, Bullerdiek et al. 2021, Zhao et al. 2021).

Owing to these limitations, there is a pressing need for policies to promote emission reduction measures and the uptake of alternative fuels in aviation (Dean et al. 2018, IEA 2020). To contribute in this direction, international policy action has put forward aircraft efficiency, CO_2 emission standards, and carbon offsetting schemes such as CORSIA (ICAO 2021a, 2021b). In the European Union (EU), for example, recent legislative proposals and amendments focus on strengthening market-based measures such as the EU Emissions Trading Scheme (ETS) by phasing out free emission allowances from aviation, on removing fuel tax exemptions from intra-EU flights, and on introducing sustainable aviation fuel blending and usage obligations to reduce the carbon intensity of fuels that aircrafts use (EC 2021a, 2021b, 2021c).

To address impacts of decarbonization options for the sector through policies and instruments, research addressing regions such as the US and the EU has focused on analysing market-based policy frameworks such as offsetting schemes (e.g., CORSIA) and the EU ETS (see e.g., Eythimiou et al. 2019, Scheelhaase et al. 2017, Chao et al. 2019). An ex-post analysis on jet fuel tax imposed on domestic flights in Japan concluded that it has similar effects with a carbon tax in reducing CO_2 emissions (Gonzales et al. 2016). A comparison between a blending mandate and a carbon tax revealed that under certain conditions the more ambitious an emission target is the more likely for a quota is to outperform a carbon tax system (Jiang et al. 2021). A study that assumed high blending mandate under an emission reduction obligation for various alternative fuels reached the conclusion that sub-mandates (i.e., quotas on specific fuel types e.g., different mandates between biofuels and synthetic fuels) are more effective to bridge the price gap induced by alternative fuels (Bullerdiek et al. 2021). Research on blending mandates examined primarily biofuels as the main alternative fuel for aviation. However, in the advent of large-scale hydrogen production and conversion to renewable fuels of non-biological origin (RFNBOs), synthetic kerosene (henceforth referred to as e-jet fuel) has also emerged as a competing alternative. Such policy and technology aspects have only loosely been part of scenario-based quantitative assessments (Kousoulidou et al. 2016, de Jong et al. 2018, Wise et al. 2018). Despite that the above have not been extensively examined under the scope of deep emission reduction pathways, recent research highlights that while projected demand growth for aviation will increase by 2050, deep decarbonization of the sector (90% compared with 2019) could be achieved by continued efficiency gains and by the use of sustainable biofuels and synthetic fuels, inducing an increase in airfares of about 15% (NCC 2022).

In the context of the project NDC Aspects and deliverable D2.1 (“Contribution of International Bunker Fuels to the Paris Agreement”), the above background provides the motivation to develop an international aviation model (Global Aviation Model; GAM) that can explicitly assess the impact of technology improvement and alternative fuel uptake in aviation to achieve deep decarbonization. This section presents briefly the modelling approach that we followed on global aviation (section 2.2.1) and the scenarios developed (section 2.2.2). The results of the scenarios developed are presented in section 3.

2.2.1 Aviation: modelling approach and data

Model description

The aim of the Global Aviation Model (GAM) is to perform long-term fuel consumption and emission projections for international passenger aviation under scenario assumptions.

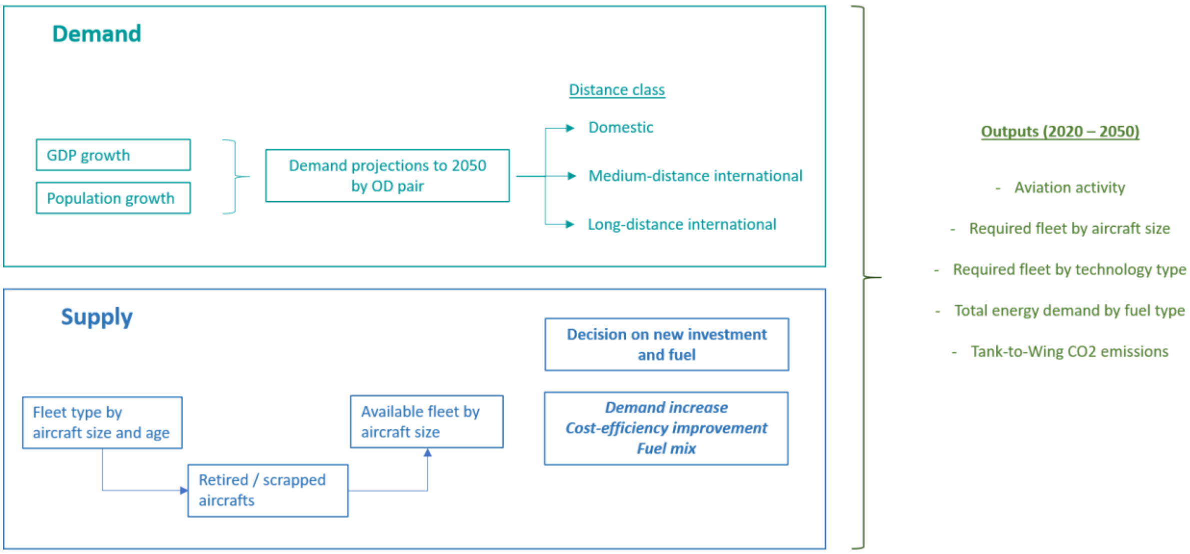
The demand for aviation is based on exogenously derived macro-economic and demographic projection inputs of the GEM-E3 model (E3-Modelling 2017), thus also capturing the impact of and recovery from the COVID-19 pandemic. The GAM model has a global scope, covering in detail passenger trips per Origin and Destination countries (OD pairs) between 105 countries, representing approximately 97-98% of passenger air transport demand in 2019 (ICCT 2020).

The trips are distinguished in three different distance bands, namely: domestic (i.e., within a country), medium-distance international flights (i.e., between countries for a distance below 7,000 km) and long-distance international flights (i.e., between countries for a distance above 7,000 km). The demand of the different distance classes is met by aircrafts of two different sizes (i.e., airplanes for distances below 7000 km and airplanes covering distances greater or equal to 7000 km such as jumbo jets). Moreover, different aircraft technologies, different propulsion systems and different fuel types (i.e., conventional kerosene, alternative jet fuels, hydrogen and electricity) are explicitly included in the model.

The model provides detailed projections on activity, fuel consumption related CO_2 emissions, required stock of aircrafts and aircraft technologies with different propulsion systems that are used in the aviation fleet into the future. It does so in 5-year steps from 2020 until 2050. The GAM model can quantify projections by incorporating several policy instruments such as a global carbon tax (price) and/or a mandate on aviation fuels as means to reduce CO_2 emissions.

A schematic representation of the model is presented in Figure 8.

Figure 8 Schematic overview of the Global Aviation Model (GAM)



As shown in Figure 8, GAM has two modules, namely a demand module that project international aviation activity into the future and a supply module that decides on new investments by technology type and fuel supply. The mathematical formulations of these modules are described in detail below and the model sets are described in Table 7.

Table 7 Global Aviation Model sets

Sets	Description	Detail
c	country	106 countries
reg	Aggregate, region	EUR, ASI, AFR, NAM, SAM, CAM, OCE
d	Distance (domestic, medium and long-distance international)	Domestic, medium-distance international, long-distance international
dt	Distance type	Short, long
Age	Age bands	0-4, 5-9, 10-14, 15-19, 20-24, 25-29, 30+
f	Fuel type	Kerosene (fuel jet), SAF, p2x, fuel cells, batteries, hydrogen
Eng	Engine type	Fossil, electric, fuel cell, H_2O

(a) Demand

The demand projections for passenger transport activity by air is described in Equation 8 and is estimated based on country-specific projections of population growth, growth rates for income per capita (GDP/cap), and relative difference of growth rates per capita per OD pair. In particular for domestic flights, country-specific income growth rates and population growth are use. The relative difference of income per capita between countries is used to project the international travel demand. Data on income elasticity of travel demand are based on IATA (2008) and are described in Equation 9.

Equation 8

$$PAS_{c,d=dom,t} = PAS_{c,d=dom,t-1} \cdot \left(\frac{IPC_{c,t}}{IPC_{c,t-1}}\right)^{\varepsilon_{inc}}$$

$PAS_{c,d=dom,t}$: annual passengers in domestic flights at time *t*

$PAS_{c,d=dom,t}$: annual passengers in domestic flights (previous period)

$IPC_{c,t}$: income per capita at time *t*

$IPC_{c,t-1}$: income per capita previous period

ε_{inc}: estimated elasticity of air travel demand w.r.t income

Equation 9

$$PAS_{c,d,t} = \sum_{reg} PAS_{c,d\neq dom,reg,t-1} PAS_{c,d\neq dom,reg,t-1} \cdot \sum_{reg} PAS_{c,d\neq dom,reg,t-1} \cdot \left(\frac{IPC_{c,t}}{IPC_{c,t-1}}\right)^{\varepsilon_{inc}} \cdot \left(\frac{IPC_{reg,t}}{IPC_{reg,t-1}}\right)^{\varepsilon_{inc}}$$

$PAS_{c,d\neq dom,reg,t-1}$: International passengers by O-D pair (O=country, D= aggregate regions)

$IPC_{reg,t}$: Regional income per capita at time t

$IPC_{reg,t-1}$: Regional income per capita at time t-1

Equation 10

$$PAS^{scen}_{c,d,t} = PAS^{ref}_{c,d,t} \cdot \left(\frac{ticket^{ref}_{c,d,t}}{ticket^{scen}_{c,d,t}}\right)^{\varepsilon_{inc}}$$

$PAS^{scen}_{c,d,t}$: passengers (Scenario)

$PAS^{ref}_{c,d,t}$: passengers (Reference – derived from equations (8)-(9))

$ticket^{ref}_{c,d,t}$: unit cost of ticket in the reference scenario

$ticket^{scen}_{c,d,t}$: unit cost of ticket

(b) Supply

In the modelling, total costs (operational costs, capital costs) are a key determinant of the decision-making for the supply of new aircrafts and fuels. Equations 11 through 14 describe the main formulations for cost estimates use in the modelling.

Operational costs include variable fuel and non-fuel costs and depend on the utilisation of the aircraft. Other indirect costs represent any other type of costs that the airliners bear.

Equation 11

$$OPEX_{d,eng,age,t} = CFUEL_{d,eng,t} + \sum_{f} SHFUEL_{d,eng,f,age,t} \cdot \overline{CMTN_{d,f,t}}$$

$OPEX_{d,eng,aget}$: unit operation cost of aircrafts by engine type and age at time *t*

$CFUEL_{d,eng,t}$: unit fuel cost of aircrafts by engine type at time *t*

$SHFUEL_{d,eng,f,t}$: fuel mix of aircrafts by engine type and age at time *t*

$\overline{CMTN_{d,f,t}}$: unit maintenance of aircrafts by fuel at time *t* (exogenous)

Fuel costs depend on the unit costs of the fuels used, energy and CO_2 taxes. The total fuel costs depend on the specific fuel consumption if each propulsion engine and the weighted average of fuel price with respect to the fuel mix. It should be noted that in the model maintenance costs do not participate in the purchase or utilization decision for aircrafts, as they are assumed the same for all aircraft technologies, as data was limited. Data on maintenance costs are based on the PRIMES-TREMOVE model (E3-Modelling 2018).

Equation 12

$$CFUEL_{d,eng,t} = \sum_{f} SHFUEL_{d,eng,f,age,t} \cdot CFUELF_{d,f,age,t}$$

$CFUELF_{d,eng,t}$: unit fuel cost of aircrafts using fuel source f at time t

$$CFUELF_{d,f,age,t} = m\_engine\_fuel_{eng,f,t} \cdot \overline{FCONS_{d,eng,age,t}} \cdot activity_{d,t} \cdot \left(fprice_{f,t} + ctax_{f,t} \cdot emf_{f}\right)$$

$m\_engine\_fuel_{eng,f}$: available fuels by engine type

$\overline{FCONS_{d,eng,age,t}}$: fuel consumption by engine type and age at time ***t*** (exogenous assumptions)

$activity_{d,t}$: activity in kilometers per aircraft

$fprice_{f,t}$: fuel prices at time t

$ctax_{f,t}$: carbon tax at time t *(€/tCO_2)*

emf_{f}**:** emission factor

Capital costs represent the annuity payment for purchasing new aircrafts that depends on the economic lifetime of the aircraft and the weighted average cost of capital (WACC) of the firms. The model distinguishes different types of aircraft categories, each of which is associated with different purchasing price. They are annualized based on a 7% discount rate over a 10-year period.

Equation 13

$$CAPEX_{d,eng,age,t} = \overline{CAPEX_{d,eng,age,t}}$$

$\overline{CAPEX_{d,eng,age,t}}$: annualized capital cost of aircrafts (exogenous assumptions)

Total costs are the aggregated of capital and operational costs shown in the equation below.

Equation 14

$$TOTEX_{dt,eng,age,t} = CAPEX_{d,eng,age,t} + OPEX_{d,eng,age,t}$$

$TOTEX_{dt,eng,age,t}$: unit cost of aircrafts by engine type and distance type at time *t*

The model's decision is taken on two levels. Firstly, on the fuel supply that will be used that is determined based on fuel prices, energy and CO_2 taxes, as described with Equation 15.

Equation 15

$$SHFUEL_{d,eng,f,age,t} = \frac{m\_engine\_fuel_{eng,f,t} \cdot \left(CFUELF_{d,f,age,t}\right)^{-\varepsilon}}{\sum_{ff} m\_engine\_fuel_{eng,ff,t} \cdot \left(CFUELF_{d,ff,age,t}\right)^{-\varepsilon}}$$

$m\_engine\_fuel_{eng,f}$: available fuels by engine type

$fpref_{d,eng,f,t}$: preference parameter reflecting non-market barriers

ε: speed of adjustment

The second decision is made on the purchase of new aircrafts (new investments). For that, first the required stock needs to be determined as shown in Equation 16.

Equation 16

$$StockAir_{dt,age,eng,t} = \begin{matrix} StockAir_{dt,age-1,eng,t-1} & age > "0-4" \\ ShNewAir_{dt,eng,t} \cdot NewAircrafts_{dt,t} & age = "0-4" \end{matrix}$$

$StockAir_{dt,age,eng,t}$: airplanes by distance type, age, and engine type at time *t*

$ShNewAir_{dt,eng,t}$: technology mix of new aircrafts by distance type at time *t*

$NewAircrafts_{dt,t}$: additional aircraft requirements by distance type at time *t*

The new aircrafts (by technology types) are deployed based on the cost-optimal option taking into account total expenditures to satisfy each trip purpose.

Equation 17

$$NewAircrafts_{dt,t} = m\_d\_dt_{d,dt} \cdot \sum_{c} \frac{PAS_{c,d,t}}{airconv_{d,t}} - \sum_{age \neq "30+"} StockAir_{dt,age,eng,t-1}$$

$m\_d\_dt_{d,dt}$: mapping of trip distances to aircrafts' range

$airconv_{d,t}$: conversion factor of passenger's demand to number of airplanes (number of passengers by flights, number of annual flights)

Equation 18

$$ShNewAir_{dt,eng,t} = \frac{acpref_{dt,eng,t} \cdot \left(\frac{1}{TOTEX_{dt,eng,age="0-4",t}}\right)^{\varepsilon 1}}{\sum_{ff} acpref_{dt,eng,t} \cdot \left(\frac{1}{TOTEX_{dt,eng,age="0-4",t}}\right)^{\varepsilon 1}}$$

preference parameter reflecting non-market barriers

$\varepsilon 1$: speed of adjustment

Finally, a ticket price is composed as follows:

Equation 19

$$ticket_{c,d,t} = m\_d\_dt_{d,dt} \cdot \sum_{age} \frac{StockAir_{dt,age,eng,t}}{\sum_{age1,eng1} StockAir_{dt,age1,eng1,t}} \cdot TOTEX_{dt,eng,age,t}$$

Inputs and data

The key inputs that are used in the model are: (a) activity in the base year, demographic, and macro-economic projections, (b) global aircraft fleet by age per country in the base year, (c) techno-economic characteristics of different aircraft technologies, (d) fuel (and carbon) prices. Input data and input data preparation is based on a compilation from a variety of sources (e.g., various airport websites, civil aviation websites), IATA, the US Bureau of Transportation Statistics data, Eurostat, ASEAN, the ICCT, other open source databases such as www.planespotters.net, and www.openflights.org. The year 2019 is the base year in which the model is calibrated.

An overview of the input data sources is provided in Table 8, and are discussed in further detail below.

Table 8 Overview of main data sources used in GAM

Main data input	Source
GDP projections per country	EU: DG ECFIN, Ageing report 2021 Non-EU: IEA WEO 2020 for short term projection (until 2025) and OECD 2018 for long term projection

Main data input	Source
Population growth	EU: DG ECFIN, Ageing report 2021 Non-EU: UN World Population Prospects 2019
Passenger aviation activity	ICCT 2020
Passengers	Eurostat, Civil Aviation and Airport Authorities, US Bureau of Transportation Statistics (country-by-country analysis), ASEAN, World Bank, Statista
Price elasticity	IATA 2008
Income elasticity	Empirical estimate based on historical data series
Distances	www.openflights.org
Aircraft fleet (stock, age)	www.planespotters.net
Techno-economic data	Compilation based on various sources (e.g., Clean Sky 2021, NRL and SEO 2021, Schäfer et al. 2018)
World fossil fuel prices	JRC POLES

(f) Aviation activity in base year

In order to derive the demand projections for passenger aviation (in passenger-kilometres; pkm) we first need to establish the activity of the sector in the base year (2019). The activity in the base year is based on the ICCT (ICCT 2020). Specifically, in 2019, global aviation activity was 8,710 Gpkm (billion pkm or Gpkm)[15], of which 36% was domestic demand and the remaining 64% was international flights.

The activity of the base year is further decomposed to passengers traveling over domestic, medium, and long-distance trips. The number of passengers is based on a variety of sources (e.g., national civil aviation authorities). Passengers are allocated to the different trip distance bands based on the regional destination allocation of IATA's Air Transport Statistics[16] and on airport-to-airport weighted distances. When passenger data is not available, the estimate is based on the number of passengers traveling in domestic flights based on the average distance of the airports within the country, and for international trips based on a weighted average distance between trips to other continents. According to this analysis, about 70% of the trips were domestic, and the 30% remaining international. The number of total passengers for 2019 is estimated to approximately 4.32 billion, which is in line with the respective aggregate figures provided by ICAO (4.48 billion), IATA (4.543 billion O-D passengers) and the World Bank (4.5 billion).

[15] Similar estimations are provided by ICAO's Annual Report of 2019 (8,685 Gpkm) and by IATA'S World Air Transport Statistics 2020 (8,679 Gpkm)

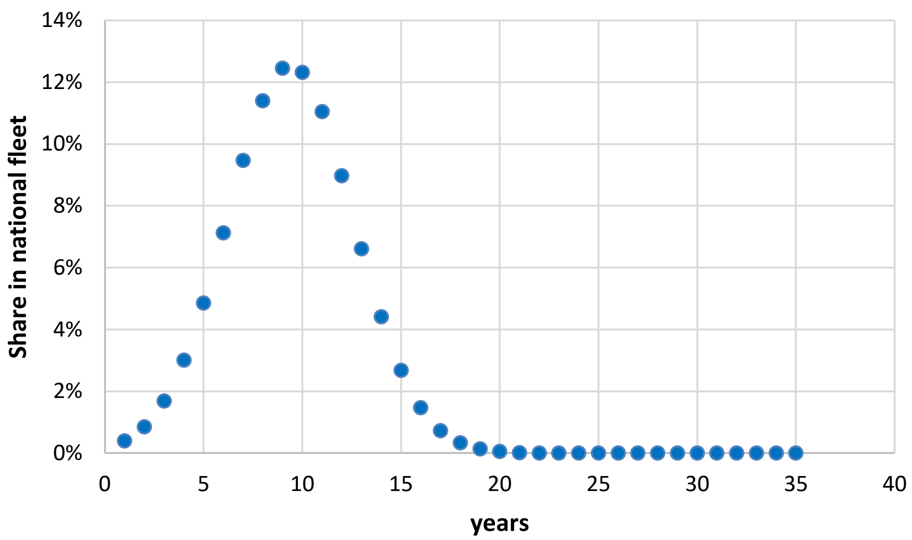
[16] The outlook provides data on the aviation activity for 8 aggregate regions: Europe, Asia, Southwest Pacific, Middle East, Africa, North America, Central America & the Caribbean and South America.

(g) Global aircraft fleet

The global aviation fleet in the base year is compiled with bottom-up data that are collected on a country-by-country basis derived from open-source information (www.planespotters.net). It is estimated that the global aircraft fleet in 2019 amounted to approximately 28,000 aircrafts that is in line with other sources (e.g., Statista 2022).

For each country, next to the total number of aircrafts, the average age of the aircraft fleet is provided (www.planespotters.net). In order to derive the age distribution of aircrafts per country we assume a truncated normal distribution[17] (as shown in the example in Figure 10). Figure 11 shows the estimated age distribution of the global fleet, based on the assumption that the age distribution of aircrafts per distance covered is the same.

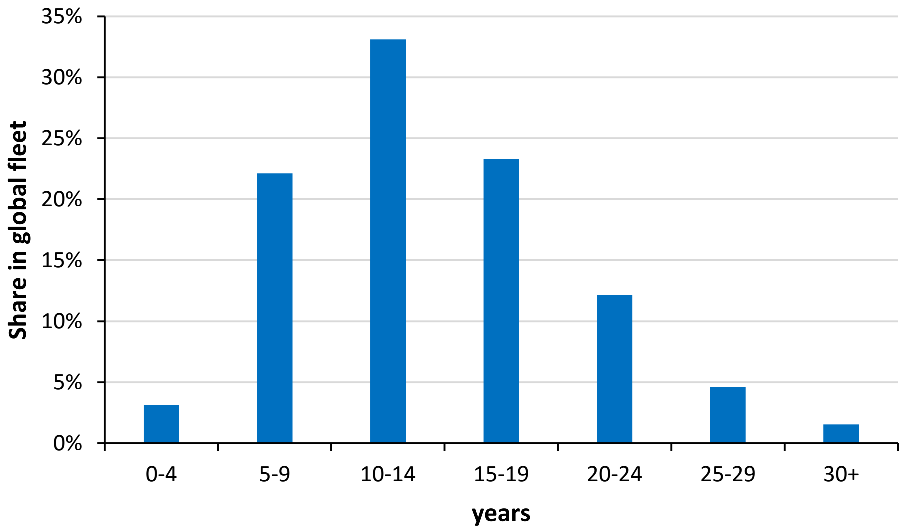
Figure 9 Truncated normal distribution (example for China)



Furthermore, the aircraft fleet is disaggregated into two different size groups. The first group includes medium-sized aircrafts (e.g., narrow-body jet aircrafts are assumed to cover domestic and medium-distance trips below 7,000 km) and the second group includes large-sized aircrafts (e.g., jumbo jets that cover long-distance trips (i.e., above 7,000 km). The number of medium- and large-sized aircrafts is estimated assuming a 75-80% load factor for the former (i.e., about 145 passengers per narrow body aircraft) and 75-84% load factor for the latter (i.e., 245 passengers per jumbo jet aircraft), taking into account the maximum number of flights that an aircraft can make per day (based on distance). These assumptions are also used in the model to estimate the demand for new aircrafts (see next section).

[17] The truncated normal distribution allows us to better capture the distribution of fleet by age. This would not happen (especially in countries with high mean aircraft age) in the case of a normal distribution due to its properties (as the normal distribution will assume that a relatively high number of aircrafts would exceed 40 years of age while lowering the standard deviation would lead to a higher concentration across the mean). The distribution was chosen as most representative when its results were compared with countries where the detailed fleet by age is available.

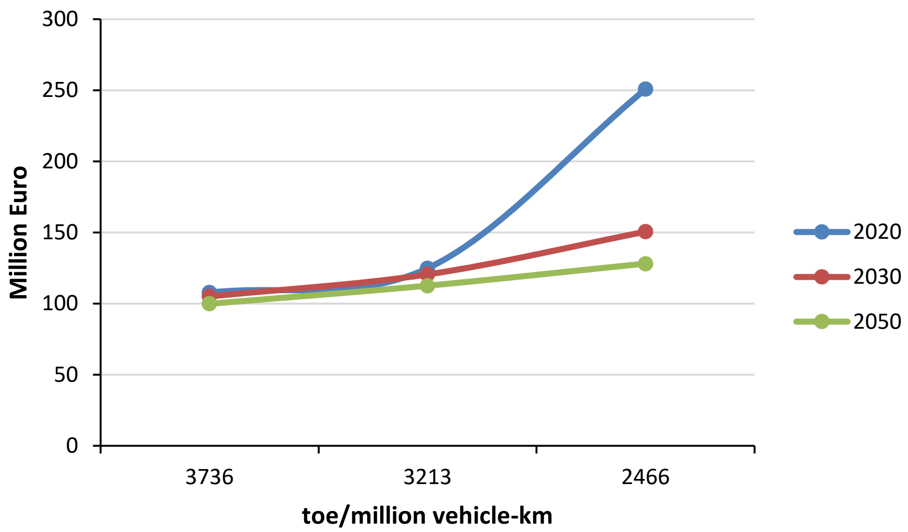
Figure 10 Estimated age distribution of the global aircraft fleet



(h) Techno-economic characteristics of aircraft technologies

The model includes different technology types distinguished by propulsion technology. The technologies are conventional jet fuel aircrafts, electric aircrafts, hydrogen fuel cell aircrafts and hydrogen turbine propulsion aircrafts. The techno-economic inputs per technology are based on a characterization stemming from an analysis of different efficiency cost-curves (see example for conventional jet fuel aircrafts; Figure 11).

Figure 11 Cost-efficiency curve for a narrow-body conventional jet fuel aircraft



Higher efficiency gains are associated with higher capital costs, for example owing to improvements in aerodynamics of efficiency improvements on the propulsion systems. Battery electric aircrafts are characterized by improvements in the energy density of battery technologies over time allowing the battery electric aircrafts to cover increasing distances. In addition, specific costs of battery (and fuel cell) technologies reduce over time due to technological learning. Different aircraft sizes are characterized by different costs.

Besides conventional jet fuel technologies, the other technologies are available after a certain point in time (hybrid, electric and fuel cell aircrafts are available after 2030, while hydrogen propulsion aircrafts after 2040). Moreover, electric and fuel cell aircrafts can cover only domestic and medium-distance trips (below a certain distance). Importantly, electric airplanes are a technology option for distance trips under 7,000 km, however the technology as it develops may be used in short-distance trips (i.e., around 1,000 km (Schäfer A.W. et al. (2019)) – that are not explicit in the model but included within the distance band of 7,000 km); the modelling includes bounds such that electric airplanes to be assigned only to a fraction of the trips within that that distance bound.

(i) Fuel prices

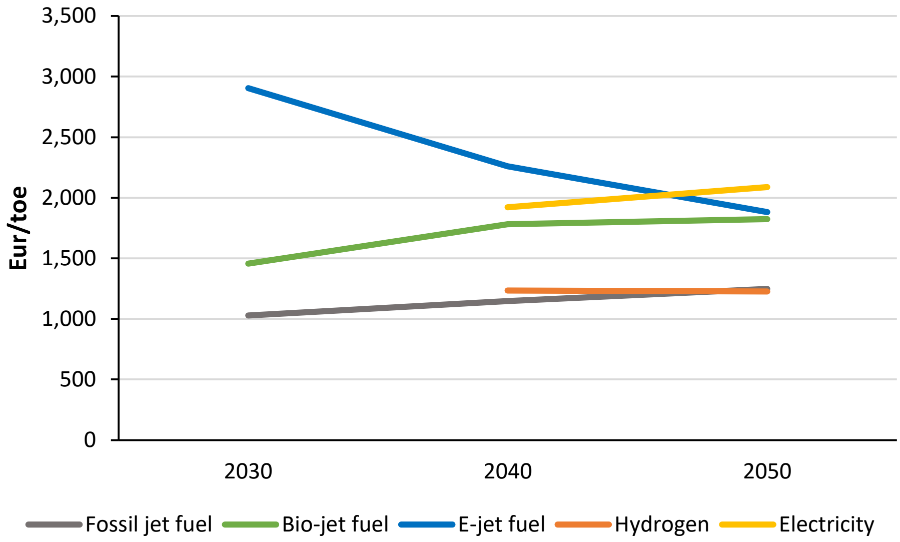
The fossil kerosene price is based on an international oil price trajectory as in Table 9, that is based on JRC POLES.

Table 9 International oil price trajectory

$/boe	2020	2030	2040	2050
Oil price	39.8	80.1	97.4	117.9

Such international oil prices lead to a (fossil) kerosene price increase from about 540 Eur/toe in 2020 to 1,250 Eur/toe in 2050. Regarding alternative jet fuels, their price today and in the near-term is notably higher than that of fossil kerosene. For example, the price of bio-jet fuel (biokerosene produced by hydroprocessed esters (HEFA)) is around 1,100 Eur/toe. However, in the future, these prices may increase owing to competing demand for biomass from other sectors. The bio-jet fuel price is based on different production pathways, from lignocellulosic biomass and waste lipid sources (feedstock). The price of e-jet fuel (in 2030) is estimated at around 3,000 Eur/toe. Technological progress driven by the global ambition for climate neutrality may reduce the alternative jet fuel price over time due to capital cost reduction. Moreover, different pathways (e.g., for bio-jet) may emerge enabling diversification of supply and lower costs. Continuous cost reduction of electrolysers and power-to-liquid technologies reduce further the price of e-jet fuel. Figure 12 shows the assumed fuel price trajectory for jet fuels, hydrogen and electricity used in the modelling (hydrogen and electricity price is presented after 2035, as the aircraft technologies are not available today). It is shown that in 2050 bio-jet and e-jet price is by about 50% higher than fossil kerosene. The price trajectory shown in Figure 12 are based on the ReFuelEU Aviation policy initiative (EC 2021d). A global CO_2 tax of about 190 Eur/tCO_2 would be needed for prices to converge. It should be noted that the modelling considers only synthetic kerosene (e-jet fuel) produced by renewable electricity (i.e., associated with no emissions from production to use) and not other synthetic fuel alternatives (such as natural gas-based with Carbon Capture and Storage). No differentiation has been made on fuel prices between regions.

Figure 12 Jet fuel price trajectory assumed in the modelling in the decarbonization scenarios



Outputs

The main model outputs include (a) aviation activity per country in passenger-kilometres over time (split into domestic and international flights), (b) the required global fleet of aircrafts to meet the demand for air travel (in number of aircrafts), (c) the different technology uptake of the required stock, and (d) the energy demand by fuel type and the related tailpipe (i.e., Tank-to-Wing) CO_2 emissions[18].

2.2.2 Aviation: scenario description

In order to quantify the contribution of international aviation bunker fuels to the Paris Agreement goals with GAM, we define three scenarios. The scenarios are designed to explore a baseline projection of the sector, the impact of a global carbon price and the impact of obligatory mandates until 2050.

In particular:

- The Reference ("**Ref**") scenario, is a baseline scenario and assumes that no global action is taken up by the sector to contribute to global decarbonization efforts
- The carbon price ("**C-price**") scenario assumes a gradually increasing carbon price on fossil kerosene thereby gradually reducing the price gap with alternative jet fuels while at the same time increasing the ticket price paid by passengers
- The mandate ("**Mandates**") scenario assumes that mandates on alternative jet fuels are put in place that, in addition to the carbon price, they promote the uptake of fuels and create long-term certainty to fuel suppliers

All scenarios share the same macro-economic drivers, techno-economic assumptions and based fuel price development over time.

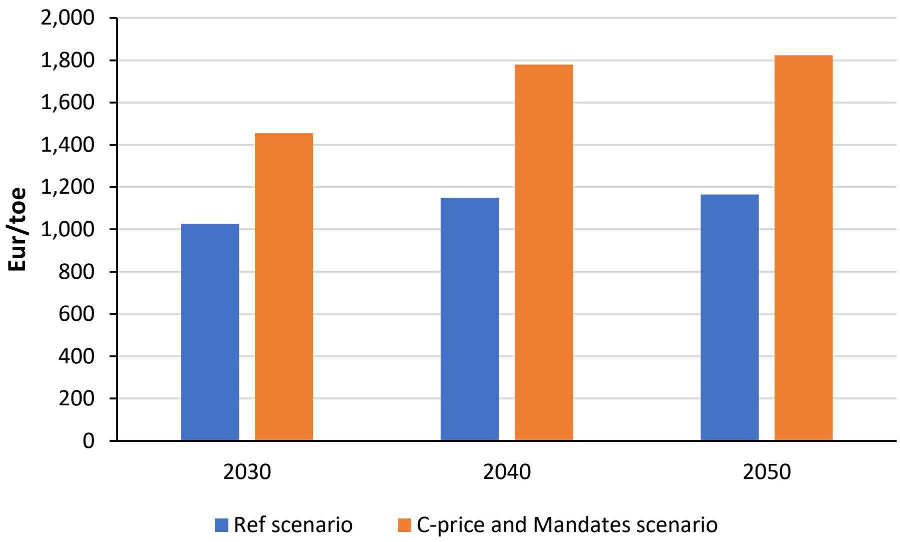
A more detailed description of the scenarios follows.

[18] The model does not include emissions from other parts of the chain (e.g., from feedstock/fuel production, or Well-to-Tank).

Ref scenario

The Ref scenario does not incorporate a carbon price, therefore the choice for jet fuel is based mainly on fuel prices (as shown earlier in Figure 12). While some regions (e.g., in the EU), the aviation sector participates in carbon pricing systems (EU ETS), such regional policies have not been incorporated in the Ref scenario. In the Ref scenario the fossil fuel price (without a tax) is the same as in the C-price and Mandates scenario. However, in the Ref scenario the price of bio-jet fuel differs notably, owing to feedstock supply considerations. In particular the price of bio-jet fuel in Ref is lower by about 30-35% compared to the other scenarios in 2030-2050 (Figure 13). The Ref scenario context assumes that limited efforts are taken towards decarbonisation (hence no uniform carbon price), and that only conventional technologies supply alternative jet fuels. As in the scenario there are no demand drivers for uptake of bio-jet fuels the latter are produced by low-cost feedstock (e.g., waste oils).

Figure 13 Difference in bio-jet fuel price between the Ref and the C-price and Mandate scenarios



C-price scenario

In this scenario a carbon price on fossil kerosene is applied. The carbon price increases the overall fuel price and therefore the implied ticket price for passengers also increases. Through income effects based on the assumed price elasticities the demand for aviation is impacted and in particular it is lower compared to the Ref scenario. Moreover, as noted above the price of bio-jet fuel is higher in the C-price scenario than in the Ref scenario.

With respect to the assumed carbon prices and the fuel price trajectory assumed, approximately 200 Eur/tCO_2 would be required in 2050 so that the price gap between fossil kerosene and alternative jet fuels to converge (Figure 12). On the other hand, based on an overview of carbon prices across various global impact assessment models (Meyer et al. 2021), it was shown that depending on the climate ambition and different trajectories with respect to emissions overshoot, the carbon price varies significantly from 176 up to almost 4,000 \$/tCO_2 in 2050 based on a range of models and scenarios (lowest mean values in 2 ^oC scenarios and highest in below 1.5 ^oC scenarios). In the scenario developed in the present report a carbon price trajectory that is closely aligned with a 1.5 ^oC scenario with high overshoot in Meyer et al. (2021) is applied (Table 10).

Table 10 Carbon price trajectory in the C-price and the Mandates scenarios

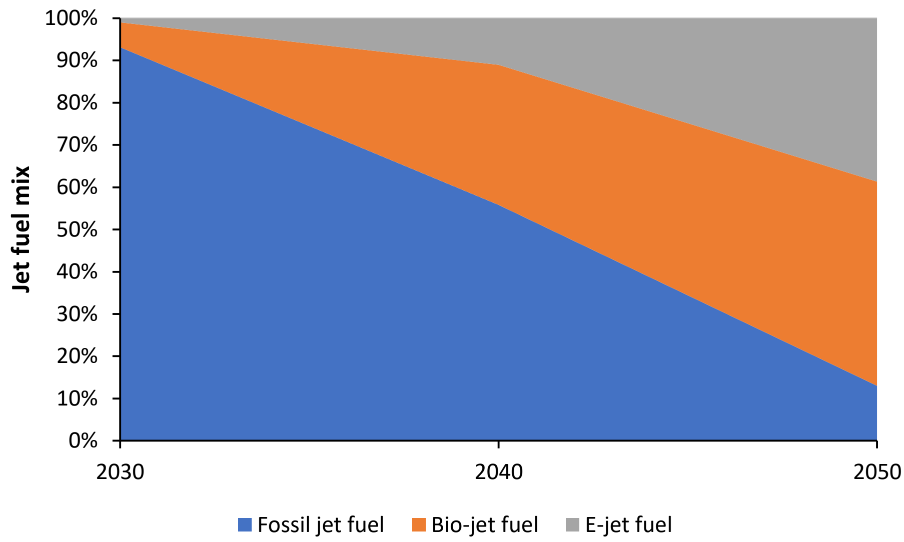
Eur/tCO_2	2020	2030	2040	2050
Carbon price	0	50	250	530

Mandates scenario

In the Mandates scenario, measures complementary to the carbon price are taken up globally. Such measures are technically viable solutions offered by blending alternative jet fuels (drop-in solutions) with fossil kerosene such as bio-jet fuel and e-jet fuel. In particular, a mandate at the level of the alternative jet fuel is placed that increases over time, increasing the overall zero carbon fuel share in the kerosene blend as presented in Figure 14.

The fuel mix of the Mandates scenario is based on IATA (2022) that projects that in a net zero emissions target context in 2050 (compliant with Paris Agreement goals) about 13% carbon offsetting of emissions from aviation would be required. Such emissions would be a result of persisting fossil fuels in the jet fuel mix. In such a scenario, alternative jet fuels would comprise 87% of the jet fuel mix. The respective relative shares of bio-jet fuel and e-jet fuel are based on discrete choice modelling that considers the price differential of alternative jet fuels and the different stage of technology development and penetration.

Figure 14 Jet fuel mix in the Mandates scenario



Next to the three scenarios (Ref, C-price, Mandates) developed and quantified with GAM, we present a case study on the European aviation sector with the aim to address implication of different policy instruments, namely a ticket price (“TickTax”) vis à vis technology neutral mandates (“NeutralMand”). A description and quantification of the scenarios is presented in Box 3.

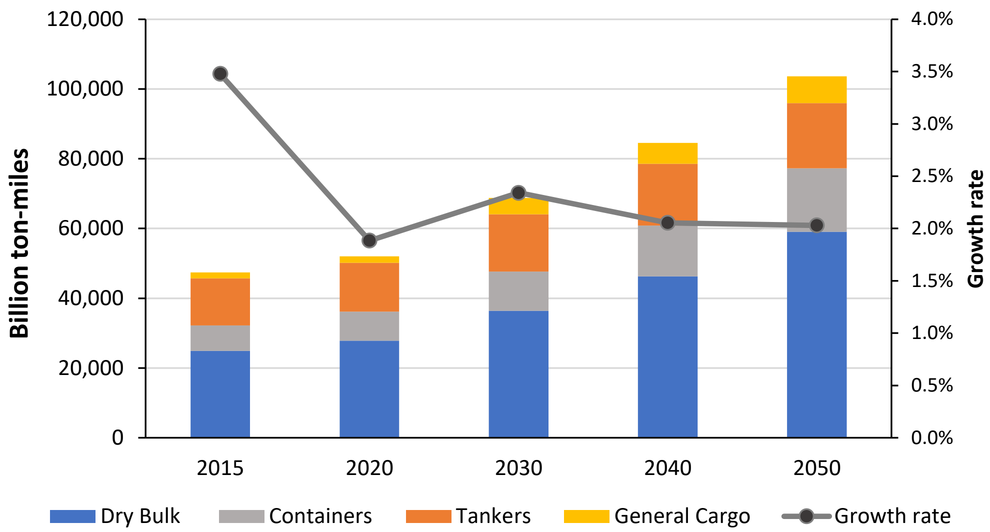
3 Results of bottom-up modelling

3.1 International maritime

The PRIMES-International Maritime model is used to quantify the trajectory of activity over time, until 2050 in the Base scenario. The Base scenario is developed in a context of moderate climate and energy policies[19]. The results show that total maritime trade activity for the major shipping segments (i.e., dry bulk, tankers and containers) grows by almost 90% in 2050 compared to 2018 mainly driven by dry bulk and containers (Figure 15). The combined growth of dry bulk and containers is more than 115% over the same period. The projected growth rate of total maritime activity is comparable with the growth rate of IRENA (2021), that is projected to be 90% in 2050 compared to 2018 in their Baseline Energy Scenario (BES).

Dry Bulk continues to dominate maritime activity in absolute terms. The activity growth for tankers in ton-miles is projected to accelerate in the short term, following a post-COVID oil and products demand surge, leading to an increase in shipping distances, even without factoring in the expected structural trade flow shift driven by recent geopolitical events (e.g., Russia-Ukraine war). However, the main growth driver from 2030 onwards comes from chemicals products trade, despite the overall growth deceleration of the sector, as the global economy transits towards GHG emissions mitigation in major developed oil consuming industries. Such findings corroborate the expectations that international maritime demand will continue to grow if no specific actions are put in place to change the spatial organisation of supply chains and that the shipping sector will therefore require implementing measures to reduce emissions from ship operations.

Figure 15 International maritime activity projections in the Base scenario



Box 2 presents a case study on the European maritime sector

[19] The baseline scenarios developed for the bottom-up models for international maritime (Global and EU case study) and international aviation are not identical and therefore not directly comparable. The main premise of the baseline scenarios, however, is that of a continuation of existing policies and the absence of deep decarbonization drivers.

Box 2 Decarbonization of the European maritime bunker fuels sector

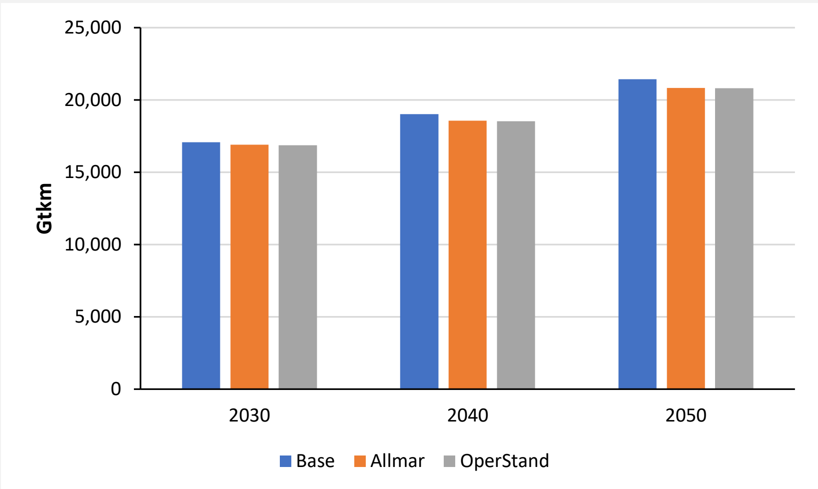
Case study: Decarbonising the European maritime bunker fuels sector

The EU international maritime sector (i.e., covering intra-EU and extra-EU voyages) consists of 16% of global maritime activity, about 19% of global bunker consumption and about 16% of global maritime emissions in 2015. As a result of its notable contribution, the EU has taken action via new policy proposals to make sure that the sector contributes to the climate neutrality goal in the region by 2050.

The case study utilizes the PRIMES-Maritime model that is aligned in philosophy, method, and inputs with PRIMES-International Maritime. The scenarios that are quantified for the EU are in line with the contribution required by the sector so that region achieves its ambition to climate neutrality in 2050. The scenarios include policy instruments specific to the maritime sector (e.g., fuel carbon intensity targets, operational standards, operational carbon intensity standards) and others that are cross-sectoral (e.g., carbon price). The scenarios are described in detail in section 2.1.2.

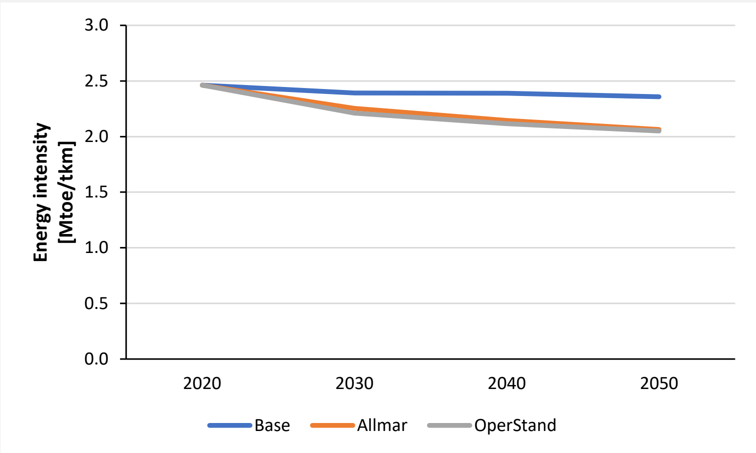
The results in Figure 16 demonstrate that under all scenario assumptions the sector demand is projected to grow between 2030 and 2050. The impact of the different instruments, however, namely carbon price (Allmar) and in addition certain standards in vessel operation (OperStand) as means to achieve decarbonization may impede the projected Period-Over-Period growth of the sector, especially early in the time horizon. It should be noted, however, that compared to Base, the absolute difference in activity in the Allmar and OperStand scenarios is around 1% in 2030 (about 16,900 Gtkm) and around 3% in 2050 (20,800 Gtkm).

Figure 16 Activity projections in European maritime in the Base, Allmar and OperStand scenarios in 2030 – 2050



Beyond the activity differences described before, the energy consumption per transport unit improves significantly from 2020 to 2050 (Figure 17). In Base, incremental efficiency improvements lead to about 4% lower energy consumption per transport work in 2050 compared to 2020. Carbon price induces an intensification of energy efficiency owing to the adoption of new technologies (e.g., LNG and/or electric vessels in short distances). The impact in the energy intensity improvements is notable, as in the Allmar scenario the energy use per tkm is lower by 16% in 2050 compared to 2020. Operational standards are shown to further lead to improvements in energy consumption per transport work, particularly early in the time horizon (i.e., from about 0.5% p.p. to about 1.5% p.p. in the period 2020-2050).

Figure 17 Energy intensity improvement of transport work in the Base, Allmar and OperStand scenario in 2020-2050



Activity reduction, operational and technical energy consumption improvements are projected to reduce fuel consumption in Allmar and OperStand compared to the Base. Bunker fuel consumption is lower by about 7% and 9% in Allmar and OperStand compared to Base, respectively in 2030, and about 15% and 16% in 2050 (Figure 18).

Figure 18 Bunker fuel consumption in European maritime in 2030 and 2050 in the Base, Allmar and OperStand scenario

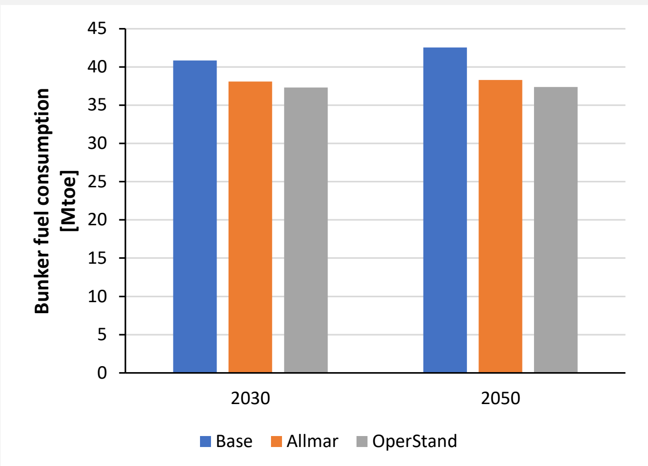
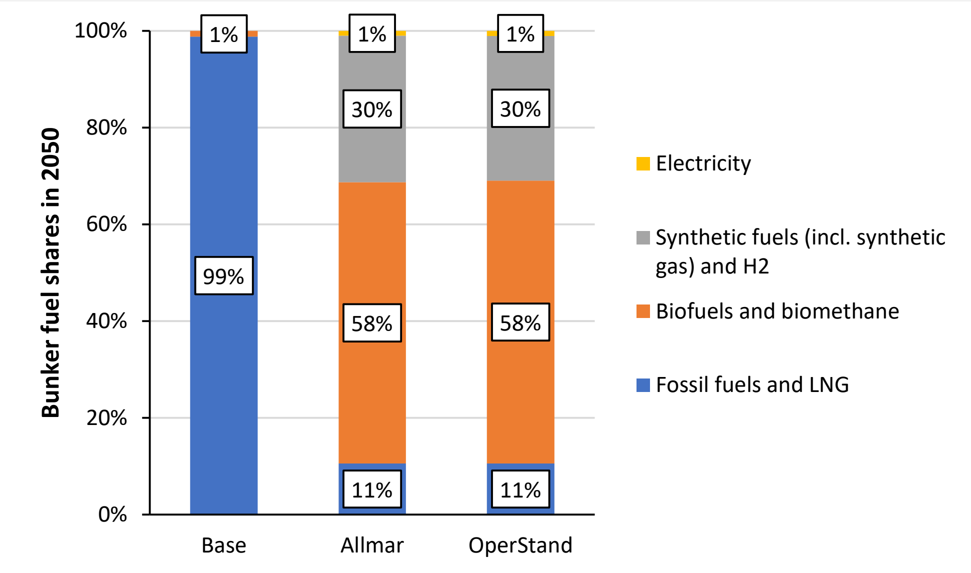


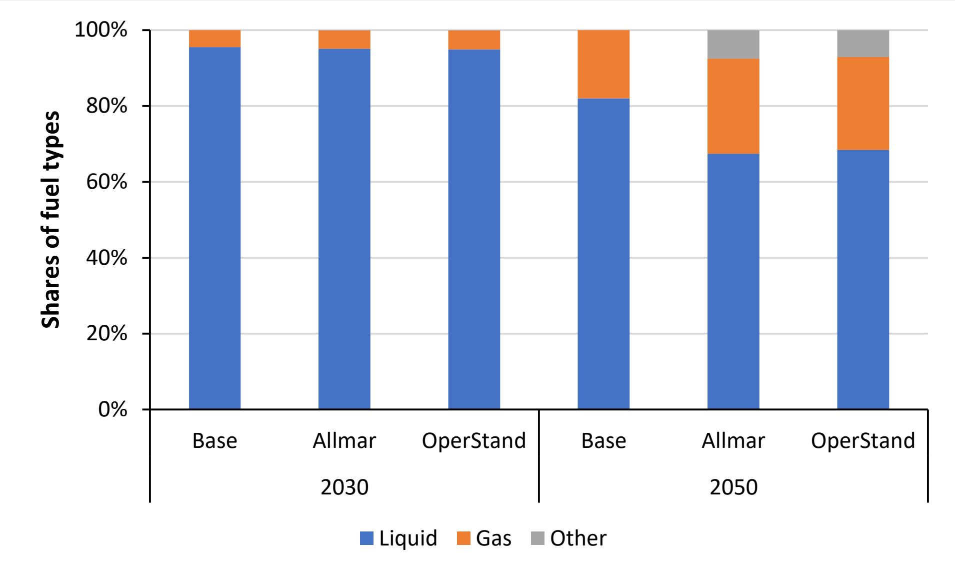
Figure 19 presents the bunker fuel mix in the European maritime sector in 2050. It should be noted that the decarbonization scenarios include a GHG intensity target promoting the use of alternative marine fuels in the bunker fuel mix, in line with the FuelEU Maritime initiative (i.e., as a carbon intensity reduction target compared to a base year with increasing ambition over time). Such targets are a strong signal to fuel suppliers and operators especially for the short to medium term so that a market for alternative low-emission fuels for maritime can be developed. Applying such shares leads to the penetration of zero emission fuels in the maritime sector (on a Tank-to-Wake basis) to about 90% in 2050. Such high level of alternative maritime fuels in the mix is due to the ambition of the region to achieve climate neutrality and thus contribute to the Paris Agreement goals. In comparison, in the Base scenario where no such mandates or targets apply the alternative maritime fuels comprise about 1% of the fuel mix (mainly liquid biofuels). Biofuels are the main alternative maritime fuel used in the shipping sector in both decarbonization scenarios (Allmar, OperStand). The main driver for the higher relative uptake of biofuels compared to synthetic fuels is their price differential; biofuels are assumed to cost about 25% less than e-liquids. Synthetic fuels and hydrogen are assumed to be produced by renewable electricity in 2050. Finally, there is a small uptake of electric vessels (see also section 2.1.1). It should be noted no differentiation on the carbon intensity target is made between the fuel use in intra-EU and extra-EU voyages.

Figure 19 Fuel shares by fuel type used in European maritime in the Base, Allmar and OpenStand scenarios in 2050



Regarding bunker fuels by type (Figure 20; synthetised from fuels by fuel type), the bunker composition changes from mainly liquid fuels today (heavy fuel oil, very low sulphur oil, diesel) to increasing penetration of gaseous fuels and engines (LNG vessels). It should be noted that the post-2025 orderbook is comprised to a large extent by LNG-ready or LNG-fuelled vessels. The types of fuels used do not differ substantially across the scenarios in 2030. While the penetration of gaseous fuels (LNG) increases towards 2050 (Base scenario in Figure 20), it becomes evident that the ambition to reduce emissions by means of a carbon price and additional operational standards requires notably higher shares of gaseous fuels in maritime (AllMar and OperStand in Figure 20). In 2050, about 18% of bunker fuels is gaseous fuels in Base, which increases to 25% in the decarbonization scenarios. This implies also impact on infrastructure and supply chains of gaseous fuels.

Figure 20 Shares of liquid, gaseous and other fuels used in European maritime in the Base, Allmar and OperStand in 2030 and 2050 (other includes electricity and hydrogen)



The fuel mix owing to the introduction of a carbon price (e.g., in Allmar) and additional efficiency gains owing to operational standards (e.g., in OperStand) lead to a notable reduction of CO_2 emissions in European maritime compared to Base. Figure 21 shows the Well-to-Wake (WtW) emissions broken down to Tank-to-Wake (TtW) and Well-to-Tank (WtT) in the three scenarios in 2030 and 2050. The impact of policies is directly noticeable in 2030, when WtW emissions are lower by almost 15% in Allmar and almost 30% in OperStand compared to Base. In 2050, the two scenarios lead to almost 40 $MtCO_2$, i.e., a reduction of 90% compared to Base. Interestingly, the main reduction in emissions is owed to zero-emitting fuels despite the large biofuel quantities used and their associated WtT emissions.

Whilst in 2050, both decarbonization scenarios lead to similar annual emissions levels, their difference in the trajectory from 2020 to 2050 leads to notably lower cumulative CO_2 emissions on a WtW basis. In particular, Figure 22 shows that in the Base scenario, cumulative WtW emissions may exceed 5 $GtCO_2$ in 2020-2050, while in scenarios that contribute to the Paris Agreement goals, the cumulative emissions of the sector may reach 3.5 $GtCO_2$ in Allmar and 3.1 $GtCO_2$ in OperStand in 2020-2050. The difference in cumulative CO_2 emissions between AllMar and OperStand in the period 2020-2050 reaches 0.4 $GtCO_2$ and can be attributed to efficiency improvements owed to early adoption of operational standards. This result demonstrates the importance that certain policy and scenario assumptions may have on the emissions trajectory.

Figure 21 CO_2 emissions in European maritime transport in the Base, the Allmar and the OperStand scenarios in 2030 and 2050

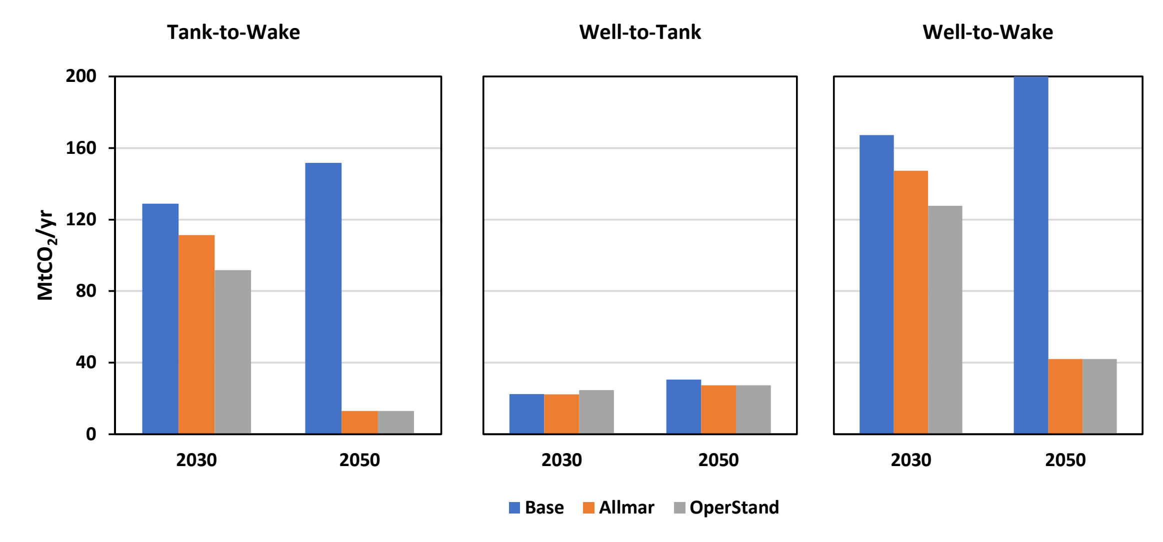
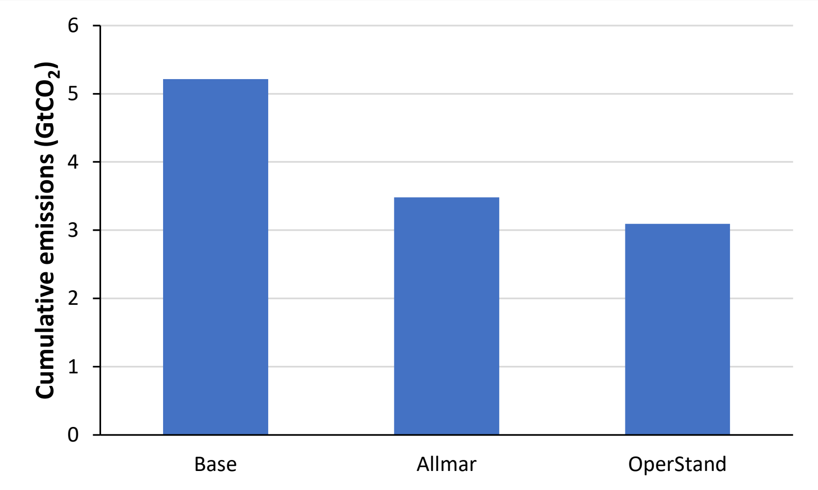


Figure 22 Well-to-Wake cumulative emissions in European maritime transport in the Base, the Allmar, and the OperStand scenarios in the period 2020-2050

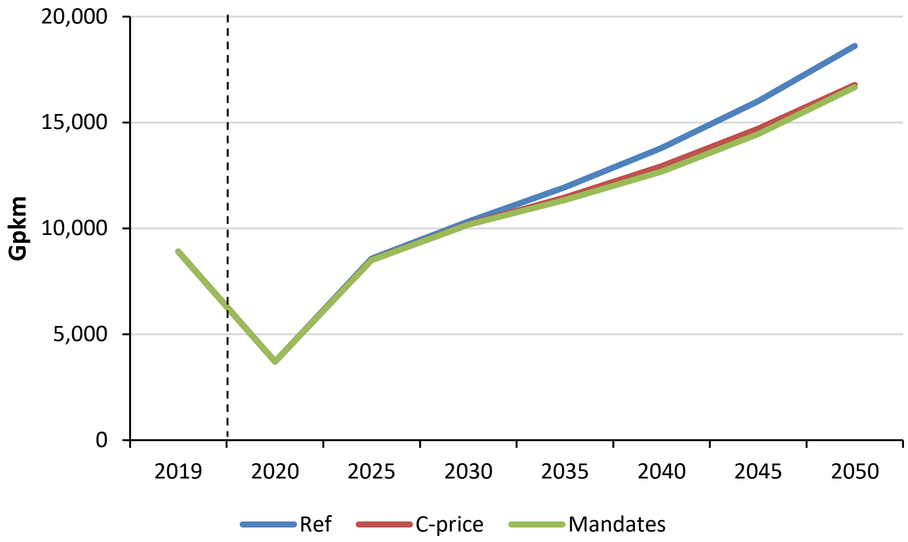


3.2 International aviation

The section below presents results for at a global level for the aviation sector from 2020 to 2050 in the three scenarios that are quantified with GAM, namely Base, C-price, and Mandates. Results are presented for activity, the development of the fleet, the technology uptake, energy use by the sector and resulting CO_2 emissions.

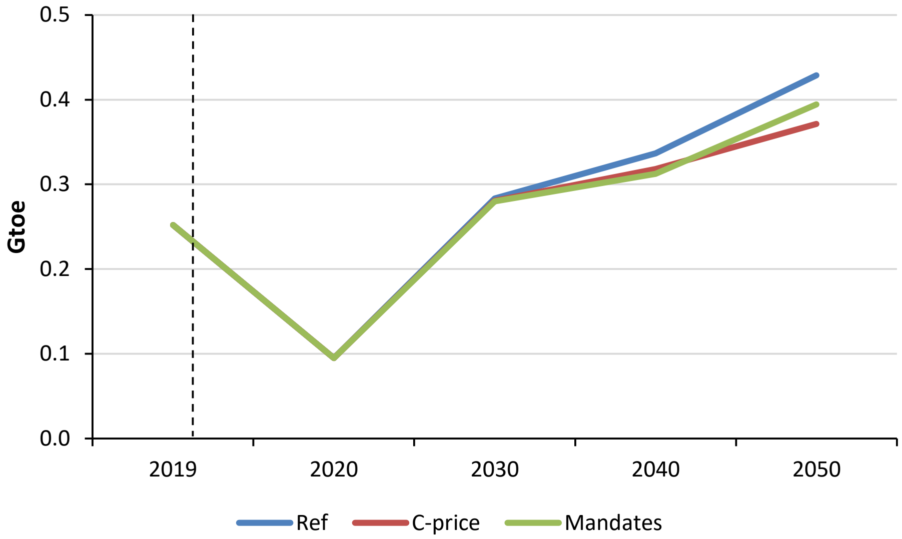
Global passenger aviation activity is projected to increase notably from about 8,900 Gpkm in 2019 to more than 18,500 Gpkm in 2050 (Ref scenario in Figure 23). This is more than a doubling of activity over 30 years and is in line with the Baseline projections of the ICCT (2022). Figure 23 also shows the impact of the COVID-19 pandemic in 2020, and the recovery that takes place thereafter. In 2020, the activity is reduced by almost 60%, swiftly increasing to exceed 2019 levels after 2025. Based on the scenario assumptions, activity is projected to reduce by up to 10% in 2050 in C-price and Mandates, compared to Base, owing to the higher ticket price faced by consumers due to carbon pricing and blending mandates of more costly alternative jet fuels. A higher ticket price entails that less passengers can afford travelling by plane and thus shift to other modes or lose utility (they stop travelling). The effect of activity reduction in the decarbonization scenarios is primarily noticed after 2030 when carbon price (C-price scenario) and in addition blending mandates (Mandates scenario) increase.

Figure 23 Global passenger aviation transport activity in the Base, C-price, and Mandates scenarios



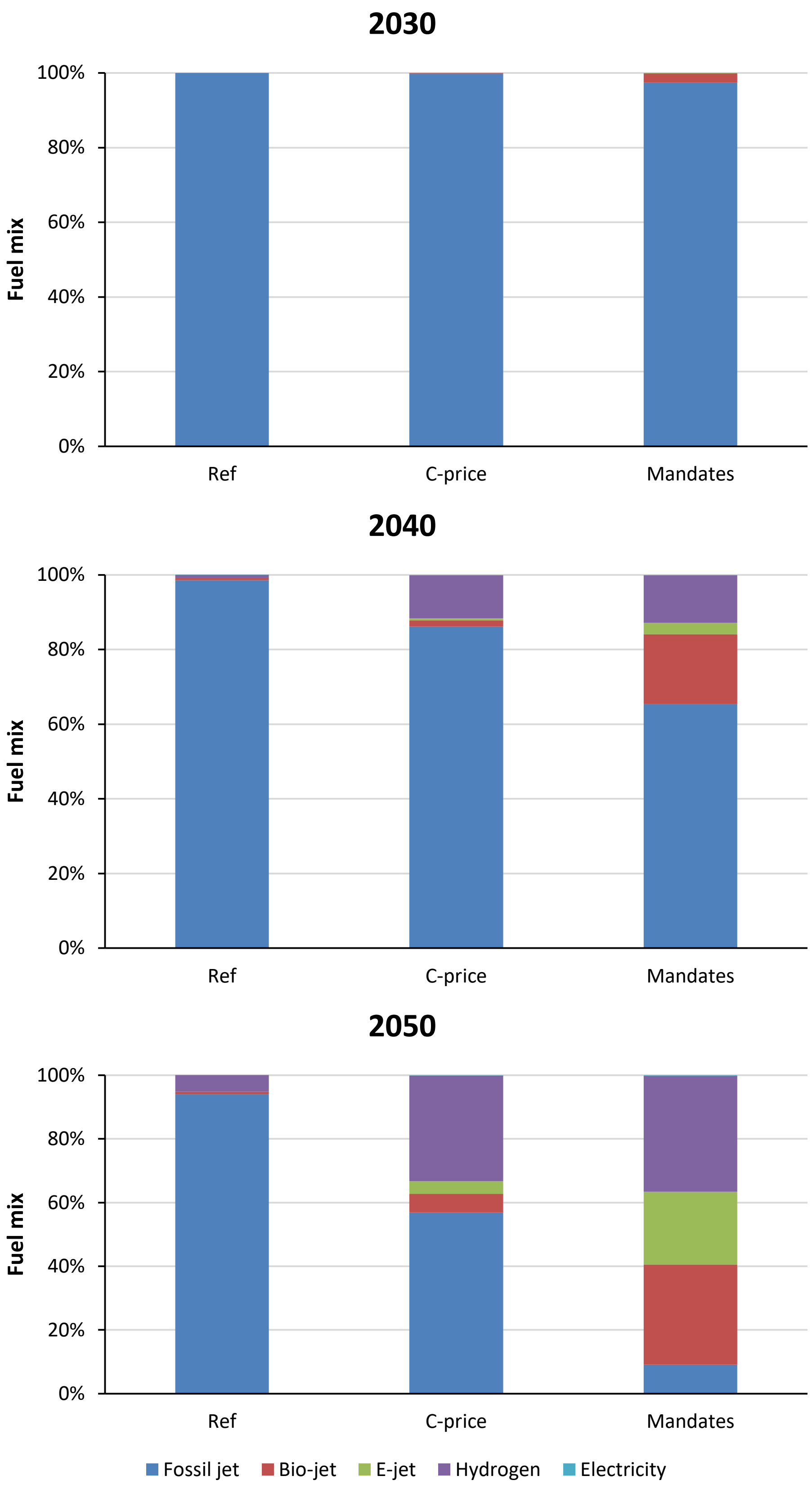
Owing to the increase in passenger aviation activity, the energy use by the sector also increases by 70% in 2050 compared to 2019 in the Ref scenario (Figure 24). The increase is disproportionate (i.e., lower in relative terms) compared to the activity growth, owing to incremental efficiency improvements in aircraft technologies and adoption of more efficient technologies). Notably, the decarbonization scenarios lead to lower energy use by 13% in the C-price scenario and by 8% in the Mandates scenario compared to the Ref in 2050. On the one hand the lower activity in the decarbonization scenarios due to higher fuel costs (owing to the blending mandate and the carbon price), but also the adoption of more efficient technologies (e.g., electric and fuel cell aircrafts) explain the reduction of fuel consumption in aviation. Notably, the Mandates scenario leads to slightly higher energy consumption in 2050 compared to the C-price scenario, which can be explained by the technology uptake in the preceding years.

Figure 24 Total energy use in global passenger aviation in the Base, C-price and Mandates scenarios



The breakdown of fuel consumption by fuel type in aviation (Figure 25), shows that without the adoption of policy measures (whether these are price signals or also blending mandates), only a minor uptake of alternative jet fuels is projected. In particular, almost 95% of fuel use in aviation is fossil jet fuel, whilst hydrogen (owing primarily to new fuel cell aircrafts) and in lesser extent bio-jet in the kerosene is also taken up. The C-price scenario shows a notable uptake of hydrogen in 2050. In contrast, in the Mandates scenario owing to the alternative jet fuel quotas, their uptake is significant (i.e., more than 50% of fuel consumption in aviation, while retaining an 86% share in the pool of liquid jet fuels. Provided that alternative jet fuels are considered necessary for decarbonization, this result shows that alternative jet fuel quotas may be necessary.

Figure 25 Fuel mix in Base, C-price, and Mandates scenarios in 2030, 2040, and 2050



The three scenarios lead to different CO_2 emissions trajectories, especially after 2030 (Figure 26). In the Ref scenario emissions are projected to exceed 1 $GtCO_2$/year in 2050, which is substantial considering the effort required to reach the Paris Agreement goals. The C-price scenario shows that through carbon pricing and the penetration of new technologies the emissions in 2050 may reduce to 2019 levels despite the doubling of activity. Yet, this entails a more than 0.6 $GtCO_2$ residual emissions. The Mandates scenario projects emissions to decline sharply after 2030 to reach around 0.1 $GtCO_2$ in 2050, owing to the penetration of alternative jet fuels. Annual emissions in aviation peak in 2030 in the deep decarbonization scenarios. The impact of the emissions reduction trajectory in Mandates is also prominent when looking into cumulative emissions of the global passenger aviation sector over the period 2020-2050. Figure 27 shows cumulative emissions to reach 28, 23 and 19 $GtCO_2$ in Base, C-price and Mandates in 2020-2050, respectively. The emission trajectory reflects Tank-to-Wing (tailpipe) emissions, and not emissions resulting from the production of the fuels (Well-to-Tank). Looking into the increase of bio-jet fuel (see e.g., Figure 25) globally, upstream emissions from the production of biofuels (e.g., land use change emissions) may also take place that could reduce the net effect of emissions reduction from the penetration of liquid fuels. Such emissions may decline over time should forestry or agricultural residues be used for the production of bio-jet, with increasing deployment of advanced lignocellulosic biomass conversion technologies. All scenarios follow a similar trajectory until 2030, and therefore the action assumed in the scenarios post-2030 is the main driver of this outcome.

Figure 26 CO_2 emissions in global passenger aviation in Ref, C-price and Mandates scenarios in 2019-2050

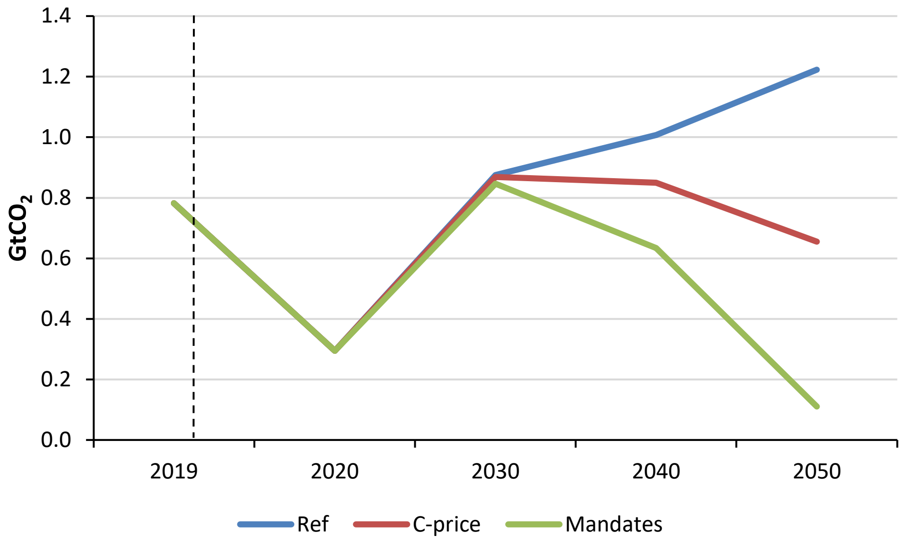
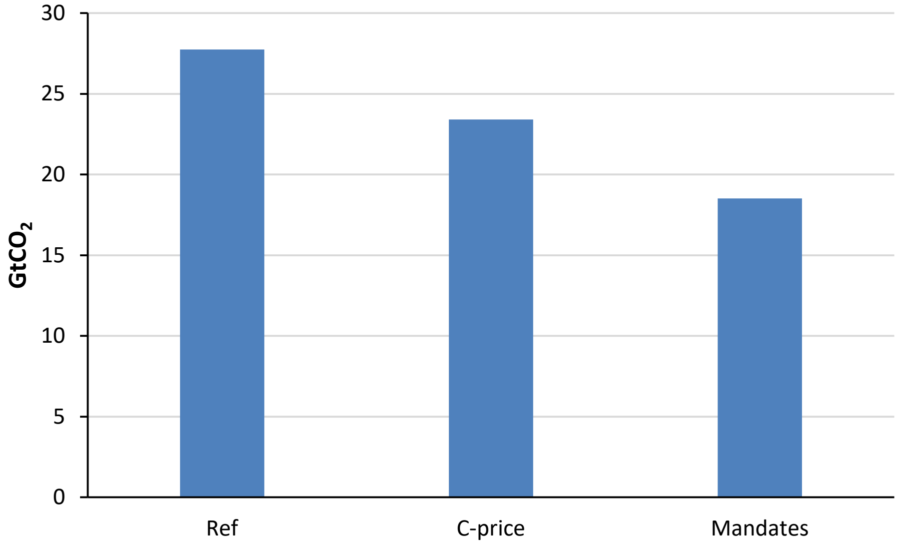


Figure 27 Cumulative emissions of global passenger aviation in the Ref, C-price and Mandates scenarios in the period 2020-2050



Box 3 presents a case study on the European maritime sector.

Box 3 Contribution of European aviation bunker fuels to the Paris Agreement goals and implications of different policy instruments

Case study: Contribution of European aviation bunker fuels to the Paris Agreement goals and implications of different policy instruments

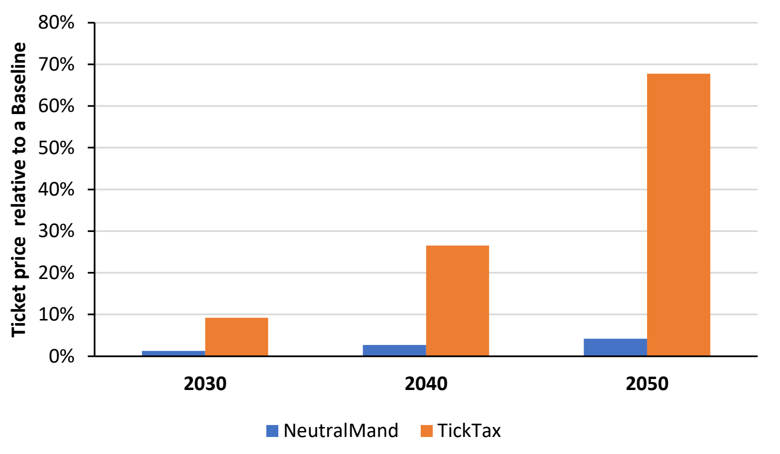
The scenarios that were quantified with GAM and were presented in the sections above assess carbon pricing (taxation) and mandates as means to stimulate deep decarbonization of the sector globally.

This section presents a case study that zooms in the European region (EU) to assess implications of different instruments other than those assessed in the global model, namely a travel taxation (ticket tax) and an alternative jet fuel mandate, however, without sub-quotas on specific alternative jet fuels. Importantly, in this case study we incorporate substitution effects of air travel demand by land modes in the EU region, where possible. To that end, we develop and quantify the following two scenarios: (a) the Ticket taxation ("**TickTax**") scenario that assumes an additional fixed cost on the ticket price that increases gradually to about 180 Eur/ticket in 2050. This ticket price is considered sufficient to induce modal shifts to fast rail, (b) the technology neutral mandates ("**NeutralMand**") scenario considers that mandates on alternative jet fuels apply, however, unlike the Mandates scenario, they are technology agnostic. In this scenario by 2050, about half of the jet fuel mix is decarbonized.

Both scenarios, achieve emission reduction by 2050 such that the EU contributes to the international goals of the Paris Agreement on climate change mitigation consistent with 2 ^{o}C temperature increase. It should, however, be mentioned that the ambition in these scenarios is lower than in the Mandates and the C-price scenario that aims towards net zero emissions by 2050 globally. In these scenarios, assumptions on GDP, population and fuel prices are aligned with the inputs presented in section 2.2.

The scenario results show that ticket taxation would increase substantially the ticket price to induce the necessary modal shifts to less carbon intensive modes so that it can lead to the necessary emissions reduction (Figure 28).

Figure 28 Increase in ticket price due to ticket taxation and alternative jet fuel mandates



The TickTax scenario also leads to lower air transport activity as transport by air becomes more expensive for households and in this scenario the sector contracts substantially, especially when compared to the NeutralMand scenario. About two-thirds of the activity shifts from air transport mainly to fast rail, and partly to road transport modes and about one-third of air transport activity is lost utility (Figure 29).

Another important finding of the analysis is that the in the TickTax scenario the carbon intensity of air travel is notably higher than that of the Mandates scenario. As such, despite that the sector has stimuli for efficiency improvements to avoid contraction, it underperforms compared to the NeutralMand scenario (Figure 30).

Figure 29 Development of aviation demand due to ticket taxation and alternative jet fuel mandates

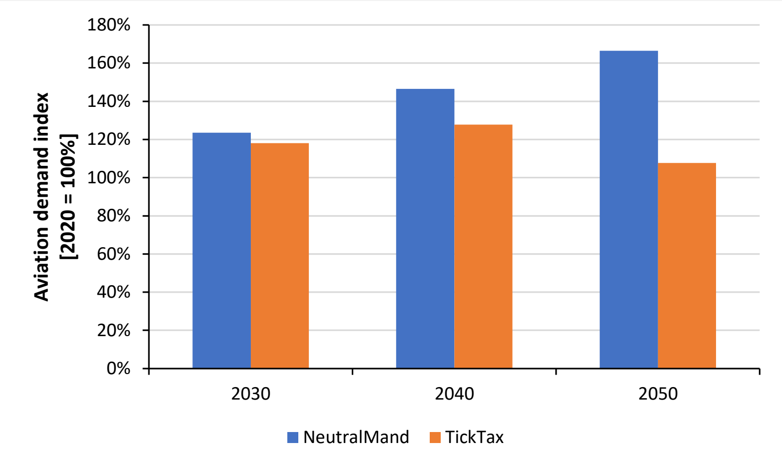
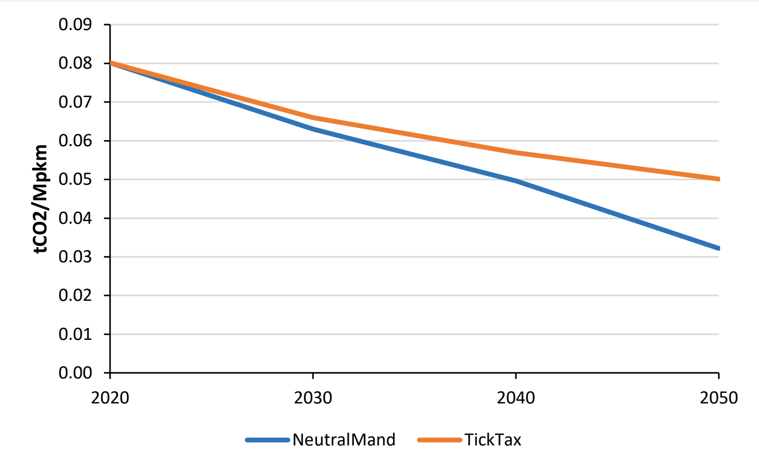


Figure 30 CO_2 intensity of air travel in the ticket taxation and the alternative jet fuel mandates scenarios



The results of this case study are consistent with the findings of the global analysis as well in that they demonstrate that mandates are necessary for the sector to decarbonize in the long term.

4 Decarbonising the international shipping and aviation sector

4.1 Abstract[20]

The Paris Agreement requires a drastic reduction of global carbon emissions towards the net zero transition by mid-century. The implementation of these ambitious targets requires the large-scale transformation of the global energy system and major emitting sectors. The international shipping and aviation sectors currently account for about 4% of global emissions. Under current climate policies, emissions from these sectors are expected to more than double by 2050, which is clearly not compatible with the Paris goals. The large-scale electrification of these sectors is challenging with current technology, making these the hardest-to-abate emissions from the transport sector. Here, I use the global energy system model PROMETHEUS, enhanced with a detailed representation of the shipping and aviation sector, to explore transformation pathways for these sectors and their emission, activity, and energy mix impacts. The most promising alternative towards de-carbonizing these sectors is the large-scale deployment of low-carbon fuels, including biofuels and synthetic clean fuels, accompanied with energy efficiency improvements. The analysis shows that ambitious climate policy would reduce the trade of fossil fuels and lowers the activity and the mitigation effort of international shipping, indicating synergies between national climate action and international transport.

Keywords: international shipping; aviation; PROMETHEUS energy model; decarbonization; low-emission fuels

4.2 Introduction

Limiting climate change is one of the most important challenges of our time and has been the subject of international negotiations for more than three decades. Within this process, goals have been suggested, especially under the Paris Agreement (PA), aiming to keep global temperature rise at well below 2 °C compared to pre-industrial times and pursue efforts to limit it to 1.5 °C (UNFCCC, 2022). Following the PA, a large majority of countries representing more than 95% of global greenhouse gas (GHG) emissions have submitted cli-mate pledges labelled as Nationally Determined Contributions (NDCs). Although the Paris Agreement in principle covers emissions from all sectors, most Parties to the Paris Agreement have not included emissions from international shipping and flights in their NDCs. These emissions are explicitly addressed by the International Maritime Organization (IMO) and International Civil Aviation Organization (ICAO) respectively. However, the global nature of these sectors and their limited consideration in domestic climate strategies and NDCs creates additional challenges for climate policy implementation.

Decarbonising the transport sector implies radical changes such as curbing demand, a shift to cleaner and more efficient transport modes and a large-scale uptake of new energy sources, to pave the way towards net zero emissions (Cambridge University Press, 2014). Both demand and supply mitigation options are needed to reduce transport emissions as no single solution is sufficient for decarbonization. This is particularly the case for international aviation and shipping, where technical solutions are limited and face large uptake and commercialization barriers, making these sectors the most challenging to decarbonize. The lack of robust emission reduction policies, the challenge to shorten supply

[20] The current section has been submitted for peer-review in a scientific journal, has received positive comments, and is now close to acceptance.

chains, the technical difficulties to electrify these sectors, the projected high activity growth, the limited additional potential for energy efficiency improvements, and the lack of mature, economically competitive, and commercially viable options and low-carbon fuels creates additional difficulties for the decarbonization of shipping and aviation.

Reducing the emissions from the aviation sector is crucial to meeting the Paris agreement targets. However due to the specific technological requirements and safety standards, the sector decarbonisation presents unique challenges (Dray, et al, 2022; Gössling, & Lyle, 2021). In addition, the demand for aviation is expected to vigorously grow in the future, due to the expected in-come increase and the associated increase in aviation activity, especially in developing countries with currently low aviation demand. The decarbonisation of the shipping sector is also very difficult given increasing international trade activity and the lack of cost competitive and technologically mature mitigation options. To reduce emissions from the sector, more efficient vessel design can provide efficiency gains using lightweight materials, or new hull shapes and sizes (Bouman, et al, 2017). Operational measures, such as speed and voyage optimization, facilitated by digitalisation, could also play an important role (Rantanen, et al 2019), accompanied by the use of auxiliary propulsion devices and waste heat recovery, (Rehmatulla et al. 2017), or reduced shipping activity, especially for fossil fuel transport (Sharmina et al, 2020). However, most of the decarbonisation of the shipping sector will rely on the development and commercial uptake of alternative low-emission fuels (Balcombe et al, 2018). From a technical perspective, several low-emission fuels could be considered, such as vegetable oils, synthetic biofuels, bio-LNG, hydrogen, and clean synthetic fuels produced from green electricity (e-fuels) (Lloyds, 2018). In any case, the use of alternative low-emission fuels will imply additional costs and might have relevant impacts on other energy chains and land use (DNV GL, 2020). (Traut et al 2018) have explored a range of scenarios of international shipping, and demonstrate that in the near term, immediate and rapid exploitation of available efficiency mitigation measures, including changes to speed, ship size and utilisation, available retrofit technologies, is of critical importance to deliver emission reductions. Although some studies have carefully assessed the decarbonization potential of renewable marine fuels (DNV GL, 2020; Lloyds, 2020), an integrated perspective of the different options is lacking.

Therefore, this study aims to provide a comprehensive system-wide perspective on the potential decarbonization strategies for the international shipping and aviation sector. Large-scale energy system models and Integrated Assessment Models (IAMs) are well positioned to inform the pathways and policy measures required to address the growing emissions from these international transport sectors. These models are extensively used to develop and assess mitigation pathways in which GHG emissions are reduced to limit warming to specific temperature limits (Rogelj, J., et al, 2018). A key strength of these models is the consistent representation of the complex interlinkages between different sectors of the economy, the energy and transport sectors, and other environmental systems (Müller-Casseres, et al 2020). They provide the majority of global mitigation scenarios in the literature, and strongly feed into the evidence compiled in the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports (IPCC, 2018).

However, most of them fail to represent adequately the sectoral dynamics and the emission reduction options and strategies of the international aviation and maritime sectors. This raises critiques to the models related to the inadequate input assumptions for low-emission fuels (costs and potentials), the representation of innovation, and behavioural and activity changes (Gambhir A., et al 2019; Keppo, et al. 2021). In particular, (Esmeijer et al 2020) conducted an analysis of aviation and shipping emissions projections from IAMs and sector specific models. They concluded that the representation of these sectors in current modelling tools is inadequate, with no differentiation of national and international activity, and limited representation of low-emission fuels, while efficiency standards and specific policy measures are commonly not captured by the models.

The decarbonization of maritime transport has been the topic of a few studies, often based on the sectoral modelling of the shipping sector (DNV GL 2020; IRENA 2021; European Commission 2021), while limited studies have focused on the transformation of the aviation sector (Singh, et al 2018). On the other hand, Integrated Assessment Models (IAMs) have paid little attention to shipping (Müller-Casseres et al. 2021b). Only recently, with the development of aspirational emission goals and relevant strategies for shipping and aviation by IMO and ICAO respectively, the modelling community has started to explore the specificities of international transport segments and the potential mitigation options (Esmeijer et al. 2020; Sharmina et al. 2021). These improvements allow an integrated perspective of the decarbonization strategies of international transport sectors, adding value to the existing literature, largely based on sectoral models (IRENA, 2021; European Commission, 2021). Therefore, these system-wide models can treat international shipping and aviation in the context of the over-all mitigation strategies, covering the linkages to the rest of the energy sectors. In this study, possible futures of international transport sectors are assessed in terms of activity, emissions, energy demand, fuel mix and costs using an integrated assessment framework.

The current study aims to improve the representation of the international transport sectors in the PROMETHEUS global energy system model (Fragkos et al, 2015; Marcucci et al. 2019) in order to better inform decision makers of the possible decarbonization pathways and strategies of international shipping and aviation sectors. This responds to the limited focus on such sectors by IAMs, and recent broader critiques of these models (Keppo et al, 2021). The modelling framework (Harmsen *et al* 2021) has been significantly enhanced with an improved representation of the international shipping and aviation sector, fully endogenizing the emission reduction options in these sectors and incorporating recent estimations for activity growth and sectoral policies and strategies. The modelling estimations of decarbonization strategies in these sectors have thus been considerably improved through integration of the costs and deployment potential of emission reduction technologies (e.g., advanced biofuels, clean synthetic fuels, hydrogen, electricity) as well as accelerated energy efficiency and operational improvement. To achieve the above objectives, sector models for international transport (EC, 2021) are used to provide the required data to enhance the representation of international transport in the PROMETHEUS model, including the links with the supply side in terms of production of low-emission fuels. Using the enhanced PROMETHEUS modelling framework, the study investigates how deep decarbonisation could be achieved in international shipping and aviation sectors, both in terms of technical possibilities and structural changes in the long term and the feasible actions that can be taken in the medium-term. In particular, the significantly enhanced PROMETHEUS model is used to quantify the impacts of Paris-compatible mitigation pathways for the international maritime and aviation sectors and to explore potential synergies or trade-offs between domestic climate action and international transport. The analysis also explores whether the emission goals of ICAO and IMO are compatible with the Paris temperature goals or if these sectoral goals need strengthening by 2050 and which mitigation options can be deployed.

The study proceeds as follows. Section 4.3 presents the landscape of the maritime and aviation sector, while Section 4.4 describes the methodological approach, the modelling improvements implemented and the scenario design. Section 4.5 presents the results of the model-based assessment on decarbonising international aviation and air transport. Section 4.6 discusses policy relevant insights and provides recommendations.

4.3 The landscape of the international maritime and aviation sector

The section presents the current context and policy measures for the international transport sectors.

4.3.1. International Maritime

International shipping accounts for about 2% of global energy-related emissions (IEA, 2022). In the last decade, emissions from international shipping amounted to about 600-700 Mt CO2/year (Faber et al 2021). Analysing the recent trends, there is a relative stabilisation of international shipping emissions since 2010-2011, when they peaked at around 670 Mt CO2. The growth of international maritime emissions was slowed down due to the 2008-2009 financial crisis that resulted in a decline of international seaborne trade activity from 42 to about 40 trillion tonne-miles (Tt-nm) (UNCTAD 2021). This was followed by a period of economic recovery leading to continuous growth of the shipping activity accompanied by considerable energy efficiency gains especially in the period until 2014, enabling a temporary decoupling of emissions and shipping activity growth. Since then, however, shipping emissions follow an increasing trajectory as efficiency gains have been decelerating. Due to COVID-19 and general lockdowns, international maritime emissions dropped by 8.2% in 2020, which is the largest annual reduction recorded. However, in 2021 emissions from the international shipping sector grew by 5%, rebounding from the sharp decline in 2020 to reach 2015 levels of about 670 MtCO2. In case that seaborne transport activity follows historic trends, it can double by 2050 (Faber et al 2021) and with current carbon intensity, this would represent about 1.35 Gt CO2/yr, being clearly incompatible with the Paris Agreement goals.

The International Maritime Organization (IMO) is responsible for regulating global maritime transport. In April 2018, the IMO agreed to reduce GHG emissions by at least 50% by 2050 compared to 2008. As part of its strategy including energy efficiency and carbon intensity goals, IMO aims to ensure an emission pathway compatible with the Paris Agreement goals, since international transport was not covered by the treaty (IMO, 2018). However, (IEA, 2022) shows that the newly approved technical and operational measures established by the IMO are not sufficient to curb emissions from international shipping in the long term. The short-term measures entail an average annual efficiency improvement of the global vessel fleet (measured as emissions per tonne-kilometre) of about 2% in 2020-2030 decade, which is only slightly higher than the historical average improvement rate of 1.6% p.a. after 2000. In contrast, average annual improvements of more than 4% until 2030 are required to put international shipping on the Net Zero Emissions pathway (IEA, 2022) triggered by ambitious operational measures (e.g., slow steaming, better vessel de-sign).

While measures approved by the IMO are likely to curb the growth of emissions over the 2020s, higher policy ambition is required to ensure that the maritime sector development is compatible with Paris goals. Therefore, the stringency of existing IMO policies, such as operational emission intensity standards, should increase to facilitate the uptake of low- and zero-carbon technologies and fuels for vessels. Innovation is crucial to ensure that low- and zero-emission oceangoing vessels are made commercially available during the current decade. Robust technological innovation, ambitious supportive policies and collaboration across the value chain are needed to drive the adoption of low- and zero-carbon fuels and technologies for large vessels.

Historically, energy consumption for international shipping was dominated by petroleum products, having a share higher than 99%, while in 2021 biofuels accounted for less than 0.5% of international maritime consumption (IEA, 2022). To achieve deep decarbonization of international shipping, energy efficiency alone is not sufficient and should be combined with fuel switch and the uptake of clean energy forms and technologies. Recent studies consider several low-carbon options and fuels for the sector, including liquified natural gas (LNG), biofuels, hydrogen, ammonia, and renewable electricity (IEA 2021). Accelerated innovation dynamics should be combined with ambitious deployment plans and robust policies to ensure that low-carbon fuels make inroads in the shipping sector already by 2030 and have significant contribution in the sectoral fuel mix by 2050 to reduce sector's dependency on oil-based fuels. The high diversity of potential low-emission fuels poses challenges in terms of technological standards, since shipping industry is concentrated in bunkering hubs (e.g., Rotterdam). Biofuels can be used in existing vessels and thus their deployment is easier in the current decade compared to mitigation options like ammonia and hydrogen, which require innovation, technological development, new infrastructure, and strong policy support for their deployment. In addition, hydrogen and ammonia have low energy density, which impacts the economics of the shipping industry (IEA, 2022). As vessels have long lifetimes and their stock turnover is slow, accelerated innovation and uptake of zero-emission technologies is crucial to ensure that international shipping would achieve deep decarbonization by 2050.

The existing vessel fleet is almost entirely based on compression ignition engines, which can only work with bunker- and diesel-like fuels (DNV, 2020). The deployment of clean fuels depends on the timely development of new technologies, including dual-fuel engines and electrochemical powertrains. Recently, there are some small, positive developments as 85 zero-emission vessel pilots and demonstrations were initiated during 2021 and the first quarter of 2022 using ammonia or hydrogen technologies for shipping, battery-powered vessels, and methanol vessels (Global Maritime Forum 2022). The share of alternative fuels and zero-emission technologies in the orders for new ships is also increasing, especially for ammonia-ready and hydrogen-ready vessels. New fuelling infrastructure will be required to support the use of zero-emission fuels for international shipping, with ammonia and hydrogen bunkering infrastructure projects already under construction. In addition to bunkering infrastructure, efforts are needed to establish the entire fuel supply chain for zero-emission fuels, including fuel production, transport, distribution, and storage.

In recent years, sulphur regulations have pushed LNG into the international shipping industry, with vessels equipped with LNG systems becoming increasingly common. The demand for LNG as shipping fuel is expected to further increase by 2030 (EC, 2021). Although LNG is relatively free of atmospheric pollutants, it is a fossil resource, with limited emission reduction potential. Furthermore, fugitive methane emissions may occur throughout its supply chain and even on ships, worsening LNG's performance as an alternative fuel (IRENA 2021).

Recently, there is increasing awareness on the need to reduce emissions from the shipping sector. In 2021 the IMO adopted a series of measures, which are expected to enter into force in late 2022, to achieve the target of reducing the carbon intensity of shipping by 40% by 2030. These measures include mandatory goal-based technical and operational requirements, to pave the way for meeting the IMO target of reducing emissions by at least 50% in 2050 relative to 2008 levels. In mid-2021, the European Commission proposed the FuelEU Maritime initiative (EC 2021), which imposes constraints on the average annual emission intensity of energy used by ships. These constraints become stricter over time, starting with a 2% reduction in 2025, increasing to 6% in 2030 and further to 75% in 2050 relative to 2020. The implementation of these constraints would lead to a gradual uptake of low-carbon fuels for voyages within the EU countries and for voyages to and from the EU. However, there are concerns that this initiative risks supporting the deployment of LNG and constraining the transition towards zero-emission shipping. In addition, the US House of Representatives introduced the Clean

Shipping Act of 2022 (Clean Air Act, 2022), which would set carbon intensity standards for marine vessel fuels, based on the EU's framework. The limits in the US proposal are more stringent than those proposed by the European Union, requiring 100% zero-emission fuels from 2040 onwards.

Several declarations about the uptake of low- and zero-emission fuels in the shipping industry were made at the UN Climate Change Conference in 2021 (COP26). The most remarkable of these was the Clyde-bank Declaration for green shipping corridors (COP26 Department for Transport, 2022), signed by more than 20 countries, aiming to support the establishment of at least six zero-emission shipping corridors between ports by 2025. In addition, at COP26, 14 countries signed the Declaration on Zero Emission Shipping by 2050 (UN Climate Change Conference 2021) pledging to push the IMO to adopt a target of full decarbonization of international shipping by 2050. Since the declaration, a green corridor was already announced through a partnership between Shanghai and Los Angeles, in addition to the announcement for a European Green Corridors Network. At COP26, 55 countries declared to call on the IMO to establish a mandatory GHG levy on international shipping to align the sector with the 1.5°C goal set out in the Paris Agreement.

As the current IMO targets fall short of ensuring compatibility with Paris goals and the shipping sector is challenging for national governments to regulate, private businesses can also contribute to the sector's transformation. An example of collaboration between the private and public sectors is the establishment of Clean Energy Marine Hubs in 2022 to support the uptake of low-emission fuels in international shipping. In parallel, various industry players related to the shipping sector established an alliance to accelerate emissions reductions through the accelerated innovation and deployment of cost-efficient zero-emission vessels in the current decade. Lastly, there is an active policy debate on how to integrate climate aspects and decarbonization targets into the decisions of the shipping industry.

4.3.2 International Aviation

Aviation accounted for over 2% of global energy-related CO2 emissions and has grown faster in recent decades than other transport segments. After increasing at an average of 2.3% per year over 1990-2019, the Covid-19 pandemic led to a significant decline of aviation emissions, which dropped from over 1000 Mt CO2 in 2019 to 600 Mt in 2020 (IEA, 2022). Global aviation emissions rose again in 2021 to about 720 Mt CO2, re-bounding to a level between their pre-pandemic peak in 2019 and the level in 2020. Aviation emissions are expected to grow rapidly in the future, surpassing their 2019 peak level in the coming years. As a result of this projected emissions growth, the aviation industry could potentially consume 27% of the global carbon budget for 1.5 °C by 2050 (Pidcock, R., & Yeo, S., 2016).

Global aviation passenger demand recovered gradually in 2021 after the COVID disruption, with domestic traffic at 68% of 2019 levels and international traffic at just 28% (IEA, 2022). This represents an overall increase of 28% versus 2020, but traffic is not expected to fully recover to 2019 peak levels until 2023. Air cargo, however, showed stronger growth in 2021, rising by nearly 7% above the pre-pandemic peak. New aircrafts are up to 20% more efficient than those they replace (IEA, 2022), but this has been insufficient to keep up with rapidly growing activity. The average fuel efficiency in aviation has improved by 2.4% per year between 2000 and 2010 and by 1.9% from 2010 to 2019, showing that additional incremental efficiency improvements are becoming increasingly difficult. Following Covid-19, ICAO revised the projected annual growth of aviation activity to 2050 from 4.2% to 3.6%, while aviation emissions are set for a rapid growth due to constantly increasing aviation activity, limited efficiency improvements in aircrafts, and the continued dominance of oil-based fuels.

Aviation is one of the most challenging sectors to decarbonise (Hall et al, 2022), illustrated by a rapid increase of sectoral emissions in the last decades. This trend was interrupted in 2020 due to the COVID-19 and subsequent lockdowns, but (in the absence of strong policies) aviation activity and carbon emissions are set for a strong rebound. Although the Paris Agreement covers emissions from all sectors, including aviation, most Parties have not included emissions from international flights in their NDCs). These emissions are explicitly addressed by the ICAO that represents the 'appropriate forum' to regulate emissions arising from aviation (ICAO, 2016). In 2010, ICAO established the goal of carbon-neutral growth from 2020 onwards, that is, to stabilise international aviation's CO2 emissions at 2020 levels. In 2016 a market-based mechanism was adopted – the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) – to address the sector's rapidly rising emissions (ICAO, 2016). CORSIA is a global offsetting scheme complementing other measures towards meeting the sector-wide goal of carbon-neutral growth from 2020 onwards (ICAO, 2016). Under the scheme, airlines and other aircraft operators are required to offset any increase in their CO2 emissions from international flights above 2020 levels (ICAO, 2019). Operators can minimize their offsetting obligations by using CORSIA eligible fuels, including sustainable aviation fuels (SAFs, renewable or waste-derived), as well as lower-carbon aviation fuels (ICAO, 2018).

The expected impact of CORSIA was assessed in the UNEP Gap report (UNEP, 2017), which concluded that CORSIA could reduce emissions from international aviation between 0 and 0.3 GtCO2 by 2030, com-pared to an increase from 0.5 to 1.1 GtCO2 under a no policy scenario in the period 2017–2030. The large range of estimations highly depends on the way the offsetting rules will be set, and on the quality of the off sets allowed under CORSIA. Larsson, (Larsson et al., 2019) showed that existing aviation policies will not deliver large emission reductions and stronger international policy instruments are needed to ensure that the sector con-tributes to achieving the Paris goals.

Sustainable aviation fuels (SAFs), low-carbon substitutes for fossil jet kerosene, are critical to decarbonizing aviation. The uptake and commercialization of SAFs is subject to blending limits, but recent flight trials (ATR, BRA, NESTE, 2022) have demonstrated the prospects towards 100% SAF. To ensure compatibility with the transition towards net zero, the share of SAFs in aviation should increase from less than 0.1% in 2021 to around 10% in 2030 (IEA, 2022). This requires massive investment in production capacities and transportation networks as well as ambitious policies, including low-carbon fuel standards, fuel taxes and mandatory blending. However, the upscale of sustainable aviation fuels faces challenges, as the recently proposed EU legislation (Council of the European Union, 2021) excludes purpose-grown crops from SAFs due to sustainability concerns, while volumes of SAF from wastes are limited. Renewable synthetic kerosene is relatively far from commercialization, due to its techno-logical immaturity and high production costs, but it is also highly scalable and has a superior carbon balance than biofuels (IEA, 2022). In addition to the uptake of low-emission fuels, accelerated efficiency improvements of the aircraft fleet are required based on improvements to engines, aerodynamics, and mild hybridization. Measures to curb aviation demand can also be introduced to reduce aviation emissions (IEA, NZE 2021), including a shift to high-speed rail, reducing business flights (e.g., more teleconferences) and a frequent flyer levy.

Electrified or hydrogen-powered aircrafts, can also reduce emissions in short- to medium-range operations by switching to alternatives to jet kerosene fuel. However, alternative propulsion has limited near-term potential, as commercial availability of such designs is expected after 2030. Battery electric aircrafts have no direct emissions, potentially much lower operational and maintenance costs (depending on battery durability), and high efficiency relative to the current aircraft fleet. However, current battery energy density and weight severely restrict the range of battery electric flights and the size of aircrafts. The current energy density of Li-ion batteries should be at least quadrupled to make them viable for short-haul flights over 1000km; until then, batteries are only used in prototypes and pilots (Schäfer, *et al., 2019*). Hydrogen can be used via direct combustion in jet engines, through fuel cells to generate electricity for electric motors, or a combination of both with Airbus leading the way in large hydrogen-powered aircrafts. However, using hydrogen in aircraft poses high challenges including the need for innovative fuel storage and delivery methods, low-cost and lightweight cryo-genic tanks, and redesigned airframes to accommodate them.

There is a growing number of regulatory and policy frameworks addressing the aviation sector, including the EU's proposed ReFuelEU Aviation (European Commission, 2021), which includes incentives for SAF uptake and blending mandates, and the United States' proposed SAF Grand Challenge (IATA, 2021). The ReFuelEU proposed regulation includes an obligation to integrate a minimum share of SAFs into fossil kerosene (blending mandate) starting in 2025 and increasing to 63% in 2050. In addition, a sub-target is also introduced for synthetic kerosene starting in 2030 and increasing gradually to 28% by 2050. The intra-EU flights are subject to the EU ETS system, while other measures can be utilized to drive the sector's transformation (e.g., tax on fossil kerosene). The aviation decarbonization requires strong collaboration between governments, consumers, and the private sector along the supply chain, including low-carbon fuel producers, infrastructure developers and airlines.

Under the CORSIA scheme, airlines are required to offset emissions growth from pre-pandemic level, covering most international flights after 2027. The success of CORSIA will highly depend on the quality of carbon offsets, which currently have lower costs than SAFs. In 2021, the member airlines of IATA (International Air Transport Association) pledged to achieve net zero CO2 emissions by 2050 (IATA, 2021). IATA covers 83% of global air traffic and aims to reduce aviation emissions using SAFs, more efficient technologies, and infrastructure, while residual emissions will be dealt with using offsets. The Air Transport Action Group (ATAG), including aviation stakeholders and businesses, has also developed a pathway to net zero emissions by 2050 (Air Transport Action Group, 2021), with ICAO expected to also introduce a long-term aspirational climate goal.

4.4 Materials and Methods

The section presents the methodological improvements implemented in PROMETHEUS to enhance the representation of the international maritime and aviation sectors and the study design.

4.4.1. The PROMETHEUS energy system model

PROMETHEUS is a comprehensive global energy system model focusing on energy and climate policy analysis, energy system planning and the development of mitigation pathways (Fragkos 2021, Fragkos and Kouvaritakis, 2018). It captures the interactions between energy demand and supply at regional and global level and provides detailed projections of energy consumption and fuel mix by sector, power generation by technology, carbon emissions, energy prices and investment. It provides medium- and long-term projections of detailed energy balances by region up to 2050. The model is used to analyse the energy, emissions, and cost implications of mitigation pathways, low-emission development strategies and climate policy measures differentiated by region and sector. It also explores the economics of energy production and assesses the interplay of climate policies with the future development of international energy prices. PROMETHEUS is a technology-rich model that represents major low or zero-carbon technologies, and includes disruptive, negative-emission technologies (Biomass with CCS and Direct Air Capture).

PROMETHEUS is a recursive dynamic energy system simulation model. The decisions about the investment and operation of the energy system are based on myopic anticipation of future parameters (e.g., technology costs) and constraints. Market equilibrium is ensured where each representative agent (e.g., consumer or energy producer) uses information on costs and prices of energy commodities and decides on the allocation of resources. Market dynamics determine the interactions between agents with market-derived prices to balance energy demand and supply by region and sector.

Energy demand arises from three main sectors, i.e., transport, buildings, and industries, while several subsectors are identified, including private cars, freight transport, electric appliances, space and water heating, cooking, industrial processes etc. The evolution of energy demand by sub-sector is determined by the development of socio-economic or activity indicators (e.g., industrial production, transport activity, heating requirements etc.) and by the average cost (or price) of energy services through econometrically estimated elasticities. Specific technologies are represented in the model, e.g., different car types including conventional Internal Combustion Engine (ICEs), hybrids, plug-in hybrids, electric and fuel cell vehicles.

Power requirements are determined by the electricity consumption of buildings, industries and transport, grid losses, the security of supply margin (and other flexibility constraints), and own consumption of power plants (van Soest, et al 2020). Capacity investment on power generating technologies is determined by the total levelized cost of competing options (coal, oil, gas, nuclear, Carbon Capture and Storage, and several renewable energy technologies), which includes capital expenditure, Operating and Maintenance costs, fuel costs, and potential carbon costs. Low-carbon technology progress is endogenous in PROMETHEUS through learning by doing and learning by research.

PROMETHEUS quantifies CO2 energy-related and industrial process emissions and incorporates emission abatement technologies and policy instruments. The latter include both market-based instruments such as carbon pricing or cap-and-trade systems with differential application per region and sector, but also sector-specific regulatory policies and measures. The modelling framework incorporates various emission reduction options in all demand and supply sectors, including renewable power generation technologies (solar, wind onshore and offshore, hydro, biomass), mitigation options in transport (e.g., electric vehicles, biofuels, fuel cells), green hydrogen, Carbon Capture and Storage, and detailed electrification and energy efficiency options in all demand sectors. It also includes Carbon Dioxide Removal options, e.g.,Biomass with CCS (BECCS). PROMETHEUS can thus be used for the impact assessment of energy and climate policies at regional and global levels, including price signals, such as carbon pricing or energy taxation, subsidies, energy efficiency and renewable energy supporting policies, and technology standards (Fragkos et al 2015).

4.4.2 Model improvements related to international transport

PROMETHEUS has been significantly enhanced with an improved representation of the international maritime and aviation sectors, based on more granular modelling, the inclusion of various technologies, emission reduction options and low-emission fuels, and the integration of new data and information on mitigation potentials and activity projections from recent literature. The model fully incorporates data on COVID-19 impacts on international trade and transport.

In particular, the aviation sector activity is split into domestic and international aviation in the new PROMETHEUS version to better represent the emission, energy, and technology dynamics as well as the emission abatement options in each sector. The (domestic and international) aviation activity is calculated based on the evolution of GDP and population with price elastic demand reflecting the sensitivity of demand to fuel prices and carbon taxes by region (equation 20).

$$AV_{r,t} = AV_{r,t-1}\left(\frac{GDP_{r,t}}{GDP_{r,t-1}}\right)^{\alpha}\left(\frac{price_{r,t}}{price_{r,t-1}}\right)^{\beta}$$

Where $AV_{r,t}$ represents the aviation services demand for time t and region r, α is the income elasticity, β is the price elasticity, $GDP_{r,t}$ is GDP of region r, and $price_{r,t}$ is the average price for aviation services. Required inputs are the assumptions on the socio-economic developments (i.e., GDP) until 2050 and the average price trends, which are endogenously determined by PROMETHEUS and are influenced by price dynamics of energy commodities and the potential imposition of carbon or energy taxes. There are numerous uncertainties on the exact values of elasticities. Based on a detailed literature review, different ranges can be considered based on different types and range of flights (national, international). Among all options, an average range of (1.2, 1.8) for income elasticity and a range of (-0.1, -0.25) for fuel price elasticity is chosen across regions (Gallet, 2014; InterVISTAS, 2007). Income elasticities take positive values, implying that increasing levels of GDP (or income) would result to higher aviation activity. On the other hand, negative values for fuel price elasticities mean that increasing fuel prices would lead to lower aviation activity.

Efficiency improvements in the sector are mostly prescribed based on investments made (e.g., through the introduction of new more efficient planes), representing operational efficiency developments. Energy intensity projections of aviation are updated based on ICAO goals (annual improvement of 2% between 2020 and 2050) and on PRIMES Aviation model (E3MODELLING, 2018). In addition, the potential of modal shift from short-haul flights to high-speed rail is introduced in the model based on the relative costs of passenger modes and the impact of climate policies. The enhanced PROMETHEUS version represents various fuels that can be used in aviation, especially fossil fuel based (kerosene), bioenergy-based (biokerosene), and synthetic kerosene. It also includes hydrogen as a potential aviation fuel and represents an electric plane technology, but its uptake remains limited in alternative scenarios due to high costs and limited commercialisation potential.

In the Reference scenario, aviation demand is calibrated to reproduce the projections from the AIM parametric aviation model (Dray, et al, 2022). Aviation demand changes in alternative scenarios driven by changes in fuel prices and the potential imposition of carbon or energy taxes. Aviation activity has been separated between domestic and international flights, based on the data and estimates from the AIM parametric aviation model (Dray, L., et al, 2022) and a detailed mapping of country-level data of AIM model with the PROMETHEUS regions (Fragkos, Kouvaritakis 2018).

The second major modelling improvement in PROMETHEUS is related to the incorporation of detailed data on fuel prices and technology costs from the sectoral detailed PRIMES Aviation module, which was used for the ReFuel EU Aviation impact assessment (European Commission, 2020). In addition, new, clean technologies and low-emission, sustainable fuel types are introduced in the model, which can be deployed to reduce aviation emissions towards meeting the Paris Agreement goals. In particular, the model now includes biokerosene (split into HEFA and biokerosene produced by advanced processes like Fischer Tropsch), produced using biomass resources. The production of synthetic aviation kerosene has also been introduced, using green hydrogen and renewable-based electricity. The aviation activity and demand in PROMETHEUS can be met with a combination of conventional kerosene, bio-kerosene, hydrogen, and synthetic kerosene. In the absence of decarbonization policies, the price of oil products is projected to gradually increase due to increasing global demand combined with tighter supply, as low-cost oil resources are gradually depleted. This is reflected in the increasing price of fossil kerosene, which becomes comparable with the one of HEFA biokerosene by 2030 and beyond (Figure 32). The technologies used to produce synthetic kerosene will gradually become commercially mature by 2040 through accelerated innovation, technology learning and uptake combined with economies of scale. However, even in 2050 they do not reach parity with fossil gasoline.

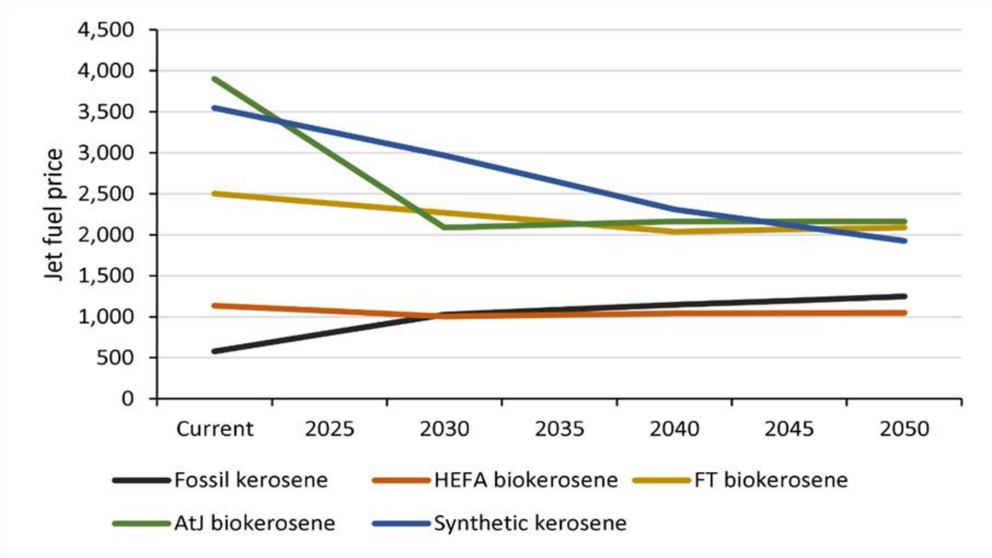


Figure 31: Global average prices of fuels used (in Eur/tonne)

In the shipping sector, PROMETHEUS distinguishes inland navigation and international shipping; activity in the latter is split by shipping segments i.e., dry bulk carriers, general cargo, containers, and tankers. In the latter, activity is endogenously estimated in PROMETHEUS driven by the regional trade of fossil fuels, while in other shipping segments activity is exogenous, calculated using GEM-E3 bilateral trade projections (Paroussos, et al 2015) mapped into PROMETHEUS regions. The activity of tankers depends on the evolution of fossil fuel trade across regions, which is determined endogenously as part of the global energy demand and supply projections of PROMETHEUS. This allows us to analyse the linkages between domestic climate policy and international shipping through the reduction of demand and thus international trade of fossil fuels.

The representation of shipping sector in PROMETHEUS has been improved with an incorporation of detailed data on fuel prices and technology costs from the PRIMES Shipping module (European Commission, 2021). In addition to the conventional fossil fuels (RFO, Marine Gas Oil or LNG), new, low-emission, sustainable fuel types and clean vessel technologies are introduced in the model (e.g., biofuels, synthetic e-fuels, ammonia, hydrogen), whose uptake is triggered by ambitious climate policies and the introduction of emission or technology standards. The different technologies and fuels compete with each other based on the evolution of their total costs, including capital, operating, fuel and carbon costs, technical efficiencies, energy densities and other characteristics (e.g., infrastructure barriers, innovation potentials). Energy efficiency is also represented endogenously, based on technological improvement, operational efficiency, engine improvements, and increased energy prices. The various emission reduction options, including energy saving possibilities, speed reduction, and use of alternative low-emission fuels (IMO, 2020), have been explicitly introduced in the model, based on data from PRIMES-Maritime model (EC, 2021), enabling PROMETHEUS to quantify the transformational dynamics in the shipping sector towards deep decarbonization.

There are important inter-linkages between international shipping and the global energy system, with the bulk transportation of fossil fuels being the most evident example. In addition, marine fuels are usually a by-product of the production of gasoline, kerosene, and road diesel, which have greater value added. As such, oil refineries are rarely focused on the production of bunker fuels. The decarbonisation of the shipping sector would increase the demand for hydrogen and ammonia, whose production and transport are integrated in the global energy modelling framework. Hydrogen is needed to produce synthetic fuels, while ammonia production requires nitrogen and synthetic methanol carbon. In PROMETHEUS, hydrogen is produced by electrolysis or steam methane reforming (with or without carbon capture and sequestration) and carbon can be used from carbon capture and utilisation (CCU)or direct air capture (DAC) technologies (Capros et al 2019). For ammonia production, the air distillation technique is applied to produce nitrogen. The Haber Bosch process is then used to produce ammonia that needs to be stored and distributed to harbours. For synthetic methanol, we use carbon from DAC or CCU from biomass but not from fossil fuels to ensure the carbon neutrality of synthetic fuel. The methanol is then synthesized by the catalytic reaction and used in the shipping sector. Technology costs are harmonized with the official EC Reference scenario (EC, 2020).

4.4.3 Scenario design

The modelling enhancements, updates and improvements of PROMETHEUS described above are then used to quantify alternative scenarios aiming to achieve global decarbonisation. The climate mitigation scenarios assume that the Paris Agreement temperature goals of well-below 2°C and 1.5°C are achieved through a universal carbon pricing across regions and sectors. As the study focuses on assessing the role of international transport towards global decarbonisation, the scenario design does not impose any sectoral targets, but harmonizes input assumptions for socio-economic development and climate policies and car-bon budgets to those commonly used in IAMs (Rogelj et al 2018).

The Reference scenario (REF) assumes that global population and GDP develop in line with the Shared Socioeconomic Pathway (SSP2) scenario with short-term updates to account for the Covid-19 impact. In this scenario, all countries achieve their Nationally Determined Contributions as submitted in COP21 in Paris by 2030. In the period after 2030, the climate policy effort is extrapolated, by assuming that its stringency re-mains constant (but does not increase)- in line with (Van Soest et al 2021) with regional carbon prices in-creasing after 2030 with the same growth rate as GDP of each region.

In the 1.5deg scenario, a global carbon budget (i.e., cumulative carbon emissions) of 650 GtCO2 over the period 2020-2100 is imposed, while in the 2deg scenario the carbon budget amounts to 1000 GtCO2 in line with the IPCC AR6 (IPCC, 2022). The scenario achieves the Paris Agreement goals with the least total cost, by equalising the marginal abatement costs (i.e., carbon prices) among regions and sectors, and using all mitigation options in energy demand and supply sectors. The activity of international shipping and aviation sectors is influenced by the imposition of carbon prices and is projected to decline by 15%-20% from REF levels due to the increase of energy prices, while the socio-economic drivers remain identical as in REF. The choice of carbon budget values is based on model capabilities and warming categories, as defined by the IPCC AR6 (IPCC 2022; Riahi et al. 2022), with a carbon budget of 650GtCO2 considered compatible with a warming of 1.5oC or slightly above, while 1000Gt scenarios would reflect a world likely below 2oC.

In addition, two variants of the 1.5deg scenario are developed, with modified activity assumptions, aiming to evaluate the robustness of modelling results with respect to the uncertain evolution of transport activity. The 1.5deg Low Demand scenario (1.5deg_LD) assumes lower aviation activity than 1.5deg (about 35% reduction after 2030) due to lifestyle changes towards more environmentally sustainable behaviours in line with the "Green-Push scenario" (Kikstra et al., 2021), where aviation activity is lower than REF and 1.5deg levels and consumer preferences shift towards domestically produced goods thus reducing the need for global trade and shipping activity. In contrast, in the High Demand scenario (1.5deg_HD) the international shipping and aviation activity stands at REF scenario levels, i.e., higher than in 1.5deg scenario.

Table 11: Scenario assumptions used in the study

Scenario name	Description	Carbon budget
REF	Considers current policies and 2015 NDC pledges, SSP2 socioeconomic assumptions	-
2deg	Meets the 2C carbon budget with a cost-optimal manner	1000 $GtCO_2$
1.5deg	Meets the 1.5C carbon budget with a cost-optimal manner	650 $GtCO_2$
1.5deg_LD	Meets the 1.5C carbon budget with lower aviation and shipping activity than 1.5deg	650 $GtCO_2$
1.5deg_HD	Meets the 1.5C carbon budget with higher aviation and shipping activity than 1.5deg	650 $GtCO_2$

4.5 Model-Based Results

This section presents the model-based scenario results on decarbonization pathways for the international shipping and aviation sector using the enhanced PROMETHEUS model described above.

4.5.1. Transformation of the aviation sector

In the Reference scenario, the aviation sector is set for a major expansion with the global aviation activity projected to increase by 4.2% per year over 2015-2050 (Figure 33). A relatively fast recovery from COVID-19 disruption is assumed, in line with IMO forecasts of aviation activity. This is driven by a strong and efficient vaccination programme, limited lockdowns, and no further major outbreaks of the Coronavirus. The aviation activity will grow even more rapidly in emerging economies (e.g., 5.2% p.a. in China and 6.8% p.a. in India over 2015-2050), driven by fast GDP growth, increasing population and risings standards of living, with a rapid expansion of business and touristic trips, as flight tickets become increasingly accessible to the local population.

Global CO2 emissions from aviation are projected to increase in REF from about 880 MtCO2 in 2015 to 1800 Mt CO2 in 2050, driven by strong activity growth. In the absence of strong climate policies and carbon pricing, fossil kerosene continues to dominate the energy mix of aviation by 2050. However, the gradual deployment of more efficient technologies, the improved operational management of the aircraft fleet and overall efficiency improvements imply that energy demand and CO2 emissions increase a lot less than the aviation activity; the annual growth of aviation-related CO2 emissions is 2.1% p.a. in REF over 2015-2050 (mostly driven by developing economies), while the growth rate of aviation activity is estimated at 4.2% p.a.

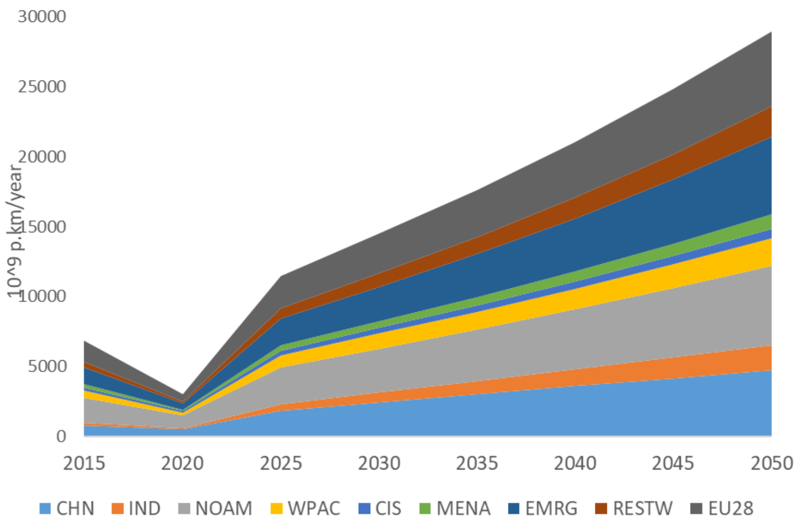


Figure 32: Aviation activity by region in PROMETHEUS REF scenario

The evolution of aviation activity is endogenously determined in PROMETHEUS, based on socio-economic drivers and energy prices. Therefore, in the mitigation scenarios, where carbon pricing increases the prices of energy commodities, the aviation activity is reduced from REF levels by about 13% in 2deg and 27% in 1.5deg scenario in 2050 (Figure 34). The 1.5deg_LD scenario assumes even lower aviation activity due to lifestyle changes towards more environmentally sustainable behaviours in line with the “Green-Push scenario” (Kirkstra et al 2021). In this scenario, global aviation activity stands at 32% lower levels than 1.5deg scenario in 2050 (and 50% lower than REF scenario). In contrast, aviation activity in the 1.5deg_HD scenario is the same as in REF scenario to explore the impacts of high activity levels on sector’s decarbonization.

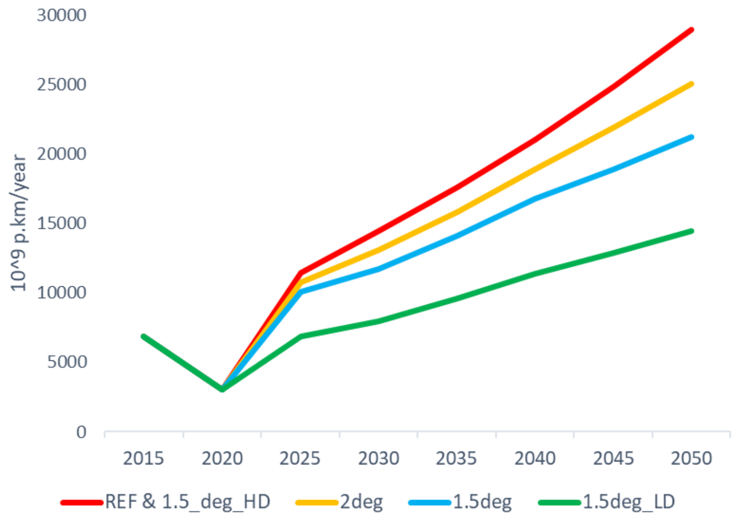


Figure 33: Global aviation activity in the series of scenarios over 2015-2050

Figure 35 shows the evolution of global CO2 emissions from aviation in the series of scenarios. In the REF scenario, emissions are set to strongly increase as fossil kerosene continues to be the lowest cost fuel in the sector (in the absence of strong carbon pricing) and other low-emission aviation fuels are not massively deployed due to their high costs and immaturity. However, in the decarbonisation scenarios, the high carbon pricing induces large changes in the fuel mix used in aviation, as fossil kerosene price increases substantially, while the competitiveness of low-emission fuels (i.e., biokerosene, synthetic kerosene) increases and their uptake accelerates especially after 2030. The costs of these new clean technologies decline substantially triggered by economies of scale, innovation, and accelerated learning-by-doing effects.

As the deployment of low-emission jet fuels increases, CO2 emissions from aviation are projected to de-cline rapidly, especially in scenarios with high climate policy ambition (1.5deg) and with low activity assumptions (1.5deg_LD). Aviation-related CO2 emissions in REF are projected to reach 1800 MtCO2 in 2050, while in 2deg they amount to 1140 MtCO2 and in the series of 1.5deg scenarios they decline to [320-580] MtCO2 indicating an emissions reduction of 68%-82% below REF levels. Emissions are higher when aviation activity is higher (1.5deg_HD), while the combination of strong mitigation efforts and low aviation activity drives a rapid emissions reduction by 2050. The 1.5deg scenarios achieve the ICAO goal of carbon-neutral growth until 2050 and lead to a reduction of cumulative emissions over 2020-2050 of about 35%-57% below REF levels. In the period to 2030, the differences in emission profiles reflect mostly differences in aviation activity and energy efficiency improvements rather than in the uptake of low-carbon fuels, which are massively deployed in the period after 2030.

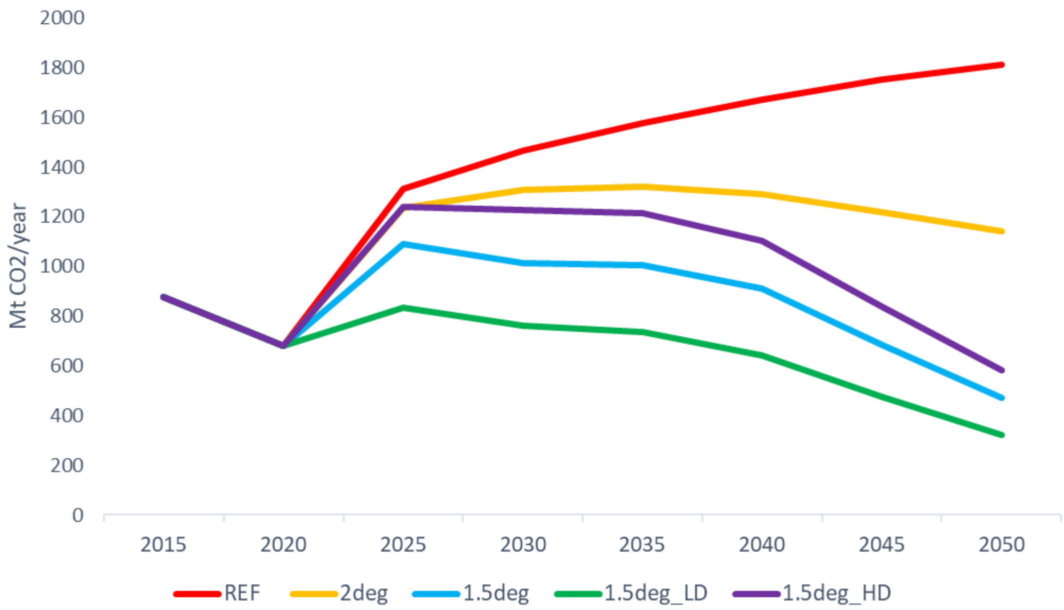


Figure 34:: CO2 emissions from the aviation sector in alternative policy scenarios

Fossil kerosene is currently the dominant fuel option in the aviation sector and is projected to remain so in REF scenario (Figure 35) with only a limited deployment of biokerosene (2% of sector's fuel mix in 2050). The consumption of fossil kerosene for aviation is projected to more than double, from 12.2 EJ in 2015 to 25.3 EJ in 2050 driven by the strong activity growth and despite the efficiency and operational improvements incorporated in REF scenario. As most Sustainable Aviation Fuels (SAFs) are not commercially available and currently have high costs and limited commercialisation, their deployment is limited by 2030 in all scenarios examined. The analysis shows that the decade 2021-2030 does not suffice to drive significant changes in the aviation energy mix, as fossil kerosene remains the lowest-cost option, despite moderate carbon prices until 2030. The innovation, development, commercialisation, and market uptake of SAFs cannot materialise in such a short period of time given the large technical and economic uncertainties and the lack of investment and appropriate infrastructure to develop large quantities of biokerosene and synthetic kerosene. However, after 2030, the rapidly increasing carbon pricing in the 1.5deg scenarios and the development of relevant technologies and infrastructure support the massive uptake of low-emission jet fuels. Therefore, while in 2030 low-carbon fuels account for [7%-9%] of sector's energy mix, in 2050 their share increases to about 60% in the 1.5deg scenarios (Figure 36). Both biokerosene and synthetic kerosene are projected to be massively deployed in the 1.5deg scenarios to replace fossil-based kerosene, and they contribute relatively similar amounts to the decarbonisation of aviation by 2050. The choice of low-emission fuels is determined endogenously by the model and depends on their production and transport costs and related implementation barriers (e.g., the sustainable supply of biomass or the potential for variable RES production by region). The uptake of SAFs has impacts beyond the aviation sector, influencing the development of the entire energy system, technology scale-up and resource use. In particular, the uptake of synthetic kerosene is based on the assumption that green hydrogen production and power-to-liquid technologies mature at sufficient rate to supply about half of the global demand for SAFs in 2050 but requiring large amounts of renewable energy stressing the solar and wind potentials in some regions (EC, 2021). On the other hand, the deployment of biokerosene has impacts on the biomass supply system in terms of resource consumption and competition for biomass with other sectors (especially other transport modes and industries).

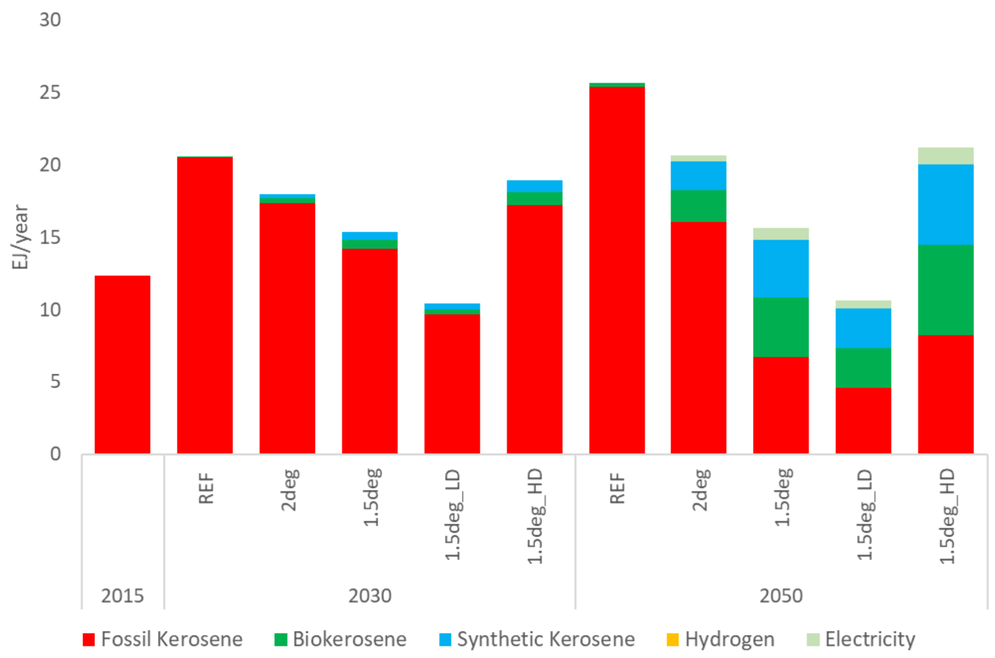


Figure 35: Global fuel consumption for aviation in alternative scenarios in 2030 and in 2050

The aviation sector could manage the associated cost increases, with ticket prices rising by no more than 15%-20% compared with the REF scenario. The modelling captures the full-scale market feed-backs and projects that the aviation sector could fully cover the costs of the transition towards 1.5deg or 2deg with limited cost increases leading also to modest reduction in aviation activity from REF levels (Figure 3). The highest cost increases in aviation are projected in the 1.5deg_HD scenario due to the combination of strong cli-mate action with high aviation activity levels requiring the largest uptake of expensive low-emission fuels. The increasing fuel costs (due to the large-scale deployment of Sustain-able Aviation Fuels, which are more expensive than fossil kerosene) are partly offset by energy effi-ciency improvements and learning-by-doing effects that may reduce the production costs of low-emis-sion fuels (Figure 37). Consequently, the air transport sector could continue to grow through the low-carbon transition, thereby enabling larger shares of the global population to use and benefit from air transportation. However, profitability of some airlines might decline, creating additional market chal-lenges; however, these changes are not captured by the model.

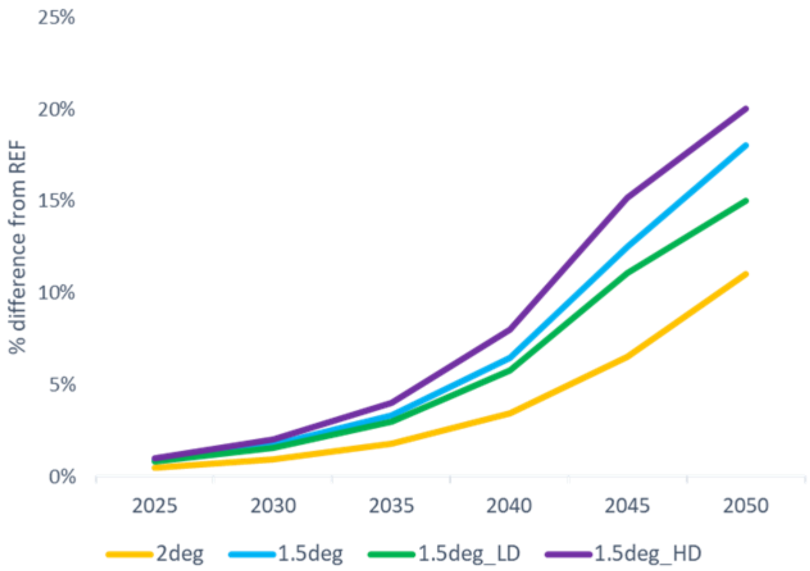


Figure 36: Increase in average aviation cost and airfare price from REF levels

4.5.2. Transformation of the international shipping sector

The international shipping activity is modelled to be driven by the evolution of global trade across regions for key shipping segments (containers, dry bulk, tankers) based on GEM-E3 trade projections (Fragkos et al 2021) mapped into PROMETHEUS regions. International maritime trade has doubled in the last twenty years (from 30,000 to about 60,000 billion ton-miles in 2020) and our REF scenario projects that it will continue increasing, albeit with a decelerated growth rate, to about 110,000 ton-miles in 2050 (Johnston et al. 2017). In the 1.5deg scenarios, the shipping activity is lower than in REF, due to rising energy prices that reduce the inter-regional trade flows, and most importantly due to the reduced fossil fuel consumption and trade, which is projected to decline by more than 60% by 2050, reducing the international maritime activity by around 20% in 2050 in line with the findings of (Müller-Casseres et al 2021). The impact of the 2deg scenario is found to be about half, causing a 10% decline in shipping activity from REF levels in 2050. The 1.5deg_LD scenario assumes even lower shipping activity than 1.5deg due to consumer preferences shifting towards domestically produced goods thus reducing the need for inter-regional, large-distance trade. In contrast, international shipping in 1.5deg_HD scenario is the same as in REF to explore the impacts of different activity levels on sector's decarbonization strategies (Figure 38).

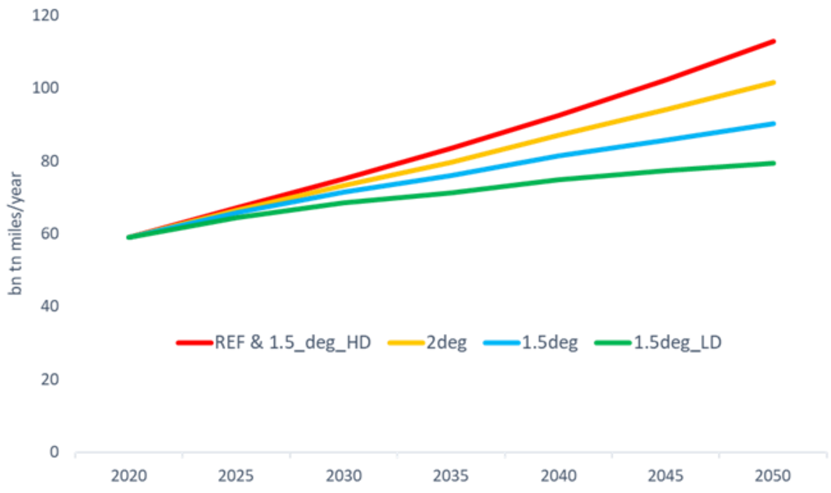


Figure 37: International shipping activity in the series of scenarios

The absence of strong climate policy in REF scenario means that the shipping sector continues to use fossil oil products (especially Heavy Fuel Oil and Marine GasOil), with only limited introduction of LNG especially in regions that have relevant plans. This implies that emissions from international shipping are projected to continuously increase from about 700 MtCO_2 in 2015 to 990 Mt CO_2 by 2050 driven by increasing maritime activity combined with limited changes in energy mix and energy efficiency improvements (Figure 39). However, the implementation of ambitious climate policies in the mitigation scenarios results in a transformation of international shipping sector, with the rapid introduction of LNG by 2030 (to achieve limited emission reductions relative to oil products) and the upscale of low-carbon fuels (e.g., ammonia, hydrogen, biofuels) after 2030 to replace fossil fuels. Consequently, CO_2 emissions from international shipping are projected to decline to 332 MtCO_2 in the 2deg scenario and even more to [100-250] MtCO_2 in the 1.5deg scenarios. Therefore, all mitigation scenarios achieve the IMO goal of 50% reduction of shipping emissions in 2050 relative to 2008 levels, while in the 1.5deg scenarios emission reduction reaches more than 70% in 2050. This is translated to a reduction of emissions from international shipping of more than 80%-90% below REF levels, aiming to align with the transition to net zero by mid-century with oil-derived fuels phased out by 2050.

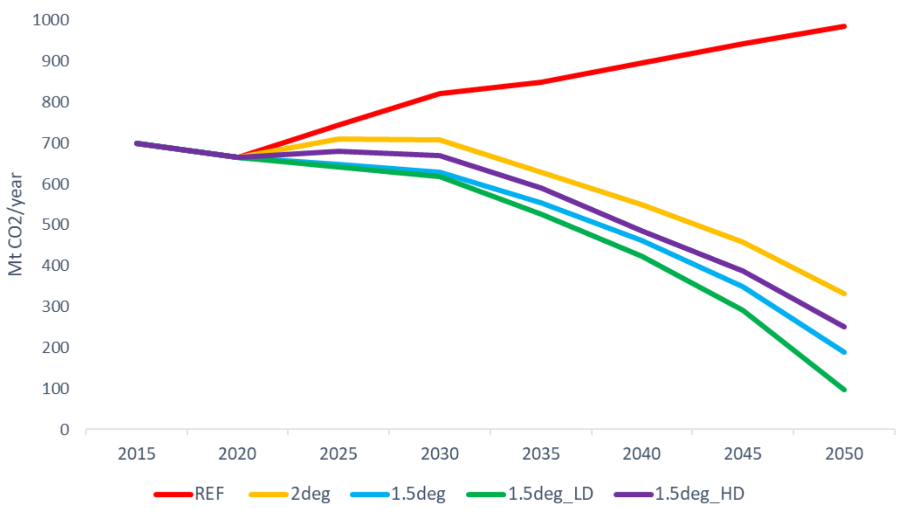


Figure 38: CO2 emissions from international shipping over 2020-2050

Historically, oil products have constituted over 99.5% of total energy for international shipping (Figure 40), while in recent years there is a limited deployment of LNG and biofuels, which currently cover less than 0.5% of energy demand in the sector. The REF projections show that the dominance of oil products will continue until 2050, due to their cost-competitiveness in the absence of strong climate policies and the lack of development and wide commercial uptake of alternative low-emission fuels. The REF scenario incorporates the current increase in the orders for new ships and vessels using LNG as a fuel, and thus shows that the share of LNG in sectoral energy consumption will increase from less than 0.3% in 2020 to 3% in 2030 and further to about 6% in 2050. The uptake of biofuels follows similar trends as LNG, resulting in improvement in the carbon intensity of international shipping. However, the bulk of maritime activity growth will be covered by oil products, whose consumption is projected to increase by about 0.9% p.a. over 2015-2050.

To get on track with the ambitious mitigation scenarios, the penetration of alternative fuels, including biofuels, hydrogen, ammonia, and electricity, will need to rapidly increase. By 2030, low-carbon fuels represent about 14%-18% of energy demand in the mitigation scenarios. More than half of the low-carbon fuel use in 2030 is projected to be in the form of biofuels, which can be used in existing vessels and do not require significant investment in new engines, vessels, and infrastructure. In the mitigation scenarios, LNG is used as a bridge between the use of petroleum products and the large availability of low-carbon fuels in the longer term. LNG deployment is projected to increase somewhat by 2030, covering about 7% of the sector's energy consumption, but this share stagnates and even declines by 2050 driven by the technology improvements and commercial uptake of low-emission fuels, like ammonia, hydrogen, and biofuels.

In the decade 2020-2030, technological development and associated policy support will be important to enable the use of other low-emission fuels, particularly ammonia and hydrogen, to reduce dependency of the sector on oil-based fuels. Due to the long lifetimes of vessels and the slow stock turnover, near-term innovation and zero-emission technology adoption are critical to putting international shipping on the deep de-carbonization pathway. In the 1.5deg scenarios, low-emission fuels cover 87% of energy use in the shipping sector in 2050, based on a combination of biofuels -including Bio-LNG- (about 50%) and ammonia/hydrogen (about 30%). The fuel shares are endogenously determined in PROMETHEUS based on their emission re-duction potential and relative costs which lead to a somewhat higher contribution of biofuels to the detriment of the more expensive synthetic fuels, as the latter have higher costs. The sector has limited mitigation options and biofuels are expected to play a large role in the shipping transformation, despite the competition for biomass resources with other energy sectors (e.g., road transport, aviation, power generation), which is considered in PROMETHEUS modelling (in contrast to sectoral modelling studies like (Bouman et al 2017). In addition to fuel switching and the large uptake of low-emission fuels, emission reductions are also achieved due to energy efficiency improvements and the reduced international shipping activity as a result of fuel price increases and reduced international trade of fossil fuels. The latter indicates a positive feedback effect of clean energy transition on the shipping sector, with domestic climate action reducing the inter-regional trade of fossil fuels and maritime activity thus facilitating the decarbonization of international shipping. The 1.5deg_LD scenario combining ambitious decarbonization and low activity growth (e.g., due to shortened value chains and trade re-organization) reduces the need for biofuels and synthetic fuels (ammonia, hydrogen) and thus contributes to lower the pressure on the global energy system. However, the potential activity effects due to the increase trade of clean energy products (e.g., solar panels, batteries, wind turbines) is not captured by the modelling framework.

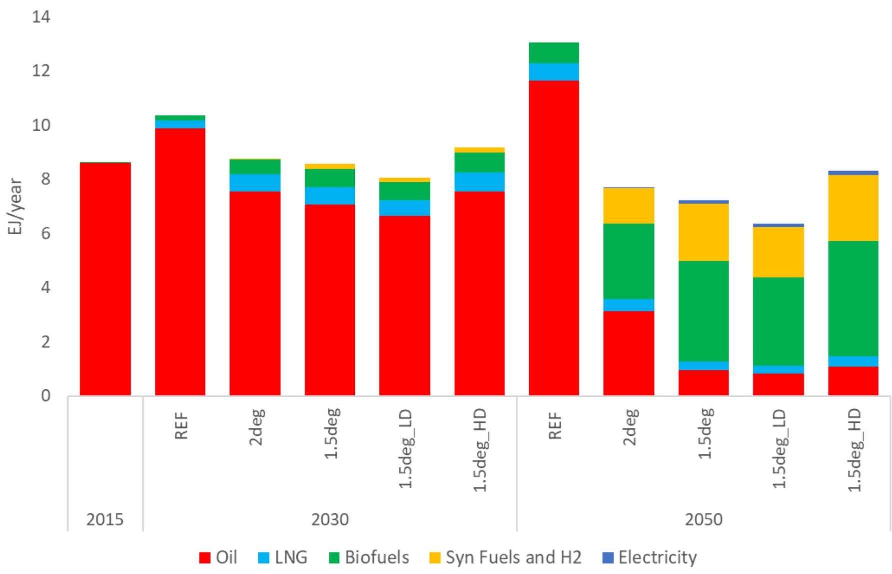


Figure 39: Energy consumption by fuel for international shipping in 2030 and in 2050

The total costs of maritime (including capital costs, operation and variable non-fuel costs and fuel costs) increase in all scenarios from current levels driven by the constantly increasing activity of international shipping. Fuel costs account for more than 50% of the total maritime costs, while capital costs account for about one third and variable and variable non-fuel costs for about 20%. The implementation of strong cli-mate policies would lead to fuel switches in the sector towards lower emission but more expensive fuels (like biofuels and synthetic fuels) and energy efficiency improvements, which require high upfront capital costs. The model-based analysis shows that the shipping sector would face modest cost increases with the average shipping cost projected to increase by 8%-14% in the alternative mitigation scenarios relative to REF levels in 2050. The highest cost increases are projected for the 1.5deg_HD scenario (Figure 41), given that in this scenario the deployment of expensive low-emission fuels is the largest as they are needed to cover the strong growth of shipping activity.

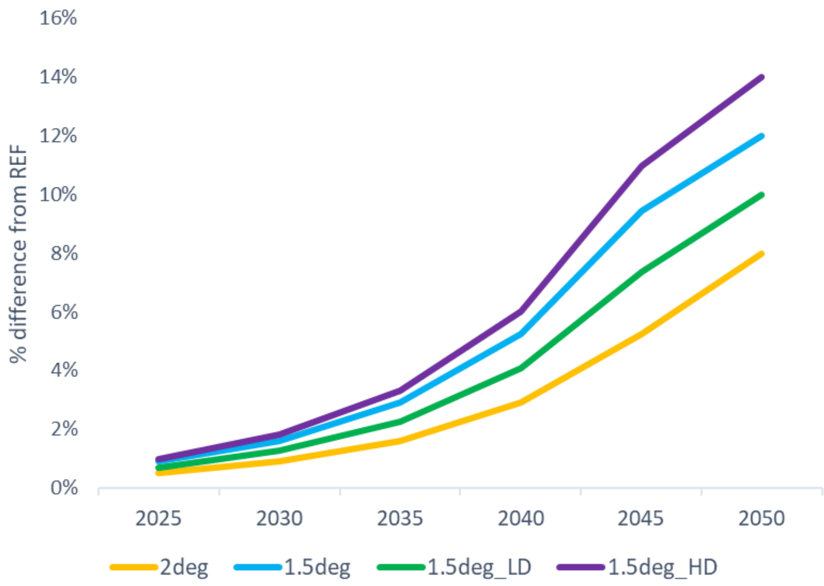


Figure 40: Cost differences in the shipping sector between the scenarios

4.6 Discussion

The international shipping and aviation sectors are set for a significant increase in their emissions if current policies are implemented, driven by rapid activity growth (Faber et al 2020). However, to be compatible with Paris goals, both aviation and shipping sectors need to rapidly reduce their CO2 emissions. Since the electrification of both sectors is technically challenging and the energy efficiency gains provide only limited mitigation potential, supply-side mitigation option such as low-carbon fuels are the most important emission reduction strategies in these sectors, with the uptake of biofuels and synthetic e-fuels being the most prominent options. However, it is worth noting that deep emission reductions in the international shipping and aviation sectors require both demand and supply mitigation options as the uptake of low-carbon fuels is not a silver bullet and faces also large uptake and commercialization barriers. Our analysis shows that the decarbonisation of international transport requires radical changes to reduce demand and massively develop and use low and zero-emission sustainable fuels, which currently face large uptake and commercialization barriers due to their high costs and lack of technical and commercial maturity.

In the shipping sector, operational emission standards with mandatory requirements for ships to reduce their carbon intensity can pave the way for the deployment of low-emission fuels. These standards al-low market participants (e.g., shipping companies) to choose the most convenient and suitable compliance strategy while gradually tightening requirements for lowering the carbon intensity of vessels. However, to pave the way towards deep decarbonization, such standards should be tightened in the next decade, as progress in decarbonising the shipping sector must be made before 2030 given the slow stock turnover in the sector. The increased stringency of operational carbon intensity standards would encourage the uptake of low-carbon fuels, especially if material non-compliance measures are implemented. In addition, regulating well-to-wake emissions, including all emissions associated with fuel extraction, production, processing, de-livery, and onboard combustion, can support the transition to truly low-carbon fuels and avoid incentivizing the reallocation of emissions from onboard operations to upstream fuel production processes. The combination of carbon pricing (as in the scenarios presented above) with regulatory measures (i.e., intensity standards, blending mandates) can drive the transformation of the international shipping sector. In this context, the combination of ambitious decarbonization policies with low activity growth (e.g., due to shortened value chains and trade re-organization) reduces the need for biofuels and synthetic fuels (ammonia, hydrogen) and thus contributes to lower the pressure on the global energy system.

The required transformation of international shipping requires additional investment to develop the required infrastructure, new vessels, ports and to produce the low-emission fuels. It requires an ambitious and predictable policy landscape and clear regulations to support sector's decision makers into investing in low-emission fuels and infrastructure. Directly mandating quotas of certain zero-emission fuels and technologies is essential to create a guaranteed demand for the technology providers and green fuel suppliers and to incentivise investment in clean fuel production and supply. Direct mandates are increasingly used in other transport sectors, including the zero-emission vehicle mandates for road transport and the proposed ReFuelEU Aviation regulation (EC, 2021), which set minimum quotas for the deployment of zero-carbon fuels and/or technologies. Such measures can help avoid unintended effects that could stem from carbon in-tensity standards that are not sufficiently ambitious and/or do not incorporate well-to-wake emissions, i.e., a large uptake of LNG to provide a medium-term option to reduce emissions, which may later need to be phased out quickly as policies become more ambitious, creating stranded assets and additional costs. The low-carbon transition of the sector should be based on ambitious and strong policy instruments that give investors the required signals to invest in low-emission technologies in this decade. The ability of shipping sector to decarbonize crucially depends on investment in new vessels that are implemented today given the long lifetime of vessels. New ships should be designed to be able to convert to zero-emission fuels in the future (e.g., ammonia-ready vessels) to avoid sunk costs on fossil-fuelled vessels. In this context, both public and corporate RD&D investment on zero-carbon fuel technologies needs to be ramped up quickly.

In the aviation sector, our model-based analysis showed that strong carbon pricing beyond the CORSIA scheme is critical to drive the transformation in the sector towards a low-emission paradigm and ensure compatibility with the Paris Agreement goals. Carbon pricing would also reflect the negative externalities of air travel. Passing on the decarbonization costs to passengers can help curb demand growth through limited increases in tickets, while revenues generated could be used to foster low-carbon innovation and address potential economic hardship faced by airlines. Although not examined in the current study, progressive tax rates penalizing the higher-frequency flyers and business tickets could discourage excessive flying, especially as jet kerosene is taxed at lower levels than automotive fuels in many jurisdictions. In addition, our modelling shows that measures supporting mode switch from short-haul aviation to e.g., fast-speed rails can also help reduce aviation activity and the required uptake of sustainable aviation fuels (SAF).

Ambitious climate policies, combining strong carbon pricing with regulatory measures (e.g., technology standards, blending mandates) can boost demand growth for low-emission aviation fuels, which is required to realise economies of scale and therefore reduce their production costs. In this context, action from leading airports can generate the market pull that is needed to catalyze SAF adoption. Supply-side and demand-side policies should work consistently to scale up the SAF production and demand. On the supply side, financial de-risking policies and low-cost funding will be required to promote continued innovation around sustain-able production processes including novel feedstocks (wastes, residues, marginal land) and to promote the leap from demonstration to commercial plants for biokerosene. It will also be needed to drive investment at all stages of research, development, and deployment, to enable power-to-liquids (i.e., synthetic) jet kerosene to scale up rapidly overcoming current barriers related to technology commercialization and high costs. On the demand side, carbon prices, low-carbon fuel standards and blending mandates can provide clear long-term demand signals beyond offtake agreements. In all cases sustainability protection must be established and enforced to avoid other environmental or social impacts while increasing supply of SAFs (e.g., land use impacts, stresses on renewable energy potentials). This requires a systemic analysis capturing the complex interlinkages of the air transport sector with the entire energy and economy system, identifying both synergies and trade-offs of aviation transformation with the broad low-emission transition.

A stringent global climate policy framework is aligned with the aviation sector's long-term interests. While carbon offsetting using the CORSIA mechanism could be useful to compensate for any residual emissions, all countries should ultimately try to address all emissions generated within the aviation sector, focusing on the phase-out of fossil kerosene and the efficient and timely uptake of Sustainable Aviation Fuels as well as the related low-carbon engines and technologies. The deployment of SAFs is eligible under COR-SIA as a way to directly reduce emissions. Robust certification requirements for SAF have been integrated into the CORSIA scheme; this regulatory framework can be leveraged and improved further by national pol-icy frameworks seeking to promote the uptake and use of SAF. CORSIA should effectively ensure that both offsets and SAF are used to reduce emissions. Only then, CORSIA can offer additional and robust life cycle emission reductions and a clear pathway for decarbonizing aviation. The modelling study clearly showed that the implementation of strong carbon pricing and regulatory measures (e.g., blending mandates) can pave the way towards the decarbonization of air transport in a cost-effective and timely manner.

In the aviation transformation process, sectoral stakeholders and air travel businesses can lead by example. Providing customers with the option to pay additional cost for SAF and facilitating other emission offsets, can stimulate early demand for SAFs. For those residual emissions that are particularly difficult to reduce through technical or policy measures, airlines and consumers can follow through on their "green" signalling by purchasing offsets on international carbon markets. Action from leading airlines and airports that serve as key international and domestic hubs can generate the market pull that is needed to catalyse adoption of efficient operations, best-in-class technologies, and the uptake of SAFs. Those stakeholders (airlines, governments) that act early will have multiple benefits, including gaining experience in innovative low-carbon technologies and practices (that will eventually be taken up broadly), reducing the risks of stranded assets in fossil-powered aircrafts (that may become obsolete before the end of their lifetimes), and asserting their leadership in corporate social responsibility.

5 Conclusions

This report presents the development of two bottom-up sectoral international bunker fuel models, for maritime (PRIMES-International Maritime) and aviation (Global Aviation Model) sectors that assess the potential contribution of the sectors to achieve deep emission reductions in line with Paris goals. In the short-term the models consider the impact and recovery from the COVID-19 pandemic, and include mechanisms that can incorporate different fuel prices, policies, and technologies. The bottom-up models are validated with latest statistical data and information from various organizations. The bottom-up global maritime model is used to quantify a global baseline scenario on the projected growth of the sector by sub-sector; a regional case study is also presented in order to assess the implications of policy instruments specific to the European maritime sector. The bottom-up global aviation model (GAM) is used to quantify a global baseline scenario and global decarbonization scenarios; a regional case study is also developed to assess the implications of policy instruments specific to the European aviation sector. The data and insights from the bottom-up sectoral modelling tools are integrated in the global energy model PROMETHEUS, which captures the complex interactions among sectors, fuels, and transition pathways. The report also presents pathways for decarbonising the international maritime and aviation sectors using the PROMETHEUS model, enhanced with a detailed representation of the shipping and aviation sector, to explore transformation pathways for these sectors and their overall systemic impacts on emission pathways, investment, energy consumption and fuel mix.

The results of PRIMES-International Maritime show total maritime trade activity for major shipping segments to grow by almost 90% in 2050 compared to 2018 under business as usual considerations. This outcome is comparable to IRENA's (2021) scenario that also projects global activity growth of 90% in 2050 (BES scenario). Such outcomes signify the importance to decarbonize the sector as future projections corroborate its vast potential growth. Several studies address the important contribution of alternative marine fuels in mitigating the sector's emissions. IRENA (2021), in their 1.5C scenario for sector's decarbonization by 2050 find that a 70% share of renewable fuels is needed in the mix for international maritime to contribute to the Paris Agreement goals (improved energy efficiency is expected to contribute by 20% on reducing emissions, assuming lower maritime activity levels compared to BES (17% effect of reduced demand). Such shares are within the range of DNV GL's Maritime Forecast (2020) that includes a set of decarbonization scenarios, showing a significant uptake (between 60% to 100%) of carbon neutral fuels by 2050. Halim et al. (2018) examined the technical possibility of decarbonizing international maritime with regards to the Paris Agreement goal of 1.5 °C temperature limit, by modelling dry bulk, containers, oil chemical and gas tankers, general cargo. They found that a combination of technical and operational measures along with a significant uptake of alternative fuels will be necessary to lead to CO_2 reductions of between 82% and 95% by 2035. More specifically, for a 95% reduction to be achieved, zero carbon fuels (e.g., hydrogen and ammonia) need to take up more than 70% of the fuel mix by 2035, assuming also that electric ships will constitute approximately 10% of the global fleet. Whilst the above-mentioned studies address the global sector, similar findings have been found in the regional case study based on PRIMES-Maritime. In particular, in the regional case study for Europe, the important contribution of alternative marine fuels in mitigating the sector's emissions is demonstrated. The results show 90% shares of renewable fuels in the EU bunker fuel mix in both deep decarbonization scenarios (AllMar and OperStand). Moreover, the study presented in this report finds that operational measures have a substantial impact on cumulative emissions if implemented early in time, alongside carbon intensity improvements of the fuel mix. Regarding the transition costs of the sector these are not quantified in the present report. Looking into available literature, in their latest Maritime Forecast, DNV GL (2022) presents 24 decarbonization scenarios split by IMO ambitions and decarbonization by 2050 and shows several potential variations in the fuel mix and costs to achieve the above targets. For the 2050 decarbonization specifically, most of the 12 scenarios developed show that large amounts of alternative maritime fuels is needed in the mix, entailing large onboard and onshore investments of 8-28 billion USD and 30-90 billion USD, respectively.

With respect to global aviation, the modelling shows a vast growth of the sector to almost 19 Gpkm in 2050 under baseline scenario considerations. Such projections are within the range of ICAO (2022) and ICCT (2022) estimates. The Global Aviation Model also includes key means to mitigate emissions in aviation, namely alternative jet fuels, new zero emission propulsion technologies and efficiency improvement. The Global Aviation Model results on decarbonization show that price signals alone may not be adequate to achieve the emission reduction required for the ambitious Paris Agreement emissions reduction trajectories. To that end, alternative jet fuel mandates may be necessary to achieve further emission reduction. Other measures that have not been extensively explored by this study could provide alternative pathways for decarbonizing aviation. In line with conclusions of the ICCT (2022) the present study shows a peak of emissions in 2030. The report also shows that residual emissions in aviation are likely to remain, and therefore interactions with other emission mitigation systems such as the offsetting mechanism CORSIA, may be needed.

The decarbonization of international transport is commonly analysed with sectoral bottom-up tools, which however do not capture the systemic feedbacks and interplay with the entire energy system. On the other hand, the full-scale energy system models and Integrated Assessment Models capture these interactions among sectors, but until now they do not represent international shipping and aviation with the appropriate detail and sophistication. The report describes the integration of data and insights from the bottom-up sectoral tools into the global energy system model PROMETHEUS to improve the representation of international transport and assess potential decarbonization strategies for the shipping and aviation sectors. The modelling enhancements capture the short-term impacts of the COVID-19 pandemic and are validated with the latest statistical data and information.

Under current climate policy and technology trends, emissions from international transport are projected to massively increase until 2050 driven by strong activity growth and the continued dominance of oil-based products. This increasing emissions trajectory is not compatible with the Paris Agreement goals, which require rapid emission reductions towards carbon neutrality by mid-century. The study shows that the international transport should also be massively transformed to ensure compatibility with the Paris goals, based on accelerated energy efficiency, moderation of activity growth and large uptake of low-carbon fuels, especially advanced biofuels, hydrogen, ammonia, and synthetic kerosene. Advanced biofuels play a key role for the transformation of both international shipping and aviation sectors, contributing more than half of their energy requirements by 2050 in scenarios compatible with the 1.5°C goal. The study shows that the combination of technical and operational measures along with a significant uptake of alternative low-carbon fuels is critical to ensure large emissions reductions in these sectors, with limited cost increases as more expensive fuels are increasingly deployed.

The emissions reductions achieved in international transport in 1.5°C-compatible scenarios range between 65% and 85% relative to 2015 levels, indicating that the sectoral goals of IMO and ICAO for 2050 are over-achieved. More ambitious goals should be established for international transport to ensure that the sectoral transition is compatible with the 1.5°C Paris goal, as declared by several countries in COP26 towards net zero shipping. The combination of ambitious decarbonization effort with activity growth moderation (due to lifestyle changes and shortened supply chains) achieves even larger emission reductions by 2050, with lower costs and smaller pressure on the global energy supply, due to the lower requirements for biofuels and synfuels. The analysis shows that decarbonization of international shipping and aviation should be driven by a combination of market-based policy mechanisms (carbon pricing) with regulatory instruments (e.g., blending mandates, technology, or efficiency standards).

Given the slow stock turnover in international shipping and aviation sectors, accelerated transformational dynamics even in this decade are needed to pave the way for decarbonisation by 2050. Large amounts of both direct and indirect investment are needed to infrastructure and technologies related to the production, transport, trade, and use of sustainable, low-emission fuels. In addition, the uptake of low-carbon fuels would also imply large changes in the entire energy system via complex interlinkages, which are captured through the global system-wide modelling framework. The decarbonisation of international transport may generate synergies or trade-offs with the low-carbon transition in other sectors, e.g., increasing the competition for the limited biomass resources or creating stresses in the renewable energy potentials in case of large synfuel uptake. On the other hand, domestic climate policy results in a lower demand for international shipping due to reduced fossil energy trade, indicating positive feedback of the energy transition with the decarbonisation of the shipping sector.

Future work

Several aspects of the bottom-up work using the sectoral models presented in this report need further elaboration to explore the contribution of international bunker fuels to the Paris Agreement goals. In PRIMES-International Maritime, the activity-based approach that was followed in order to calibrate the model may lead to discrepancies between energy and emissions estimates across different sectors when compared to different data sources. Furthermore, the level of activity resolution in the initial dataset for global maritime (excluding the EU) is challenging to precisely estimate trade flows by origin and destination, and thus exact disaggregation of trade in a top-down approach. In addition, the international nature of the sector leads to an underlying dislocation between where most activity takes place and where most bunkering takes place. This requires data alignment to assign fuel consumption to regions. The data input is more robust on a regional and aggregate basis. Last but not least, regional differentiation on alternative fuels prices to the future is also a challenge, as assumptions of the same bunkering hubs maintaining their current bunkering share to the future may not be valid, due to different regional production potential of biofuels, synthetic fuels and hydrogen. In the Global Aviation Model, the representation of aircraft types could be expanded to include various airplane types and sizes (e.g., regional jets, narrow body, wide body). The inclusion of several airplane types would allow to better reflect the potentials and limitations in the uptake of clean energy technologies. It would also allow to examine more specific policy measures in the road towards carbon neutrality. Furthermore, for a sector such as aviation, differentiation of travel by purpose (e.g., business, tourism, other). Alternative transport purposes are associated with different response in market developments. This would also allow to consider additional elements associated to air transport demand. For a global-scale model, learning rates of clean energy technologies could be endogenized and thus feedback to the costs used in the analysis. The modelling exercise is also faced with several shortcomings in data. For instance, in the development of the aviation model several data are proprietary. Publicly available information on origin-destination matrices by country (passenger or pkm or number of flights) matrices by country or activity by travel purpose (e.g., business, tourism, other) may prove to be useful in increasing the sophistication of the model. Sensitivity analysis in several parameters can help in the direction of improving the robustness of certain assumptions taken in the modelling.

The above elements are inherent to the bottom-up sectoral models that were developed. Certain model results point to the potential implications on systems outside of the international bunker fuel sectors, that may in turn feed back into the modelling as critical model inputs and influence outcomes. An example is that of biofuel uptake that in the long term is found to be significant in both sectors (e.g., based on the bottom-up model results in 2050 almost 60% in the regional case study on maritime, and 30% in global aviation). An important aspect is that of emissions induced by the production of biofuels due to pressure on land, whether directly or indirectly. While the volumes of biofuels consumed in global aviation and maritime in a decarbonization context alone may not justify significant contribution of such upstream emissions, a global decarbonisation context would imply high bioenergy consumption also by other sectors. Therefore, the pressure on land systems may be induced due to competition for feedstock with other sectors. At such scale, emissions from land use and production of biofuels globally may shift the impact from the international bunker fuel sectors to other sectors (e.g., LULUCF), at least in part. Furthermore, the assumed biofuel price is a key driver for their uptake in the alternative fuel mix, as it has been assumed to be lower than that of other zero carbon fuel alternatives. Competition for biofuels from other sectors or significant cost reduction of synthetic fuels production may reverse this price differential, inducing a higher uptake of synthetic fuels to the detriment of biofuels. To quantify the impact of the assumed price trajectories a sensitivity analysis on fuel prices needs to be carried out.

For both maritime and aviation, the implied system changes are vast so that the sectors can decarbonize. Direct and indirect investments are needed for infrastructure and technologies related to alternative fuel supply. It is therefore important that future work also examines the economic implications of the scenarios explored in this report. Other aspects that are important to explore are potential synergies and tradeoffs with other environmental impact categories (e.g., air pollutants, noise, resources/ critical materials) that have been outside of the scope of the present analysis. Finally, in the context of emissions mitigation to meet the Paris goals, the annual emission trajectories alone, as assessed in the scenarios developed in the present study, may have certain weaknesses. The scenarios do not directly consider that to limit temperature increase, certain carbon budgets may need to be respected. While it can be debated what the appropriate budget level for international aviation and maritime may be, operationalizing the models in such scenarios would provide a better understanding on the implications of the contribution of international bunker fuels in meeting the Paris Agreement goals.

The integration of international bunker fuels into a global comprehensive energy system model can be further improved in various directions that were not fully captured in this report and could be the basis of future research. First, the modelling of the international shipping and aviation sectors can be enhanced through more detailed representation of the sectors further using data and methodologies from the bottom-up tools, e.g., activity differentiated by origin and destination, introduction of different aircraft types and shipping vessels, higher regional granularity. Second, the modelling framework can be expanded to represent potential activity growth due to the increased trade of products associated with the decarbonisation, such as batteries, solar panels, and electric motors, to consistently capture the complex interlinkages between energy transition and shipping decarbonisation. The model-based projections crucially depend on the assumptions made, especially on the values of specific elasticities, including the income and price elasticities that determine the evolution of transport activity. A sensitivity analysis on the values of these elasticities or on the costs of low-carbon fuels is required to consistently assess decarbonization strategies.

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PARTICIPANTS

Wuppertal Institut

VUB Brussels School of Governance

IDDRI

DLR Deutsches Zentrum für Luft- und Raumfahrt German Aerospace Center

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