International shipping in a world below 2 °C

Müller-Casseres, Eduardo; van den Berg, Maarten; Dessens, Olivier; Naghash, Hesam; Tagomori, Isabela S.; Tsiropoulos, Ioannis; van Vuuren, Detlef P.; Portugal-Pereira, Joana; de Boer, Harmen Sytze; Schaeffer, Roberto

DOI
10.1038/s41558-024-01997-1

Publication date
2024

Document Version
Final published version

Published in
Nature Climate Change

Citation (APA)
Müller-Casseres, E., van den Berg, M., Dessens, O., Naghash, H., Tagomori, I. S., Tsiropoulos, I., van Vuuren, D. P., Portugal-Pereira, J., de Boer, H. S., Schaeffer, R., & More Authors (2024). International shipping in a world below 2 °C. *Nature Climate Change*, *14*(6), 600-607. https://doi.org/10.1038/s41558-024-01997-1

nature climate change

Article

https://doi.org/10.1038/s41558-024-01997-1

International shipping in a world below 2 °C

Received: 19 May 2023

Accepted: 26 March 2024

Eduardo Müller-Casseres[1], **Florian Leblanc**[2,3], **Maarten van den Berg**[4], **Panagiotis Fragkos**[5], **Olivier Dessens**[6], **Hesam Naghash**[7], **Rebecca Draeger**[1], **Thomas Le Gallic**[3,8], **Isabela S. Tagomori**[4], **Ioannis Tsiropoulos**[5], **Johannes Emmerling**[9], **Luiz Bernardo Baptista**[1], **Detlef P. van Vuuren**[4,10], **Anastasis Giannousakis**[5], **Laurent Drouet**[9], **Joana Portugal-Pereira**[1,11], **Harmen-Sytze de Boer**[4], **Nikolaos Tsanakas**[5], **Pedro R. R. Rochedo**[12], **Alexandre Szklo**[1] & **Roberto Schaeffer**[1] ✉

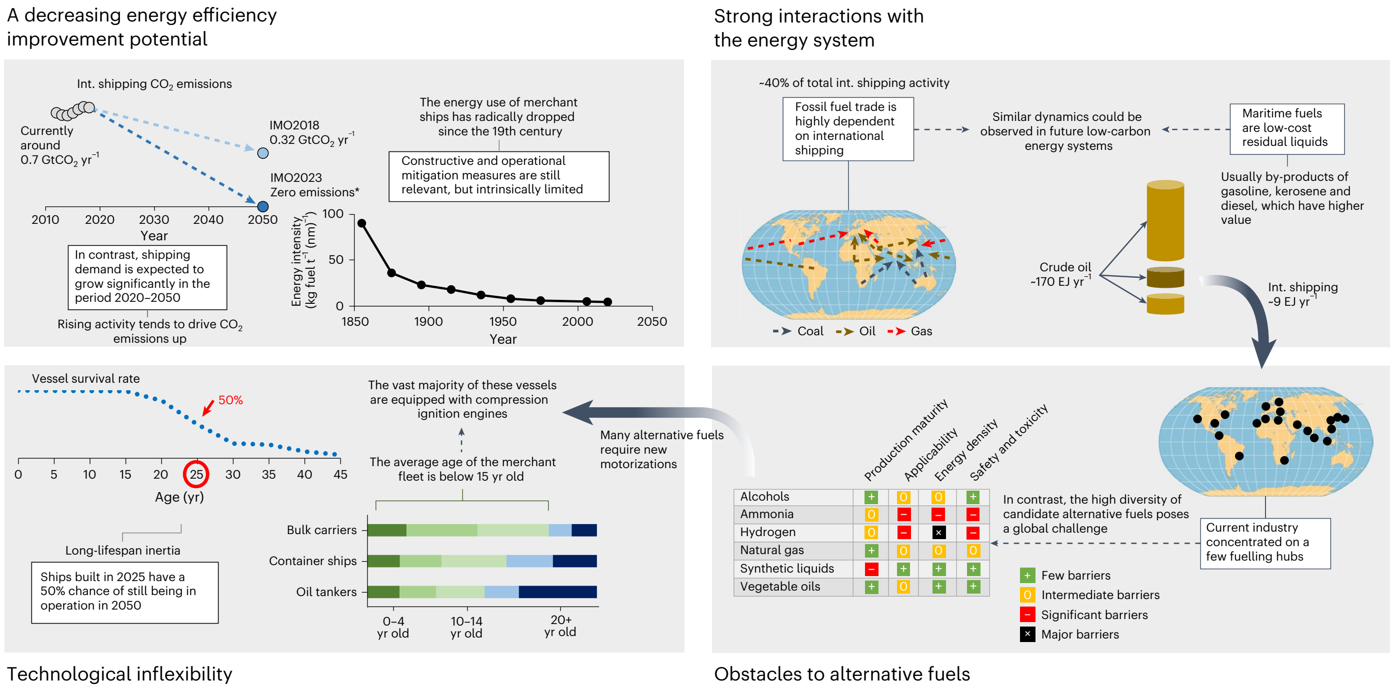
The decarbonization of shipping has become an important policy goal. While integrated assessment models (IAMs) are often used to explore climate mitigation strategies, they typically provide little information on international shipping, which accounts for emissions of around 0.7 $GtCO_2\ yr^{-1}$. Here we perform a multi-IAM analysis of international shipping and show the potential for decreasing annual emissions in the next decades, with reductions of up to 86% by 2050. This is primarily achieved through the deployment of low-carbon fuels. Models that represent several potential low-carbon alternatives tend to show a deeper decarbonization of international shipping, with drop-in biofuels, renewable alcohols and green ammonia standing out as the main substitutes for conventional maritime fuels. While our results align with the 2018 emission reduction goal of the International Maritime Organization, their compatibility with the agency's revised target is still subject to a more definitive interpretation.

Maritime shipping has accounted for CO_2 emissions of roughly 1.0 $GtCO_2\ yr^{-1}$ in recent years (or ~2.8% of global CO_2 emissions). Around 70% of this total originated from international shipping[1,2]. Over the past decades, the International Maritime Organization (IMO), responsible for regulating global maritime transport, has mainly dedicated efforts to energy efficiency policies, including the EEDI (Energy Efficiency Design Index, an indicator of carbon intensity for new ships), a similar index for existing ships (the EEXI—Energy Efficiency Existing Ship Index) and an operational rating system (the CII—Carbon Intensity Indicator)[1,3,4]. In 2018, the IMO reached an agreement to reduce international shipping GHG emissions by at least 50% by 2050 when compared with 2008 (hereinafter IMO2018). In 2023, the strategy was revised to deepen the ambition of shipping's contribution to climate mitigation (hereinafter IMO2023). The main objective now is to reach net-zero life-cycle GHG emissions around 2050[5]. Unlike IMO2018, IMO2023 allows room for carbon dioxide removal (CDR), as it pertains to life-cycle emissions rather than direct emissions only.

However, the role of shipping in a world with deep decarbonization is unclear (Fig. 1). While energy efficiency may help lower the carbon intensity of ships, an efficient shipping sector fuelled by fossil energy would still entail CO_2 emissions. Low-carbon fuels are then regarded as key mitigation options for shipping[2]. Candidate alternative fuels

---

[1]Centre for Energy and Environmental Economics (CENERGIA), Energy Planning Program (PPE), COPPE, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil. [2]Ecole des Ponts ParisTech, CIRED, Nogent-sur-Marne, France. [3]CNRS, CIRED, Nogent-sur-Marne, France. [4]PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands. [5]E3Modelling, Athens, Greece. [6]University College London (UCL), London, UK. [7]Delft University of Technology, Delft, The Netherlands. [8]Société de mathématiques appliquées et de sciences humaines (SMASH), Paris, France. [9]Centro Euro-Mediterraneo sui Cambiamenti Climatici, RFF-CMCC European Institute on Economics and the Environment (EIEE), Milan, Italy. [10]Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands. [11]IN+, Center for Innovation, Technology and Policy Research—Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal. [12]Research and Innovation Center on CO2 and Hydrogen (RICH Center) and Management Science and Engineering Department, Khalifa University, Abu Dhabi, United Arab Emirates. ✉e-mail: roberto@ppe.ufrj.br



	Production maturity	Applicability	Energy density	Safety and toxicity
Alcohols	+	0	0	+
Ammonia	0	–	–	–
Hydrogen	0	–	×	–
Natural gas	+	0	0	0
Synthetic liquids	–	+	+	+
Vegetable oils	+	0	+	+

+ Few barriers
0 Intermediate barriers
– Significant barriers
× Major barriers

Fig. 1 | Decarbonization challenges in the shipping sector. Upper left: historical international shipping emissions based on IEA's dataset[2], and IMO2018 and IMO2023 based on the agency's GHG strategy[5,43]. In the case of IMO2023, the strategy refers not to direct emissions, but to life-cycle emissions. As such, the association of this target with zero direct emissions can be seen as the most stringent possible way of reaching net-zero emissions in the sector. The historical evolution of merchant vessels' energy intensity comes from ref. 44. Upper right: estimation of shipping activity linked to energy trade (mainly oil, oil products, gas and coal) based on the United Nations Conference on Trade and Development's *Review of Maritime Transport*[45]. Data on final energy consumption are from IEA[46] and IMO[1]. On the map, arrows representing selected flows of coal, oil and gas are based on information from the *BP Statistical Review of World Energy*[47]. Lower right: illustration of bunkering hubs based on the academic literature[48,49] and on bunkering websites[8]. The classification of energy carriers according to different criteria is based on qualitative studies of advantages and disadvantages of alternative maritime fuels[6,50,51]. Lower left: graph of vessel age based on information from the United Nations Conference on Trade and Development[52]. Finally, the vessel survival curve is derived from the technical literature[53,54]. Additional references support more general aspects of the figure[7,12,29,55,56].

are diverse in terms of production routes and final energy carriers[6]. Using some of them depends on implementing new motorization options: for example, dual-fuel engines and electrochemical powertrains. Contrastingly, the existing fleet is based almost entirely on compression ignition engines, which can only work with bunker- and diesel-like fuels[7]. The long lifespan of ships and the low average age of existing vessels therefore imply substantial technological inertia. Furthermore, low-carbon shipping would require fuel-specific bunkering infrastructure[2], in contrast with today's standard global hubs of heavy fuel oil and marine gas oil[8]. In view of these challenges and of the important linkages between shipping and the global energy system, we argue that international shipping emission scenarios should be put into the context of global GHG emission scenarios.

A limited number of studies, often based on sectoral modelling, have explored the decarbonization of international shipping using scenarios[2,9–11]. Economy-wide integrated assessment models (IAMs) have historically paid little attention to shipping[12]. These models have been used to explore the consequences of different long-term climate mitigation strategies, with notable impacts on climate governance and policy[13–24]. Currently, IAMs are the backbone of scenario analyses reviewed by Working Group III of the Intergovernmental Panel on Climate Change (IPCC), which focuses on mitigation response strategies to global warming[22,24–26]. The IAM community has recently started to explore the specificities of international shipping, which also made possible a better representation of the sector's demand and mitigation options within models[12,27–29]. These improvements allow an integrated perspective of the sector's decarbonization strategy, adding value to the existing literature.

In this Article we explore possible futures of international shipping in terms of energy carriers and CO_2 emissions under an IAM framework. We perform a multi-model comparison of shipping, relying on the results from six global IAMs. Rather than thinking of maritime emission reductions as the final objective, our analysis sees international shipping as part of a wider challenge, in which the goal is to halt global warming. We argue that a myopic mitigation strategy for shipping could not only cause harmful economic impacts but also imply spillover effects on GHG emissions[29]. One of the objectives of our analysis is to compare shipping emission reductions observed in IAM-based scenarios with those suggested by IMO2018 and IMO2023, which are currently the landmark of maritime emissions.

Our modelling strategy is summarized in Extended Data Fig. 1. In the context of the NAVIGATE project[30], which aims to enhance the capabilities of IAMs, our work starts with the selection of models suited for the exercise. The selection comprises those IAMs in the project that have both (1) global scale and (2) a satisfactory representation of the international shipping sector. Using the same socioeconomic assumptions and carbon budgets, we develop scenarios of the global energy system for 2020–2100 and concentrate our analysis on international shipping.

The IAMs used in this exercise differ in terms of overall structure and modelling dynamics, and in the way they represent shipping mitigation options and freight demand (Table 1). Four of our models (COFFEE, IMAGE, PROMETHEUS and TIAM-UCL) have relatively high technological resolution in the shipping sector, meaning that they include numerous low-carbon maritime fuel production routes and vessel motorization options. The other two models (IMACLIM-R and WITCH) work with fewer low-carbon alternatives, with IMACLIM-R relying mainly on lignocellulosic biofuels and WITCH on hydrogen and hydrogen-based synthetic fuels. Despite the few low-carbon alternatives, these models

https://doi.org/10.1038/s41558-024-01997-1

Table 1 | Key features of global IAMs

	Time horizon	Type	Solution method	Solution concept	International shipping demand	Discount rate (% per annum)
COFFEE 1.5	2100	Bottom up	Intertemporal optimization with perfect foresight	Partial equilibrium, focusing on energy, agriculture and land use	Endogenous for main energy and agricultural products. General cargo driven by GDP. For most products, international shipping demand is a result of the global model optimization	5.0
IMACLIM-R 2.0	2100	Hybrid	Recursive dynamic	General equilibrium (closed economy)	Endogenous to trade activities of all economic sectors	Not applicable
IMAGE 3.2	2100	Bottom up	Recursive dynamic	Partial equilibrium (price elastic demand)	Demand is projected with constant elasticity of the industry value added, and demand sensitivity to transport prices depends on its share of energy costs in the total service costs	10.0
PROMETHEUS 1.2	2050	Hybrid	Recursive dynamic	Energy system simulation model, focusing on demand and supply	Semi-endogenous driven by trade of energy products and GDP developments	8.0
TIAM-UCL 4.1.2	2100	Bottom up	Intertemporal optimization with perfect foresight	Partial equilibrium, focusing on the energy system	Endogenous for main energy commodities. General non-energy cargo driven by GDP	3.5
WITCH 5.0	2100	Hybrid	Intertemporal optimization with perfect foresight	General equilibrium	Demand evolution based on calibrated income and price elasticities	Ramsey rate (3.0–5.0)

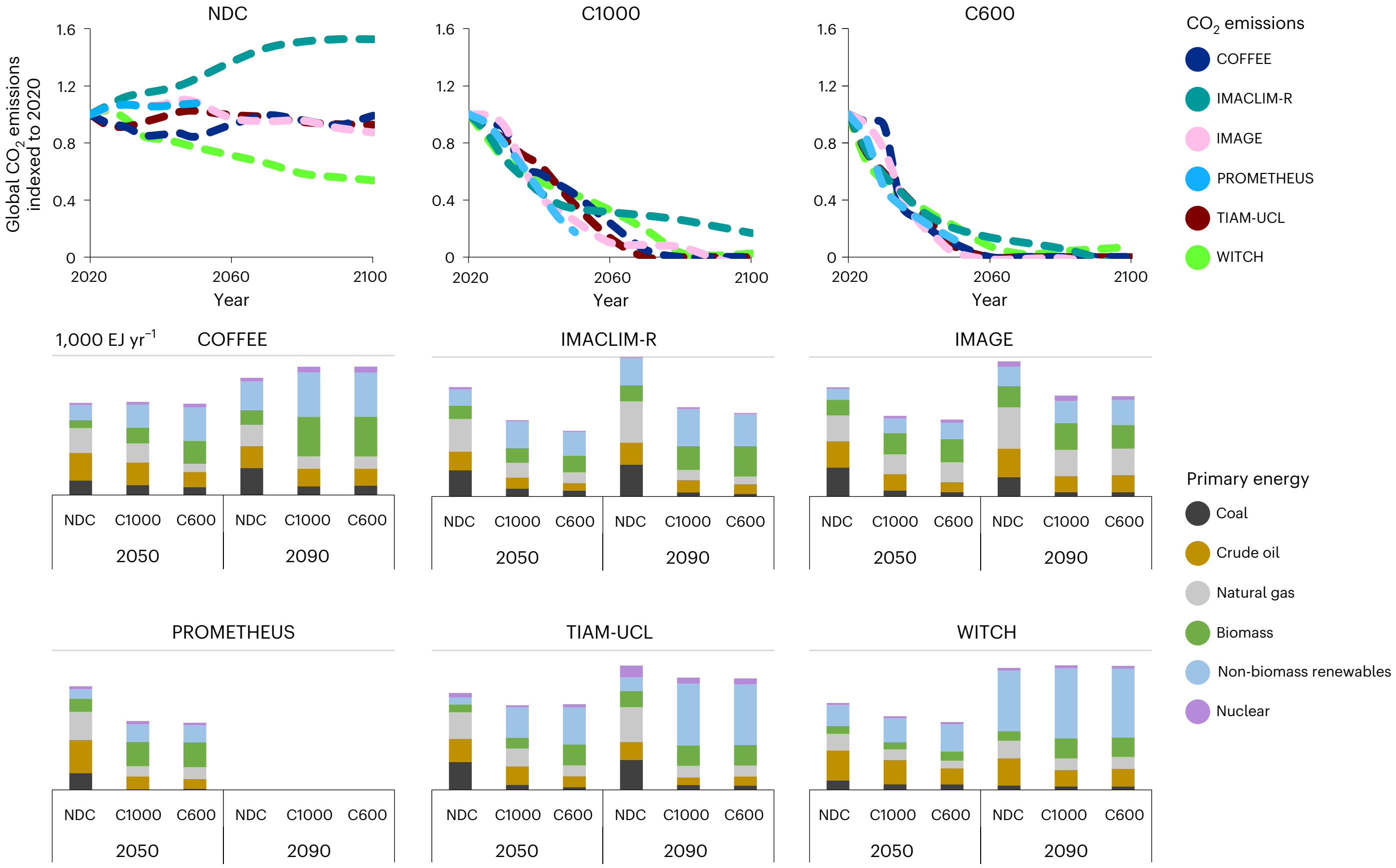


Fig. 2 | Global CO$_2$ emissions and primary energy. Upper panels: variation of annual global CO$_2$ emissions when compared with 2020 across models and scenarios. The six IAMs differ in terms of scope, with some only accounting for fossil fuel and industry emissions. As such, each of the depicted trajectories is tied to the absolute annual emission value in 2020 generated by its own model. Lower panels: global primary energy across models and scenarios (direct equivalent method).

remain interesting for the overall analysis (for example, IMACLIM-R exhibits macroeconomic feedback that makes carbon price affect the demand for shipping not only through fuel prices but also indirectly through the aggregate economic output response). One of the purposes of our analysis is precisely to assess the impact of having a few or several mitigation options for shipping represented in IAMs.

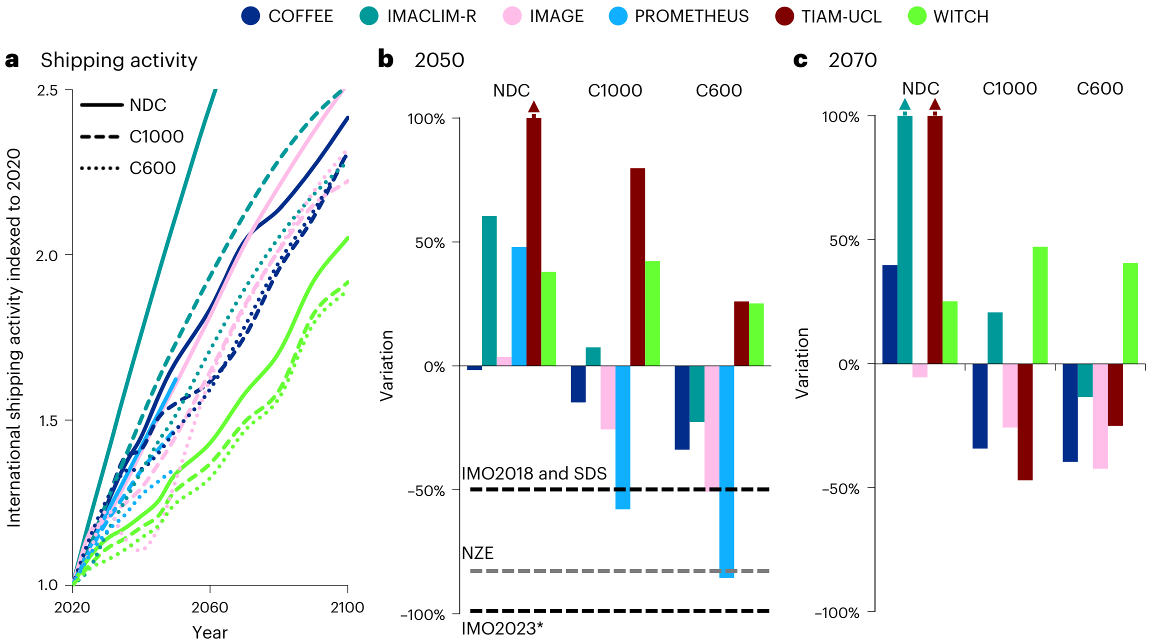


Fig. 3 | International shipping CO$_2$ emissions. a, International shipping activity level between 2020 and 2100 across scenarios, indexed to 2020. Shipping activity from TIAM-UCL is not shown because the model uses only fuel and efficiency assumptions to project shipping emissions (IMACLIM-R value in 2100: 3.2). **b**, Variation of the annual CO$_2$ emissions from international shipping in 2050 when compared with 2020 across scenarios (for clarity, on the *y* axis we use the range of −100% to +100%, with the arrow indicating that the TIAM-UCL NDC variation is slightly above this range, with a value of 115%). IMO2018 indicates the 50% emission cutback associated with IMO's preliminary strategy[43] (total 2020 international shipping emissions are very close to total 2008 emissions, used as the baseline year for IMO2018), while NZE refers to the IEA's net-zero scenario[57]. IMO2023* indicates a 100% cutback, that is, zero direct international shipping emissions. As discussed, the revised IMO strategy sets a target of achieving zero life-cycle emissions by 2050[5]. This objective cannot be directly compared with the rest of the chart, which addresses direct emissions only. Theoretically, in cases where negative emissions are factored in during the production of certain maritime fuels, it could become feasible to meet IMO2023 with non-zero direct emissions (this discussion would involve criteria for CDR allocation—for example, in biorefineries). As such, the chart's depiction of a 100% reduction represents the most stringent way of complying with IMO2023 (i.e., not only life cycle but also direct emissions are reduced to zero). **c**, Variation of the annual CO$_2$ emissions from international shipping in 2070 when compared with 2020 across scenarios (for clarity, on the *y* axis we consider the range −100% to 100%, with arrows indicating that the IMACLIM-R NDC and TIAM-UCL NDC variation is above this range, with values of 105% and 165% respectively).

Our scenario design does not impose any sectoral storyline (e.g., IMO2018 and IMO2023 are not implemented as constraints) but harmonizes input data by using Shared Socioeconomic Pathway 2 (SSP2)[31]. We work with three scenario groups, with the reference group (NDC) assuming the fulfilment of nationally determined contributions (NDCs) as stated in the 2015 pledges. In these scenarios, total global emissions are not restricted in any way. The other scenario groups (C1000 and C600) also assume the fulfilment of NDCs but additionally impose carbon budgets of 1,000 and 600 GtCO$_2$ for the period 2020–2100. While C600 scenarios can be seen as in line with a warming slightly above 1.5 °C by 2100, C1000 scenarios would reflect a world probably below 2 °C by that time (Supplementary Section 4). Both C1000 and C600 scenarios follow a peak-budget dynamic, that is, net negative emissions are not allowed after reaching the point of net zero[22].

In addition to our global analysis, in Supplementary Section 7 we present detailed results for the European Union. This regional analysis was performed using the PRIMES-Maritime model and is consistent with C1000 and C600 global carbon budgets.

Results

From a global emission perspective (Fig. 2), results vary more across scenarios than among models, with NDC scenarios being somewhat of an exception. The largest discrepancy is observed between IMACLIM-R and WITCH. These discrepancies arise from the challenge of distinguishing which technological pathways belong to a reference scenario, as some that were conventionally regarded as part of deep mitigation scenarios can now be interpreted as an extension of present-day trends. This can be exemplified by wind and solar power, whose recent breakthroughs have enabled renewable-based electrification as a potential component of an NDC scenario (this is precisely what the WITCH model portrays, with its NDC scenario demanding over 150 EJ yr^{-1} of wind and solar primary energy by 2050).

Results from carbon budget scenarios exhibit a more cohesive pattern, with reductions in annual global emission in both C1000 and C600 scenarios. These two sets of scenarios are characterized by the spread of renewable electricity, and by strategies aimed at eradicating deforestation, reducing final energy demand, increasing energy efficiency and replacing fossil energy carriers with biofuels and e-fuels. Furthermore, C1000 and C600 scenarios include a growth of specific CDR technologies (i.e., bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage—Supplementary Section 5).

Stable or lower shipping emissions in carbon budget scenarios

Under current policies (NDC), our models project international shipping emissions to stabilize or rise in the long term (Fig. 3), with values in the range of 0.5–1.4 MtCO$_2$ yr^{-1} in 2050, 0.6–1.7 MtCO$_2$ yr^{-1} in 2070 and 0.7–2.0 MtCO$_2$ yr^{-1} in 2090. From a decomposition perspective, this uptrend is due to total shipping activity, which is projected to continuously increase through the century (Fig. 3a). Higher reference emissions are associated with strong activity growth and more pessimistic efficiency assumptions.

On the other hand, most models show international shipping emissions to fall substantially in the Paris-compatible scenarios, even with rising activity. This is made possible by efficiency improvements and fuel switching (Fig. 4). With a carbon budget of 1,000 GtCO$_2$,

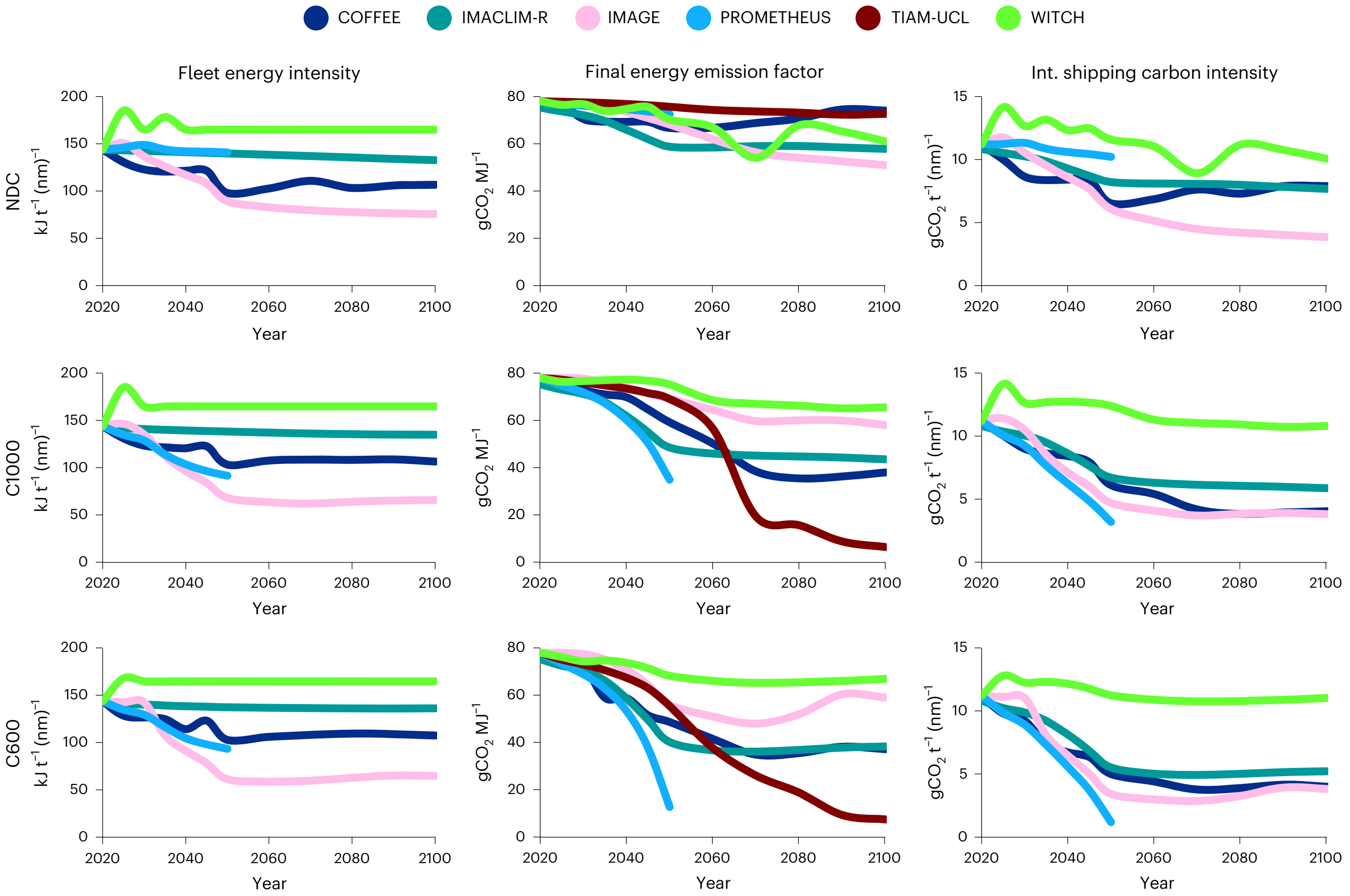


Fig. 4 | Evolution of key indicators of energy and carbon intensity in international shipping over the century across models and scenarios. First column: average fleet energy intensity (energy per transport work, kJ t^{-1} (nm)$^{-1}$). Second column: average CO_2 emission factor of the final energy used by the international shipping sector (mass per energy, gCO$_2$ MJ^{-1}). Third column: resulting carbon intensity (mass per transport work, gCO$_2$ t^{-1} (nm)$^{-1}$). TIAM-UCL is not included in the first or third columns since the model uses only fuel and efficiency assumptions to project shipping emissions.

international shipping emissions lie between 0.3 and 1.1 GtCO$_2$ yr^{-1} in 2050. In particular, the most technology-detailed models indicate reductions relative to the 2020 level. While COFFEE and IMAGE show cutbacks lower than that of IMO2050 (15 and 26%), PROMETHEUS shows a reduction of 58%, going beyond IMO2050 and the Sustainable Development Scenario of the International Energy Agency (IEA)[32]. IMACLIM-R, TIAM-UCL and WITCH show increases of 7, 80 and 42% in 2050. For IMACLIM-R, this is explained by a low flexibility of the demand, which is endogenous, and limited low-carbon fuel alternatives. In the case of TIAM-UCL, this effect is the combination of a fast-rising demand with a relatively slow development of low-carbon fuels, which takes place mostly after 2050. This time lag makes its variation go from the most positive in 2050 (+80%) to the most negative in 2070 (−47%). WITCH is the only exception, depicting stable international shipping emissions throughout the century. This is partly due to the low technological granularity of the shipping sector in WITCH, which mainly includes blue/green hydrogen-based fuels as potential energy alternatives. Considering these limited mitigation options, the intertemporal economic growth optimization of the model prioritizes the abatement of CO_2 emissions elsewhere.

With a carbon budget of 600 GtCO$_2$, reductions are more pronounced in 2050. COFFEE and IMAGE show reductions of 34% and 51%, in line with IMO2050 and the Sustainable Development Scenario, while PROMETHEUS depicts emissions as low as those of the IEA net zero emissions by 2050 scenario, with a cutback of 86%. In C600 scenarios, even low-shipping-resolution models show at least stable emissions in 2050. In TIAM-UCL, the more stringent carbon budget engenders a faster maritime fuel transition, making international shipping emissions only 26% higher in 2050 when compared with 2020. In the second half of the century, models project international shipping emissions to stabilize, in both C1000 and C600 scenarios. This pattern is due to the rise of BECCS after 2040 (Supplementary Section 5). In some cases, this even leads to counterintuitive increases in shipping carbon intensity (e.g., IMAGE). Although our carbon budget scenarios do not allow net negative emissions, this does not exclude the use of some level of CDR strategies. This result should be tempered by the uncertainties surrounding large-scale deployments of BECCS (e.g., land and water requirements[33,34]). Restrictions on the implementation of BECCS would mean a higher decarbonization pressure on the shipping sector.

Fossil shift associated with model granularity for shipping

International shipping fuel demand reaches 9–11 EJ yr^{-1} in 2030 and 7–18–EJ yr^{-1} in 2050. These discrepancies stem from differences in activity projections and energy intensity. Scenarios with high activity and low efficiency gains (e.g., NDC scenarios from IMACLIM-R and TIAM-UCL) have a total demand of 16–18 EJ yr^{-1} in 2050. At the opposite end, IMAGE and PROMETHEUS have C1000 and C600 fuel demands of 7–8 EJ yr^{-1} in 2050, slightly below the current international shipping consumption. When compared with their NDC scenarios, this represents reductions of 15–45%, with a proportion of these reductions originating from avoided fossil fuel transportation. In the case of COFFEE, although the transportation of coal, oil and gas is modelled in detail, no

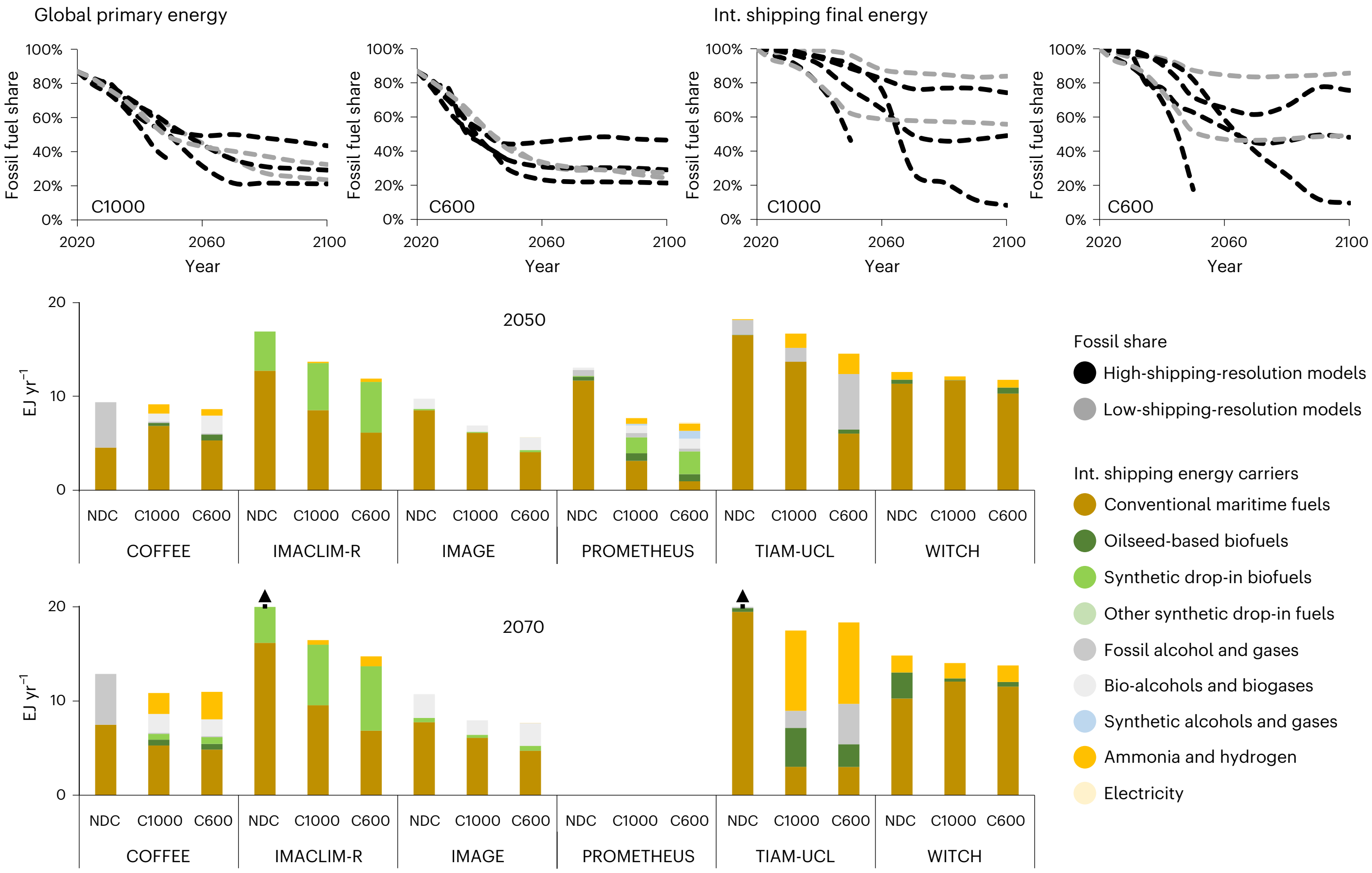


Fig. 5 | International shipping in the context of the global energy transition. Upper left: fossil fuel share in global primary energy across models in C1000 and C600 scenarios. To convey the effect of shipping technological resolution, models are grouped into two categories instead of being colour-coded individually. High-shipping-resolution models include COFFEE, IMAGE, PROMETHEUS and TIAM-UCL. Low-shipping-resolution models include IMACLIM-R and WITCH. Upper right: fossil fuel share in international shipping final energy across models in C1000 and C600 scenarios. Lower: international shipping energy supply across models and scenarios in 2050 and 2070. For clarity, on the *y* axis we use the range of 0–20 EJ yr^{-1}, with the arrows indicating that IMACLIM-R NDC and TIAM-UCL NDC values are slightly above this range. In the IMACLIM-R NDC scenario, total fuel consumption reaches 21 EJ yr^{-1} in 2070, with 5 EJ yr^{-1} supplied by the 'Synthetic drop-in biofuels' category. In the TIAM-UCL NDC scenario, total fuel consumption reaches 23 EJ yr^{-1} in 2070, with 3 EJ yr^{-1} supplied by the 'Fossil alcohol and gases' category.

noticeable impact is observed. The mitigation strategy indicated by the model includes the conservation of a large intercontinental fossil fuel market (thereby utilizing only lower-cost and lower-carbon-intensity resources, while phasing out less efficient production fields).

As a hard-to-abate sector, international shipping tends to have higher shares of fossil energy in mitigation scenarios when compared with sectors such as electricity supply, heating and road transportation. Our results confirm this (Fig. 5), depicting conventional maritime fuels as relevant energy sources until the second half of the century. This gap between shipping and the rest of the energy system is partly associated with the level of detail of the shipping sector in each IAM. For instance, in C600 scenarios, while high-shipping-resolution models show fossil energy with a share of 40–51% in international shipping in 2070, low-shipping-resolution models indicate a fossil share of 46–84% in the same year. IMAGE is the only high-shipping-resolution model that keeps fossil fuels above 60% of maritime final energy in the second half of the century in the C600 scenario. This is because the model reacts to a carbon budget mainly by reducing shipping energy intensity, achieving quite low energy consumption, and thus reducing the need for alternative fuels.

Fuel selection linked to primary energy trends

Our models point to a set of various mitigation responses, with the choice of specific alternative maritime fuels related to the global trends observed in the different IAMs. Carbon budget scenarios from TIAM-UCL, for example, include aggressive electrification based on solar and wind power, with these sources reaching ~300 EJ yr^{-1} of primary energy in 2070 (in recent years, non-biomass renewables accounted for ~30 EJ yr^{-1}). This context favours the adoption of maritime fuels based on renewable electricity, especially ammonia (with an energy density advantage compared to hydrogen), which reaches around 9 EJ yr^{-1} in 2070 and 18 EJ yr^{-1} in 2090. In contrast, pathways resulting in higher biomass shares in primary energy (such as IMACLIM-R and IMAGE) show a preference for bio-based maritime fuels, especially bio-alcohols and Fischer–Tropsch hydrocarbons. However, models that rely on bio-based fuels to decarbonize transport always face competition for feedstock in generating negative emissions with the power sector[35]. This largely explains the limit reached by low-carbon maritime fuels in IMACLIM-R scenarios. Carbon budget scenarios from COFFEE and PROMETHEUS show a more diverse maritime energy mix. In COFFEE scenarios, vegetable oils and renewable alcohols (with higher technological maturity) are the first options for fuel switch in the 2040s. In the second half of the century, green ammonia (~3 EJ yr^{-1}) and residual lignocellulosic biofuels (~2 EJ yr^{-1}) become the dominant alternative energy carriers. PROMETHEUS scenarios depict a faster transition and richer fuel portfolio based on ammonia, hydrogen and oilseed-based fuels, while lignocellulosic bioenergy rapidly becomes the most important low-carbon alternative, reaching more than 2 EJ yr^{-1} in 2050 in its C600 scenario.

Discussion

Our multi-IAM exercise shows that the role of international shipping in a world below 2 °C involves stabilizing or reducing annual CO_2 emissions in the next decades. However, it also reveals an important variability among IAMs in their portrayal of shipping's energy matrix in a low-carbon world. Although this partly arises from the differing number of maritime fuel options across models, it is also a consequence of more structural trends in their representation of the energy system (e.g., propensity for electrification). The quality of model results is mainly impacted by the detailing of the demand, the endogeneity of shipping energy efficiency and the diversity of candidate alternative fuel production routes. Models that best combine these elements point towards (1) a more modest growth of shipping final energy demand and (2) the deployment of a portfolio of alternative fuels, strengthening the concept of green corridors. Furthermore, IAMs that represent a smaller number of types of low-carbon maritime fuel tend to retain a larger share of fossil energy in carbon budget scenarios, possibly underestimating the true decarbonization potential of the sector and contributing to higher reliance on CDR strategies.

Drop-in biofuels (e.g., FAME-biodiesel, SVO and HVO-diesel) and renewable alcohols (e.g., ethanol and methanol) seem the most promising short-term alternative fuels, while ammonia and synthetic energy carriers (especially lignocellulosic biofuels) become essential towards 2050 and beyond. International shipping has a high level of technological inertia. As such, if the industry is to be prepared for a substantial amount of renewable energy from 2030 onwards, it is essential to start investing in low-carbon fuels, new motorizations and infrastructure (storage and bunkering) as soon as possible.

Our findings exhibit a good alignment with IMO2018. While lower-shipping-resolution models indicate stable emissions by mid-century, a 50% reduction remains reasonably consistent with the outcomes of the other IAMs, particularly within the C600 scenario. Comparing our results with IMO2023 is more challenging, since we address direct shipping emissions only, whereas IMO2023 deals with life-cycle emissions, using a different methodology[5]. Given that IMO2023 deals with a net-zero emission metric, it is reasonable to assume that achieving this target allows for residual consumption of fossil fuels in the maritime final energy mix in 2050, as long as the negative CO_2 emissions attributable to the sector are equal to the emissions from these fuels. Such a scenario is potentially compatible with some of our deep mitigation pathways, since they include negative emissions associated with BECCS. Determining whether these negative emissions could be considered as part of international shipping life-cycle emissions would depend on the allocation criteria deployed (due to the multi-fuel dimension of biorefineries).

Our results need to be interpreted considering the uncertainties associated with the long-term modelling of complex systems. Major systemic uncertainties include socioeconomic assumptions (all scenarios were based on a single SSP) and projections of advancements in energy conversion and CDR technologies. More specifically, our study is limited by the simplified representation of maritime transport in IAMs. An important source of uncertainty lies in the modelling of shipping demand, as it typically does not account for factors such as the impact of imperfect markets and increasing geopolitical tensions. Another key point of uncertainty is vessel technology, which directly affects the energy and carbon efficiencies of ships. Recent studies have shown a combination of constructive and operational strategies that could result in energy intensities lower than those considered here[36–38], or even promote ship-based carbon capture[39,40]. Finally, our analysis focuses on physical/energy aspects, paying less attention to economic matters such as the impact of mitigation on freight costs. Considering the ongoing discussions of a carbon tax in international shipping[41,42], exploring this topic could be relevant in future works.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-024-01997-1.

References

1. Faber, J. et al. *Fourth IMO GHG Report* (International Maritime Organization, 2021).
2. International shipping. *International Energy Agency* https://www.iea.org/reports/international-shipping (2023).
3. EEXI and CII—ship carbon intensity and rating system. *International Maritime Organization* https://www.imo.org/en/MediaCentre/HotTopics/Pages/EEXI-CII-FAQ.aspx (2019).
4. *EEXI—Energy Efficiency Existing Ship Index* (DNV GL, 2021).
5. Comer, B. & Carvalho, F. *IMO's Newly Revised GHG Strategy: What It Means for Shipping and the Paris Agreement* (ICCT, 2023).
6. Carvalho, F. et al. Prospects for carbon-neutral maritime fuels production in Brazil. *J. Clean. Prod.* **326**, 129385 (2021).
7. Vermeire, M. B. *Everything You Need to Know about Marine Fuels* (Chevron Marine Products, 2021).
8. World bunker prices. *Ship & Bunker* https://shipandbunker.com/prices (2022).
9. *Maritime Forecast to 2050* (DNV, 2021).
10. Englert, D. & Losos, A. *Charting a Course for Decarbonizing Maritime Transport: Summary for Policymakers and Industry* (World Bank, 2021).
11. *A Pathway to Decarbonise the Shipping Sector by 2050* (IRENA, 2021).
12. Müller-Casseres, E., Edelenbosch, O. Y., Szklo, A., Schaeffer, R. & van Vuuren, D. P. Global futures of trade impacting the challenge to decarbonize the international shipping sector. *Energy* **237**, 121547 (2021).
13. Moss, R. H. et al. The next generation of scenarios for climate change research and assessment. *Nature* **463**, 747–756 (2010).
14. van Vuuren, D. P. et al. The representative concentration pathways: an overview. *Clim. Change* **109**, 5–31 (2011).
15. Clarke, L. et al. in *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. et al.) Ch. 6 (IPCC, Cambridge Univ. Press, 2014).
16. van Vuuren, D. P. et al. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Glob. Environ. Change* **42**, 237–250 (2017).
17. Gambhir, A. et al. Assessing the feasibility of global long-term mitigation scenarios. *Energies* https://doi.org/10.3390/en10010089 (2017).
18. Fujimori, S. et al. SSP3: AIM implementation of Shared Socioeconomic Pathways. *Glob. Environ. Change* **42**, 268–283 (2017).
19. Kriegler, E. et al. Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century. *Glob. Environ. Change* **42**, 297–315 (2017).
20. Grubler, A. et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat. Energy* **3**, 515–527 (2018).
21. Rogelj, J. et al. Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nat. Clim. Change* **8**, 325–332 (2018).
22. Riahi, K. et al. Cost and attainability of meeting stringent climate targets without overshoot. *Nat. Clim. Change* **11**, 1063–1069 (2021).
23. van Soest, H. L. et al. Global roll-out of comprehensive policy measures may aid in bridging emissions gap. *Nat. Commun.* **12**, 6419 (2021).

24. Riahi, K. et al. in *Climate Change 2022: Mitigation of Climate Change* (eds Shukla, P. R. et al.) Ch. 3 (IPCC, Cambridge Univ. Press, 2022).
25. van Beek, L., Hajer, M., Pelzer, P., van Vuuren, D. & Cassen, C. Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science–policy interface since 1970. *Glob. Environ. Change* **65**, 102191 (2020).
26. Guivarch, C. et al. in *Climate Change 2022: Mitigation of Climate Change* (eds Shukla, P. R. et al.) AIII (IPCC, Cambridge Univ. Press, 2022).
27. Esmeijer, K., den Elzen, M. & van Soest, H. L. *Analysing International Shipping and Aviation Emission Projections of IAMs* (PBL, 2020).
28. Sharmina, M. et al. Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2 °C. *Clim. Policy* **21**, 455–474 (2021).
29. Müller-Casseres, E. et al. Production of alternative marine fuels in Brazil: an integrated assessment perspective. *Energy* **219**, 119444 (2021).
30. Next generation of advanced integrated assessment modelling to support climate policy making. *NAVIGATE* https://www.navigate-h2020.eu/ (2023).
31. Riahi, K. et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob. Environ. Change* **42**, 153–168 (2017).
32. Transport sector CO_2 emissions by mode in the Sustainable Development Scenario, 2000–2030. *International Energy Agency* https://www.iea.org/data-and-statistics/charts/transport-sector-co2-emissions-by-mode-in-the-sustainable-development-scenario-2000-2030 (2019).
33. Hanssen, S. V. et al. The climate change mitigation potential of bioenergy with carbon capture and storage. *Nat. Clim. Change* **10**, 1023–1029 (2020).
34. Stenzel, F. et al. Irrigation of biomass plantations may globally increase water stress more than climate change. *Nat. Commun.* **12**, 1512 (2021).
35. Leblanc, F. et al. The contribution of bioenergy to the decarbonization of transport: a multi-model assessment. *Clim. Change* **170**, 21 (2022).
36. Lindstad, E., Stokke, T., Alteskjær, A., Borgen, H. & Sandaas, I. Ship of the future—a slender dry-bulker with wind assisted propulsion. *Marit. Transp. Res.* **3**, 100055 (2022).
37. Lindstad, E., Polic, D., Rialland, A., Sandaas, I. & Stokke, T. Reaching IMO 2050 GHG targets exclusively through energy efficiency measures. *J. Ship Prod. Des.* **39**, 194–204 (2023).
38. Chou, T., Kosmas, V., Acciaro, M. & Renken, K. A comeback of wind power in shipping: an economic and operational review on the wind-assisted ship propulsion technology. *Sustainability* **13**, 1880 (2021).
39. Feenstra, M. et al. Ship-based carbon capture onboard of diesel or LNG-fuelled ships. *Int. J. Greenh. Gas. Control* **85**, 1–10 (2019).
40. Ros, J. A. et al. Advancements in ship-based carbon capture technology on board of LNG-fuelled ships. *Int. J. Greenh. Gas. Control* **114**, 103575 (2022).
41. Rojon, I., Lazarou, N.-J., Rehmatulla, N. & Smith, T. The impacts of carbon pricing on maritime transport costs and their implications for developing economies. *Mar. Policy* **132**, 104653 (2021).
42. Pereda, P., Lucchesi, A., Diniz, T. & Wolf, R. *Carbon Tax in the Shipping Sector: Assessing Economic and Environmental Impacts* Working Paper No. 2023-04 (Department of Economics—FEA/USP, 2023); http://www.repec.eae.fea.usp.br/documentos/Pereda_Lucchesi_Diniz_Wolf_04WP.pdf
43. *UN Body Adopts Climate Change Strategy for Shipping* (International Maritime Organization, 2018).
44. Stopford, M. *Maritime Economics* (Routledge, 2009).
45. United Nations Conference on Trade and Development in *Review of Maritime Transport 2022* Ch. 1 (United Nations, 2022).
46. Final consumption. *Key World Energy Statistics 2021* (International Energy Agency, 2021); https://www.iea.org/reports/key-world-energy-statistics-2021/final-consumption
47. *BP Statistical Review of World Energy* (BP, 2022); https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf
48. Stefanakos, C. N. & Schinas, O. Forecasting bunker prices; a nonstationary, multivariate methodology. *Transp. Res. C* **38**, 177–194 (2014).
49. Lam, J. S. L., Chen, D., Cheng, F. & Wong, K. Assessment of the competitiveness of ports as bunkering hubs: empirical studies on Singapore and Shanghai. *Transp. J.* **50**, 176–203 (2011).
50. *Comparison of Alternative Marine Fuels* Report No. 2019-0567 (DNV GL, 2019).
51. Gray, N., McDonagh, S., O'Shea, R., Smyth, B. & Murphy, J. D. Decarbonising ships, planes and trucks: an analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. *Adv. Appl. Energy* **1**, 100008 (2021).
52. United Nations Conference on Trade and Development in *Review of Maritime Transport 2022* Ch. 2 (United Nations, 2022).
53. *Propulsion Trends in Bulk Carriers* (MAN, 2022); https://www.man-es.com/docs/default-source/marine/tools/propulsion-trends-in-bulk-carriers.pdf?sfvrsn=d851b1c6_14
54. *Propulsion Trends in Tankers* (MAN, 2022); https://www.man-es.com/docs/default-source/marine/tools/propulsion-trends-in-tankers_5510-0031-03ppr.pdf?sfvrsn=399654ef_4
55. Bouman, E. A., Lindstad, E., Rialland, A. I. & Strømman, A. H. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping—a review. *Transp. Res. D* **52**, 408–421 (2017).
56. Sharmina, M., McGlade, C., Gilbert, P. & Larkin, A. Global energy scenarios and their implications for future shipped trade. *Mar. Policy* **84**, 12–21 (2017).
57. *Net Zero by 2050* (International Energy Agency, 2021); https://www.iea.org/reports/net-zero-by-2050

Methods

Model exercise

Our work evaluates the role of international shipping as part of the much broader challenge of limiting global warming to relatively safe levels. To this end, we use IAMs to develop low-carbon scenarios for the energy and industrial systems (and, in some cases, for agriculture and land-use systems as well), focusing our analysis of results on international shipping, a sector whose modelling has been recently improved across these models.

Integrated assessment models

IAMs describe key processes in the interaction of human development and natural environment. Typically, they are designed to assess the implications of achieving climate objectives, such as limiting global warming to 1.5 or 2 °C[22,58]. The six global models used in this study are COFFEE[59,60], IMACLIM-R[35,61], IMAGE[12,16], PROMETHEUS[60,62], TIAM-UCL[63,64] and WITCH[65,66].

COFFEE is a process-based IAM[25] that utilizes intertemporal linear programming optimization with perfect foresight to model global energy, agricultural and land-use systems. The energy sector is at the core of the model. Each of the model's regions has a detailed representation of energy extraction and conversion technologies, and individualized estimates of energy resources (in terms of both volumes and costs) in the form of cost–supply curves. Divided into five main sectors (energy, industry, transportation, buildings and agriculture), the model accounts for all primary energy produced by energy systems and its later transformation into secondary and final energy. The detailed modelling of international shipping is one of the most recent refinements in COFFEE. The approach used for modelling this sector focused on accurately representing the demand and potential alternative fuels. Shipping demand is based on the representation of 31 products/product groups, with most of them modelled endogenously. The energy modelling of ships is based on ten illustrative motorizations, ranging from conventional two-stroke diesel engines to advanced electrochemical powertrains. Meanwhile, candidate fuels are grouped into eight categories, with each one potentially applicable to different powertrain types. In their turn, technological routes that produce these fuels are represented in each COFFEE region, ranging from technologically mature processes (e.g., oil refining, vegetable oil extraction) to advanced energy conversion processes (e.g., Fischer–Tropsch synthesis). The improvement of ship energy efficiency over time is modelled exogenously on the basis of conservative assumptions. Detailed information on COFFEE can be found in Supplementary Sections 2.2 and 3.1.

IMACLIM-R is a multi-sectoral computable general equilibrium model representing the global economy as a set of 12 production sectors with input–output trade links. It is primarily based on macroeconomic theory, featuring consistent input–output accounting of both economic and physical energy flows. The demand for international shipping is influenced by the trade volume of physical goods but also by the price of freight transport. In turn, this price is strongly influenced by energy carrier prices and energy efficiency. Maritime energy sources are determined by the relative prices of energy, also considering carbon taxation and exogenous hypotheses for energy efficiency improvement. Detailed information on IMACLIM-R can be found in Supplementary Sections 2.3 and 3.2.

IMAGE is an intermediate-complexity IAM that provides a process-oriented representation of human and earth systems, which are connected by emissions and land use. The model is driven by various factors, including demographic, economic and technological development, as well as resource availability, lifestyle changes and policy. The model's energy module simulates long-term trends in final energy use, depletion, energy-related GHGs and other air pollution emissions, as well as land-use demand for energy crops. The results are obtained using a single set of deterministic algorithms, which derive the system state in any future year entirely from previous system states. The model projects freight service demand using a constant elasticity of the industry value added for each transport mode, with international shipping being one of six freight transport modes. The competition between vessels with different energy efficiencies, costs and fuel type characteristics is described using a multinomial logit equation. These substitution processes capture the price-induced energy efficiency changes, and over time more efficient technologies become more competitive due to exogenous decreases in costs, representing the autonomous-induced energy efficiency changes. The model assumes that each type of vehicle uses only one fuel type. Therefore, this process also describes the maritime fuel selection. Detailed information on IMAGE can be found in Supplementary Sections 2.4 and 3.3.

PROMETHEUS is a global energy system model covering in detail the interactions between energy demand, supply and prices. Its main objectives are to assess mitigation pathways, analyse the implications of policy measures and quantify impacts of climate policies on energy prices. The model quantifies CO_2 emissions and represents abatement technologies and policy instruments (e.g., carbon pricing, efficiency standards). In terms of mathematical formulation, PROMETHEUS is a recursive dynamic simulation model, with investment and operation decisions mostly based on the current state of knowledge of parameters such as cost and performance. Recently, PROMETHEUS was enhanced with an improved representation of international shipping. Several technologies and emission reduction options were included in the model, with focus on low-carbon fuels. Maritime activity is split by segments (i.e., dry bulk, general cargo, container and tanker). For tankers, the demand is endogenously estimated from interactions with the energy sector, while other segments have exogenous projections based on the literature. Emission reduction options include energy-saving alternatives, speed reduction and the deployment of a wide range of alternative fuels. Detailed information on PROMETHEUS can be found in Supplementary Sections 2.5 and 3.4.

TIAM-UCL is an energy-economy model of the global energy system that uses a linear programming optimization approach to explore cost-optimal systems. Features of its formulation include perfect competition and foresight. The representation of the global energy system encompasses primary sources from production through their conversion into final energy and utilization to meet service demands across a range of economic sectors. Using a scenario-based approach, the evolution of the system to meet future energy service demands can be simulated driven by the least-cost objective solution. Decisions around investments are determined on the basis of cost-effectiveness, using the existing system in 2015 as a starting point. Energy resource potential, technological availability and policy constraints are other important aspects considered by the optimization. In TIAM-UCL, the transport sector is also fully based on this cost-optimization paradigm, with international shipping being a part of the freight module. The demand for shipping is split by product group. For non-energy commodities, activity is exogenous, calculated and mapped using trade projections from an auxiliary sectoral model. For energy commodities, activity is endogenously estimated in TIAM-UCL, driven by the trade of fossil fuels and other energy carriers. Emission reductions are mostly achieved by the deployment of low-carbon fuels, whose selection is based on fuel and carbon prices. Ship and logistic efficiency are introduced exogenously in the model. Detailed information on TIAM-UCL can be found in Supplementary Sections 2.6 and 3.5.

WITCH is a comprehensive tool designed to examine the interplay between climate change, energy systems and economic development. It has a hybrid structure, combining top-down and bottom-up features. The top-down component includes a macroeconomic intertemporal optimization model while the bottom-up component captures technological details of the energy sector. The model generates optimal mitigation and adaptation strategies in response to climate damage or emission constraints. Strategies result from a maximization process involving regional welfare, capturing free-riding behaviours and interactions induced by externalities. An iterative algorithm implements the open-loop Nash equilibrium in a non-cooperative, simultaneous, open membership game with full information. The model uses a social planner to maximize the sum of regional discounted utility, with a constant relative risk aversion utility function derived from per capita consumption. Climate impacts affect gross output, with fossil fuel and GHG mitigation costs subtracted from them. Energy services are provided by a combination of physical energy input and a stock of energy efficiency knowledge. Shipping demand for each region is the total global demand allocated with respect to its gross domestic product (GDP) share. Then, future demand is estimated using the elasticity of GDP. Elasticities are distinguished for different cargo types. The international shipping module within WITCH is currently in its early stages and remains highly aggregated. On the supply side, the maritime sector has access to conventional oil-based fuels and a few alternative fuels. Energy efficiency improvement is modelled exogenously. Detailed information on WITCH can be found in Supplementary Sections 2.7 and 3.6.

Scenarios

We work with three sets of scenarios, resulting in a total of 18 scenarios. Reference scenarios (NDC) do not restrict total global emissions in any way but assume the fulfilment of NDCs as stated in the 2015 pledges. These policies (e.g., GHG reduction targets, energy and land-use policies) are assumed to be fully implemented for the period 2010–2030 according to information from the NDCs[58,67] and considering the regional aggregation of each model. For the longer term (2030–2100), we assume that mitigation efforts continue at a pace consistent with that observed during the period covered by the NDCs. Demographic, socioeconomic and technological assumptions follow SSP2, which describes a middle-of-the-road development in mitigation and adaptation challenges space. In many aspects, SSP2 can be seen as in line with historical trends[31,68].

The other two scenario groups (C1000 and C600) derive from the first one, but additionally impose carbon budgets of 1,000 and 600 $GtCO_2$ for the global economy in the period 2020–2100. Net negative CO_2 emissions (and therefore temperature overshoot[22]) are not allowed, meaning that budgets refer to the sum of annual net CO_2 emissions until the year of net zero ('peak-budget' scenarios). The choice of carbon budget values is based on model capabilities and warming categories defined by the IPCC in its most recent assessment report[24,69] (Supplementary Section 4). More stringent carbon budgets (e.g., 400 $GtCO_2$) were not assessed because most of our models do not find solutions for such low values.

In all three scenario groups, international shipping emissions are not restricted in any aprioristic way. As shipping is the focus of our analysis, leaving its emissions unconstrained is a way to compare the results of our models with existing sectoral targets such as IMO2050.

Organization of results for shipping energy carriers

Since the modelling of fuel conversion processes is not identical across the six IAMs, we use energy carrier categories to harmonize and compare our results (Supplementary Section 6). These categories seek to group energy carriers according to common features, such as feedstock type, energy density and applicability. The Conv category corresponds to conventional fuels based on petroleum, such as heavy fuel oil and MDO. The Oilseed category represents fuels based on vegetable oils obtained from oily crops, such as palm, soybean and sunflower, and eventually also from animal fats such as beef tallow. The D-synt bio and D-synt other categories include fully drop-in renewable fuels produced through advanced processes such as the Fischer–Tropsch synthesis that are often chemically indistinguishable from fossil products. While the former relates to bio-based feedstocks, the latter includes every other type of resource, most notably renewable-based electricity. The three AG categories correspond to groups of alcohols and gases (e.g., ethanol, methanol and liquefied natural gas), whose use in ships is typically made possible using dual-fuel engines. As in the case of drop-in fuels, they differ from each other in the type of primary source. Finally, the H_2/NH_3 category includes hydrogen and ammonia, while the Elec category refers to the direct use of electricity.

Calibration

Due to small differences between our IAMs, we recalibrate final transport work, fuel and emission results using 2020 as the base year. This choice aligns with the final historic time step in models. Furthermore, 2020 international shipping emissions closely approached those of 2008, the IMO2018 baseline year, allowing for a direct comparison with the goal. The transport work calibration is based on the United Nations Conference on Trade and Development's *Review of Maritime Transport*[45], while the fuel data calibration follows IEA's shipping dataset[2].

Data availability

The underlying data are available via Zenodo at https://doi.org/10.5281/zenodo.10815601 (ref. 70). Source data are provided with this paper.

Code availability

The models are documented on the common IAM documentation website (https://www.iamcdocumentation.eu/index.php/IAMC_wiki). Some of them have published open-source code (for example, WITCH, https://github.com/witch-team/witchmodel). For a brief documentation of the models and main concepts, see Supplementary Sections 2 and 3.

References

58. Roelfsema, M. et al. Taking stock of national climate policies to evaluate implementation of the Paris Agreement. *Nat. Commun.* **11**, 2096 (2020).
59. Rochedo, P. R. R. *Development of a Global Integrated Energy Model to Evaluate the Brazilian Role in Climate Change Mitigation Scenarios*. PhD thesis, Univ. Federal do Rio de Janeiro (2016).
60. Rochedo, P. R. R. et al. Is green recovery enough? Analysing the impacts of post-COVID-19 economic packages. *Energies* **14**, 5567 (2021).
61. Waisman, H., Guivarch, C., Grazi, F. & Hourcade, J. C. The IMACLIM-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight. *Clim. Change* **114**, 101–120 (2012).
62. Prometheus model—model description.*E3-Modelling* https://e3modelling.com/modelling-tools/prometheus (2018).
63. Pye, S. et al. *The TIAM-UCL Model (Version 4.1.1) Documentation* (Univ. College London, 2020); https://www.ucl.ac.uk/energy-models/sites/energy_models/files/tiam-ucl-manual.pdf
64. Welsby, D., Price, J., Pye, S. & Ekins, P. Unextractable fossil fuels in a 1.5 °C world. *Nature* **597**, 230–234 (2021).
65. Bosetti, V., Carraro, C., Galeotti, M., Massetti, E. & Tavoni, M. WITCH—a world induced technical change hybrid model. *Energy J.* **27**, 13–37 (2006).
66. Colelli, F. P., Emmerling, J., Marangoni, G., Mistry, M. N. & De Cian, E. Increased energy use for adaptation significantly impacts mitigation pathways. *Nat. Commun.* **13**, 4964 (2022).
67. NDC Registry. *United Nations Framework Convention on Climate Change* https://unfccc.int/NDCREG (2023).
68. Fricko, O. et al. The marker quantification of the Shared Socioeconomic Pathway 2: a middle-of-the-road scenario for the 21st century. *Glob. Environ. Change* **42**, 251–267 (2017).
69. IPCC: Summary for Policymakers. In *Climate Change 2022: Mitigation of Climate Change* (eds Shukla, P. R. et al.) (Cambridge Univ. Press, 2022).
70. Müller-Casseres, E. et al. International shipping in a world below 2 °C. *Zenodo* https://doi.org/10.5281/zenodo.10815601 (2024).

Acknowledgements

E.M.-C., F.L., M.v.d.B., P.F., O.D., H.N., R.D., T.L.G., I.S.T., I.T., J.E., L.B.B., D.P.v.V., A.G., L.D., J.P.-P., H.-S.d.B., N.T., P.R.R.R., A.S. and R.S. received funding from the European Union's Horizon 2020 research and innovation programme under grant agreements 821124 (NAVIGATE) and 821471 (ENGAGE). E.M.-C., R.D., L.B.B., A.S. and R.S. were also supported by the Brazilian National Council for Scientific and Technological Development (CNPq). F.L. has benefited from the support of the long-term modelling chair for sustainable development (Ponts ParisTech–Mines ParisTech) funded by ADEME, GRTgaz, Schneider Electric, EDF and the French Ministry of Environment. P.F. also received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement 101003866 (NDC-ASPECTS).

Author contributions

E.M.-C., P.R.R.R., A.S. and R.S. conceptualized the study and coordinated the design of scenarios. F.L., P.F., D.P.v.V. and J.P.-P. provided key input for the research question and article structure. E.M.-C., R.D., L.B.B. and P.R.R.R. performed the COFFEE model runs. F.L. and T.L.G. performed the IMACLIM-R model runs. M.v.d.B., I.S.T., D.P.v.V. and H.-S.d.B. performed the IMAGE model runs. P.F., I.T., A.G. and N.T. performed the PROMETHEUS model runs. O.D. performed the TIAM-UCL model runs. H.N., J.E. and L.D. performed the WITCH model runs. E.M.-C., R.D., L.B.B. and P.R.R.R. organized and standardized the results. E.M.-C. led the writing process, to which P.F., D.P.v.V., J.P.-P., A.S. and R.S. also contributed considerably. All other authors engaged in review and editing. E.M.-C. and T.L.G. conceptualized and produced the main figures. E.M.-C. and A.S. edited the Article according to reviewer comments. E.M.-C. and R.S. were responsible for the executive coordination.

Competing interests

The authors declare no competing interests.

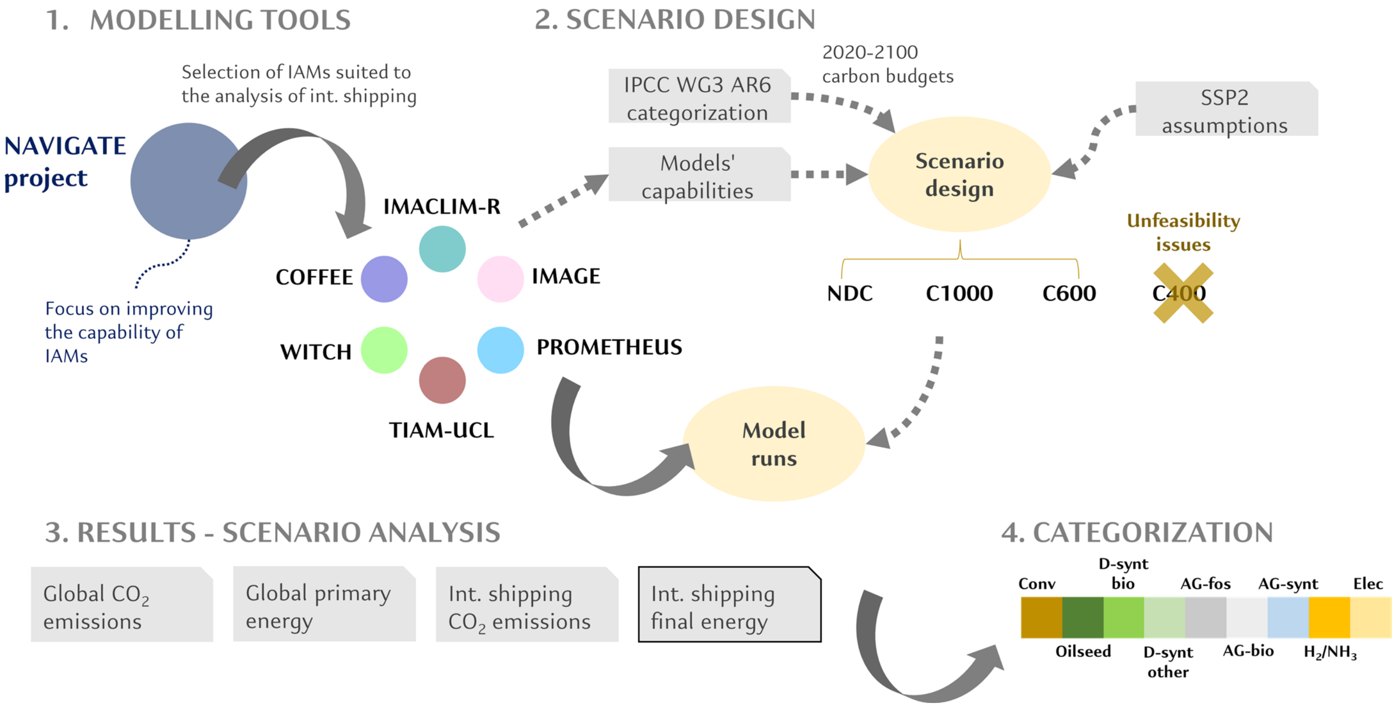
Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41558-024-01997-1.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41558-024-01997-1.

Correspondence and requests for materials should be addressed to Roberto Schaeffer.

Peer review information *Nature Climate Change* thanks Patricia Fortes, Paula Pereda and Runsen Zhang for their contribution to the peer review of this work.



Extended Data Fig. 1 | Overview of the modelling strategy. Categorization of energy carriers: Conv – conventional maritime fuels; Oilseed – oilseed-based biofuels; D-synt bio – drop-in synthetic biofuels; D-synt other – other synthetic drop-in fuels; AG-fos – fossil alcohols and gases; AG-bio – bio-alcohols and biogases; AG-synt – Synthetic alcohols and gases; H2/NH3 – Hydrogen and ammonia; Elec – electricity.