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Decarbonizing the International Shipping and Aviation Sectors

Panagiotis Fragkos

E3Modelling Societe Anonyme, 11523 Athens, Greece; fragkos@e3modelling.com

Abstract: The Paris Agreement requires a drastic reduction of global carbon emissions towards the net zero transition by mid-century, based on the large-scale transformation of the global energy system and major emitting sectors. Aviation and shipping emissions are not on a trajectory consistent with Paris goals, driven by rapid activity growth and the lack of commercial mitigation options, given the challenges for electrification of these sectors. Large-scale models used for mitigation analysis commonly do not capture the specificities and emission reduction options of international shipping and aviation, while bottom-up sectoral models do not represent their interlinkages with the entire system. 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 decarbonizing these sectors is the large-scale deployment of low-carbon fuels, including biofuels and synthetic clean fuels, accompanied by energy efficiency improvements. The analysis shows that ambitious climate policy would reduce the trade of fossil fuels and lower 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

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1. 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 [1]. Following the PA, a large majority of countries representing more than 95% of global greenhouse gas (GHG) emissions have submitted climate pledges labeled 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.

Decarbonizing 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 [2]. 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 technical difficulties in electrifying these sectors, 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's decarbonization presents unique challenges [3,4]. In addition, the demand for aviation is expected to vigorously grow in the future, due to the expected income increase and the associated increase in aviation activity, especially in developing countries with currently low aviation demand. The decarbonization 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 [5]. Operational measures, such as speed and voyage optimization, facilitated by digitalization, could also play an important role [6], accompanied by the use of auxiliary propulsion devices and waste heat recovery [7], or reduced shipping activity, especially for fossil fuel transport [8]. However, the decarbonization of the shipping sector will mostly rely on the development and commercial uptake of alternative low-emission fuels [9]. 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) [10]. 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 [11]. Traut et al. [12] explored a range of scenarios of international shipping, and demonstrated that in the near term, immediate and rapid exploitation of available efficiency mitigation measures, including changes to speed, ship size and utilization, and available retrofit technologies, is of critical importance to deliver emission reductions. Although few studies have carefully assessed the decarbonization potential of renewable marine fuels [10,11], 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 [13]. 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 [14]. 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 [15].

However, the majority of IAMs fail to represent adequately the sectoral dynamics and the emission reduction options and strategies of the international aviation and maritime sectors. This raises critiques of the models related to the inadequate input assumptions for low-emission fuels (costs and potentials), the representation of innovation, and behavioral and activity changes [16,17]. In particular, [18] 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 modeling 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 [11,19,20], while limited studies have focused on the transformation of the aviation sector [21]. On the other hand, Integrated Assessment Models (IAMs) have paid little attention to shipping [22]. Only recently, with the development of aspirational emission goals and relevant strategies for shipping and aviation by IMO and ICAO, respectively, has the modelling community started to explore the specificities of international transport segments and the potential mitigation options [8,18]. 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 [19,20]. Therefore, these system-wide models can treat international shipping and aviation in the context of the overall 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 [23–25] 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 [26,27]. The modelling framework [28] 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 [20] 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 decarbonization 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 2 presents the landscape of the maritime and aviation sector, while Section 3 describes the methodological approach, the modelling improvements implemented, and the scenario design. Section 4 presents the results of the model-based assessment on decarbonizing international transport. Section 5 discusses relevant policy insights and recommendations, while Section 6 concludes.

2. The Landscape of the International Maritime and Aviation Sector

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

2.1. International Maritime

International shipping accounts for about 2% of global energy-related emissions [29]. In the last decade, emissions from international shipping amounted to about 600–700 Mt CO_2/year [19]. Analyzing the recent trends, there has been a relative stabilization of international shipping emissions since 2010–2011, when they peaked at around 670 Mt CO_2. 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) [29]. 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 Mt CO_2. If seaborne transport activity follows historic trends, it may double by 2050 [30] and, with current carbon intensity, this would represent about 1.35 Gt CO_2/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 [30,31]. However, Ref. [29] 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-kilometer) of about 2% in the 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 [26] triggered by ambitious operational measures (e.g., slow steaming, better vessel design).

While the measures introduced by the IMO are expected to reduce the growth of emissions in the current decade, higher climate policy stringency is required to ensure that the shipping 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 support the commercialization of low- and zero-emission oceangoing vessels during the current decade. Ambitious policies, robust technological innovation, and active participation of all actors in the supply chain are required to increase the uptake of zero-carbon fuels for 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 [29]. 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 [11,26,28]. 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 by 2030 and make a significant contribution in the sectoral fuel mix by 2050 to reduce the dependency of the sector 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 such as 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 [26]. 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 [11]. The deployment of clean fuels depends on the timely development of new technologies, including dual-fuel engines and electrochemical powertrains. Recently, there have been some small, positive developments as more than 80 zero-emission vessel pilot demonstrations started during

2021 and the first months of 2022 using ammonia or hydrogen technologies for shipping, battery-powered vessels, and methanol vessels [31]. 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 fueling 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. Efforts are also required to develop the entire supply chain of 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 [20]. 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 to reduce emissions from the maritime sector [19].

Recently, there has been increasing awareness of the need to reduce emissions from the shipping sector. The IMO recently introduced a series of measures to reduce the carbon intensity of maritime activity by 40% until 2030, including target-based technical and operational requirements, to pave the way for achieving the IMO target of reducing shipping emissions by at least 50% in 2050 from 2008 levels. The European Commission introduced the Fuel EU Maritime initiative [20], which aims to reduce the emission intensity of energy used by vessels. The targets become increasingly more stringent, with a 6% reduction in 2030 increasing to 75% in 2050 compared to 2020. The implementation of these constraints would lead to a gradual uptake of low-emission fuels for voyages within the EU countries. However, there are concerns that this initiative risks supporting the deployment of LNG and constraining the longer-term transformation towards zero-emission shipping. The Clean Shipping Act [32] has also been recently introduced in the US, suggesting even more ambitious standards for carbon intensity reduction than those suggested by the EU, aiming for the use of 100% zero-carbon fuels after 2040.

Several declarations about the uptake of low- and zero-carbon fuels in the maritime sector were made at the UN COP26 in 2021. The most remarkable was the Clydebank Declaration for green shipping corridors [33,34], aiming to facilitate the development of at least six zero-carbon shipping corridors by 2025. In COP26, 14 countries signed the Declaration on Zero Emission Shipping [35,36] pledging to push the IMO to adopt a target of full decarbonization of international shipping by 2050. Since the declaration, a green corridor has already been announced through a partnership between Shanghai and Los Angeles, in addition to the announcement for a European Green Corridors Network [37]. At COP26, 55 countries requested the establishment by the IMO of instruments to decarbonize shipping by 2050 to ensure compatibility with the 1.5 °C goal set out in the Paris Agreement [38].

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.

2.2. International Aviation

Aviation accounted for over 2% of global energy-related CO_2 emissions and has been growing faster than other transport segments. After a strong growth of aviation emissions in the last 30 years, the COVID-19 pandemic led to a significant decline of aviation emissions, which dropped by about 40% in 2020 relative to 2019 [39]. Global aviation emissions rose again in 2021, rebounding to a level higher than their peak in 2019. Aviation emissions are expected to grow vigorously in the next decades, triggered by the strong aviation activity growth. As a result of projected emissions growth, the aviation sector could potentially consume 25% of the global carbon budget for 1.5 °C by 2050 [40].

Global aviation passenger demand recovered gradually in 2021 after the COVID-19 disruption, especially the domestic aviation segment [39], but traffic will reach its 2019 peak levels only in 2023. New aircrafts are more efficient than those they replace [39], but this only moderates the rapidly growing activity. The average fuel efficiency in aviation has been improving by about 2% per year in the last two decades, but this rate has decelerated recently, showing that additional 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 decarbonize [41], illustrated by a rapid increase of sectoral emissions in the last decades. This trend was interrupted in 2020 due to the COVID-19 pandemic 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, most Parties have not included emissions from international flights in their NDCs. These emissions are addressed by the ICAO that represents the ‘appropriate forum’ to regulate aviation-related emissions [42]. ICAO has established the goal of carbon-neutral growth from 2020 onwards, that is, to stabilize aviation-related 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 increasing emissions [42]. CORSIA is an offsetting scheme complementing other measures towards meeting the goal of carbon-neutral growth of aviation [42,43]. Under the scheme, airlines and other aircraft operators are required to offset any increase in their CO_2 emissions from international flights above 2020 levels [42]. Operators can minimize their offsetting obligations by using CORSIA eligible low-carbon fuels, including sustainable aviation fuels (SAFs) [40].

The expected impact of CORSIA was assessed in the UNEP Gap report [43], which concluded that CORSIA could reduce international aviation emissions by up to 0.3 Gt CO_2 by 2030. The large range of estimations highly depends on the way the offsetting rules will be set, and on the quality of the emission offsets allowed under CORSIA. Larsson [44] showed that existing aviation policies will not deliver large emission reductions and stronger international policy instruments are needed to ensure that the sector contributes to achieving the Paris goals.

Sustainable aviation fuels (SAFs) that can replace fossil jet kerosene are critical to decarbonizing aviation. The uptake and commercialization of SAFs is subject to blending limits, but recent flight trials [45] have demonstrated the prospects of 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 [46]. 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 [46] excludes purpose-grown crops from SAFs due to sustainability concerns. Synthetic kerosene (produced from green electricity) is far from commercialization, due to its technological immaturity and high production costs, but it has a superior carbon balance than biofuels [26] and high scalability potential. 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 emissions, including a shift to high-speed rail, reducing business flights (e.g., with more teleconferences), and a frequent flyer levy.

Electrified or hydrogen-powered aircrafts can also reduce the consumption of kerosene and aviation emissions from short- and medium-range flights. However, alternative propulsion has limited near-term potential, as commercial availability of such designs is expected after 2030. Electric aircrafts have no direct emissions and are efficient relative to the current aircraft fleet, but their uptake in aircrafts is constrained by their current energy density and weight. The current energy density of Li-ion batteries should be at least quadrupled to make them viable for short-haul flights over 1000 km [47]. Hydrogen can either be used via direct combustion in jet engines or through fuel cells to generate electricity, with Airbus leading the way in large hydrogen-powered aircrafts. However, hydrogen use in aviation faces difficulties related to the need for fuel storage and delivery and redesigned airframes to accommodate storage tanks.

There is a growing number of regulatory and policy frameworks addressing the aviation sector, including the EU's proposed ReFuelEU Aviation [48], which includes incentives for SAF uptake and blending mandates, and the SAF Grand Challenge [49] of the US. 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 CO_2 emissions by 2050 [50]. 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 [51], with ICAO expected to also introduce a long-term aspirational climate goal.

3. 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.

3.1. The PROMETHEUS Energy System Model

PROMETHEUS is a comprehensive technology-rich global energy system model focusing on energy and climate policy analysis, energy system planning, and the development of mitigation pathways [23,24]. It captures the interactions between energy demand and supply and provides 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 analyze the energy, emissions, and cost implications of climate mitigation pathways, 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 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 representative agents (e.g., consumers or energy producers) use information on costs and prices of energy commodities and decide on the allocation of resources. Market dynamics determine the interactions between agents with market-derived prices to balance energy supply and demand by region.

Energy demand is derived from 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), plug-in hybrids, and electric and fuel cell vehicles.

Power requirements are based on the evolution of electricity consumption, grid losses, the security of supply margin (and flexibility constraints), and own consumption of power plants [24]. 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.

PROMETHEUS quantifies CO_2 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 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, including price signals, such as carbon pricing or energy taxation, subsidies, energy efficiency and renewable energy supporting policies, and technology standards [23,26,52].

3.2. 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, calculated with Equation (1).

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

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 regarding 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 [53,54]. Income elasticities take positive values, implying that increasing levels of GDP (or income) would result in 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 [55]. 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 commercialization potential.

In the Reference scenario, aviation demand is calibrated to reproduce the projections from the AIM parametric aviation model [56]. 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 [56] and a detailed mapping of country-level data of the AIM model with the PROMETHEUS regions [24].

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 [57]. 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 such as 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 will become comparable with that of HEFA biokerosene by 2030 and beyond (Figure 1). 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.

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 [58] 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 analyze the linkages between domestic climate policy and international shipping through the reduction of demand and thus international trade of fossil fuels.

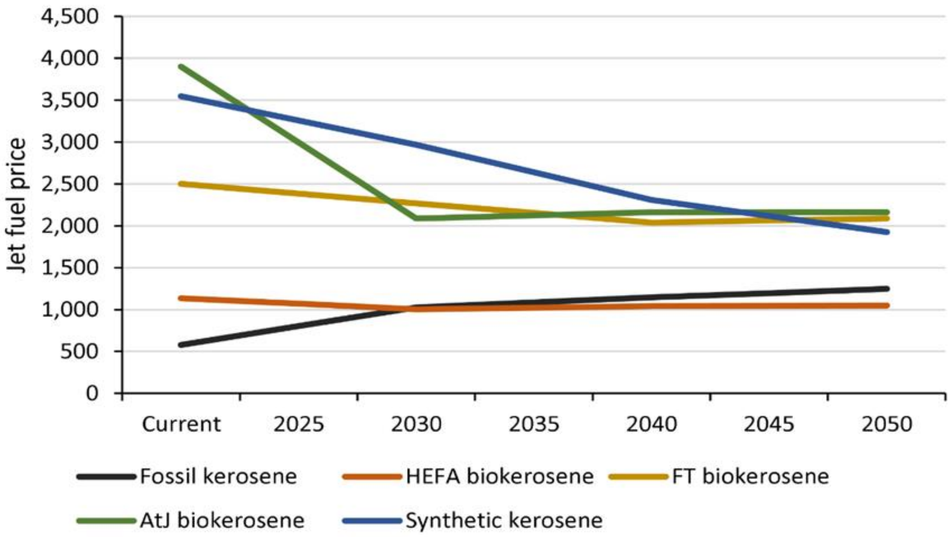

Figure 1. Global average prices of fuels used in aviation (in Eur/tonne).

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 [20]. 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 [27], have been explicitly introduced in the model, based on data from PRIMES-Maritime model [59], 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 byproduct 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 decarbonization 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 utilization (CCU) or direct air capture (DAC) technologies [60]. 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 harbors. 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 [61].

The overall research study design and modelling methodology is displayed in the schematic flow below (Figure 2).

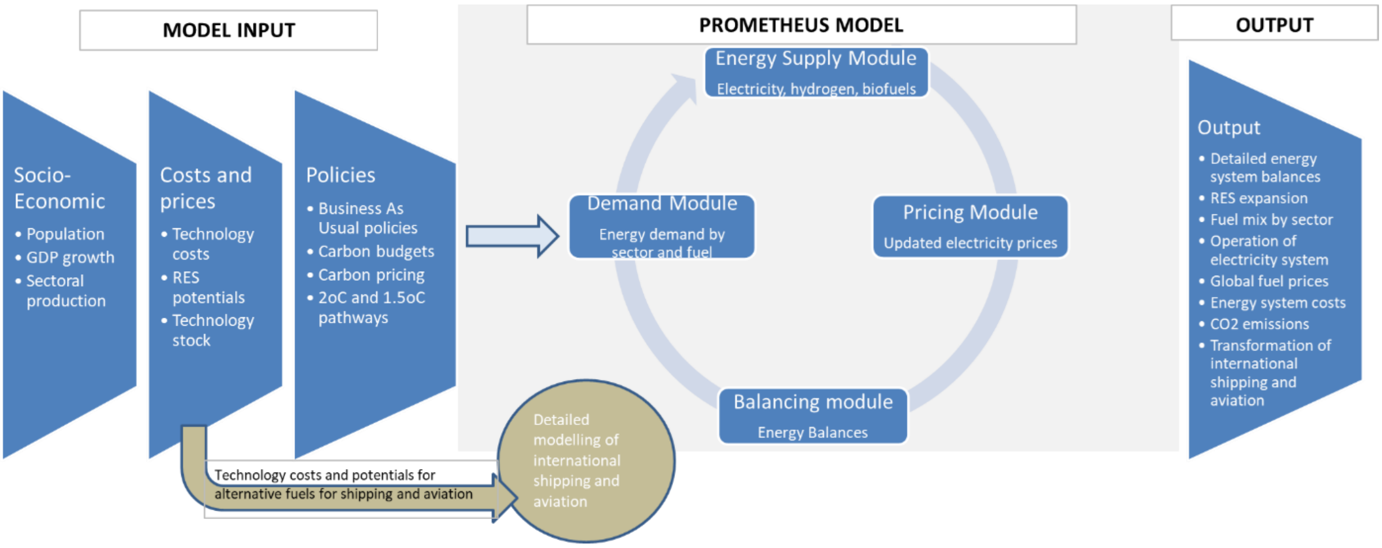

Figure 2. Schematic flow of the research study design.

3.3. Scenario Design

The modelling enhancements, updates, and improvements of PROMETHEUS described above are then used to quantify alternative scenarios aiming to achieve global decarbonization. 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 (Table 1). As the study focuses on assessing the role of international transport towards global decarbonization, the scenario design does not impose any sectoral targets, but harmonizes input assumptions for socio-economic development and climate policies and carbon budgets to those commonly used in IAMs [13].

Table 1. 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 2 °C carbon budget with a cost-optimal manner	1000 Gt CO_2
1.5deg	Meets the 1.5 °C carbon budget with a cost-optimal manner	650 Gt CO_2
1.5deg_LD	Meets the 1.5 °C carbon budget with lower aviation and shipping activity than 1.5 °C.	650 Gt CO_2
1.5deg_HD	Meets the 1.5 °C carbon budget with higher aviation and shipping activity than 1.5 °C.	650 Gt CO_2

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 remains constant (but does not increase), in line with [62] with regional carbon prices increasing 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 Gt CO_2 over the period 2020–2100 is imposed, while in the 2deg scenario the carbon budget amounts to 1000 Gt CO_2 in line with the IPCC AR6 [63]. The scenario achieves the Paris Agreement goals with the least total cost, by equalizing 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 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 [63,64], with a carbon budget of 650 Gt CO_2 considered compatible with a warming of 1.5 °C or slightly above, while 1000 Gt scenarios would reflect a world likely below 2 °C.

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 behaviors in line with the "Green-Push scenario" [65], 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.

4. 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.

4.1. Transformation of Aviation

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 3). 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 program, 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.

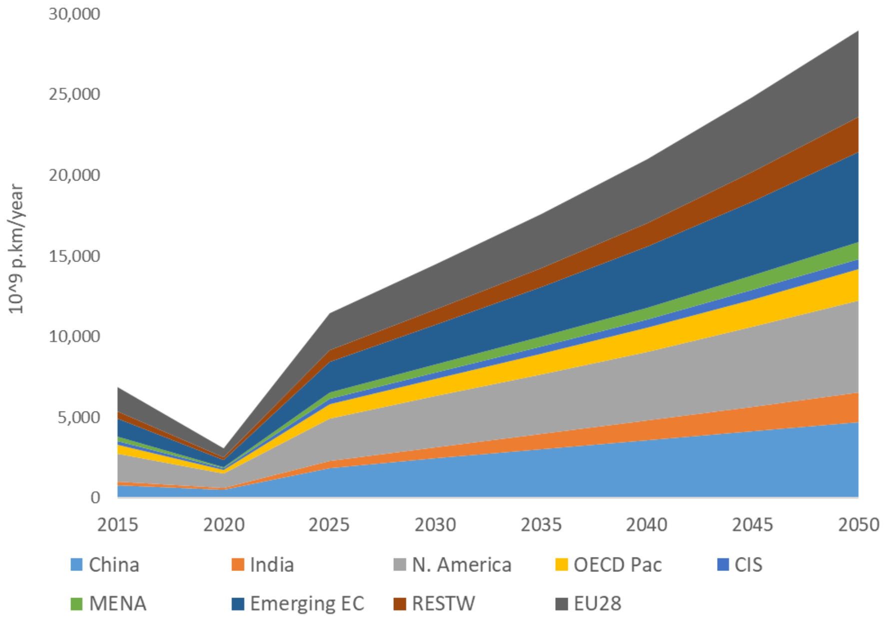

Figure 3. Aviation activity by region in PROMETHEUS REF scenario.

Global CO_2 emissions from aviation are projected to increase in REF from about 880 Mt CO_2 in 2015 to 1800 Mt CO_2 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 CO_2 emissions increase a lot less than the aviation activity; the annual growth of aviation-related CO_2 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.

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 4). The 1.5deg_LD scenario assumes even lower aviation activity due to lifestyle changes towards more environmentally sustainable behaviors in line with the "Green-Push scenario" [65]. 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.

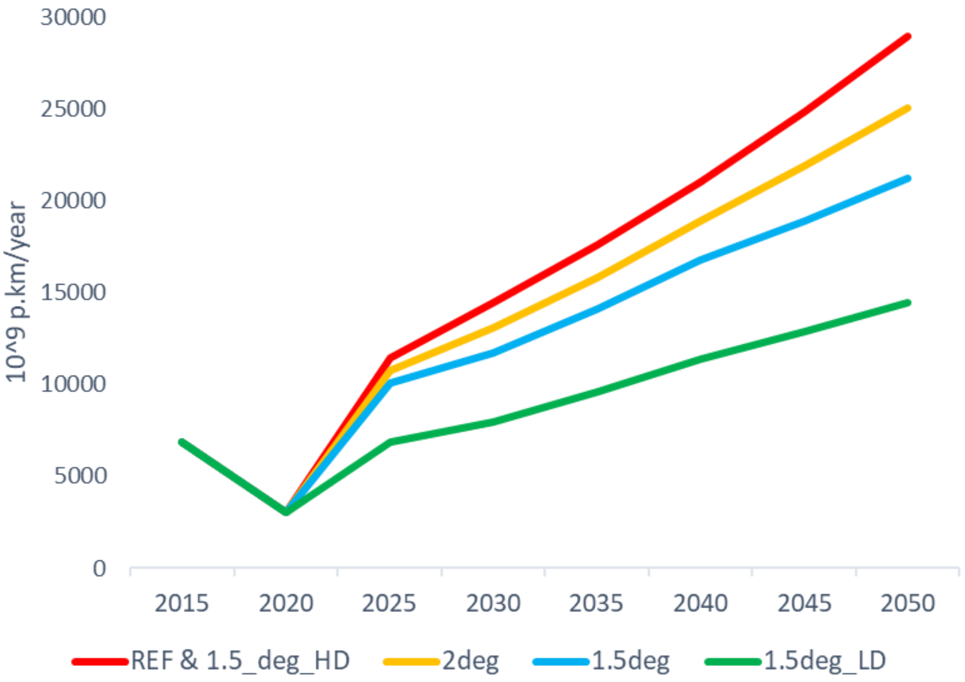

Figure 4. Global aviation activity in the series of scenarios over 2015–2050.

Figure 5 shows the evolution of global CO_2 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 decarbonization 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.

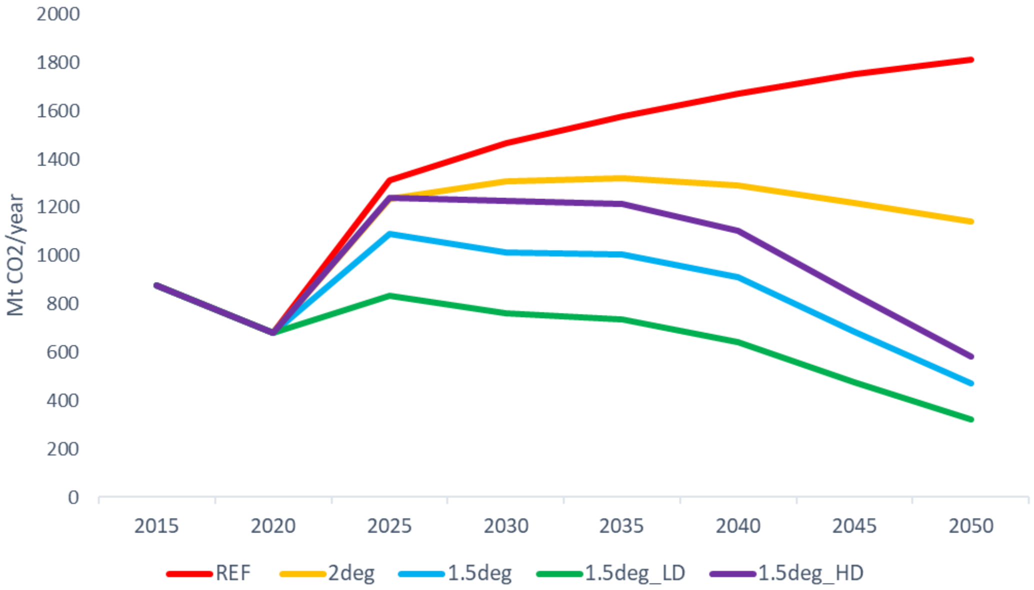

Figure 5. CO_2 emissions from the aviation sector in alternative policy scenarios.

As the deployment of low-emission jet fuels increases, CO_2 emissions from aviation are projected to decline rapidly, especially in scenarios with high climate policy ambition (1.5deg) and with low activity assumptions (1.5deg_LD). Aviation-related CO_2 emissions in REF are projected to reach 1800 Mt CO_2 in 2050, while in 2deg they amount to 1140 Mt CO_2 and in the series of 1.5deg scenarios they decline to [320–580] Mt CO_2, 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.

Fossil kerosene is currently the dominant fuel option in the aviation sector and is projected to remain so in REF scenario (Figure 6) 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 commercialization, 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, commercialization, and market uptake of SAFs cannot materialize 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 6). 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 decarbonization 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 specific regions [20]. 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).

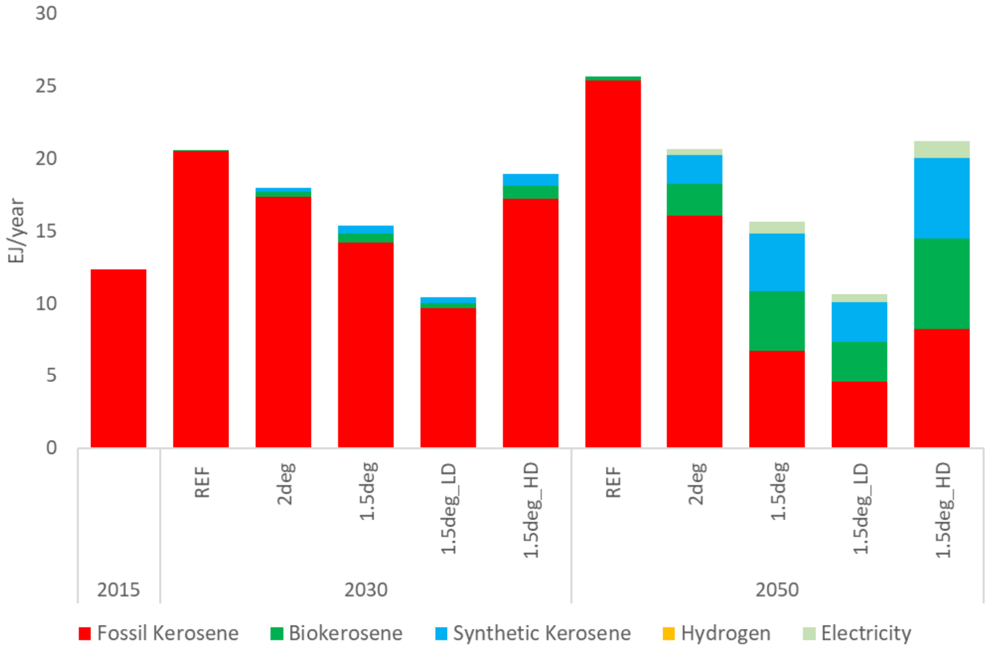

Figure 6. Global fuel consumption for aviation in alternative scenarios in 2030 and in 2050.

The aviation industry could manage the associated cost increases, with ticket prices increasing by less than 15–20% relative to the REF scenario. The modelling captures the full-scale market feedbacks 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 4). The highest cost increases in aviation are projected in the 1.5deg_HD scenario due to the combination of strong climate 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 sustainable aviation fuels, which are more expensive than fossil kerosene) are partly offset by energy efficiency improvements and learning-by-doing effects that may reduce the production costs of low-emission fuels (Figure 7). Consequently, the air transport sector could continue to grow through the low-carbon transition, thereby enabling increasingly more people to use and benefit from aviation. However, profitability of several airlines might decline, creating additional market challenges; however, these changes are not captured by the model.

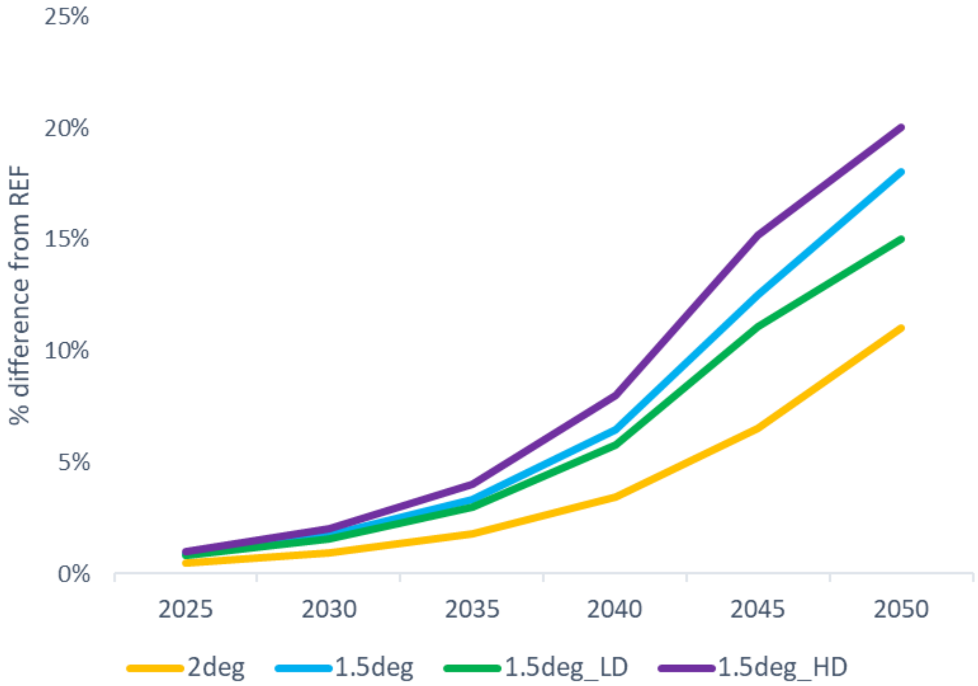

Figure 7. Increase in average aviation cost and airfare price from REF levels.

4.2. 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 [58,66] 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 [67]. 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 [22]. 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 activity 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 8).

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 gas oil), 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 Mt CO_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 9). 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 Mt CO_2 in the 2deg scenario and even more to 100–250 Mt CO_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.

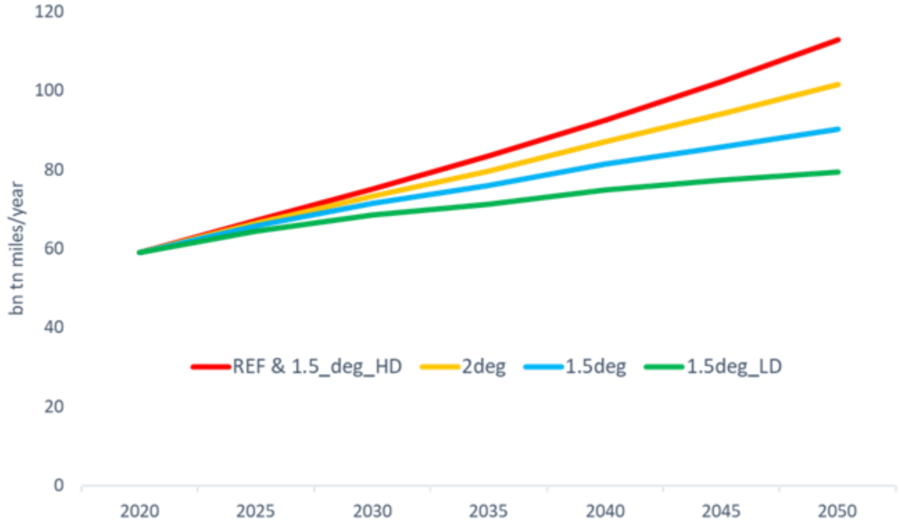

Figure 8. International shipping activity in the series of scenarios.

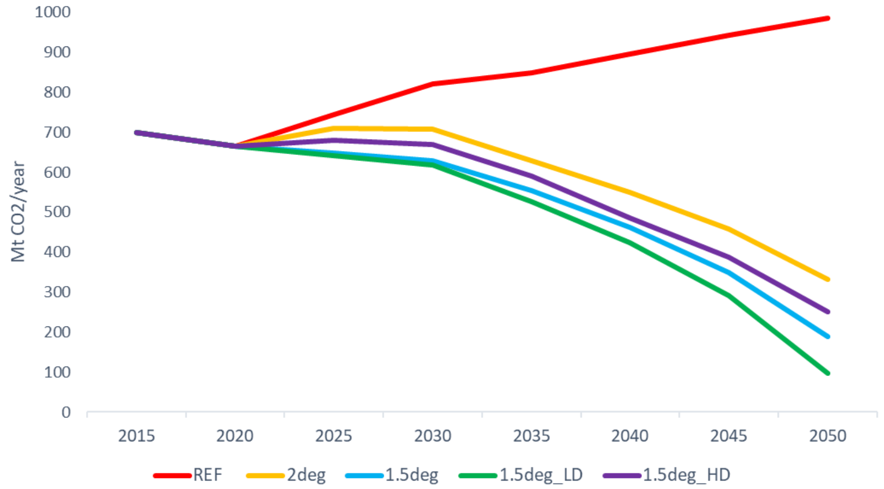

Figure 9. CO_2 emissions from international shipping over 2020–2050.

Historically, oil products have constituted over 99.5% of energy used in international shipping (Figure 10), while in recent years there has been 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.

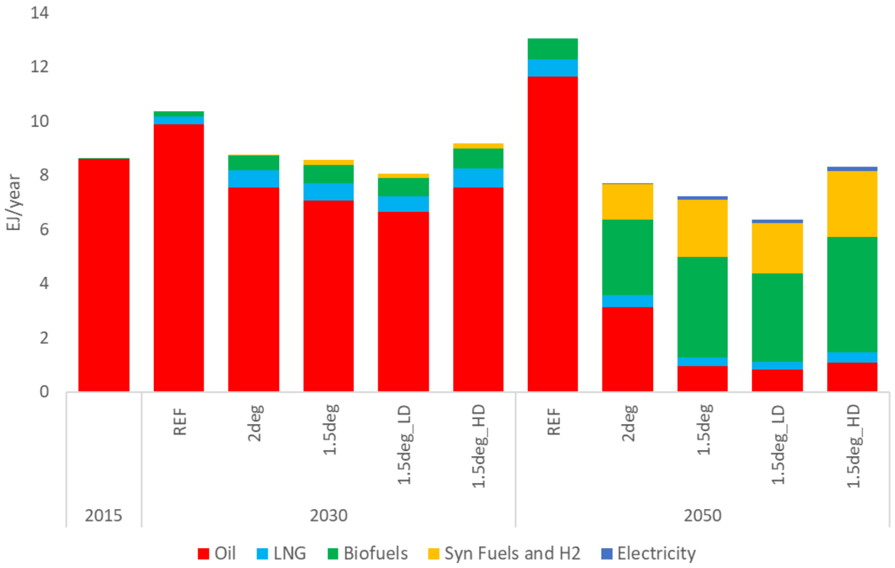

Figure 10. Energy consumption by fuel for international shipping in 2030 and in 2050.

The uptake of low-emission fuels, including biofuels, hydrogen, ammonia, and electricity, will need to rapidly increase to ensure compatibility with the Paris goals. By 2030, low-emission fuels represent about 14–18% of energy consumptions in the mitigation scenarios. Biofuels account for more than 50% of the low-carbon fuel use in 2030, as they 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, such as ammonia, hydrogen, and biofuels.

In the decade 2020–2030, technological development and targeted policy support are needed to increase the deployment of other low-emission fuels, particularly ammonia and hydrogen. Due to the long lifetimes of vessels and the slow stock turnover, near-term low-carbon innovation and technology adoption are crucial to pave the way towards shipping decarbonization. In the 1.5deg scenarios, low-emission fuels cover 87% of energy consumption 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 reduction 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, electricity generation), which is considered in PROMETHEUS modelling (in contrast to sectoral modelling studies such as [5,66]). 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. However, the potential activity effects due to the increase trade of low-carbon technologies (e.g., batteries, PV panels) are not captured by the modelling framework.

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 climate policies would lead to fuel switches in the sector towards lower emission but more expensive fuels (such as 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 11), 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.

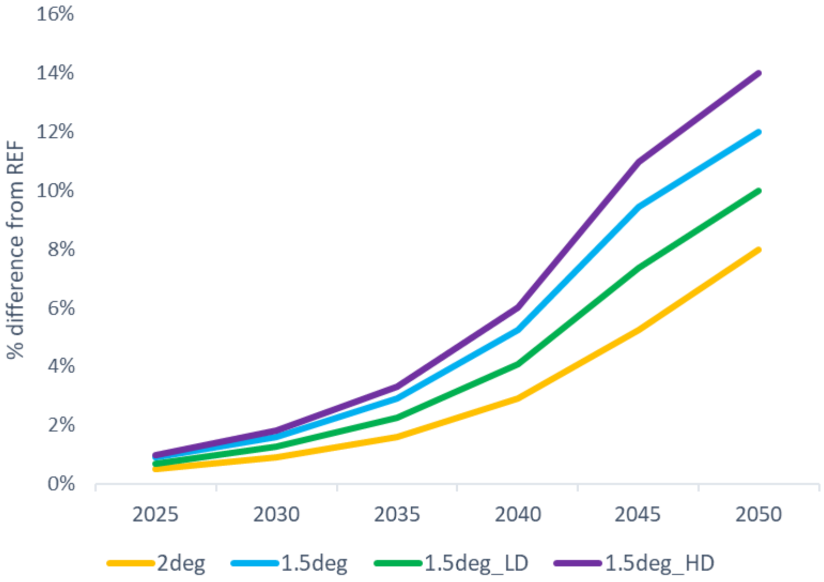

Figure 11. Cost differences in the shipping sector between the scenarios.

5. 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 [30,67]. However, to be compatible with Paris goals, both aviation and shipping sectors need to rapidly reduce their CO_2 emissions. Since the electrification of both sectors is technically challenging and the energy efficiency gains provide only limited mitigation potential, 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.

In the shipping sector, operational emission standards requiring a reduction in carbon intensity can pave the way for the deployment of low-emission fuels. These standards allow market participants (e.g., shipping companies) to decide the most cost-effective and suitable strategy to comply with the declining carbon intensity goals in ships. However, to pave the way towards deep decarbonization, such standards should be tightened in the next decade, given the slow stock turnover of vessels requiring accelerated transformation dynamics before 2030. The increased ambition of carbon intensity standards would increase the uptake of low-carbon fuels, especially if material non-compliance measures are implemented. In addition, regulating well-to-wake emissions, including emissions related to fuel extraction, processing, transport, and onboard combustion, can facilitate the uptake of zero-emission fuels reducing emissions in the entire supply chain of fuels and 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 international shipping towards a low-emission paradigm.

The required transformation of international shipping requires additional investment to develop the required infrastructure, new vessels, and 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 in investing in low-emission fuels and infrastructure. The introduction of blending mandates for low-carbon emissions is needed to create a predictable demand for green fuel producers and suppliers, thus supporting investment in relevant clean production facilities and infrastructure. Blending mandates are also used to decarbonize the road transport and the aviation sector in the EU [20]. These measures can overcome the potential negative impacts of unambitious carbon intensity standards which may lead to a large uptake of LNG as 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 converted to zero-emission fuels (e.g., ammonia-ready vessels) to avoid sunk costs on vessels. In this context, public and corporate R&D investment on zero-carbon fuels has to be increased quickly.

In the aviation sector, our model-based analysis showed that strong carbon pricing is critical to drive the transformation in the sector towards a low-emission paradigm and ensure compatibility with the Paris Agreement goals. Passing on the decarbonization costs to passengers can reduce aviation demand through limited increases in tickets. Although not examined in the current study, progressive tax rates penalizing the higher-frequency flyers and business tickets could discourage excessive flying, especially given that jet kerosene commonly faces lower taxes than automotive fuels. 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 (including technology standards and blending mandates) can boost demand growth for low-emission aviation fuels, which is required to realize economies of scale and therefore reduce their production costs. In this context, action from leading airlines and airports may produce the market pull needed to accelerate the innovation and adoption of SAFs. Supply- and demand-side policies should work consistently to scale up the SAF market in the next decade. On the supply side, financial de-risking policies and low-cost funding will be required to support innovation for sustainable production processes including novel feedstocks (wastes, residues, marginal land) and to actively promote the commercialization of biokerosene. The scale-up of synthetic kerosene requires additional investment for technology innovation, development, and uptake to overcome current barriers related to commercialization and high costs. The imposition of strong carbon prices and low-carbon fuel blending mandates can provide clear and long-term signals for demand growth, while also limiting potential environmental or social impacts from the increased uptake of SAFs (e.g., land use impacts and 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.

The aviation sector's long-term interests are aligned with the adoption of strong global climate policy framework. While carbon offsetting using the CORSIA mechanism could be useful to compensate for any residual emissions, all countries should try to reduce emissions generated from the aviation sector, focusing on the phase-out of fossil kerosene and the efficient and timely uptake of SAFs as well as the related low-carbon engines and technologies. The deployment of SAFs is eligible under CORSIA as a way to reduce emissions. Robust certification requirements for SAF are integrated in CORSIA, which can be further leveraged by national policymakers to incentivize the deployment of SAFs.

CORSIA should ensure that both offsets and SAF are used to reduce emissions, thus offering additional and robust emission reductions towards decarbonizing aviation. The modelling study clearly shows that the implementation of strong carbon pricing and regulatory measures (including 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. The demand for SAFs can increase if airlines provide their customers with the option to pay additional cost for SAF, while offsets can be purchased in carbon markets for emissions that are difficult to reduce through policy and technical measures. Action from leading airlines and airports can support a widespread uptake of efficient operations and technologies, and the early uptake of SAFs. Those stakeholders (airlines and 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.

6. Conclusions

Aviation and shipping emissions are not on a trajectory consistent with Paris Climate Agreement goals, as they are projected to constantly increase driven by strong activity growth, unambitious climate policies, and the lack of cost competitive and commercially mature low-emission fuels and technologies. The current study presents the international landscape, technological options, and policy measures under examination to reduce emissions from the international shipping and aviation sectors, which are often excluded from the domestic climate policies and NDC pledges. The decarbonization of international transport is commonly analyzed 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 have not represented international shipping and aviation with the appropriate detail and sophistication [18]. The current study describes the integration of modelling enhancements in the well-established 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, especially in developing regions, and the continued dominance of oil-based products. This increasing emissions trajectory is clearly not compatible with the Paris Agreement goals, which require a large-scale transformation of the global energy and transport systems with rapid emission reductions towards carbon neutrality by mid-century. The model-based analysis shows that the international transport sectors should also be massively transformed to ensure compatibility with the Paris goals, based on accelerated energy efficiency improvements, 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 Paris goal. The study is consistent with other detailed bottom-up studies showing 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 [4,10,11,19]. The estimated cost increases amount to 10–20% in 2050, relative to baseline levels, driven by the high carbon price, the investment in energy efficiency, and the large uptake of expensive low-carbon fuels.

The emissions reductions achieved in international transport in the series of 1.5 °C-compatible scenarios range between 65% and 85% relative to 2015 levels. This implies that the sectoral goals of IMO and ICAO for 2050 are over-achieved in these scenarios; 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 [35,38]. The combination of ambitious decarbonization effort with activity growth moderation (due to lifestyle and behavioral changes) achieves even larger emission reductions by 2050, due to lower energy demand in the sector. However, decarbonization scenarios with high activity growth show smaller emission reductions by 2050 and have commonly higher transition costs, due to the high use of expensive low-carbon fuels. The analysis shows that deep decarbonization in international shipping and aviation should be driven by a combination of market-based policy mechanisms (such as carbon pricing) with regulatory instruments (e.g., blending mandates, technology, or efficiency standards).

The decarbonization of the international maritime and aviation sectors requires large systemic changes based on accelerated transformational dynamics, even in this decade, to pave the way for decarbonization by 2050, given the slow stock turnover in these sectors. Large amounts of both direct and indirect investment are needed in 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 PROMETHEUS. The decarbonization of international transport may generate synergies or trade-offs with the low-carbon transition in other sectors, through increasing the competition for use of the limited biomass resources or creating stresses in the renewable energy potentials in specific regions in case of large uptake of 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, which is not compensated by the increased biofuel or hydrogen trade. These results indicate a positive feedback and synergies of the energy transition with the decarbonization of the shipping sector.

This study can be expanded and further improved in various directions that were not fully captured in this paper and could be the basis of future research. First, the modelling of the international shipping and aviation sectors can be improved through more detailed representation of the sectors, e.g., activity differentiated by origin and destination, introduction of different aircraft types and shipping vessels, and higher regional granularity in the model. Second, the modelling framework can be expanded to represent potential activity growth due to the increased trade of products associated with the decarbonization, such as batteries, solar panels, and electric motors, to consistently capture the complex interlinkages between energy transition and shipping decarbonization. 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. Finally, the addition of other energy system models in the study estimating the impacts of the same set of policy scenarios would enhance the robustness of the modelling results and the relevant policy recommendations.

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