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Marine fuel choices and related life-cycle environmental impacts under global shipping policies

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Shipping is a transnational sector competing for energy on a global market and needs effective policies to decarbonize. Here we assess energy transitions under different shipping policies using a sector-coupled global energy system model and connected life-cycle environmental impacts. We find that postponed International Maritime Organization's 'net-zero framework' could increase biofuel use in shipping to 40% by 2050 but might fall short of net-zero targets, which require broader adoption of low-carbon fuels. A combined levy and global fuel standards mechanism accelerates low-carbon fuel adoption, achieving 60% of ammonia penetration as marine fuel. Ammonia emerges as most cost-effective fuel under cross-sectoral competition for several assessed policies, whereas electrification is preferred for vessels with daily bunkering possibilities. To reach global climate targets, ammonia from bioenergy with carbon capture (yielding negative emissions) and e-ammonia are found potentially crucial for shipping. However, this transition risks increasing other environmental impacts, including land use and mineral resource depletion.

Ships transport approximately 80% of world trade by volume[1] and account for about 3% of total global greenhouse gas (GHG) emissions[2]. Without decarbonization measures, shipping emissions could reach 130% of 2008 levels by 2050 as trade expands[3]. In alignment with the climate target of the Paris Agreement, the International Maritime Organization (IMO) revised its GHG emissions reduction strategy in 2023 (relative to 2008 levels), targeting a minimum reduction of 20% by 2030, 70% by 2040 and net-zero emissions by around 2050[4]. To reach the above reduction targets, the Marine Environment Protection Committee (MEPC) has proposed the 'IMO net-zero framework'[5] and the final approval at IMO is now postponed. This framework is intended to promote the adoption of alternative energy carriers, including methanol, ammonia, hydrogen and methane. The framework includes two sets of 'mid-term measures': first, a goal-based marine fuel standard that includes a well-to-wake (WtW) perspective; and second, a pricing mechanism for GHG emissions[5].

Ships currently burn mostly heavy fuel oil in compression ignition engines but achieving emissions reduction targets require switching to alternative fuels such as ammonia, hydrogen or methanol. The use of simpler molecules as alternative fuel also enables the use of more efficient technologies such as fuel cells (FCs)[6]. These alternative fuels can be produced from different production pathways—from biomass, renewable electricity or natural gas with carbon capture[7,8]. The prospects for alternative energy carriers in the shipping sector depend on their technical maturity, performance, environmental impact, cost and so on[6]. Whereas several studies have assessed the costs and environmental impacts of individual ships utilizing various alternative energy carriers produced from different feedstocks[6–11], their feasibility largely depends on the specific supply infrastructure[12], bunkering facilities[11], energy cost[7] and feedstock availability[13]. The cost and availability of feedstock and the development of fuel infrastructure rely on developments in other sectors[13–15]. Thus, alternative fuel use in ships creates a

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Table 1 | Summary of policies assessed

Policy name	Economic measure	Technical measure	Scope
Marine levy	Levy for direct GHG emissions. 2030: US$50 tCO_{2eq}^{-1}, 2040: US$100 tCO_{2eq}^{-1}, beyond 2050: US$150 tCO_{2eq}^{-1}	–	Levy for GHG emissions from ship operational emissions, including CO_2, CH_4 and N_2O (including non-fossil CO_2 from biofuels and e-fuels).
Net-zero framework	Cost for remedial units based on deficit (non-compliance). tier 2 deficit: US$380 tCO_{2eq}^{-1} tier 1 deficit: US$100 tCO_{2eq}^{-1} Surplus units rewarded for low-emissions technologies.	GFI targets for fuel consumed. Two reduction targets with different penalties based on the reference (93.3 gCO_{2eq}/MJ_{fuel}). tier 2: Base compliance tier 1: Direct compliance (stricter target)	GFI target for fuel consumed based on GHG emissions over life cycle (ship operation and fuel production) as per IMO-LCA guidelines. Ships need to purchase remedial units if relying on the deficit to comply with either tier 1 or tier 2 target. Revenue for surplus units received for low-emissions technologies.
Marine levy + GFI	Levy for direct ship GHG emissions 2030: US$50 tCO_{2eq}^{-1}, 2040: US$100 tCO_{2eq}^{-1}, beyond 2050: US$150 tCO_{2eq}^{-1}	Mandatory for vessels to reach GFI direct compliance (tier 1).	Levy for GHG emissions from ship operational emissions, including CO_2, CH_4 and N_2O (including non-fossil CO_2 from biofuels and e-fuels). GFI requirement for fuel consumed based on GHG emissions over life-cycle (ship operation and fuel production) as per IMO-LCA guidelines.
High marine levy	Levy for direct ship GHG emissions 2030: US$150 tCO_{2eq}^{-1}, 2040: US$200 tCO_{2eq}^{-1}, beyond 2050: US$250 tCO_{2eq}^{-1}	–	Levy only for GHG emissions from ship operational emissions, including CO_2, CH_4 and N_2O (including non-fossil CO_2 from biofuels and e-fuels).
GFI	–	Mandatory for vessels to reach GFI direct compliance (tier 1).	GFI requirement based on GHG emissions over life-cycle (ship operation and fuel production) as per IMO-LCA guidelines.
Marine levy + subsidy	Levy for direct ship GHG emissions 2030: US$50 tCO_{2eq}^{-1}, 2040: US$100 tCO_{2eq}^{-1}, beyond 2050: US$150 tCO_{2eq}^{-1} Levy is used to subsidize zero and near-zero technological investment.	–	Levy for GHG emissions from ship operational emissions, including CO_2, CH_4 and N_2O (including non-fossil CO_2 from biofuels and e-fuels).

All policies are tested without a global climate target and with global carbon climate target as in RCP26 (RCP-Representative Concentration Pathway).

complex web of energy system interactions that extend far beyond the maritime sector. Therefore, it is essential to assess the energy transition of shipping fleet within the larger context of the global energy system transition. This is particularly important considering the international nature of shipping, which is generally not included in national goals[16]. Due to the differences in ship designs, transport functions (for example, passenger, liquid cargo, containers) and operational patterns, a detailed representation of ships are important for analysing specific decarbonization strategies for shipping. Müller–Casseres and Leblanc[13] evaluated international shipping under 2 °C climate target using different global energy system models (ESM) including COFFEE 1.5, IMACLIM-R 2.0, IMAGE 3.2, PROMETHEUS 1.2, TIAM-UCL 4.1.2 and WITCH. This study also indicates lack of comprehensive representation of the shipping fleet in different global energy system model[13]. Overall, there is a lack of studies that use global ESMs to evaluate shipping policies to understand decarbonization from a larger context of global energy system.

We explore this knowledge gap by evaluating different global shipping policies using a sector-coupled, global, bottom-up energy system model: the Global Energy Transition (GET) model v11. Earlier GET versions were used to assess the shipping sector under broader climate scenarios[17,18], considering ten different geographic regions. GET v11 is specifically developed to include a detailed shipping module represented by eight different ship segments (container, cargo and bulk, oil tanker, gas tanker, cargo-short, ferry-short, ferry-long and other ships), more alternative marine fuels (liquid hydrogen, compressed hydrogen, liquid methane, electricity and ammonia), fuel-production routes (biomass gasification, bioenergy with carbon capture and storage (BECCS) and natural gas (NG) liquefaction) and shipping powertrains (FC and battery-electric). This model also considers projected changes in new energy-related transport of methanol, biomass and ammonia trade across different regions, in addition to changes in the transportation of coal, oil and gas under different scenarios. Six policies related to shipping are investigated—marine levy, IMO net-zero framework, marine levy and GHG fuel intensity (GFI), marine levy and subsidy, GFI only regulation and high marine levy.

The GET model, as in other ESMs, emphasizes cost-efficient pathways to achieve climate objectives, primarily addressing direct CO_2 and CH_4 emissions. For informed decision-making, it is important to understand the environmental implications of energy transition beyond GHG emissions. Another key aspect of this study is the inclusion of life-cycle assessment (LCA) to understand trade-offs of shipping energy transition that consider impacts related to the direct emissions, use of materials, embodied energy, fuel infrastructures, fugitive emissions, land-use changes and process emissions. This is achieved by integrating life-cycle environmental indicators from process-specific LCAs into the GET model. This integrated approach elucidates the environmental impacts of the energy transition in the energy sector[19,20]. The scenarios are designed considering that all sectors are aligned with the Shared Socioeconomic Pathway 2 (SSP2) 'middle-of-the-road' scenario, with the global climate target (limiting global temperature change to <2 °C) and without any climate target. The shipping fleet is specifically modelled using data from the Fourth IMO GHG study[21], which includes baseline transport work, logistics analysis of transport work and efficiency improvements.

Consequences of policies on shipping energy transition

The details of six shipping policies investigated in the study are shown in Table 1. The results of three policies that are mainly discussed during MEPC meetings are included in the main text and these are marine levy, IMO net-zero framework and marine levy and GFI. Results regarding other policies are included in Supplementary Figs. 1 and 2.

The cost-effective fuel mix and technology choices for shipping vary for different global climate targets, policy cases and ship categories (Fig. 1). Shipping will continue to rely on fossil oil in the absence

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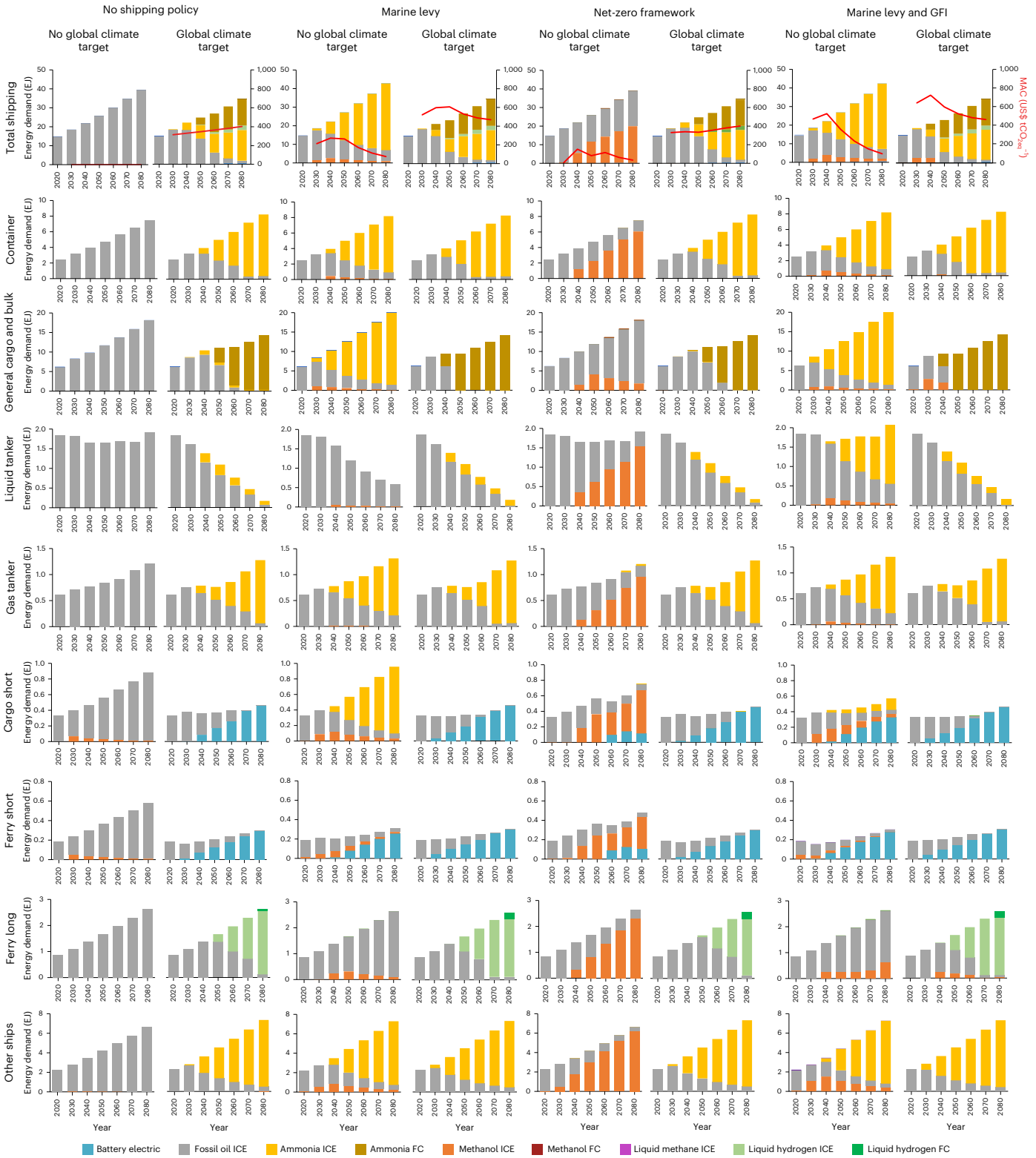

Fig. 1 | Cost-effective fuel and technology mixes for global shipping under different scenarios. Energy carriers and technology mixes for global shipping and specific ship categories (in EJ) under different shipping policy scenarios, with and without a global climate target. In the case of liquid tankers, there is a decrease in the transport demand as the global demand for oil for energy purposes decreases. In the case of gas tankers, even though there is less demand for natural gas, the model shows an increase in ammonia trading. For the bulk tankers, the transport demand for coal is replaced by increased trade in biomass. The red line in the first row for total shipping represents the marginal carbon abatement cost (MAC) (US$ tCO_{2eq}^{-1}), that is, the cost associated with reducing an additional tonne of CO_2 in shipping sector during the specified timestep.

of policy support in a world without carbon constraints. Fossil oil is observed in the fuel mix beyond 2050 for all the assessed policies. Ammonia is the cost-effective fuel option for most ship categories and scenarios. For ships that are operating over shorter distances (ferry-short and cargo-short), electrification is cost effective in most scenarios. An exception to this is the net-zero framework without a global climate target, where methanol engines are found cost effective for most ship categories (reaching more than 50% of all energy demand by 2050). A technological mix of methanol engines and battery-electric propulsion is cost effective for ferry-short and cargo-short under this policy. Many ships continue to operate with a high share of fossil oil under the net-zero framework, as they prefer to pay for remedial units rather than meeting direct compliance targets as marginal abatement cost is higher than US$100 tCO_{2eq}^{-1}. When ships need to pay a levy for GHG emissions during operation ammonia is the cost-effective non-carbon fuel. Ammonia engines only emit N_2O during operation, whereas fuels containing carbon have higher operational GHG emissions (CO_2 and CH_4).

In a carbon-constrained society (with global climate target), greater adoption of FCs is observed for all policy options when all sectors compete for the resources. FCs are cost effective mainly for bulk and general cargo ships, which have relatively low installed engine capacities (low design speeds) and higher utilization rates compared to other ship types, resulting in fuel cost savings (high efficiency of FC), and this saving compensates investment costs (low installed power means lower investment cost). Highest adoption of FC for these ships (almost 100%) can be observed in policy cases with levy. Methanol FCs do not appear cost effective as carbon-free alternatives are more attractive in carbon-constrained scenarios and FCs are generally less competitive in scenarios without carbon constraints. The adoption of hydrogen engines (liquid hydrogen) is a promising option for ferries and cruise ships operating on longer routes (ferry-long) (reaching around 100% by 2080), as ammonia is not considered a feasible option for passenger transport due to safety concerns. Methane is not a cost-effective alternative fuel in any scenario due to its higher GHG emissions compared to alternatives (due to engine methane slip and supply chain leakage). Scenarios that predominantly utilize ammonia engines exhibit an increased energy demand (low engine efficiency), whereas in those cases with greater adoption of FCs and battery-electric, the demand for energy supply decreases (high-efficiency powertrains).

The fuel-production pathway for shipping also differs with respect to policies and climate targets (Fig. 2). Without climate targets, NG-based and bio-based fuel pathways are found common (no e-fuels present). In the marine levy case, grey ammonia (involving steam methane reforming of NG) is shown, as the levy focuses exclusively on ship operational GHG emissions. This indicates the importance of including a life-cycle perspective in policies, for example, by adding a GFI, to reduce fossil fuel dependence. The net-zero framework finds the adoption of biomethanol cost effective in the scenario without a global climate target. A combination of blue ammonia, biomethanol, BECCS-ammonia and grey ammonia is cost effective with a levy and GFI. Results show shares of blue ammonia and BECCS-ammonia increase over time (since the tier 1 target becomes stringent) and with the expansion of energy conversion capacities.

In all policy options with global climate targets, ammonia mainly includes BECCS-ammonia and e-ammonia. Initially, only a small share of e-ammonia is cost effective. However, the share increases over time, reaching more than 50% by 2080. The BECCS-ammonia share increases until 2060 and then gradually declines. In these scenarios, all the biomass potential is utilized from 2050 (Supplementary Information) and onwards. The marginal energy cost for shipping is high for scenarios with a global climate target. This is due to the high marginal cost associated with cleaner primary energy sources, such as biomass and renewable electricity (Fig. 3).

The demand for primary energy to meet energy demand in all sectors including shipping results in competition for limited available resources and influences marginal cost of the primary energy (Fig. 3). The high demand for biomass is observed in the net-zero framework and in the combination of marine levy with GFI policies (biomethanol and BECCS-ammonia production) even without a global climate target. Unlike net-zero framework, for policies that include a marine levy without global climate target, there is a higher demand for NG (for grey and blue ammonia production). For scenarios with a global climate target, biomass is a crucial resource for all sectors, resulting in a high marginal cost for biomass (reaching around US$80 EJ^{-1} by 2080). In addition, e-ammonia production in these scenarios needs a higher demand for electricity from renewables and nuclear power. In all cases, compared to the scenario without a policy and climate target, there is increased demand for primary energy, which is due to substantial energy losses in the comparatively inefficient production pathways, especially for biofuels and e-fuels. This indicates that larger investments in energy supply and the cost of primary energy will be important for the energy transition.

Monte Carlo analysis (Fig. 4) demonstrates that the cost-effective choice of shipping fuel is sensitive to variation in different parameters. Biomass availability and permanent carbon storage availability each represent a substantial portion of model uncertainty (approximately 25% variance each) in determining the balance between use of biofuels and e-fuels in shipping (Fig. 4b,c). Sensitivity analysis (Fig. 5) further examines the robustness of long-term fuel mix outcomes to uncertainty parameters under the net-zero framework with global climate target. Higher biomass availability (Fig. 5a) accelerates the transition away from fossil fuels and reduces the cost-effective share of e-fuels through greater biofuel adoption. Conversely, accounting for indirect land-use change emissions (Fig. 5b) diminishes biofuel competitiveness, prolonging fossil fuel use and increasing e-fuel adoption. Limited permanent carbon storage availability (Fig. 5c) reduces the e-fuel use and increases use of biofuel as reduced storage capacity limits the net-negative emission potential of BECCS pathways.

For technology-specific parameters, very low methane leakage assumption (Fig. 5d) in the supply chain and the engine slip marginally improves the LNG competitiveness in the short term as replacement for fossil oil but do not alter ammonia's long-term dominance. Higher N_2O emissions from ammonia engines (Fig. 5e) substantially reduce the cost-effective share of ammonia internal combustion engines (ICE), with this share largely captured by ammonia fuel cells, which offer cleaner combustion. This scenario also marginally extends the use of fossil oil engines. Nevertheless, ammonia remains the dominant fuel as BECCS-ammonia's net-negative emissions offset operational N_2O contributions. Slower technology expansion rates (Fig. 5f) extend fossil fuel reliance but do not fundamentally alter the eventual transition to ammonia-dominated fuel mixes. Across all sensitivity cases, ammonia emerges as the cost-effective long-term fuel choice, demonstrating the robustness of this finding to parameter uncertainty.

Environmental impacts of shipping energy transition

Figure 6 illustrates the environmental impacts of shipping fuel and technology mixes for net-zero framework and marine levy and GFI scenarios derived from the LCA-GET integration. The environmental impacts related to other scenarios and resource use-fossil are given in Supplementary Figs. 3 and 4. It may be noted that these assessments are post processed, and the environmental impacts are therefore not optimized in the model. Instead, they are derived from cost-optimal results considering the constraints included in the different scenarios. The results include the impacts associated with the fuel infrastructure, indirect land-use changes, fugitive emissions and emissions other than CO_2, CH_4 and N_2O, which are not explicitly covered in the IMO-LCA guidelines (basis for GFI). A transition to net-zero GHG emissions from

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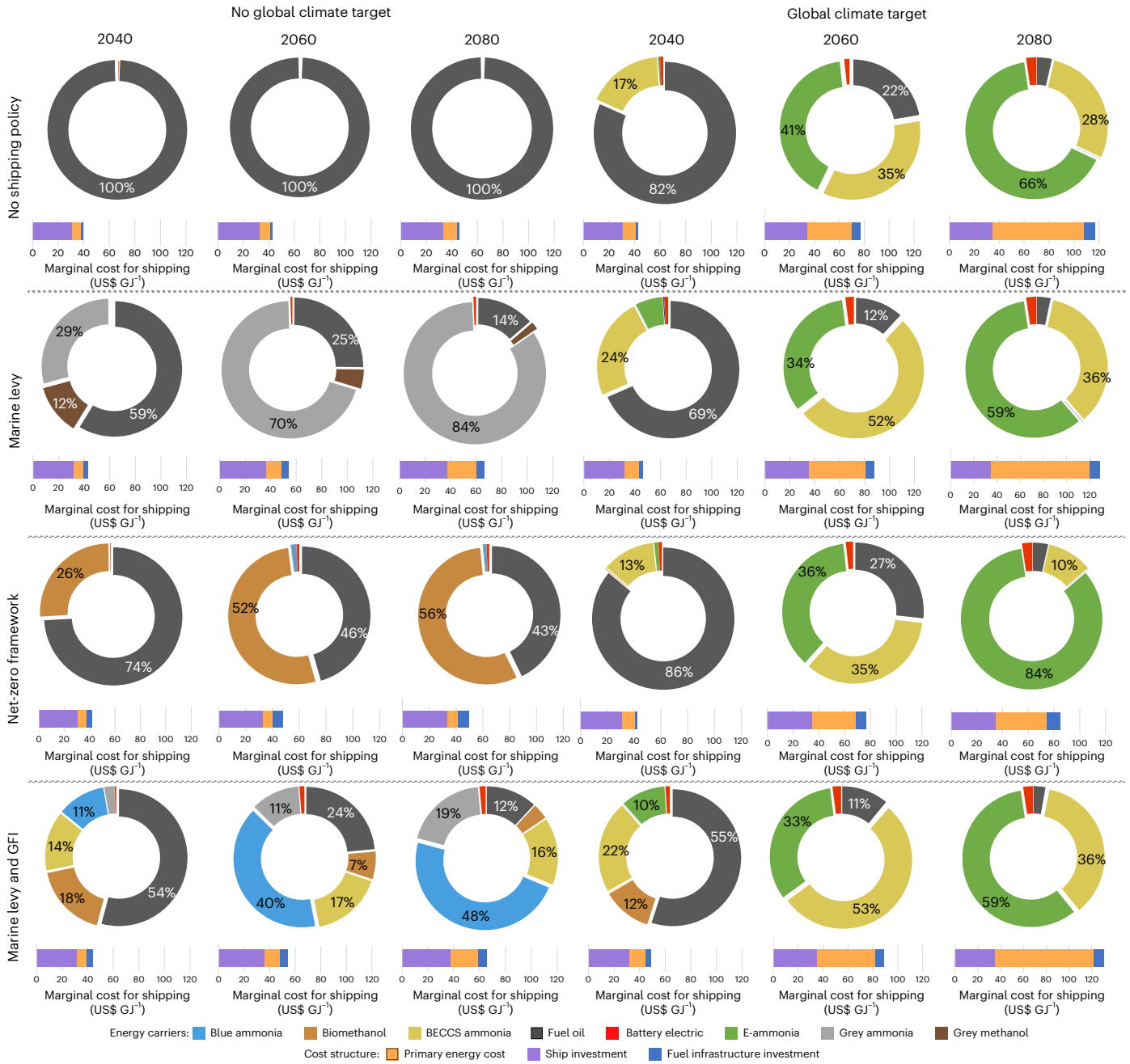

Fig. 2 | Fuel-production pathways and marginal costs for shipping under different scenarios. Fuel-production pathways under different scenarios and the related marginal costs for shipping in US$ GJ^{-1} for 2050 and 2080. Only shares >10% are shown in numbers. The marginal cost comprises three parts: the cost associated with investments in ships; the cost for the fuel infrastructure and the primary energy costs, including the costs for biomass, marginal electricity cost, natural gas, crude oil and so on. The higher cost in the climate scenario is mainly associated with the higher marginal cost of primary energy as different sectors compete for biomass and electricity.

a life-cycle perspective by 2050 is not found to be cost effective in the model without global climate targets for any of the policy scenarios. On the other hand, if there is a global climate target the shipping sector can contribute with negative GHG emissions. This is mainly due to the use of BECCS-ammonia, which involves the permanent storage of carbon from biomass, thereby reducing atmospheric CO_2 concentrations.

The use of grey ammonia in the case of the marine levy without global climate target or GFI increases most of the environmental impacts (Supplementary Fig. 4), including the climate impact (methane leakage), particulate matter formation potential (extraction and processing of NG), acidification potential (extraction and processing of NG), eutrophication potential (NO_x from ammonia engines), resource use—metals and minerals (material infrastructure) and resource use—fossil (NG use). GFI with levy and net-zero framework are found to be effective in reducing the life-cycle climate impact and resource use—fossil. Even though GFI regulation (in levy with GFI) calls for mandatory reduction to net zero by 2050 in line with the IMO-LCA guidelines, the results do not show the attainment of net-zero emissions. This difference in climate impact (higher than net zero) with this policy option (levy with GFI and without climate target) is because of the inclusion of embodied emissions in the infrastructure (material and energy), indirect land-use changes and fugitive emissions, which are not explicitly included in the IMO-LCA guidelines. In the case of the net-zero framework and GFI with levy, there are reductions in the

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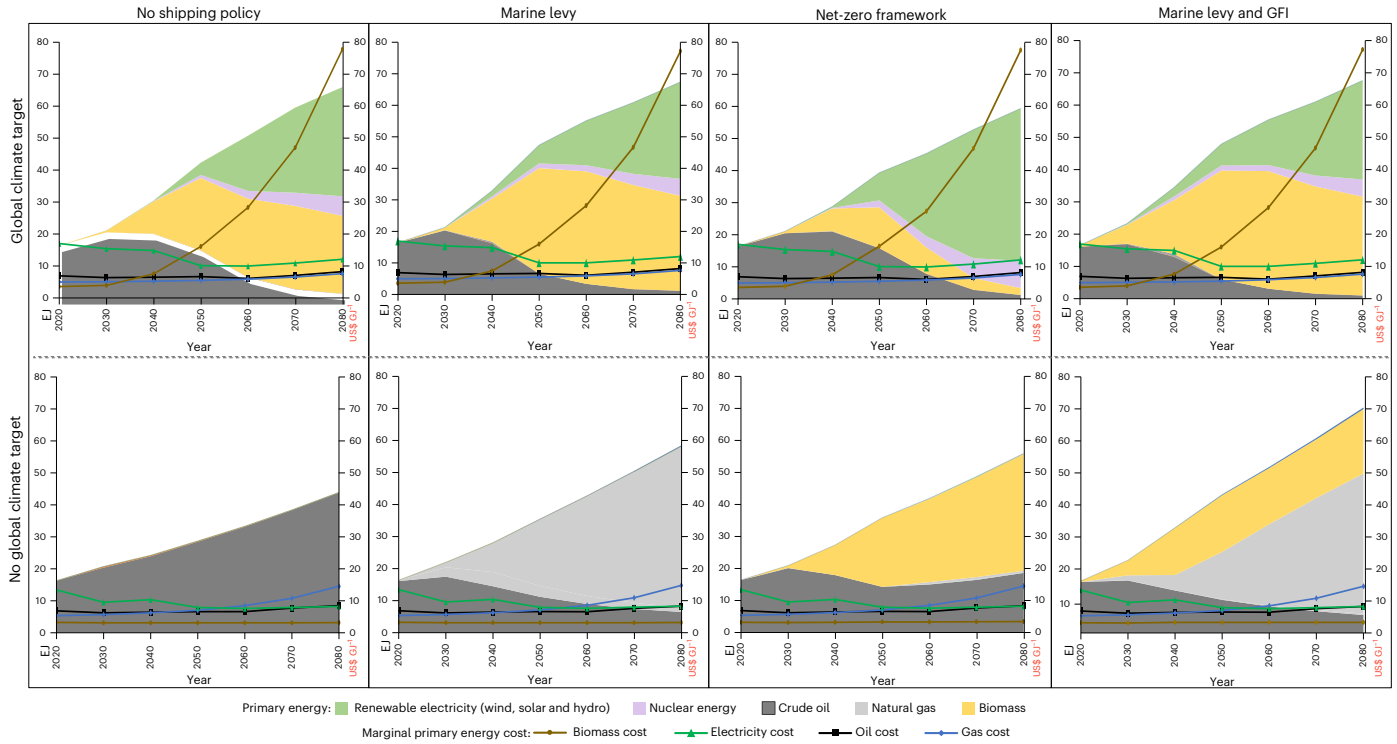

Fig. 3 | Primary energy demands and marginal energy costs across policy scenarios. Primary energy demands required for the different policy scenarios (in EJ) and the marginal energy costs related to the primary energy supply (in US$ GJ^{-1}) between 2020 and 2080. Nuclear energy and renewable electricity are mainly associated with the production of the e-fuel used in shipping (e-ammonia). The marginal cost of biomass increases with demand, whereas the marginal cost of electricity remains stable over the years as investment in renewables increases. The increase in primary energy is due to the low efficiencies of the fuel-production pathways, including biofuels, e-fuels and blue fuels.

particulate matter and acidification impacts when considering only the tank-to-wake (TtW) perspective, whereas the total WtW impact is higher due to emissions of pollutants during biomass gasification and biomass harvesting. The land-use impact also increases in these cases due to the use of BECCS-ammonia and biomethanol.

With global climate targets, a significant reduction in climate change, reaching net-negative emissions, is observed (due to the higher share of BECCS-ammonia). In these scenarios, there are also reductions in marine eutrophication (use of FCs) and fossil energy resource use. Reductions of the particulate matter and acidification impacts are observed, when considering only TtW, although the total WtW impact is higher. Although this trend resembles the scenarios without a global target, the overall increase in impact remains minimal due to the higher shares of FCs in these scenarios (lower TtW emissions and fuel savings due to high efficiency). Metals and mineral resource depletion (renewable electricity infrastructure for e-fuels) and land-use change (biomass for biofuels) significantly increase in the case of the global climate target, as compared with the base case. After 2050, due to expanded adoption of e-fuels, land-use impact remains constant.

Discussion and conclusion

To understand the energy transition of the shipping sector, different shipping-specific policies are reviewed from a global energy system perspective. Without regulatory intervention, the shipping sector will rely on fossil-derived oil in a world without carbon constraints. The assessed shipping policies can drive different levels of energy transition for shipping. In the absence of policies that provide incentives to reduce the life-cycle GHG emissions of marine fuels, there is a significant risk of increased climate impact from shipping, as illustrated by the marine levy without climate targets due to the use of grey ammonia (high climate impact in the fuel-production phase). This underscores the need to include the WtW perspective in policy considerations such as GFI, rather than adopting a standalone economic policy without a life-cycle perspective. The combination of a levy and strict GFI level shows the greatest reduction in climate impact among the policies investigated.

The model shows cost-effective use of biofuel in the net-zero framework without a global climate target. As biofuel adoption is limited to achieving the base compliance (tier 2), it is not sufficient to meet the net-zero-emissions target by 2050. This is also indicated in several reports[22,23]. Continued use of fossil oil is due to the relatively low remedial fee for direct compliance (tier 1) than carbon abatement cost, and paying this low fee is likely to be cost effective for shipping companies. Transition above this level may be attributed to the high cost of abatement required to overcome the technology transition inertia[13] and the higher costs for low-carbon fuels[7]. Large-scale deployment of alternative fuels at scale will require trillions of dollars of investment in land-side infrastructure[12], and decarbonizing the entire shipping sector in all regions will be challenging[16].

With a global climate target, CCS represents a cost-effective technology in many sectors, while sectors such as shipping adopt carbon-free energy carriers (ammonia and electricity). With global climate targets and policies with marine levies, ammonia is a cost-effective fuel choice for most ship categories. Electrification will be part of the energy transition strategy when there is a possibility for ships to charge frequently[24,25]. Ferries and cruise ships for which electrification is not practicable, and when ammonia use raises safety concerns for passengers, liquid hydrogen is the cost-effective choice. Although ammonia engines are considered to be cost-efficient in most policy scenarios, the sensitivity results show that adoption depends largely on nitrous oxide reduction potential, efficiency improvements and biomass availability. Ammonia production under stringent global carbon reduction targets mainly comes from BECCS and e-fuel routes. Ammonia from BECCS largely depends on the availability of permanent carbon storage facilities. Ammonia production from NG routes, even considering

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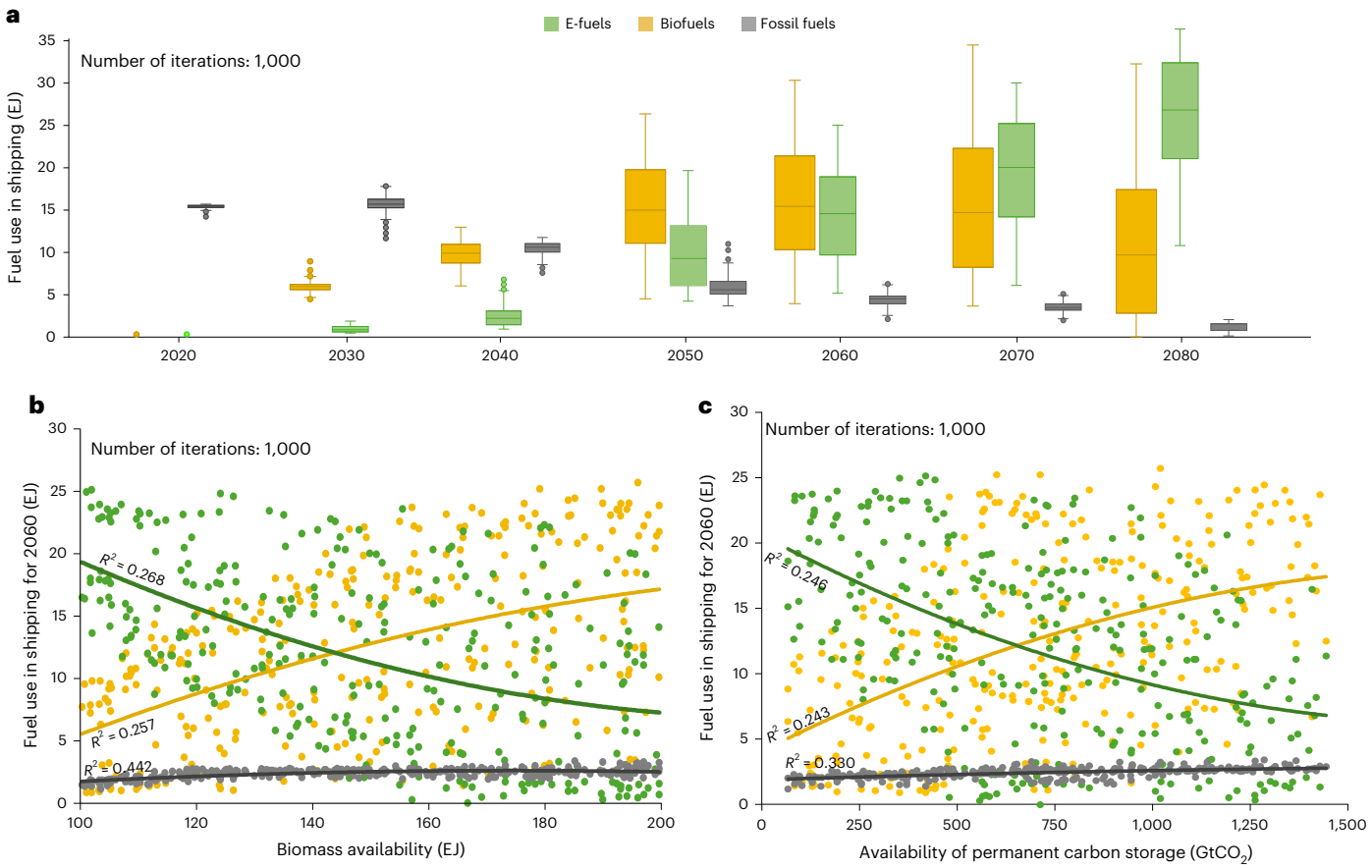

Fig. 4 | Monte Carlo analysis of cost-effective fuel choices under uncertainty in the marine levy and GFI scenario with global climate target. Monte Carlo showing the potential for cost-effective use of biofuels, e-fuels and fossil fuel under scenario marine levy and GFI with global climate target. Parameters, including biomass availability, permanent carbon storage availability, battery costs, fuel cell costs, fuel infrastructure costs and energy conversion efficiencies, are varied in the simulation run with 1,000 iterations. **a**, The uncertainty in distribution of cost-effective shipping fuel choices showing 50th percentile as line, 25th–75th percentile (whiskers) and maximum and minimum. **b**, Monte Carlo results for cost-effective fuel choice for shipping sorted by biomass availability. **c**, Monte Carlo results for cost-effective fuel choice for shipping sorted by permanent carbon storage availability. Biomass availability of 100 EJ and permanent carbon storage of 50 $GtCO_2$ are found to be the minimum requirements to meet the climate target under the RCP26 scenario in the model.

carbon capture, is not cost effective, as it is not sufficient to achieve net-zero emissions owing to the practical challenges of achieving 100% carbon capture and preventing methane leakage in the supply chain. All sectors compete for climate-neutral, primary energy sources and technologies, creating constraints on resources such as biomass. Switching to carbon-based biofuels (methanol and methane) is in general not cost effective in a world with stringent climate targets. Instead, the net-negative impact from BECCS is relatively cost effective. This allows compensation for residual emissions in other sectors, embodied emissions and other GHG emissions, including CH_4 and N_2O. Net-negative emissions can be achieved with direct air capture with CCS, albeit with high cost and uncertainty[26]. This role of BECCS as a cost-effective measure for different sectors to meet the ambitious climate targets has been described previously[27–29] and this study shows it is also important for the shipping sector. BECCS importance to compensate residual emissions is mentioned in the IPCC sixth assessment report[30]. The different energy transition paths with and without carbon constraints indicate that in the real world, considering the diverse locations of fuel bunkering, regional or national climate targets are important to achieve zero or negative WtW climate impacts for shipping.

Our study focuses on long-term regulatory equilibrium because the model does not generate results useful for near-term insights. Further research in the following areas can improve understanding of the shipping transition. First, a more detailed representation of biomass types and biofuel options could deepen the insights of cost-effective biofuel use in shipping. Second, the possibility of retrofitting could potentially speed up fuel adoption and possibly favour fuels requiring fewer extensive vessel modifications. Third, onboard carbon capture and hybrid options can also play an important role in different policy scenarios and evolving engine technologies and operating practices, particularly for methane and ammonia pathways, and thus potentially alter the results. Fourth, technology lock-in effects can create path dependencies, where, for example, methanol can utilize existing fuel infrastructure with minimal modifications. Fifth, energy efficiency measures are essential for, not least, short-term emissions reductions and enforcing policies targeting these could be a cost-effective way to reduce the climate impact from shipping. The relationship between efficiency measures and fuel selection needs further investigation, even if our model accounts for an exogenous efficiency improvement of 15–30% (depending on ship segment), which reduces the absolute energy requirement for different fuel choices.

This study highlights the importance of including climate impacts associated with embodied emissions in infrastructure (material and energy), indirect land-use changes and emissions of other GHGs in the IMO-LCA guidelines to avoid burden shifting. The transition towards grey ammonia has significant WtW impacts, indicating that transitions that are dependent upon fossil fuels (without CCS) should be avoided, as the environmental burden is shifted and worsened. The net-negative impact of BECCS-ammonia, which is important to achieve the net-zero target, requires sustainable sourcing of biomass[31]. Also, if

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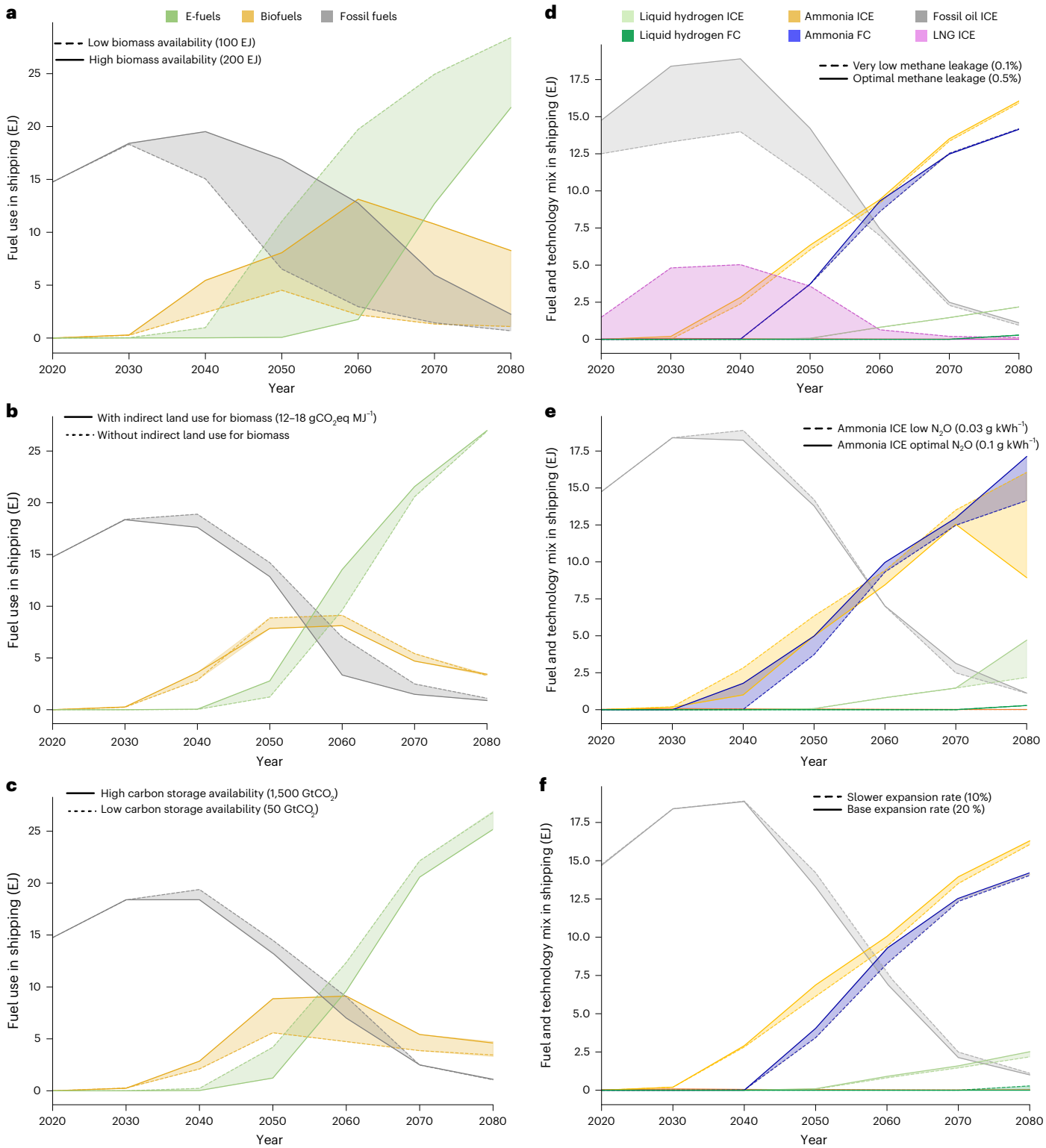

Fig. 5 | Sensitivity of cost-optimal fuel and technology mix to key parameters under the net-zero framework with a global climate target. a, Fuel mix ranges for high versus low biomass availability (200 EJ and 100 EJ, respectively). **b**, Fuel mix ranges with and without indirect land-use change emissions for biomass (12–18 $gCO_2eq\ MJ^{-1}$). **c**, Fuel mix ranges for high versus low permanent carbon storage availability (1,500 $GtCO_2$ and 50 $GtCO_2$, respectively). **d**, Fuel and technology mix ranges for very low versus base case methane leakage assumptions (0.1% and 0.5%, respectively). **e**, Fuel and technology mix ranges for low versus higher ammonia engine N_2O emissions assumptions (0.03 g kWh^{-1} and 0.1 g kWh^{-1}, respectively). **f**, Fuel and technology mix ranges for slower versus base case technology expansion rates (10% and 20% annual capacity growth, respectively). Solid lines represent base case assumptions; dashed lines represent alternative scenarios. Shaded areas indicate the range between scenarios.

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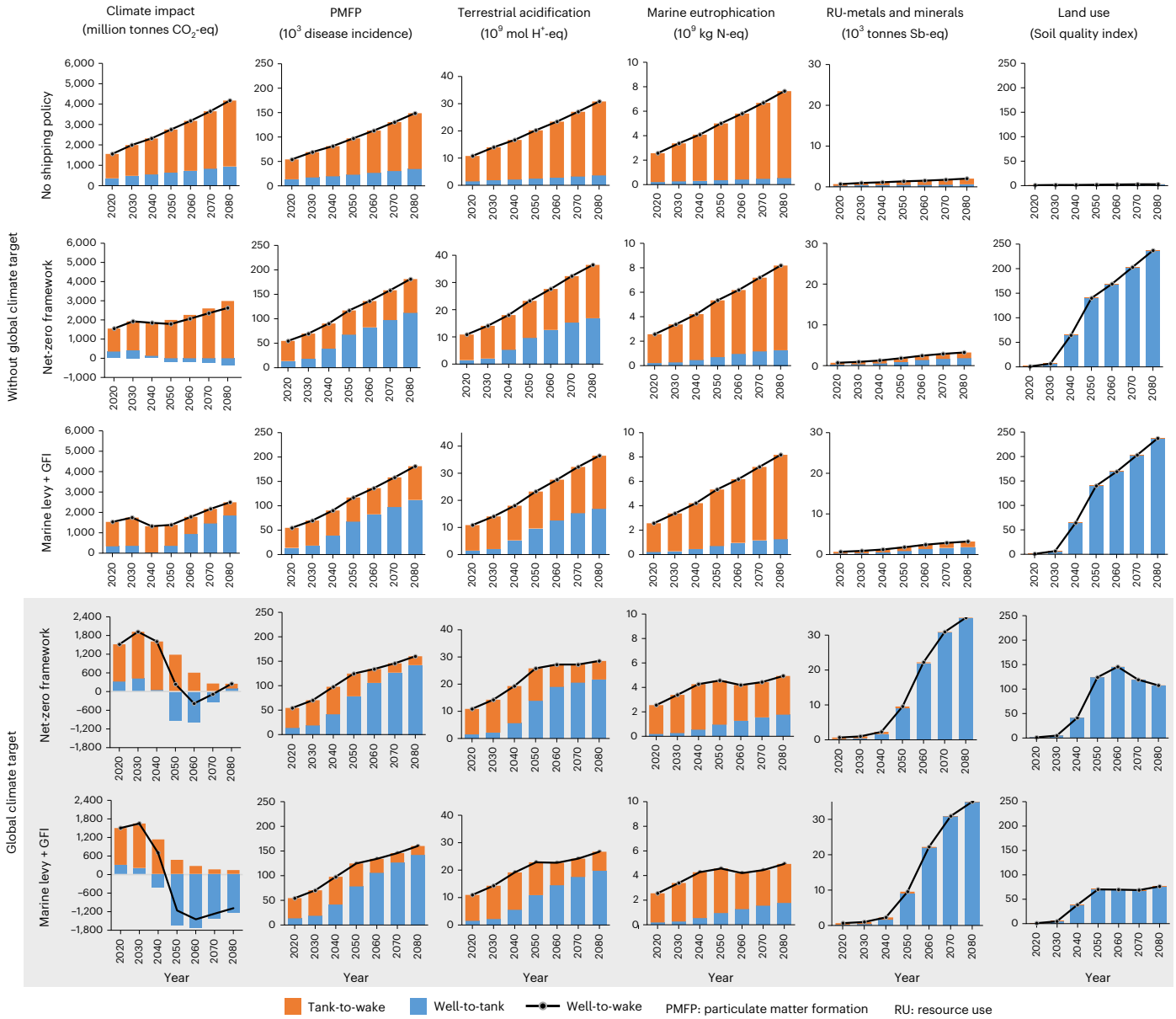

Fig. 6 | Life-cycle environmental impacts of the shipping energy transition under different policy scenarios. Tank-to-wake, well-to-tank and well-to-wake environmental impacts derived from the LCA-GET integration including climate impact, particulate matter formation potential (PMFP), terrestrial acidification potential, marine eutrophication potential, material resource use (RU-metals and minerals) and land use.

there are other potential products from biorefineries[7], then a suitable allocation needs to be performed and can result in lower reduction potential. In addition, adoption of BECCS-ammonia increases the environmental impacts linked to land use, mineral resource depletion, particulate matter and acidification. Acidification, particulate matter and eutrophication are due to the use of fertilizers and emissions from biorefineries[15,32–34]. Transitioning to e-ammonia results in higher mineral resource depletion due to infrastructure requirements, including wind and solar power and electrolysers[6].

The implementation of the IMO net-zero framework was postponed in autumn 2025, and this study offers evidence to support the continuation of talks. Our research shows that to reduce greenhouse gas emissions from shipping it is important to move forward with a strong global policy and to ensure absolute reduction it needs to consider life-cycle emission as is the case of both the IMO net-zero framework and marine levy + GFI than levying direct emissions. Although the IMO net-zero framework is a significant intermediate step, stricter regulations are most likely needed to achieve the net-zero greenhouse gas targets. The study also shows the reliability of the long-term results of decarbonization to technological uncertainties and supports a technology-neutral regulatory approach.

Methods

Global energy transition model

GET v11 is a sector-coupled, energy system optimization (linear programming), mathematical model based on a bottom-up approach set up in 10-year time steps. The model minimizes the total system cost by optimizing the energy supply and capacity expansion of all energy generation, conversion, storage and transmission, while meeting specified energy demands and carbon constraints. The model includes nine modules: primary energy supply; energy conversion and storage; carbon capture and storage or utilization; fuel trade and distribution; emission conversion using a simplified carbon cycle; the electricity sector (including time slices for regional variable renewable energy conditions); the transport sector; feedstocks and the heat sector. In the model, primary energy sources (coal, oil, NG, nuclear, wind,

hydro, solar and biomass) are converted into different energy carriers to meet end-use sector demands. Techno-economic interactions between technologies are parameterized using costs, efficiencies, load factors and lifetimes. Whereas the model minimizes the total system cost, it incorporates constraints regarding: annual or total extraction limits on available energy sources; expansion rates for technologies; load balance constraints; atmospheric CO_2 levels; restricted trading of some energy carriers (for example, electricity) and maximum allowable permanent CO_2-storage capacity. A comprehensive description of the GET v11 model is given in ref. 35, and data used are listed in Supplementary Information.

A time horizon of 2010–2150 is considered, with optimization accounting for annual operations and for wind and solar sub-annual operations. The inputs are provided for every 10-year timestep (2020, 2030, 2040, ...). The results are analysed for 2020–2080, and the period 2080–2150 is used as a dummy to avoid end-of-period distortions. The world is divided into ten geographic regions: North America (NAM); Europe (EUR); Pacific Organisation for Economic Co-operation and Development (OECD) (PAO); centrally planned Asia, mainly China (CPA); the former Soviet Union (FSU); Latin America (LAM); Africa (AFR); Middle East (MEA); South Asia, mainly India (SAS) and non-OECD Pacific Asia (PAS). The model also uses resource-based time slices based on wind and solar power generation levels. On the basis of the wind and solar resource availability in 1 year, the hours are aggregated into 16 time slices. The slices are created individually for each region. Trade in primary energy carriers and specific secondary energy carriers (for example, methanol, ammonia, liquid hydrogen and liquid methane) is allowed between regions while deciding on the investment, operation, supply and demand. The trade of energy carriers is linked with costs, considering the mass and volume of fuel transported and the distance between regions. GET v11 includes CH_4 emissions (0.5%) in the NG supply chain[36] and methane leakage (0.5%) during methane production, liquefaction and distribution when used in shipping[36]. In addition, the model considers CH_4 slips for methane/LNG engines (1 g kWh^{-1} for two-stroke ICE and 4 g kWh^{-1} for four-stroke ICE) and N_2O emissions (0.03 g kWh^{-1}) for ammonia engines[7,37]. The mathematical formulation of the emissions for different regions and times updated in GET v11 is shown in equation (1), where EM_{UP} is the emissions upstream (representing all emissions, except for transport), P is the input energy converted in the process such that ei is the input energy and eo is the energy output, EF represents the emissions factor, NG is natural gas, LNG represent liquefied NG, C_{SL} represents methane leakage in the NG supply, C_{DL} represents methane leakage during liquefaction and distribution and S_{CCS} represents the total permanent storage of carbon. The global permanent storage availability is restricted to 2,000 $GtCO_2$.

$$\mathrm{EM_{UP}} = \sum_{\mathrm{eo}} P_{\mathrm{ei,eo}} \times \eta_{\mathrm{ei,eo}} \times \mathrm{EF_{ei,eo}} + C_{\mathrm{SL}} \times \sum_{\mathrm{eo}} P_{\mathrm{NG,eo}} \times \mathrm{EF_{NG}} + C_{\mathrm{DL}} \times \sum_{\mathrm{LNG}} P_{\mathrm{ei,LNG}} \times \mathrm{EF_{NG}} - \sum S_{\mathrm{CCS}} \quad (1)$$

The upstream emissions for shipping are calculated using equation (1), specifically accounting for the share of each fuel going to shipping. The downstream emissions or operational emissions of shipping (and other transport sectors) are calculated using equation (2). The upstream and downstream emissions for shipping represent the total emissions that need to be achieved for the GFI standard. The same emissions as in the IMO-LCA guidelines are included, that is, CO_2, CH_4 and N_2O. In equation (2), EM_{SHIP} is the emissions from ship operation for each ship segment, EC represents the input energy for a specific energy converter, type represents ICE, FC or battery-electric and EF_{ei} represents the emissions factor for a specific fuel.

$$\mathrm{EM_{SHIP}} = \sum_{\mathrm{eo,type}} \mathrm{EC_{ei,type}} \times \mathrm{EF_{ei}} \quad (2)$$

Total emissions are calculated considering all upstream emissions and emissions from all end-use sectors, including all transport modes. All other mathematical formulations are adopted from GET v10[38].

The gross domestic product (GDP), population and demand projections for all sectors (except transport) for different regions are based on the SSP2 scenario from the IIASA GGI Scenario Database[39]. Transport demand scenarios for road, rail and aviation are taken from GET v10, which are calculated considering the SSP2 scenario[40]. The detailed modelling of the shipping sector (sub-module of the transport sector) and the energy conversion module (representing the demands and potentials of alternative fuels) is one of the refinements in GET v11. The shipping sector is represented by: (1) container ships; (2) bulk and general cargo carriers; (3) liquid tankers; (4) gas tankers; (5) ferry-long; (6) ferry-short; (7) cargo-short and (8) other ship type. Categories (1)–(4) have the highest global energy demands. Ferry-long and ferry-short represent ships for passenger transport, cargo-short represents inland and coastal cargo transport over short distances, and other ship type refers to all other transport work, including service vessels. Ammonia is not considered an option for passenger transport for safety reasons. All vessels are assumed to meet Tier III NO_x requirement; therefore, SCR is considered mandatory for ammonia, diesel engines, and two-stroke engines as NO_x-abatement technology and cost is added accordingly.

The projected transport work for shipping is derived through a regression equation as in the logistic analysis model used in the Fourth IMO GHG Study[2]. This approach estimates the future growth of transport work by examining historical relationships between transport work and relevant growth drivers. For non-energy-related transport work, per capita GDP serves as the growth driver, whereas for energy-related transport work, the drivers are global oil demand, coal demand, gas demand and other fuel demands. For energy-related transport work, the GET model outputs are used in the regression equation of the logistic model, and this is done by iteration. For the first run, the base values of fossil fuel and biomass consumption are taken from the respective IIASA SSP-RCP scenarios and used to derive energy-related transport work. After the first run, new consumption patterns for fossil fuels and biomass are taken as output from the GET based on cost-effective scenarios. New shipping transport demands for energy use for fossil and biomass are recalculated using the regression equation of the logistic model but this time using the new consumption pattern obtained from the first run of the GET model. This allows more consistent transport demand in line with the model values. However, there is also new transport demand for hydrogen carriers (methanol, liquid hydrogen and ammonia). This is taken separately from the export–import module of GET results in the first run. The trade of these hydrogen carriers is calculated in tonne-miles based on the energy traded in mass (energy density and energy trade) and the distance between regions. These shipping demands are then added to the model. On the basis of this updated transport demand, the GET model is run again for the final results. Demand projections are detailed in Supplementary Note 1 and are shown in Supplementary Fig. 5. This approach allows shipping demand to the dynamics of the response endogenously to energy transition: for example, oil tanker demand decreases as global oil consumption decreases under climate constraints, whereas new demand arises for ammonia and methanol transport between regions. The energy demand per unit of transport work is established using fleet data and activities from 2012 and 2018, as described in ref. 2. In addition, the change in energy demand that reflects anticipated efficiency improvements is exogenously modelled based on previous estimates[2]. Efficiency improvement mainly includes operational and technical efficiencies other than the powertrain and is considered different for different vessels (Supplementary Table 1). Fleet capacity and fuel supply infrastructure is tracked using an aggregated stock with depreciation based on assumed vessel lifetimes of 30 years for all ship segments. New investments in each 10-year timestep add to the existing

stock, whereas older capacity depreciates exponentially. The adoption of vessels with new technology is also limited to growth rate of 20%.

Monte Carlo analysis was performed to examine the sensitivity of our results to the parameter values. The parameters changed include biomass availability, permanent carbon storage availability, battery costs, fuel cell costs, fuel infrastructure costs, energy conversion efficiencies, carbon capture cost and powertrain efficiencies, and the parameters are changed considering uniform distribution. The model was run with 1,000 iterations. Sensitivity assessment is carried out considering different key parameters: (1) biomass availability, (2) indirect land-use change, (3) permanent carbon storage availability, (4) leakage of methane and methane slip of LNG engines, (5) N_2O emissions from ammonia engines and (6) expansion rate of new technology. More details on parameter assumptions for sensitivity assessment are provided in Supplementary Note 2.

Limitations

Various technologies, including onboard carbon capture, onboard energy generation (solar, wind-assisted propulsion), hybrids and nuclear power, are not considered in the model as options to reduce the GHG emissions from shipping. Biomass supply potential includes biomass sources that can be extracted in a sustainable way, including sources rich in lignin and cellulose, starch and sugar, used cooking oil and rest-flows and waste from agriculture, forestry and society, for example straw, sawdust, manure, sludge, animal fats and food waste. However, we have done simplifications by choosing the most cost-effective conversion pathway as proxy for all biomass conversions. The impact of land-use change is not included in the model constraints for the GFI and net-zero framework (even though included in the IMO-LCA guidelines). Geologic carbon sequestration and the infrastructure for CO_2 transport are assumed to expand at similar rates as carbon capture technologies in energy conversion processes. The retrofitting option and the present age of the fleet are not considered in the model. The assessment considers the SSP2 scenario only; other SSP scenarios might be explored in future work. Leakage of methane in the NG supply chain is considered to be 0.5% in the model, whereas in reality it varies significantly depending on geographic region[36]. Our model excludes several real-world technology adoption constraints: technology lock-in effects where early investments create path dependencies, learning-curve advantages for technologies deployed sooner and the additional costs associated with being first movers in unproven technologies.

Regional tariffs, trade agreements and geopolitical interactions are not considered in the logistic model-based transport demand used in the study. The relative cost-effectiveness ranking of fuel paths under the evaluated policies would be negligible, but different demand scenarios would alter the absolute amount of fuel transition requirements. The model's aggregated capacity stock approach with 30-year depreciation does not capture non-uniform fleet age distributions, strategic early retirement decisions or retrofitting options that could accelerate transitions. In practice, economic incentives from strong policy signals could induce early scraping of inefficient vessels, whereas retrofitting could allow existing vessels to adopt compatible fuels (particularly methanol and LNG) without full replacement. These dynamics could accelerate or alter transition pathways compared to our model results.

Policy measures

Six different shipping policies are investigated: three are included in the main article and the others in Supplementary Information. The policies are represented by constraints in the model, as detailed below, and more details on the policy model are given in Supplementary Information.

Marine levy: the levy applies to the levels of direct GHG emissions from the combustion of marine fuels: US$50 tCO_2^{-1} from 2030, increased by US$50 tCO_2^{-1} every 10 years until 2050 and then maintained at US$150 tCO_2^{-1} for the remainder of the century. The total levy is the product of the levy rate at different time periods and the ship emissions during different time periods, as in equation (2). The total cost of the levy is included in the total cost in the model.

IMO net-zero framework: the net-zero framework has a technical element and an economic element. The technical part is the GFI target that governs the maximum permissible GHG emissions over the life cycle per unit of energy used in shipping ($gCO_{2eq}\,MJ^{-1}$). Two targets are set as: a tier 2 base target; and a tier 1 direct compliance target (the latter being more stringent). The economic component of the mechanism penalizes, or rewards, ships based on their compliance with the tier 2 criteria. Vessels that do not comply with tier 2 must secure remedial units at a cost of US$380 tCO_{2eq}^{-1}, whereas vessels that meet tier 2 but not tier 1 are required to purchase remedial units at US$100 tCO_{2eq}^{-1}. Vessels that achieve GFI better than tier 1 earn surplus units. The system imposes a cost of US$380 tCO_{2eq}^{-1} for emissions exceeding the tier 2 threshold and US$100 tCO_{2eq}^{-1} for emissions that lie between tier 1 and tier 2. In addition, 20% of the system revenues are allocated to vessels that utilize zero-emissions fuels. The ship-specific GFI for each time period is calculated as the sum of the shipping-specific upstream emissions (equation (1)) and the shipping emissions (equation (2)), along with the ship-specific energy use.

Levy and GFI: this is implemented by imposing a charge on emissions from shipping as an additional expense in the model, similar to the marine levy. In addition, the shipping energy use must be tier 1 compliant. A constraint stipulating that the GFI of each ship must be below the tier 1 threshold is implemented in the model.

The shipping-specific policy measures are assessed for two cases: first, for a world without any climate reduction ambitions; second, for a world meeting the 2 °C climate target. In the first case, the GET model is run without any carbon constraints, and in the second case, with a carbon budget of 905 $GtCO_2$ (for 2010–2100), based on representative concentration pathway (RCP) 2.6[41].

Integration of LCA and GET

To consider wider environmental implications of the shipping energy transition, a broader life-cycle assessment is needed than the climate-focused IMO-LCA guidelines (limited to CO_2, CH_4 and N_2O emissions) used for calculating the GFI (and the cost optimization in GET). It is also important with a method that includes the fuel infrastructure, resource extraction, indirect land use and other emissions and captures temporal changes in the energy system over different time steps. Prospective LCA rather than the attribution approach is better suited for forward-looking policy analysis, as it maintains temporal consistency with energy system evolution. Hence, pLCA calculation as post-processing is performed in this work to assess the WtW environmental impacts for different fuel and propulsion mixes in the assessed shipping policy scenarios. Because the depth of the technology description is much more detailed in the pLCA, the pLCA is integrated into GET in various steps, and WtW analysis is performed in the post-processing step. The integration approach ensures that the key parameters, such as efficiency, in GET are harmonized with the process-specific pLCA in terms of energy flows. For more details see Supplementary Note 2 and ref. 35.

The WtW impacts include embodied emissions, fugitive emissions, direct and indirect land uses and primary energy extraction that are not explicitly mentioned in the IMO-LCA Guidelines considering different temporal scopes for the optimized fuel and propulsion mixes for different scenarios. The temporal scope from 2020 to 2100 is also considered in the process-specific LCA based on the time-specific parameters in the GET model for around 90 processes that are directly and indirectly connected to shipping. Inventory data for LCA are adjusted to avoid double-counting the impacts on downstream energy system supply chains, where the analysis is gate to gate. This involves setting the energy inputs of life-cycle inventory processes to zero, as these inputs are already represented as distinct processes within the GET model.

Impacts associated with energy input are added after analysing the electricity mix from the GET output. The life-cycle inventory primarily relies on process-based data sourced from earlier studies[6,7,42] and uses the pLCA data set (premise) v1.5.8 tool[43] with background data from ecoinvent v3.10[44]. Premise v1.5.8[43] is used to include the time-dependent sectoral transformation of the infrastructure, materials and embodied energy, and this temporal development is based on the IMAGE model[45] considering scenarios from SSP2 base and SSP2–RCP26, respectively[46].

Environmental impacts are assessed for seven midpoint impact categories: climate impact, particulate matter formation, terrestrial acidification, marine eutrophication, land use, resource use—fossil and resource use—metals and minerals. The climate impact is based on the global warming potential over 100 years and is estimated based on IPCC AR6[47]. The other environmental impacts are estimated based on EF 3.0.

Data availability

The Supplementary Information include major parts of the GET model and data that support the findings of this study. The GET v11 model for net-zero framework scenario is available via GitHub at https://github.com/fayaskanchiralla/Global-Energy-Transition-model-v11.git.

References

1. UNCTD *Review of Maritime Transport 2022* (United Nations, 2022).
2. Faber, J. et al. *Fourth IMO GHG Study* (CE Delft, 2020).
3. UNCTAD *Review of Maritime Transport 2023* (United Nations, 2023).
4. Marine Environment Protection Committee (MEPC). *MEPC* https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MEPC-default.aspx (2023).
5. IMO, MEPC *Circular Letter No.5005: DRAFT AMENDMENTS TO MARPOL ANNEX VI, M.E.p. committee, Editor* (IMO & MEPC, 2025).
6. Kanchiralla, F. M. et al. Life-cycle assessment and costing of fuels and propulsion systems in future fossil-free shipping. *Environ. Sci. Technol.* **56**, 12517–12531 (2022).
7. Kanchiralla, F. M., Brynolf, S. & Mjelde, A. Role of biofuels, electro-fuels, and blue fuels for shipping: environmental and economic life cycle considerations. *Energy Environ. Sci.* **17**, 6393–6418 (2024).
8. Stolz, B. et al. Techno-economic analysis of renewable fuels for ships carrying bulk cargo in Europe. *Nat. Energy* **7**, 203–212 (2022).
9. Korberg, A. D. et al. Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships.*Renewable Sustain. Energy Rev.* **142**, 110861 (2021).
10. Perčić, M., Vladimir, N. & Fan, A. Life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-sea shipping: a case study of Croatia. *Appl. Energy* **279**, 115848 (2020).
11. Kanchiralla, F. M. et al. How do variations in ship operation impact the techno-economic feasibility and environmental performance of fossil-free fuels? *A life cycle study. Appl. Energy* **350**, 121773 (2023).
12. Ovrum, E. et al. (eds) *Energy Transition Outlook 2023: Maritime Forecast to 2050* (DNV, 2023).
13. Müller-Casseres, E. et al. International shipping in a world below 2 °C. *Nat. Clim. Change* **14**, 600–607 (2024).
14. Ueckerdt, F. et al. Potential and risks of hydrogen-based e-fuels in climate change mitigation. *Nat. Clim. Change* **11**, 384–393 (2021).
15. Speizer, S. et al. Integrated assessment modeling of a zero-emissions global transportation sector. *Nat. Commun.* **15**, 4439 (2024).
16. Bullock, S., Mason, J. & Larkin, A. The urgent case for stronger climate targets for international shipping. *Clim. Policy* **22**, 301–309 (2021).
17. Taljegard, M. et al. Cost-effective choices of marine fuels in a carbon-constrained world: results from a global energy model. *Environ. Sci. Technol.* **48**, 12986–12993 (2014).
18. Hansson, J. et al. The potential role of ammonia as marine fuel—based on energy systems modeling and multi-criteria decision analysis. *Sustainability* **12**, 3265 (2020).
19. Xu, L. et al. An Environmental Assessment Framework for Energy System Analysis (EAFESA): the method and its application to the European energy system transformatio. *J. Cleaner Prod.* **243**, 118614 (2020).
20. Volkart, K., Mutel, C. L. & Panos, E. Integrating life cycle assessment and energy system modelling: methodology and application to the world energy scenarios. *Sustainable Prod. Consumption* **16**, 121–133 (2018).
21. *Reduction of GHG emissions from Ships: Fourth IMO GHG Study 2020* (IMO, 2021).
22. *IMO's New Net Zero Framework: Assessing the Potential Options and Costs of Compliance* (UMAS & UCL, 2025).
23. E, T. *IMO Net-Zero Framework: Assessing the impact of the IMO's draft Net-Zero Framework* (Transport & Environment, 2025).
24. Kanchiralla, F. M. et al. Environmental and economic assessment of electric ferries with different lithium-ion battery technologies. *Appl. Energy* **396**, 126274 (2025).
25. Moon, H. S. et al. Exploring the cost and emissions impacts, feasibility and scalability of battery electric ships. *Nat. Energy* **10**, 41–54 (2024).
26. Chatterjee, S. & Huang, K. W. Unrealistic energy and materials requirement for direct air capture in deep mitigation pathways. *Nat. Commun.* **11**, 3287 (2020).
27. Millinger, M. et al. Diversity of biomass usage pathways to achieve emissions targets in the European energy system. *Nat. Energy* **10**, 226–242 (2025).
28. Muratori, M. et al. EMF-33 insights on bioenergy with carbon capture and storage (BECCS). *Climatic Change* **163**, 1621–1637 (2020).
29. van Vuuren, D. P. et al. Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nat. Clim. Change* **8**, 391–397 (2018).
30. Arias, P. A. et al. in *Climate Change 2021: The Physical Science Basis* (eds Masson-Delmotte, V. et al.) 33–144 (IPCC, Cambridge Univ. Press, 2021).
31. Georgiadou, M. (ed.) *Development of Outlook for the Necessary Means to Build Industrial Capacity for Drop-in Advanced Biofuels* (European Commission, 2024).
32. Costa, M. et al. Sustainability assessment of the whole biomass-to-energy chain of a combined heat and power plant based on biomass gasification: biomass supply chain management and life cycle assessment. *J. Environ. Manage.* **317**, 115434 (2022).
33. Zang, G. et al. Life cycle assessment of power-generation systems based on biomass integrated gasification combined cycles. *Renewable Energy* **149**, 336–346 (2020).
34. Fuss, S. et al. Betting on negative emissions. *Nat. Clim. Change* **4**, 850–853 (2014).
35. Kanchiralla, F. M. *Energy Transition towards Sustainable Shipping: Environmental and Economic Life Cycle Considerations* (Department of Mechanics and Maritime Sciences, Chalmers University of Technology, 2025).
36. Balcombe, P. et al. The natural gas supply chain: the importance of methane and carbon dioxide emissions. *ACS Sustainable Chem. Eng.* **5**, 3–20 (2016).
37. Esquivel-Elizondo, S. et al. Climate impact of direct and indirect N_2O emissions from the ammonia marine fuel value chain. *Environ. Sci. Technol.* **59**, 9037–9048 (2025).

38. Lehtveer, M., Brynolf, S. & Grahn, M. What future for electrofuels in transport? Analysis of cost competitiveness in global climate mitigation. *Environ. Sci. Technol.* **53**, 1690–1697 (2019).
39. 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).
40. Hedenus, F. et al. Cost-effective energy carriers for transport—the role of the energy supply system in a carbon-constrained world. *Int. J. Hydrogen Energy* **35**, 4638–4651 (2010).
41. IPCC *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. et al.) (Cambridge Univ. Press, 2014).
42. Antonini, C. et al. Hydrogen from wood gasification with CCS—a techno-environmental analysis of production and use as transport fuel. *Sustainable Energy Fuels* **5**, 2602–2621 (2021).
43. Sacchi, R. et al. PRospective EnvironMental Impact asSEment (premise): a streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renewable Sustain. Energy Rev.* **160**, 112311 (2022).
44. Wernet, G. et al. The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* **21**, 1218–1230 (2016).
45. Stehfest, E. et al. *Integrated Assessment of Global Environmental Change with IMAGE 3.0: Model Description and Policy Applications* (Netherlands PBL, 2014).
46. Zampori, L. & Rana, P. *Suggestions for Updating the Product Environmental Footprint (PEF) Method, EUR 29682 EN* (Publications Office of the European Union, 2019).
47. Pathak, M. et al. in *Climate Change 2022: Mitigation of Climate Change* (eds Shukla, P. R. et al.) 51–148 (IPCC, Cambridge Univ. Press, 2022).

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Author contributions

F.M.K.: writing—original draft, conceptualization, visualization, data curation, methodology, validation, model development, formal analysis and investigation. S.B.: conceptualization, validation and editing. J.H.: conceptualization, validation and editing. M.G.: validation, data curation and editing.

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Competing interests

The authors declare no competing interests.

Additional information

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