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Full steam ahead?

Environmental impacts of expanding the supply of maritime biofuels for the International Maritime Organisation targets

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February 2025

Acknowledgements

This work was funded by Transport and Environment. We are grateful to the Tranport and Environment team (Alex Springer, Constance Dijkstra, Simon Suzan, and Faig Abbasov) for sharing their modelling and insight, and for reviewing this report.

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Summary

The UN's International Maritime Organisation (IMO) is in the process of evaluating proposals for binding targets aimed at decarbonising international shipping. This represents a step towards recognising the need to reduce greenhouse gas emissions from this global sector. This report examines the potential consequences of the IMO's decarbonisation strategy in relation to biofuels. Our findings indicate that additional safeguards will be necessary to avoid severe unintended environmental consequences. Moreover, the approach as it stands exhibits internal tensions that could undermine the consistency and effectiveness of the policy. As such, an assessment of priorities may be required.

For concreteness, the report evaluates one of the proposals under consideration – introduced by the EU and Japan – that would introduce a greenhouse gas intensity standard for maritime fuels. Under this standard, the reported average lifecycle emissions per unit of fuel consumed by ship operators would have to fall below a pre-determined threshold, which would become increasingly stringent over time. Policies of this nature are intended to support stakeholders' long-term planning and foster investment in cleaner fuel technologies; emissions standards have been implemented to cover road transport at the national level in Germany, Sweden, and Canada, and in a number of states in the USA. In the EU, the FuelEU Maritime Regulation imposes an emissions intensity standard on shipping operators making voyages to and from EU ports.

To meet the requirements of the proposed emissions standard, shipping operators will need to diversify their fuel mix, incorporating alternative liquid and gaseous fuels such as liquefied natural gas (LNG), biofuels, and electrofuels. While these alternatives may report emissions savings, they each present specific challenges. For biofuels, the regulatory assessment of greenhouse gas emissions may fail to fully account for critical contributions such as indirect land-use change (ILUC). Broader environmental impacts like competition for resources within and between economic sectors should also be considered carefully in advance.

In our analysis, we consider three scenarios for biofuel uptake, constrained by the need to deliver the proposed targets and distinguished by feedstock eligibility rules. The first scenario allows all feedstocks to contribute; the second excludes feedstocks classified as high-ILUC; the third restricts the contribution of food and feed crops. We find that without robust safeguards, the proposed policy risks driving net global emissions to increase rather than decrease. It is unclear at this stage of the IMO negotiations if and how ILUC emissions and methane leaks though the bio-LNG supply chains will be addressed in the proposed methodology. Excluding feedstocks identified as high-ILUC (i.e. palm and soybean oil) would be an easy way to enhance the robustness of the policy's climate goals.

The demand for alternative liquid shipping fuels under the IMO's targets will be vast. At present, the only mature alternative fuel technologies capable of delivering volumes approaching this scale are lipid-based biofuels; but relying on these would necessitate international shipping to consume substantial volumes of vegetable oils and a large share of the world's residual oils (meaning used cooking oil (UCO) and low-grade animal fat). It remains to be seen whether the shipping industry will be prepared to pay the price to secure these resources against competitors in aviation and road transport.

In any case, existing technologies will likely be insufficient to satisfy the IMO's decarbonisation

goals in the 2030s. This suggests that a rapid scale-up in the production of novel fuels (electrofuels and advanced cellulosic biofuels) will be required. Clear policy signals will be needed to motivate their deployment and to overcome commercial viability challenges.

These findings would suggest that the IMO's mid-term measures should be designed to rapidly accelerate investments in alternative fuel technologies that can deliver genuinely sustainable decarbonisation. Complementing these efforts with measures to reduce the energy demand of international shipping would improve the sector's chances of achieving meaningful emissions reductions while navigating the challenges of resource availability and technological maturity.

1. Introduction

1.1. Biofuel policy and the International Maritime Organisation

1.1.1. Global biofuel policy

In recent decades, governments around the world have promoted biofuel consumption through policies aiming to support their farmers and local industries, enhance energy security, and mitigate the environmental impacts of fossil fuel use. Brazil has perhaps the longest such history, having maintained high levels of ethanol demand since the 1970s. The EU adopted its first Renewable Energy Directive (RED) in 2009, and the USA adopted the second Renewable Fuel Standard in 2010; these policies (with some revisions) continue to mandate the use of renewable energy in transport. Growth in global demand since 2010 has resulted in a near tripling of biofuel production (Energy Institute, 2024).

Biofuel consumption has historically been dominated by the road sector, and has primarily involved the blending of ethanol into petrol and biodiesel into diesel. The airline industry has touted the potential of biofuels to decarbonise aviation, but the difficulty of regulating a fundamentally international sector coupled with operators' reluctance to pay the premium for more sustainable fuels has delayed progress. The UN's International Civil Aviation Authority (ICAO) agreed an international, binding framework, CORSIA, for limiting emissions growth from international aviation through offsetting and using alternative fuels. This will become legally binding on all ICAO Member States in 2027, but the price signal for biofuel supply from CORSIA is set by the price of offsets, and is therefore weak compared to the incentive from existing national biofuel support policies, and therefore it is unlikely that CORSIA alone will be sufficient to drive deployment without complementary local mandates[1]. National development of aviation fuels policy – such as the EU's ReFuelEU Aviation Regulation (European Union, 2023a) – will therefore be needed if the industry is to progress from its dependence on fossil fuels.

Like aviation, shipping is an international, multi-jurisdictional sector; it is overseen by the UN International Maritime Organisation (IMO). Greenhouse gas emissions from international shipping have tended to receive less attention than emissions from aviation despite the sector accounting for 1.6% of global CO_{2e} (carbon dioxide equivalent) emissions between 2015 and 2024[2], next to aviation's 1.4% (Climate TRACE, 2024)[3]. However, the policy landscape is changing to cover shipping both within and between countries. We introduce two major developments here.

1 For comparison, the EU's inclusion of intra-EU aviation in its Emissions Trading System (ETS) has so far failed to stimulate much alternative fuel uptake even at a significantly higher price point.

2 Cf. the IMO's estimate that in 2018 2.89% of global carbon dioxide emissions can from shipping (IMO, 2020).

3 These estimates combine international and domestic segments. They do not account for heating/cooling associated with black carbon and aerosols from ship exhausts, or the heating effect of contrails and nitrogen oxide emissions from aeroplanes.

1.1.2. FuelEU Maritime

FuelEU Maritime is an EU regulation which places binding greenhouse gas reduction requirements on the operators of ships travelling to and from EU ports (European Union, 2023c). It is currently the world's most advanced regulation aimed at decarbonisation of domestic and international shipping, and will be an example and reference point for the decarbonisation policies under consideration by the IMO.

FuelEU Maritime establishes a standard for the greenhouse gas intensity of energy used by ships. This tightens over time following the schedule shown in Table 1. Ship operators may comply by using alternative fuels, including biofuels, electrofuels[4], and natural-gas-based fuels like liquefied natural gas (LNG). There are also provisions to promote wind-assisted propulsion and the consumption of on-shore power while ships are at berth[5].

Table 1 FuelEU Maritime schedule for reducing the greenhouse gas emissions intensity of fuels used in shipping and other maritime applications

Emissions Intensity	Unit	2025	2030	2035	2040	2045	2050
Reduction	%	2%	6%	14.5%	31%	62%	80%
Target	gCO_2e/MJ	89	86	78	63	35	18

Note: Percentage reductions are with reference to a standard comparator of 91.16 gCO_2e/MJ.

FuelEU Maritime is notable for its exclusion of food-and-feed-based biofuels as compliance options[6]. Biofuel feedstocks must also satisfy the sustainability criteria laid down in RED III (Article 29), which restrict the sourcing of feedstock from certain protected lands like forests, peat bogs, wetlands, and highly biodiverse grasslands, and set thresholds for minimum reportable greenhouse gas savings.

RED III provides the methodology for calculating the well-to-tank (WtT) emissions of biofuels, including emissions from feedstock production, transport, fuel conversion, and soil carbon accumulation (for crop-based biofuels). FuelEU Maritime provides its own methodology for the tank-to-wake (TtW) emissions. Put together, the lifecycle, or well-to-wake (WtW), emissions determine whether a fuel meets the RED III minimum emissions savings threshold; for FuelEU Maritime, the lifecycle emissions score also determines the compliance value of a given fuel.

1.1.3. The IMO's 2023 Greenhouse Gas Strategy

In 2023, the IMO updated its 'Strategy on Reduction of GHG Emissions from Ships' (IMO, 2023a).

4 Known in the EU literature as 'renewable fuels of non-biological origin' (RFNBOs), these include hydrogen, e-ammonia, e-methanol, and synthetic hydrocarbons. FuelEU Maritime includes extra incentives for electrofuels: an energy multiplier for reporting (this is time-limited), and a nominal sub-target to compel consumption (though this may be waived if the fuel is deemed to be too expensive).

5 The regulation does not directly incentivise efficiency improvements in new ships or the existing fleet – such standards must be set elsewhere.

6 These are oil-, starch-, or sugar-rich crops grown during the main harvest. See RED III Article 2 for the full definition (European Union, 2023b).

The headline target is now for international shipping to reach net-zero emissions around the year 2050 (the 2018 strategy had called for an emission reduction by at least 50% by 2050). Intermediate targets aim to reduce total greenhouse gas emissions from international shipping by 20-30% in 2030, and by 7080% in 2040, both compared to a 2008 baseline.

The targets remain aspirational only, as they are non-binding and there is no enforcement mechanism[7]. The IMO has started the process of considering proposals for an implementation that will deliver the Strategy's goals, which should contain both a 'technical element' (i.e. a standard to reduce the greenhouse gas intensity of maritime fuel), and an 'economic element' (i.e. some form of pricing mechanism on maritime CO_2e emissions). Among the alternatives put forward by IMO member states, one of the leading proposals is understood to be the greenhouse gas emissions intensity standard proposed by the EU and Japan (ISWG-GHG 17/2/2, 2024)[8]; this shares certain key characteristics with FuelEU Maritime.

Under this proposed mechanism, ship operators would have to meet a declining lifecycle emissions intensity standard across their fleets, for all ships of 5,000 gross tonnage[9] and larger. Two possible reduction schedules have been presented, a 'base' case and a 'strive' case, with both approaching zero in 2050 (see Table 2). Operators would be able to 'pool compliance' between over- and under-complying vessels (effectively a form of in-sector trading for emissions reduction credits) and would have the option to 'buy out' of their obligation at a pre-arranged price, yet to be decided. This emissions standard would work in tandem with a proposed flat greenhouse gas fee of 100 USD/tCO_2e of emissions. There is no suggestion to regulate the warming effects of black carbon emitted from ship exhausts, only atmospheric greenhouse gases.

Table 2 Proposed IMO schedule for reducing the WtW greenhouse gas emissions intensity of fuels used in international shipping (in units of gCO_2e/MJ)

Scenario	2027	2030	2035	2040	2045	2050
Base	90	82	57	30	16	2
Strive	86	70	45	20	10	2

Note: The proposal sets out a diminishing annual standard in the period 2027-35, after which the schedule becomes quinquennial.

Source: ISWG-GHG 17/2/2 (2024)

The IMO will finalise the general shape of the implementation mechanism in autumn 2025 (MEPC 80/17/Add.1, 2023). As with FuelEU Maritime, it is expected that certain biofuels, electrofuels, and fossil fuels will be considered eligible to contribute to decarbonisation goals; but for the purposes of this report we shall focus on the biofuels to be introduced in Section 2.

7 Existing IMO regulations which could be used to progress towards the goals include the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI), and the Carbon Intensity Indicator (CII). But these have yet to be operationalised to drive serious decarbonisation progress (Comer & Carvalho, 2023; Transport & Environment, 2024b).

8 See also the IMO fact sheets (UN International Maritime Organisation, 2024), as well as third-party reporting (Kuehne + Nagel International, 2024; Lloyd's Register, 2024).

9 Gross tonnage is a measure of the capacity of a ship by volume. It does not measure the mass of the vessel or the mass of the cargo it can carry. This is the same threshold applied by FuelEU Maritime.

1.1.4. This report

This report examines the implications of IMO proposals to decarbonise international shipping out to 2040. We will focus in particular on the potential use of biofuels to meet alternative fuel commitments at the international level, and the associated impact on greenhouse gas emissions, land use, and competition with the food and other sectors.

The remainder of this Section 1 outlines some sustainability concerns associated with biofuels. Section 2 introduces key biofuels under consideration for maritime transport, and characterises the consumption levels observed in the world today as well as on hypothetical trips between major global ports. Section 3 forecasts future fuel demand, and introduces three feedstock mix scenarios which give rise to differing levels of modelled feedstock demand. This is analysed in Section 4 in terms of potential sustainability impacts. We conclude in Section 5. A glossary and some technical details are provided in the Annex.

1.2. Biofuels and sustainability

1.2.1. Lifecycle emissions

The production and distribution of biofuels and biofuel feedstocks is associated with greenhouse gas emissions due to energy use and other processes throughout the supply chain. In cases where there is high use of agricultural inputs, or where there is significant emission of greenhouse gases like methane and nitrous oxide to the atmosphere, biofuels' emissions savings dwindle. When 'indirect land use change' (ILUC) emissions are included (see Section 1.2.2 below), biofuels may even be identified as worse than fossil fuels. Combusting biofuels in ships is also associated with biogenic carbon dioxide emissions, but conventional treatment dictates that these are counted as zero in the maritime inventory, on the premise that the CO_2 released during combustion was previously absorbed during biomass growth.

Figure 1 gives the assumed emissions per megajoule (MJ) for biofuels made from the feedstocks considered in this report (the fuels and feedstocks under consideration will be introduced in Section 2). We base our lifecycle emissions on the typical RED II/III values (European Union, 2018, 2023b) (the details including some adjustments are discussed in Annex B.3) and the ILUC values come from Valin et al. (2015). The warming impact of non-CO_2 gases is converted to CO_2e using global warming potentials (GWPs) calculated over 100 years[10].

10 It is often argued that this underplays the near-term warming effect of methane, as the 20-year GWP is about three times the 100-year value, and is also more relevant to the 2050 timeframe. However, the standard treatment under the UNFCCC is to use 100-year accounting, and we follow that in this report.

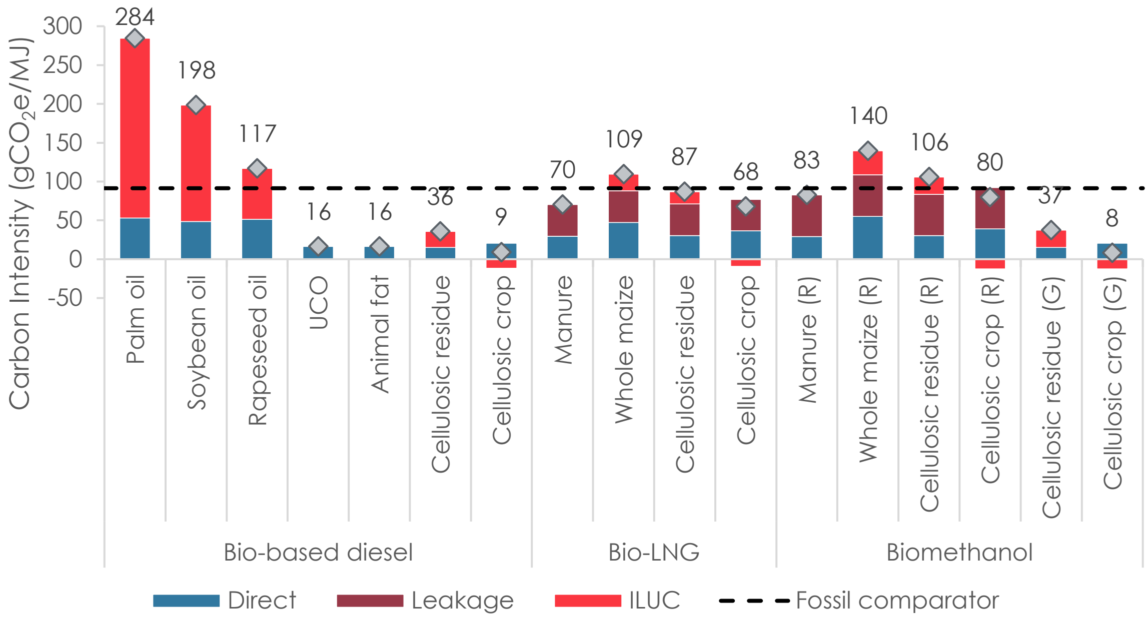

Figure 1 Assumed lifecycle greenhouse gas intensity for the major fuels and feedstocks to be considered, distinguishing direct lifecycle emissions, methane leakage, and ILUC emissions

Note: For biomethanol, '(R)' indicates the biomethane reforming pathway and '(G)' indicates biomass gasification.

1.2.2. Indirect land use change

Expanding biofuel production can create pressure for agricultural expansion and thereby be a driver of land use change and land use change emissions due to loss of carbon from biomass (e.g. deforestation) and soils. The term indirect land use change (ILUC) describes the process where the development of new sources of demand for agricultural products stimulates farm expansion around the world – potentially including into carbon-rich and biodiverse habitats like tropical rainforests and temperate grasslands. ILUC cannot be directly measured because it is a diffuse effect mediated by markets, and so estimating the size of ILUC effects requires economic modelling (Malins, 2021). For this study, we use indicative ILUC values from Valin et al. (2015), which were produced using the Global Biosphere Management (GLOBIOM) model tuned to demand from the EU.

Figure 1 above combines the 'direct' lifecycle emissions scores described in the previous section with the adopted ILUC factors, and illustrates how biofuels that ostensibly register lifecycle emissions savings may perform worse than the fossil fuels they replace when ILUC is included. For the purposes of this report (including Figure 1) the Valin et al. (2015) values are adjusted to fit each fuel-feedstock combination (described in Annex B.3). It is worth highlighting that lignocellulosic feedstocks (perennial grasses and harvested wood) are modelled by Valin et al. (2015) as having negative ILUC emissions. This reflects the potential for increased carbon storage in lowcarbon-stock EU land[11]. Not all studies are so favourable, however, and because large-scale production of cellulosic biofuel crops is yet to develop, it remains to be seen which agricultural models will be adopted, and which deliver the greatest benefits in each geography (Pavlenko & Searle, 2018; Weik et al., 2022). On the other hand, the GLOBIOM values for palm oil and soybean oil are relatively high compared to other studies; but there is nevertheless a solid body of evidence connecting them to deforestation and ILUC risks (Malins, 2019), and in this report we shall treat both as high-ILUC feedstocks.

1.2.3. Food versus fuel

Biofuels have historically been made predominantly from food and feed crops rich in oil, starch, or sugar, as energy in these forms is relatively easy to convert to fuel. This introduces a clear tension between growing crops to feed people and livestock versus growing them to reduce the transport sector's dependence on fossil fuels. To put the issue in perspective, it has been estimated that in 2023 the global biofuel industry consumed enough food and feed crops to meet the caloric needs of about 1.3 billion people (Malins, 2023a); in the USA, it is well known that 35-40% of the harvest of corn goes to make ethanol for road vehicles (U.S. Department of Agriculture, 2023), and in Brazil in 2023, 326 Mt of the 724 Mt sugarcane harvest was used for the same purpose (Degreenia & Wynne, 2023; FAOstat, 2024). In the vegetable oil market, growing demand for biofuel feedstock risks outstripping supply growth (IEA, 2022; Malins & Sandford, 2022; U.S. Department of Agriculture, 2024b).

Demand for food and feed crops as biofuel feedstock puts pressure on food availability and food prices. The adoption of major biofuel policies has been linked to long-term increases in inflation-adjusted food prices and to an increased risk of food price spikes (Malins, 2023a). The existence of a causal connection between biofuel demand and food prices is supported by economic modelling (Persson, 2016), and increases in food prices arising from biofuel uptake could lead to significantly reduced disposable income for people on limited incomes and to increased poverty rates (de Hoyos & Medvedev, 2011; Wiggins et al., 2008).

In recent years, the EU has taken a proactive approach to limiting the amount of food going into biofuels – most prominently through the crop cap in RED II/III, and through the exclusion of food-based biofuels in FuelEU Maritime and its sister regulation ReFuelEU Aviation (European Union, 2023a). Other national governments have also taken steps to mitigate market disruptions, especially in times of food crisis (Malins, 2023a). The IMO Strategy calls for the food security impacts of decarbonisation policies to be considered, and this is considered in the analysis in Section 4.

11 In Europe, this overlaps with farmlands that would otherwise be abandoned.

2. Biofuels in the fleet

2.1. Key maritime biofuels

Shipping and other forms of maritime transport are almost completely dependent on liquid fossil fuels: marine diesel, marine gas oil (MGO), heavy fuel oil (HFO), and very low sulphur fuel oil (VLSFO). For later comparisons, we shall adopt FuelEU Maritime's standard carbon intensity value for VLSFO of 91.39 gCO_2e/MJ (3.83 MtCO_2e/Mtoe) (European Union, 2023c)[12].

Strategies for reducing fuel demand

There are a number of non-fuel options that ship builders and operators can use to reduce greenhouse gas emissions. Wind propulsion systems include rigid sails and 'Flettner rotors' which can extract thrust from cross-winds). Hull cleaning and systems that create a low-friction boundary layer at the hull-water interface reduce drag and improve efficiency. 'Slow steaming' – that is, reducing vessel speed – can significantly reduce fuel demand on account of the cubic relationship between speed and required engine power under smooth sailing conditions (MAN Energy Solutions, 2018). Switching off ship engines while at harbour, and instead running on-board systems on electricity supplied from shore, reduces fuel consumption and air pollution. And of course, there is always the possibility that overall demand for shipping will diminish in future, in tandem with reduced demand for coal, petroleum, and natural gas (Fricaudet et al., 2024; International Energy Agency, 2023).

In recent years, alternative fuels of both fossil and renewable origin (see Section 1.1.2) have been put forward as decarbonisation options and as ways to reduce the emissions of air pollutants like nitrogen oxides (NO_x) and sulphur oxides (SO_x). The following sub-sections introduce the biofuels that will be analysed in this report.

2.1.1. Bio-based diesel

For brevity we shall use the term 'diesel' as a catch-all to encompass a range of hydrocarbon fuels, from conventional diesel to marine gas oil to the heavy fuel oil used in the largest ships. We use the term 'bio-based diesel' to encompass three categories of diesel replacements: biodiesel, renewable diesel, and cellulosic diesel[13].

Biodiesel and renewable diesel are lipid-based fuels made from either virgin vegetable oils such as soybean oil, or from oily residues such as used cooking oil (UCO) and animal fat; feedstocks considered for this report are listed and described in Table 3. Both can be blended with fossil diesel, but they are chemically distinct. Renewable diesel is a hydrocarbon like petroleum diesel, and can in principle be blended into regular marine fuel

12 Other estimated values can be found in the literature, e.g. 109 gCO_2e/MJ (4.57 MtCO2e/Mtoe) calculated by Comer & Osipova (2021).

13 Biodiesel is otherwise known as FAME, for fatty acid methyl ester. Renewable diesel is otherwise known as HVO, for hydroprocessed vegetable oil. Note that in the USA, the usage of the term bio-based diesel has a narrower scope, covering only diesel made from lipid feedstocks, and may not include analogues of higher-order hydrocarbons like fuel oil.

at any concentration. Biodiesel is not a hydrocarbon but an oxygenated molecule; as such, conventional engines and fuel systems may have limited tolerance of high concentrations of biodiesel. Other challenges with using high biodiesel blends include microbial growth, corrosion of rubber components, and flow separation at cold temperatures (DNV, 2020); industry research on these factors is ongoing (Thepsithar & Kuttan, 2024).

The versatility of renewable diesel as a drop-in replacement for fossil hydrocarbons means that it (together with its lipid feedstocks) is already experiencing high demand in the road sector, and rapidly increasing demand from aviation (Barbarà et al., 2024). Which segment ultimately secures use of which feedstocks will depend on the policy-defined value signals in each; or, put crudely, which end-user is willing to or is forced to pay more.

Bio-based diesel can also be made out of ligno-cellulosic (i.e. non-lipid) material, for instance through pyrolysis with catalytic upgrading or gasification with Fischer-Tropsch synthesis. Figure 1 shows that cellulosic diesel can offer significant greenhouse gas savings compared with fossil fuels. It should be borne in mind, however, that even if feedstock supply can be secured (see the next paragraph), these production technologies are yet to achieve widespread commercial-scale deployment. If production of these fuels does start to scale up, there will also be competition from the aviation and on-road sectors. Hence, these biofuels can be expected to make only a relatively minor contribution to the overall fuel mix in the near future.

Table 3 lists cellulosic crops and cellulosic residues as two feedstock groups. The former typically require fewer chemical inputs than food crops, are resilient enough to grow on poor-quality land that may not be viable for food, and may even bring local ecological benefits (BIKE, 2023b; Elbersen et al., 2022) – though as with all agricultural production, there are risks (BIKE, 2023a, 2023b; Phillips et al., 2024). Rapid development, adoption, and ramp-up of cellulosic cropping models would be needed to supply the significant volumes that would be required to make an appreciable difference to the international shipping fuel portfolio. ‘Cellulosic residues’ can cover a range of materials, including those that have no economic value and little or no ecological value, and those with existing uses (e.g. straw for mushroom cultivation) or an important ecological function (e.g. woody debris left after forest harvesting that provides ecological niches and can build soil carbon). The production volume of these residues is determined (and limited) by the activity of their source economic sectors, and making use of them for biofuel purposes will depend on the creation of viable collection systems for these sometimes highly distributed and low-density materials.

Table 3 Bio-based diesel feedstocks considered in this report

Feedstock	Description
Palm oil	A low-production-cost vegetable oil, primarily produced in Southeast Asia. High crop yields translate to relatively low direct land footprint per unit of biofuel; however, palm oil is strongly associated with tropical deforestation and peatland degradation, and it hence has extremely high ILUC emissions.
Soybean oil	A vegetable oil with production centres in South America and the USA. Tropical plantations are strongly connected to Amazonian deforestation, and to conversion of Cerrado to cropland; this is reflected in high ILUC emissions. A co-product of soybean oil production is soy meal, which is used as a protein-rich component of animal feed.
Rapeseed oil	Rapeseed oil is used for biofuel production primarily in North America (referred to there as 'canola') and the EU. It is the third most consumed vegetable oil feedstock after palm and soybean, and has the potential to be supplied at scale for use in maritime biofuels. Smaller volumes of other food-and-feed vegetable oils may also contribute, but for our purposes it is sufficient to consider rapeseed oil as the overall category.
UCO (used cooking oil)	A residual oil that can be filtered, cleaned, and converted to biofuel. It may be collected from industrial food production plants, restaurants, and homes. Supply is limited. In some geographies UCO is already used as a boiler fuel or as an animal feed component. Generous policy treatment in key jurisdictions (notably California and the EU) have raised the value of UCO and led to cases of mislabelling fraud[14].
Animal fat	Low-grade fat rendered from the remains of animal carcasses has a range of uses in animal feed (for higher quality material), oleochemicals and energy recovery. Supply is limited. As with UCO, its policy value as a biofuel feedstock has led to diversion from existing uses.
Cellulosic residue	A heterogeneous category including agricultural residues like straw, forestry residues like leaves and twigs, industrial and process residues like husks and sludges, and the biological fraction of municipal solid waste. Use of these feedstocks typically has low displacement effects and low lifecycle greenhouse gas emissions, and can have low ecological impacts. However, the feedstock may be challenging to collect, and the technology to produce fuel from cellulosic feedstocks is not yet mature and will take time to ramp up.
Cellulosic crop	Crops grown for their high cellulosic biomass content, sometimes on lessfertile land or as cover crops. Prominent examples include perennial and annual grasses (e.g. miscanthus, switchgrass, hemps, giant reed), and woody biomass from short-rotation forestry (e.g. willow, poplar). As with any crop, these feedstocks require land, and farmers in pursuit of high yields may use chemical inputs (though typically at lower intensity than food and feed crops).

2.1.2. Bio-LNG

In the maritime context, methane (and a smaller amount of other gaseous hydrocarbons) is consumed in the form of liquefied natural gas (LNG). The liquefaction process involves cooling the methane down and maintaining it at cryogenic temperatures in on-board tanks, which

14 Discussed in Suzan (2023) and van Grinsven et al. (2020).

may or may not be pressurised. At the time of writing there were 1,282 LNG-powered ships[15] in operation, and a further 1,052 to be delivered by 2030 (Clarkson's Research, 2024; cf. IMO, 2024a).

LNG is sometimes promoted as a decarbonisation option on the basis of its lower combustion emissions compared to petroleum-based fuels, but this advantage is eroded by other emissions in the lifecycle. Creating and maintaining cryogenic conditions is energy-intensive, and because methane is a powerful greenhouse gas, even minor leaks at production sites and along the supply chain may compound to undermine its lifecycle emission savings. Venting and off-gassing in the LNG supply chain, and 'slip' from engine seals, can result in a lifecycle emissions score comparable to coal (Carr et al., 2024; Comer et al., 2022; Gordon et al., 2023; Howarth, 2024). This reality has often been overlooked in policy settings, and the shipping industry appears still to be set to adopt LNG as a fuel of the future.

Biomethane (also known as renewable natural gas, or RNG) is made from the feedstocks listed in Table 4. It may be liquefied to bio-LNG and used in place of fossil natural gas by ship operators wishing to achieve lower lifecycle greenhouse gas intensities. Biomethane is a cleaned and purified form of biogas (Ajdari, 2022), which is produced from microbial action on biological material. This may happen in dedicated facilities called anaerobic digesters, or may occur semi-naturally in wastewater treatment plants and landfills.

Table 4 Biomethane and biomethanol feedstocks considered in this report

Feedstock	Description
Manure	Biogas captured from anaerobic digestion of animal manures and slurries, as well as sewage treatment plants, can be upgraded to biomethane. This can be treated as having zero land footprint[16], and is eligible for 'avoided emissions offset' credits under some existing systems (Annex B.3).
Whole maize	Whole maize and other such crops grown on agricultural land may be harvested as anaerobic digester feedstock.
Cellulosic residue	See the feedstock description in Table 3. Cellulosic materials can be used as input for anaerobic digesters for making biomethane (which can be further processed to biomethanol), or for gasification plants for making biomethanol directly.
Cellulosic crop	

2.1.3. Biomethanol

Methanol can be burned in purpose-built dual-fuel engines or retrofitted conventional engines[17]. Because methanol's specific energy is about half that of marine gas oil or heavy fuel oil, about twice the mass of fuel would be needed to be bunkered for the same transport

15 As far as we are aware, large LNG ships are always dual-fuel, capable of burning LNG or conventional liquid fuel as needed.

16 The potential for manure to be used as fertiliser is largely preserved in the digestate that remains after biogas has been produced.

17 Modifications may include measures to avoid corrosion of aluminium and titanium alloys.

energy (though this is compensated slightly by superior methanol engine efficiency (Ajdari, 2022)). In terms of air quality, the absence of sulphur impurities brings SO_x emissions close to zero[18], and methanol's lower combustion temperature means that less NO_x is produced (Deka et al., 2022; Marquez, 2023). This is especially important in clean-air zones near to shore, and can reduce costs associated with exhaust cleaning modules. As an example of industry uptake, shipping giant Maersk already operates five container ships capable of burning methanol, and recently announced the order of 20 new ones to be delivered in 2028 (Maersk, 2024a, 2024b).

Another option for the use of methanol is in fuel cell engines, where methanol is 'reformed' to hydrogen before being consumed in a conventional hydrogen fuel cell. Reforming can take place either in a standalone reformer or at the fuel cell itself in high-temperature systems. Methanol-fuel-cell technology is under development, though press releases show that a handful of ships have been built and are operational. Fuel cells and electric motors are more efficient than internal combustion engines, and modular designs could make them easy to fit and retro-fit without extensive customisation.

Nearly all methanol today is produced from fossil sources: about 65% from natural gas reforming, and 35% from coal gasification (Dolan, 2020). Both pathways involve producing a mix of hydrogen and carbon monoxide, and catalysing a reaction to form methanol. For renewable methanol, hydrogen can be produced via water electrolysis, via reforming of biomethane, or via gasification of biomass. The last two pathways can be termed biomethanol[19], and the major feedstocks are the same as for biomethane in Table 4 Announced biomethanol projects seek to reach 12 Mt of biomethanol in 2030 (Methanol Institute, 2024), and Marquez (2023) quotes annual production reaching 140 Mt in 2050.

Of the two biomethanol production pathways, existing infrastructure would tend to favour biomethane reforming, as biomethane production capacity is already growing quickly, methane is easy to transport in the gas grid, and facilities to produce methanol from methane are already widespread. However, the future availability of biomethane is likely to be limited, particularly in light of competing residential and industrial uses. The gasification route may have greater room for scale-up owing to the wider range of feedstocks that can be used (including woody material, agricultural residues, and wastes). The process of biomass gasification, where biomass is heated to high temperatures in an oxygen-controlled environment, produces a mixture of biogenic hydrogen, carbon monoxide, and carbon dioxide. Well-established industrial chemistry reactions can be used to turn this syngas into methanol and/or other compounds, but technical challenges in gasification plant design and operation, together with logistical challenges in the collection and transport of relatively bulky cellulosic biomass, mean that the technology has not yet demonstrated commercial viability.

Methanol is a liquid and can be transported and stored using existing infrastructure; but there are some additional safety considerations to note (ABS, 2021; Lloyd's Register, 2020; Marquez, 2023). Methanol vapour does not dissipate in enclosed spaces and burns with an invisible flame. Methanol is also extremely toxic if ingested or inhaled, and it can be absorbed through

18 In practice some petroleum fuels may be used alongside methanol to maintain engine performance.

19 A third biomethanol pathway is the purification of 'raw methanol' produced in wood pulping mills (Ajdari, 2022; IRENA & Methanol Institute, 2021). Potential volumes are limited.

skin, so additional precautions and training are needed for handling and dealing with leaks. That being said, methanol spilled into the ocean would pose low risk to marine life, as it dilutes and biodegrades quickly; it poses a significantly lower environmental risk from spills than petroleum-based fuels or ammonia.

Ethanol

Methanol's bigger sibling ethanol is also a potential marine fuel – either blended with methanol or used on its own in single- or dual-fuel engines. Countries with large ethanol industries, as well as ethanol industry bodies, may promote ethanol for increasing the renewable content of marine fuel and reducing reportable emissions (Aluko, 2023; BioEnergyTimes, 2024).

Today, an estimated 220 billion litres of fuel ethanol are consumed around the world (Energy Institute, 2024), largely blended with petrol. Over 90% of production is based on corn and sugarcane. Relatively small amounts of other crops like sorghum, wheat, and rice are also used. The use of crops raises all the familiar environmental and social issues associated with first-generation biofuels, and the IMO should consider how to safeguard against the potential rapid scale-up of demand.

Using ethanol at sea also poses technical and operational challenges. Its relatively low specific energy compared to diesel means that a larger volume of fuel must be bunkered and carried on each voyage. Chemically, ethanol is known to degrade certain rubber fuel system components designed for pure hydrocarbons, and its 'hygroscopic' nature can lead to corrosion of fuel tanks and other components. As with methanol, safety hazards require additional precautions for storage and handling (American Bureau of Shipping, 2022).

Ethanol may also be chemically converted to liquid hydrocarbons which are fully compatible with existing engines and fuel supply infrastructure, but this imposes additional costs and efficiency losses. See Annex B.4.

2.2. Current biofuel consumption

The IMO reports that around 70 kt of biofuel was supplied to ships[20] in 2021, accounting for 0.03% of shipping's global fuel mix (MEPC 79/6/1, 2022). This rose considerably to 230 kt in 2022 (IMO, 2023b). Since that time, company press releases and industry news platforms have highlighted partnerships between biofuel suppliers and ship operators, typically specifying the blend of the fuel supplied as B30 (30% biofuel), and UCO as the feedstock. Disclosure of the volumes involved is a little less frequent.

The ports of Singapore and Rotterdam are understood to be the top suppliers of bio-blended bunker fuel. Rotterdam first reported such supply in 2021, and Singapore in 2022; Table 5 shows total fuel supply for each, and estimates how much of this was biofuel[21]. Singapore became the front-runner in 2024 (Tunagur, 2024). Neither port provides a break-down by feedstock.

20 Only ships above 5,000 gross tonnes were monitored.

21 The datasets indicate the volume of bio-blended fuel supplied, and we assume a standard blend rate of 28% in Rotterdam and 23% in Singapore to estimate the biofuel component.

Marine biofuel announcements

The oil giant BP announced in 2021 that it was trialling a B30 blend in two ships leased to it by Maersk; the press release states that biodiesel is "largely produced from recycled cooking oils and renewable oil sources", and does not indicate the volumes of fuel used on the ships' routes (BP, 2021). Another BP project saw it supplying B30 to the mining giant Rio Tinto; again the precise feedstocks and volumes were not specified. The oil tanker operator Euronav is reported to have bunkered 1,502 tonnes of B30 from BP, for use on voyages from Europe to Africa and South America (Prevljak, 2021); and the container company Hapag-Lloyd used 4,500 t of (presumed) residual-oil-based B30 in 2024 (Global Centre for Maritime Decarbonisation, 2024).

Beyond BP, ExxonMobil reported supply of waste-based biodiesel to the shipping company Stena Bulk as early as 2020 (ExxonMobil, 2020), but other details were not provided. More recently, TotalEnergies supplied 700 t of UCO-based B100 to a car transporter operated by the Hyundai; it is unclear whether the biodiesel was used in its pure form or diluted with conventional fuel oil (TotalEnergies, 2024).

Table 5 Fuel bunkered at two major shipping ports (units of kt), indicating the estimated pure biofuel component

Fuel	Type	Rotterdam				Singapore			
		2021	2022	2023	2024*	2021	2022	2023	2024*
Fuel oil	Supplied	7,799	8,533	7,965	5,967	45,909	44,127	47,942	37,629
	→ Biofuel	70	210	195	167	0	32	120	118
Marine gas oil	Supplied	1,793	1,908	1,668	1,125	4,082	3,753	3,771	2,842
	→ Biofuel	14	11	15	11	0	0	0	0
Methanol	Supplied	0	2	1	3	0	0	0	2
	→ Biofuel	0	0	1	3	--	--	--	--
LNG	Supplied	259	174	265	291	49	16	111	338
	→ Biofuel	0	0	0	1	--	--	--	--

Note: Data for 2024 covers Q1-3 only. 'Fuel oil' includes HFO, VLSFO, and ULSFO. 'Marine gas oil' includes MGO, MDO, and LSMGO.
Source: MPA Singapore (2024); Port of Rotterdam (2023)

2.3. Illustrative shipping routes

To put the potential biofuel demand in perspective, Table 6 estimates the feedstock and implied land demand associated with a single trip between two ports. For the calculation, we assume a large container ship (20,000 TEU[22]) travelling the most direct route between the ports at an average speed of 20 knots[23] (cf. Agarwal, 2019; MAN Energy Solutions, 2018).

22 A TEU is a twenty-foot equivalent unit – a standard shipping container size.

23 As mentioned above, adopting a slower speed would have a large impact on fuel consumption.

Table 6 Fuel consumption and implied biofuel land demand for eight illustrative shipping routes

Origin	Destination	Distance (NM)	Fuel consumption (kt)	Fuel type	Net cropland (kha)	Individuals' annual calorific intake
Brazil (Santos)	Egypt (Alexandria)	6,175	3.9	Biodiesel (soybean oil)	1.9	49,144
Brazil (Santos)	Ghana (Tema)	3,263	2.0	Biodiesel (soybean oil)	1.0	25,969
Brazil (Santos)	China (Shanghai)	11,056	6.9	Biodiesel (soybean oil)	3.6	87,990
Malaysia (Port Klang)	Nigeria (Lagos / Apapa)	7,969	5.0	Biodiesel (palm oil)	1.5	64,939
Malaysia (Port Klang)	Kenya (Mombasa)	3,788	2.4	Biodiesel (palm oil)	0.7	30,868
Indonesia (Tanjung Priok)	Nigeria (Lagos / Apapa)	7,739	4.8	Biodiesel (palm oil)	1.5	63,065
Indonesia (Tanjung Priok)	Kenya (Mombasa)	4,034	2.5	Biodiesel (palm oil)	0.8	32,873
Brazil (Santos)	Argentina (Buenos Aires)	998	0.6	Bio-LNG (whole maize)	0.6	9,860

Note: NM denotes nautical miles.

Note: The last two columns indicate the cropland area associated with the calculated biofuel feedstock consumption (cf. Annex B.2), and the number of people whose nutritional energy requirements could be satisfied if the feedstock were instead used as food.

To translate feedstock mass into cropland area, we use standard crop yields associated with the origin or destination country (the meaning of 'net' land area is discussed in Section 4.2 below). Were the biodiesel in Table 6 to be made from residual oil such as UCO instead of the indicated crop oils, roughly the same mass of feedstock would be required, but the direct cropland requirement would be zero. The final column of Table 6 estimates the number of people whose nutritional energy needs could be met for a year if the feedstock were used for food rather than biofuel production. Some details of the calculation will be described in Section 4.3.

3. Charting a course to 2040

In this section we introduce and describe our model scenarios; Section 4 presents the modelling results.

3.1. Fuel demand

Energy demand by the global shipping fleet was projected to 2040 in the IMO's 4th Greenhouse Gas Study (IMO, 2020). For this report, this was broken down into contributions from different fuels based on Transport and Environment's (T&E's) simplified modelling of potential fuel mixes, which assumes full compliance with the 'striving' targets of the proposed IMO regulation (ISWG-GHG 17/2/2, 2024). Figure 2 shows the respective fuel quantities for 2030, 2035, and 2040, and shows that fossil petroleum fuels would have to be all but eliminated by 2040. More detailed notes can be found in Annex B.1.

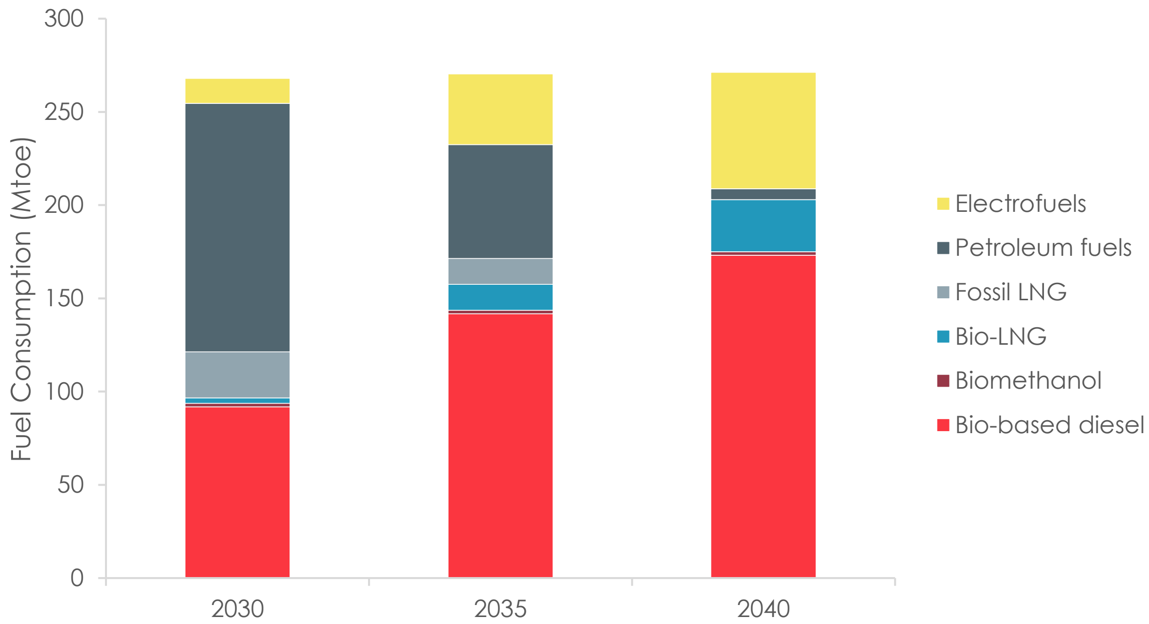

Figure 2 Demand for maritime fuels in the T&E compliance scenario

The total demand for LNG is treated as fixed throughout the period[24], and shifts from 10% to 100% bio-LNG between 2030 and 2040. Conventional petroleum fuels are progressively displaced, predominantly by bio-based diesel but with a growing contribution of electrofuels (which could be e-ammonia, e-methanol, or e-hydrocarbons). Biomethanol makes only a token contribution to the overall fuel mix.

24 Uptake of LNG fuelled ships is based on registered orders (Clarkson's Research, 2024). It is assumed that demand for these vessels is likely to decrease as more sustainable options become cost-competitive (cf. Section 2.1.2).

3.2. Feedstock demand scenarios

In this report we consider three scenarios for the biofuel feedstock mix, covering biodiesel, bio-LNG, and biomethanol. These are described in Section 3.2.2 below; first we outline some of the important inputs and constraints that are imposed on all three scenarios.

3.2.1. Common inputs and constraints

All three scenarios are built on T&E's modelled fuel demand trajectory shown in Figure 2 above. This means that the split between the energy contributions from bio-based diesel, biomethane, and biomethanol is the same in each scenario. The scenarios are also constrained to deliver compliance with the proposed IMO emissions standard (after all the fuel contributions of Figure 2 are factored in). Given that both the quantities of each type of biofuel supplied and the overall emissions are the same across scenarios, the average greenhouse gas intensity for each type of biofuel is also constrained to be the same across scenarios. The mix of biofuel feedstocks and associated feedstock specific greenhouse gas intensities in each scenario is tuned to deliver the emissions trajectory from the T&E model. For bio-based diesel, the required average emissions intensity (direct contribution only – i.e. without ILUC) starts at 44.1 gCO_2e/MJ in 2030, declining to 33.7 gCO_2e/MJ in 2035 and 23.3 gCO_2e/MJ in 2040.

Given that the assumed emissions intensity of vegetable oil bio-based diesel is already higher than the 2030 target (see Figure 1), lower greenhouse-gas-intensity bio-based diesel made from residual oils and cellulosic material will be needed to deliver compliance from the outset. This implies forms of preferential complementary support for these fuels compared to food-based biofuels, such as is supplied in the EU by the RED III. Indeed as we shall see, demand for residual lipids could rapidly outstrip what may plausibly be supplied. As such, in all three scenarios we must impose caps on the maximum consumption of UCO and animal fat. In order to satisfy the overall emissions targets and hit the required volumes of bio-based diesel, the level of these caps is set generously, entailing a significant share of the global supply flowing to the biofuel industry for use in international shipping[25]. To achieve this – i.e. for the maritime segment to outcompete aviation and road (as well as other sectors like oleochemicals and animal feed) – the IMO regulation would have to enforce extremely dissuasive penalties for non-compliance.

As an aside, an expected result of intense inter-modal competition would be to raise prices for UCO and animal fat. This would tend to raise prices for fuel consumers, while potentially delivering windfall profits to producers and suppliers of residual lipids[26]. It is at best debatable whether this reflects an efficient use of resources, and we contend that it would be preferable to use funds to more directly drive investment into longer-term solutions such as cellulosic biofuels and electrofuels.

We discuss the common parameters average crop yields and fuel lifecycle emissions in Annex B.

25 Cf. the discussions of resource availability in Annex B.4 and Section 4.4.

26 Such profits would enhance the incentive to commit fraud by mislabelling vegetable oil as residual oil by or cutting genuine residual oil with virgin oil. Were significant volumes of cheap palm oil to masquerade as 'sustainable' feedstock, the supposed climate benefits of any emissions reduction standard adopted by the IMO would be completely undermined. This kind of fraud is difficult detect, though instances have already been identified in the EU (Suzan, 2023).

3.2.2. Scenario specification

Having outlined what the scenarios have in common, we now describe their distinguishing features. The scenarios are introduced in Table 7, with a more detailed specification in the text below.

Table 7 Description of the biofuel feedstock scenarios

Scenario 1: Unrestricted	Scenario 2: No High-ILUC	Scenario 3: Food Cap
All feedstocks allowed to contribute to targets. Regulation assesses biofuels on their direct lifecycle emissions only.	Feedstocks posing a high risk of ILUC (i.e. palm and soybean oil) are replaced by other vegetable oils.	High-ILUC feedstocks excluded and the contribution of food and feed crops is capped.

In Scenario 1 – '*Unrestricted*' – all feedstocks are allowed to contribute to the IMO's decarbonisation targets in principle (subject to general sustainability criteria), provided that the resulting mix of fuels achieves the IMO target emissions trajectory. Neither ILUC factors nor ILUC-risk are taken into account. For lipid-based fuel, palm and soybean oil are likely to be the cheapest bulk options (especially given increasing competition with other transport segments for limited supplies of residual oils); but in order to hit emissions targets, the available supply of residual oils must still be close-to-fully utilised. Bio-LNG production is dominated by a combination of manure and purpose-grown maize. Biomethanol largely follows bio-LNG, except for a gradually growing fraction from biomass gasification.

In Scenario 2 – '*No High-ILUC*' – the feedstocks that we identify as most strongly associated with ILUC are not allowed to contribute to compliance with the IMO's greenhouse gas standard. This means that palm oil and soybean oil are eliminated and replaced with other vegetable oils (for our purposes, rapeseed oil – see Table 3), as there is limited scope to increase consumption of residual oils. The feedstocks for bio-LNG and biomethanol are the same as in Scenario 1. Note that excluding the oil options which have lower financial cost will increase prices for alternative marine fuels, especially as ship operators may have to compete with other transport segments and industries for residual oils.

In Scenario 3 – '*Food Cap*' – palm and soy remain excluded, and in addition we impose a cap on the amount of food-based feedstock that can contribute, reducing it below the level of Scenario 2. For bio-based diesel, the cap is modest and strengthens over time, limiting the contribution of rapeseed oil to 70% by energy in 2030, 40% in 2035, and 10% in 2040. The feedstock deficit prompts greater deployment of cellulosic technology to the maritime sector, implying a higher price to motivate increased collection and diversion from other sectors[27]. For biomethane, we limit the contribution of whole maize to 25%[28], and the deficit is

27 From the perspective of regulatory implementation, a cap on food and feed crops would require some form of two-tier compliance market where the compliance value for capped biofuel would be lower than for non-capped alternatives. These kinds of systems are already used in the USA's Renewable Fuel Standard, the UK's Renewable Transport Fuel Obligation, and in many implementations of the RED by EU Member States.

28 While whole maize is not a food crop in the sense that it may not be used to actually feed humans, the point is that it is grown on cropland which is suitable for the production of food.

filled through a combination of additional manure-based biogas and increased investment in anaerobic digestion of cellulosic materials.

Figure 3 shows the feedstock mix for bio-based diesel over time. We focus on bio-based diesel here as it is the major contributor to biofuel supply (Figure 2); refer to Annex B.4 for the feedstock mix of the other biofuels. In all scenarios, satisfying the overall emissions target requires rapid reduction in the contribution of virgin vegetable oils over time. Comparing the '*Unrestricted*' and the '*No High-ILUC*' scenarios, we see the substitution of palm and soybean oil for additional rapeseed oil. In the '*Food Cap*' scenario, the contribution of rapeseed oil and whole maize is subject to a limit that is in each time period slightly lower than the '*No High-ILUC*' scenario. The contribution of other feedstocks increases to compensate.

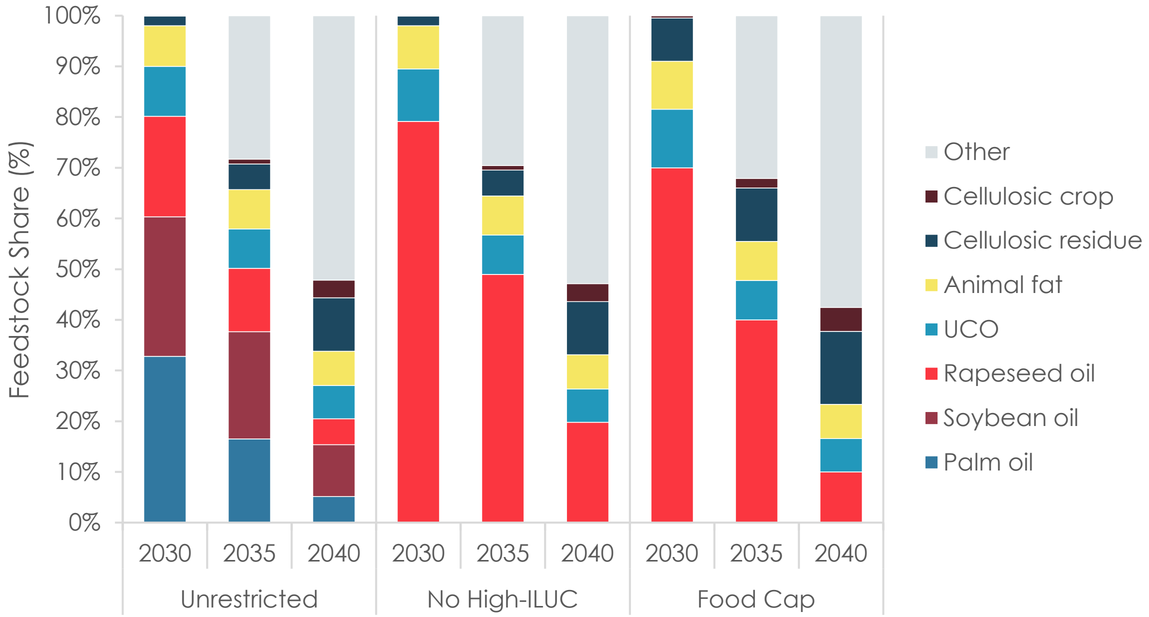

Figure 3 Bio-based diesel feedstock mix over time for the three scenarios

3.2.3. 'Other' compliance contributions

In Figure 3, a significant contribution of bio-based diesel in 2040 is marked as 'Other' – this was not covered in Section 2.1 and requires some explanation.

Given the feedstock supply restrictions on residual lipids, the uncertain future for the scale-up of cellulosic biofuel production, and the relatively high lifecycle emissions associated with vegetable oils (even excluding ILUC), necessitating their progressive replacement with lower greenhouse gas intensity fuels to meet the proposed greenhouse gas standard, it is not yet clear which existing pathways could expand production to meet this demand, or which new feedstocks and fuels could fill this gap. This is labelled 'Other' in Figure 3 and in Annex B, and rises from 0% in 2030 to comprise more than 50% of fuel volume in 2040.

One component of 'Other' could be new sources of lipids not classed as food and feed crops – e.g. additional residual oils from industrial processing, or non-food oilseeds grown in as intermediate crops in novel rotations. Another component could be extra cellulosic biofuel that is produced over and above the already ambitious industrial projections adopted here. Alternatively, the initial fuel allocation could include more e-fuels than currently projected, or total fuel demand could be lowered, for example through more stringent energy efficiency regulations. Finally, we note that the proposal to the IMO under consideration in this report (ISWG-GHG 17/2/2, 2024) features the option for operators to 'buy out' of their obligation, paying a set fee per tCO_2e of emissions in excess of the target. Based on our model results, it is possible that this facility would need to be used for a significant fraction of compliance in later years.

4. Impacts for the feedstock scenarios

4.1. Greenhouse gas emissions

Modelled direct and indirect greenhouse gas emissions under the three biofuel scenarios are shown in Figure 4, compared to counterfactual emissions if the maritime sector instead relied on petroleum-based fuels to meet this energy demand. In all cases, the volume of biofuel consumed rises steeply over time, and were the feedstock mix to remain unchanged, biofuel emissions would rise in step. However, the modelled IMO emissions reduction schedule forces concurrent changes in the mix of feedstocks used in maritime biofuels; Figure 4 shows that under our scenarios this is sufficient to reduce overall biofuel emissions between 2030 and 2040.

Significant ILUC from palm- and soybean-based biofuel in the first scenario results in estimated biofuel emissions exceeding the emissions of the fossil fuels that they replace: 87% higher in 2030 and 21% in 2035. In other cases, biofuels are able to deliver overall emissions reductions compared to fossil fuels; nevertheless, it should be understood that even when compliance with IMO's emission reduction targets is nominally delivered, performance is undermined by biofuels' ILUC emissions (should these not be included in the regulatory lifecycle emissions assessment).

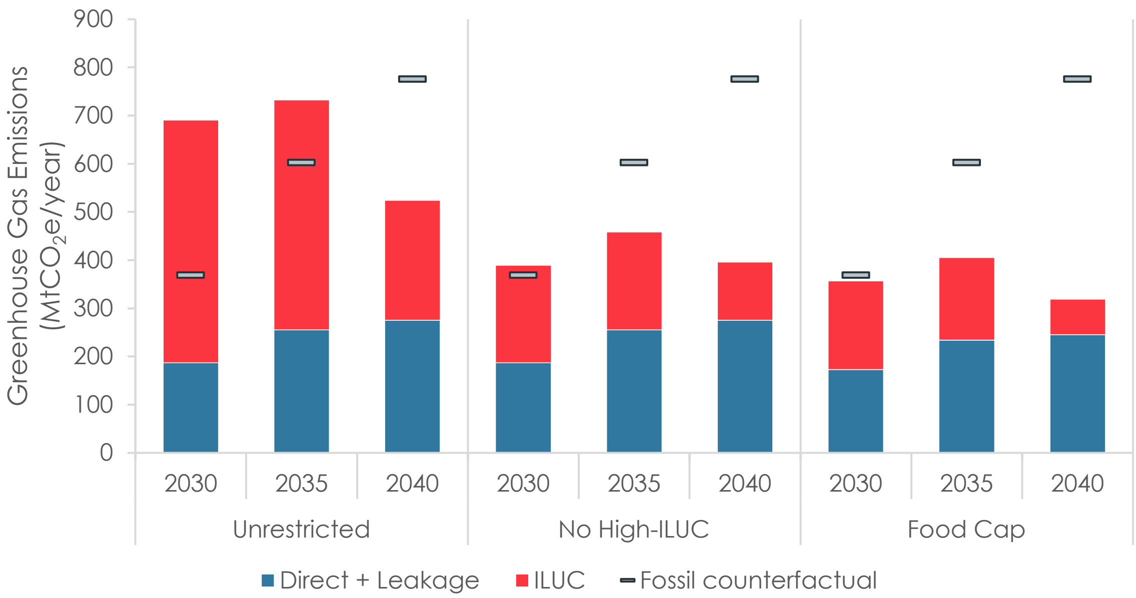

Figure 4 Biofuel greenhouse gas emissions for each scenario, indicating direct and indirect emissions, as well as the counterfactual emissions

Cutting out the high-ILUC feedstocks in the second scenario, i.e. replacing palm and soybean with other vegetable oils and residual oils, significantly reduces ILUC emissions. While there is no overall benefit with respect to fossil fuel in 2030, by 2040 the scenario delivers an average emissions intensity 49% lower than the fossil counterfactual (this figure does not account for displacement emissions due to diverting residual oils to the maritime sector). In the third scenario where the contribution of food feedstocks is capped, emissions savings reach 59% in 2040.

Methane emissions avoidance

Figure 4 does not include any contribution from 'negative emissions' that can be declared for livestock manure under some regulatory systems. Negative terms originate from the fact that stored manure often releases large quantities of methane and other gases into the atmosphere (Kupper et al., 2020). This pollution tends to go uncounted and unmitigated, but putting the manure into an anaerobic digester to produce biogas reduces release of methane (and potentially other gases too).

Members of the environmental community have long questioned whether avoided emissions from agriculture should be used to offset emissions from transport, as this prolongs the sector's ability to continue burning fossil fuels and saps the impetus for seeking genuine decarbonisation solutions (Martin, 2024). There is also the risk that, in some parts of the world, an excessive value signal could have a distortive impact on other industries (e.g. stimulating expansion and consolidation of dairy farms, (cf. Baldino et al., 2024; Martin, 2024). We have chosen not to include them in our main results, but we note that in 2040 if negative emissions were reported for the whole modelled quantity of manure-based methane, reportable emissions offsets could be worth 5972 MtCO2e/year. The emissions factors for this calculation are discussed in Annex B.3.

4.2. Land use

Crop-based biofuel feedstocks require land to grow, and in this report we consider the land requirement to produce vegetable oils, whole maize, and cellulosic crops. Assessing the land demand for these crops requires recognition that crops may produce useful resources as co-products alongside biofuel. For example, soybeans are processed into soybean oil and soybean meal (used in animal feed); as it would be misleading to attribute the whole 'gross' cropland area to the biofuel and ignore the feed product, we calculate the 'net' area by allocating gross land demand on the basis of the energy content in each product.

Figure 5 presents the net land demand for the relevant biofuel feedstocks. Consumption of virgin vegetable oils drives up land use; and due to palm's high yield, the '*Unrestricted*' Scenario 1 requires slightly less land than the '*No High-ILUC*' Scenario 2. Reducing dependence on vegetable in '*Food Cap*' Scenario 3 has the potential to reduce land demand.

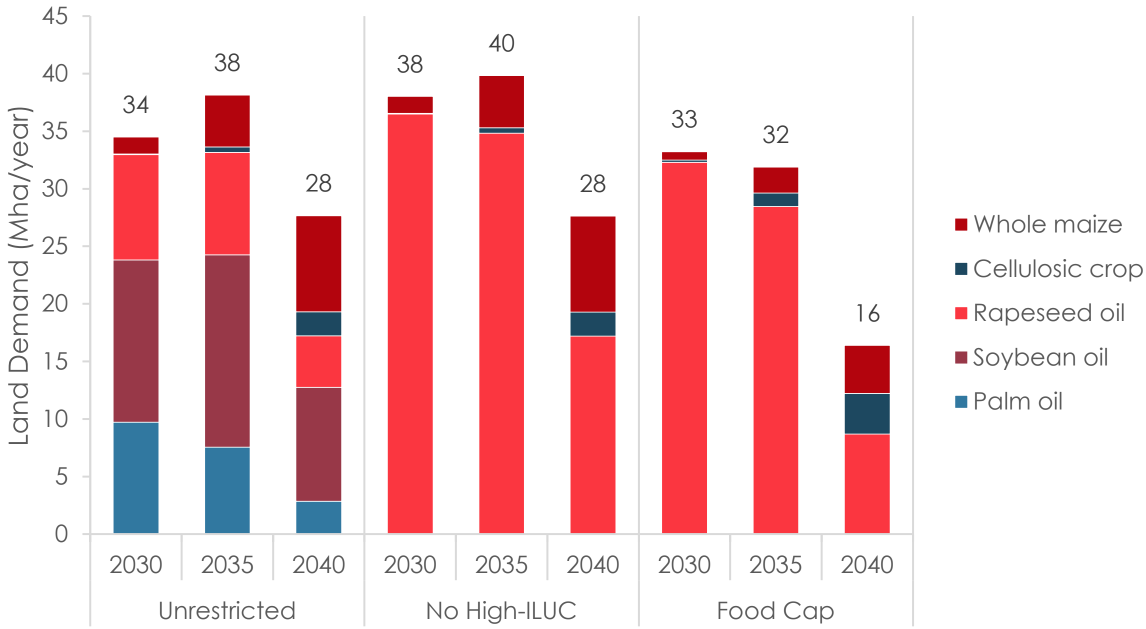

Figure 5 Net cropland requirement for biofuel feedstocks for the three scenarios

To put these numbers in perspective, the total land area of Zimbabwe is 39 Mha and Burkina Faso about 27 Mha. Even in the most restrictive *Food Cap* scenario, to supply biofuel crops for international shipping one would still need an area about the size of Ivory Coast (32 Mha) in 2030-35, and of Tunisia (16 Mha) in 2040.

4.3. Food competition

Bearing in mind the 'food versus fuel' discussion from Section 1.2.3, we calculate the calorific value that the food and feed crop feedstocks used in the scenarios (palm oil, soybean oil, rapeseed oil, and whole maize) would have if instead the material was supplied to people as food. For this analysis, we assume that the land used for whole maize could alternatively have been used to grow grain corn[29]. We do not consider the potential indirect impact on food markets from displacing residual oils, or from switching from food crops to cellulosic crops.

We find that by 2040, the energy going to biofuels would provide the basic dietary energy requirement of hundreds of millions of people, depending on the scenario – see Table 7. It is important to bear in mind, however, that issues of food security are more complex that simply deciding to divert food from biofuel facilities to consumers. Food insecurity is a product of uneven distribution, and phasing out support for biofuels would not automatically make feedstock material available to food-insecure people.

29 In the USA, we adjust the corn yield to reflect the regionality of where the whole maize crop is grown (USDA NASS, 2024).

Table 8 Nutritional energy in food crop feedstocks in 2040

Quantity	Unit	Year	Scenario		
			Unrestricted Feedstocks	High-ILUC Excluded	Capped Food Crops
Number of people whose nutritional energy needs could be met	Millions/year	2030	1,070	1,050	910
		2035	1,140	1,110	850
		2040	780	760	380

Note: We assume a minimum required caloric intake of 2,000 kcal/day.

4.4. Competition with other sectors

While food markets are the most obvious victims of distortion from growing biofuel demand, we should also consider the impacts on other sectors which vie for the same feedstocks. Increasing reliance on (and willingness to pay for) alternatives to crop-based feedstocks will in some cases lead to a shuffling of resources and nominal emissions between sectors, rather than an overall emissions reduction (Malins, 2023b; Pavlenko & Searle, 2020). For example, animal fats withdrawn from the cosmetics, oleochemical, or pet food sectors to serve shipping demand may be substituted with palm oil from the global market, undermining the effectiveness of restricting the use of food oils.

Though estimates for maximum collection potential vary, the modelled maritime demand for residual oils over time in Table 9 undoubtedly represents a huge use of resources[30]. Soubly & Riefer (2020), in the context of mapping resources for aviation, estimated a global resource of 11-13 Mt/year of UCO and 13-15 Mt/year of animal fat (this would rise over time with growth in the global food and livestock sectors)[31]. Elsewhere it has been estimated that global UCO collection could reach 18-35 Mt/year in 2030 (GlobalData, 2023), and that the maximum combined collection potential for the USA, EU, UK, China, Indonesia, and Malaysia is around 12.9 Mt/year (Stratas Advisors, 2024; Transport & Environment, 2024a). Satisfying the modelled maritime demand for UCO would require preferential access to this resource.

30 Residual lipids from other industrial processes may be included in the 'Other' feedstock category, but owing to the ambiguous identity and origin of these feedstocks, they are not shown here.

31 In addition, they quote a global availability of 11-14 Mt/year of other residual oils. The methodology for these calculations isn't described.

Table 9 Demand for residual oils under the three scenarios (Mt/year)

Scenario	Residual Oil	2030	2035	2040
Unrestricted Feedstocks	UCO	10.9	13.3	13.7
	Animal fat	8.9	13.2	14.1
	Sum	19.7	26.5	27.8
High-ILUC Excluded	UCO	11.5	13.3	13.7
	Animal fat	9.4	13.2	14.1
	Sum	20.9	26.5	27.8
Capped Food Crops	UCO	12.8	13.3	13.7
	Animal fat	10.5	13.2	14.1
	Sum	23.2	26.5	27.8

Note: By 2035, all scenarios have hit the maximum modelled availability of residual oil for the maritime fuels industry.

Of course, ship operators will be in competition with other transport segments for residual-oil-based biofuels, whose demand is set to grow significantly by 2040 under policies to scale up biofuel consumption (Sandford & Malins, 2024).

For cellulosic crops and residues, it's a different story. Scenarios 1 & 2 require 135 Mt/year of this material in 2040, and Scenario 3 just over 200 Mt/year. All these values fall within estimates of what could be sustainably produced[32]. The challenge for cellulosic material is (for now at least) not so much a fundamental lack of resources as the need to create viable feedstock collection and cultivation systems, establish reliable supply chains, develop the required fuel conversion technologies, and finance and build advanced biofuel facilities; and to ensure that any new cellulosic crop production systems are sustainable. Previous attempts to commercialise cellulosic biofuel production have struggled, and delivering such volumes would require well-designed and strong policy incentives.

32 See e.g. Phillips et al. (2024) for a review of estimated EU availability, and the 'Billion Ton Study' for a USA assessment (U.S. Department of Energy, 2023).

5. Conclusion

Having lagged behind the aviation industry and national governments on adopting legally enforceable climate commitments, the UN IMO is now in the process of establishing a system of greenhouse gas obligations for its member states. This represents a significant leadership opportunity in a key global sector, and learning from the past experience of other sectors would help the IMO to introduce critical sustainability safeguards from the outset.

In this report we have highlighted that creating incentives for the use of biofuel feedstocks associated with the highest ILUC emissions – palm oil and soybean oil – could drive land use change including deforestation and peat loss. It is likely that a nominally technology-neutral greenhouse gas standard that follows a conventional regulatory lifecycle emissions methodology would incentivise the use of these feedstocks, raising rather than reducing global emissions while stimulating habitat destruction in biodiversity-rich ecosystems. The IMO could reduce these risks by making these feedstocks ineligible to contribute to its targets.

More generally, even biofuels from other virgin vegetable oils such as rapeseed oil are believed to be associated with significant ILUC emissions, and using food commodities for biofuel production puts pressure on food markets. Limiting demand for these feedstocks would improve the greenhouse gas performance of the IMO's decarbonisation policy while reducing the risk of negative social impacts. Replacing rapeseed and other vegetable oil with available residual oils, and replacing whole maize as a biomethane feedstock with manure and cellulosic material, would free up agricultural land and avoid food security impacts.

However, when it comes to the use of residual oils for maritime biofuels, there is an acute issue of supply. Any attempt to position the shipping industry as a major global consumer of these resources would intensify competition with other transport segments and other economic sectors. While elevated alternative fuel prices act as an important investment driver for nascent sustainable fuel production technologies, this is not so for lipid-based biodiesel which is already well established, with limited potential to scale up. Inflated prices for this fuel would do nothing to hasten transport decarbonisation goals, and may even work against them by incentivising mislabelling fraud.

Even allowing for largescale consumption of residual oils by the shipping industry, there remains a significant gap between the amount of alternative fuel required to meet decarbonisation goals and what is likely to be available. It is clear that relying on existing approaches comes up against fundamental feasibility constraints. One way out of this conundrum would be complementary measures to reduce fuel demand, including through reduction in shipping volumes (a fall in global fossil fuel demand would naturally achieve some decrease) and through greater efforts to improve the energy efficiency of existing and future shipping fleets. In light of feedstock constraints, it may be difficult to deliver on the IMO's targets without serious and sustained initiatives in this direction.

Another option is to endeavour to move beyond lipid-based diesel, and invest actively and heavily in commercialising more scalable, low greenhouse gas intensity alternative fuels. At present, this category excludes bio-LNG, as methane leaks throughout the supply chain and from engines can eliminate any net climate benefit. A robust system of monitoring and suppression of leaks throughout the global supply chain would be the minimum assurance needed in order to make bio-LNG a credible decarbonisation option, and it should be established whether such a system is practically and regulatorily viable before further sums are dedicated to incentivising the building of LNG ships and infrastructure.

Cellulosic liquid biofuels (for instance biomethanol or drop-in hydrocarbons made through biomass gasification) offer more promise as a genuine low-carbon option, provided sustainable practices for feedstock collection and production are implemented. In addition, there is the familiar challenge that the technology for cellulosic biofuel production has not yet been demonstrated at commercial scale; all past efforts to do so have struggled or failed.

The other novel alternative fuel option is electrofuels based on additional renewable electricity. Here, the climate impact of hydrogen leaks and the high expected cost (at least in the near future) will be challenges to contend with. Nevertheless, use of electrofuels can avoid many of the environmental impacts associated with biofuels, and this option has been identified as the most scalable solution in the long term. There is therefore a role for governments to facilitate investment in the development and production of this more sustainable energy solution for the transport sector.

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Annex A Glossary

A.1. Physical units

Energy	
MJ	Megajoule (10^6 joules)
GJ	Gigajoule (10^9 joules)
TJ	Terajoule (10^{12} joules)
toe	Tonnes of oil equivalent
Mtoe	Million tonnes of oil equivalent
Mass	
t	Metric tonne (10^3 kg)
kt	Kilotonne (10^3 tonnes)
Mt	Megatonne (10^6 tonnes)
Distance	
km	Kilometre
NM	Nautical mile
Area	
ha	Hectare
kha	Kilohectare (10^3 hectares)
Mha	Megahectare (10^6 hectares)
Emissions	
CO_2e	Carbon dioxide equivalent
gCO_2e	Grams of CO_2-equivalent
tCO_2e	Tonnes of CO_2-equivalent
$MtCO_2e$	Million tonnes of CO_2-equivalent

A.2. Organisations

ABS	American Bureau of Shipping
DNV	Det Norske Veritas
ETIP Bioenergy	European Technology and Innovation for Bioenergy
GCMD	Global Centre for Maritime Decarbonisation
ICAO	UN International Civil Aviation Organisation
IEA	OECD International Energy Agency
IMO	UN International Maritime Organisation
IRENA	International Renewable Energy Agency
JEC	JRC-Eucar-Concawe Collaboration
JRC	EU Joint Research Centre
MEPC	IMO Marine Environment Protection Committee
MPA	Maritime and Port Authority of Singapore
ODI	Overseas Development Institute
SASHA Coalition	Skies and Seas Hydrogen-fuels Accelerator Coalition
UN	United Nations
USDA	U.S. Department of Agriculture

A.3. Other acronyms

BIKE	Biofuels production at low ILUC-risk for European sustainable bioeconomy
CO_2e	Carbon dioxide equivalent
CORSIA	ICAO Carbon Offsetting and Reduction for Sustainable International Aviation
CII	IMO Carbon intensity indicator
EEDI	IMO Energy Efficiency Design Index
EEXI	IMO Energy Efficiency Existing Ship Index
GHG	Greenhouse gas
GLOBIOM	Global Biosphere Management Model
GWP	Global warming potential
HFO	Heavy fuel oil
ILUC	Indirect land use change
LCA	Lifecycle analysis
LNG	Liquefied natural gas
LSMGO	Low-sulphur marine gas oil
MDO	Marine diesel oil
MGO	Marine gas oil
NO_x	Nitrogen oxides
RED	EU Renewable Energy Directive
RFS	USA Renewable Fuel Standard
RNG	Renewable natural gas
SO_x	Sulphur oxides
TEU	Twenty-foot equivalent units
UCO	Used cooking oil
ULSFO	Ultra-low-sulphur fuel oil
VLSFO	Very-low-sulphur fuel oil

Annex B Data sources and assumptions

B.1. Fuel demand modelling

Figure 2 in Section 3 of the main text shows the modelled demand for each type of fuel in 2030, 2035, and 2040. Overall demand was obtained using fuel consumption and ship efficiency trajectories based on data from the IMO's Fourth Greenhouse Gas Study (IMO, 2020). Within this, shares and volumes of specific fuel types were calculated to achieve compliance with the 'striving' targets put forward by the EU and Japan (ISWG-GHG 17/2/2, 2024).

Demand volumes for the novel fuel types methanol and LNG were based on existing ship orderbook data (Clarkson's Research, 2024), and allocated between fossil-, bio-, and electricity-based production pathways. The emissions factor of zero nor near-zero emission electrofuels is assumed to diminish over time with improvements in production efficiency; the average emissions factor of bio-based diesel also diminishes along with an assumed shift from predominantly food to predominantly waste feedstocks in 2040. Emissions per unit of fuel were calculated according to the FuelEU Maritime lifecycle analysis methodology (European Union, 2023c)[33], and for Scenarios 1 & 2 they are fixed in time. In Scenario 3 ('*Food Cap*') these parameters were tuned slightly (for rapeseed and residual oils) to maintain consistency with the overall fuel volumes and emissions intensity targets.

Annex B.3 presents further information about biofuel greenhouse gas intensities. Note that in the characterisation of the greenhouse gas emissions from a revised fuel slate, we have included some additional emissions terms (notably ILUC for food-oil bio-based diesel and liquefaction and WtT leakage emissions for biomethane) that we assume are excluded from the lifecycle analysis under an IMO regulation. There is therefore a difference between the emission factors used to calculate the required biofuel volumes to satisfy the proposed IMO targets on the one hand, and the values used in the analysis presented in Figure 4 of Section 4.1 on the other. More detail is provided in Annex B.3.

B.2. Biofuel land footprint

The land footprint of crop-based biofuels is the product of two factors: the agricultural yield of the crop (in units of t/ha/year), and the biofuel energy yield of biofuel per unit of feedstock (in units of MJ/t or Mtoe/Mt). The first factor can fluctuate year-on-year, but we take an average considered appropriate to the geography where the crop is presumed to be grown; the second factor depends on the biofuel-feedstock combination under consideration. Indicative cropland footprints are given in Table 10 below.

In this section we describe the assumptions and data sources used to calculate the land footprint for crop-based biofuels. In general, we have used a single value for agricultural yield

33 The IMO is yet to finalise its own methodology on fuel emissions intensity, but the draft methodology appears to echo FuelEU Maritime in many respects (IMO, 2024b).

for each crop in the period 2030-40, though we note that in general historical data tends to show a gradual linear improvement in yield over time.

Residue-type feedstocks are not assumed to be associated with any indirect land demand in this study, but it should be re-iterated that their use in the biofuel industry may stimulate substitution of resources in other sectors, potentially leading to indirect land use change emissions or other indirect emissions.

B.2.1. Bio-based diesel

Agricultural yields for palm oil are averaged over the period 2020-23 from (U.S. Department of Agriculture, 2024a). We take Indonesia as our reference country. For soybean oil and rapeseed oil, we multiply the yields of soybeans in Brazil and rapeseed in the EU (FAOstat, 2024) by an assumed oil yield during seed crushing. Cellulosic crops encompass a potentially wide range of species (e.g. miscanthus and switchgrass), growing conditions and production systems; here we assume a reference value of 15 t/ha/year (Elbersen et al., 2022; Panoutsou et al., 2022; Phillips et al., 2024). The same biomass yield value is applied to cellulosic crops used for biomethane production (and hence for bio-LNG and most biomethanol). In practice, there is a trade-off between yield and land quality – higher yields could be achieved by using better quality agricultural land, lower yields would result from utilising the lowest value land with the least competition with food supply.

Fuel conversion yields are drawn from the series of 'Biofuels Annual' reports from the U.S. Department of Agriculture's Global Agricultural Information Network. For cellulosic crops we follow O'Malley et al. (2021).

B.2.2. Bio-LNG

Crop-based biomethane feedstocks are whole maize and cellulosic crops. The biomethane yield of whole maize is calculated as the product of the average EU agricultural yield (FAOstat, 2024) and the gross biogas energy factor output by BioGrace II (Netherlands Enterprise Agency, 2021). For cellulosic crops' fuel conversion yield, we note that a wide range of values are reported in the academic literature, depending on pretreatment, digester configuration, and the precise feedstock mix (Frigon & Guiot, 2010; Garcia et al., 2019; Mayer et al., 2014; Murphy et al., 2011; Speda et al., 2017). We adopt a reasonably conservative value of around 9,000 MJ/t.

B.2.3. Biomethanol

Biomethanol made through the reforming pathway inherits the land use assumed for biomethane, with an additional energy efficiency penalty associated with the chemical conversion (Prussi et al., 2020). This penalty increases the cropland area needed to produce a unit of biomethanol when made from whole maize and cellulosic crops. For the gasification pathway based on cellulosic crops, we use the same agricultural yield as for bio-based diesel and biomethane, and again use an energy conversion efficiency from Prussi et al. (2020).

The split between the two biomethanol production pathways, biomethane reforming and biomass gasification, can be expected to change over time. The two pathways both use cellulosic crops and residues as feedstocks, but have different fuel conversion efficiencies: the overall conversion efficiency of cellulosic feedstock to biomethanol and the biofuel produced per hectare of cropland will change commensurately. We assume that reforming will initially be the preferred pathway, owing to the ready existence of biomethane production capacity, natural gas transportation, and reformer-based methanol facilities and expertise. Over time, we expect that gasification technology will mature and take on an increasing share of the fuel production mix. We also expect the balance between cellulosic residues and cellulosic crops fed into gasifiers to shift over time, initially heavily favouring the former. Both of these changes will exert a small influence the overall land footprint of biomethanol.

B.2.4. Allocation factors

As discussed in the main text, not all land use for biofuel crops should be attributed to the biofuels, as many feedstocks are associated with co-products that also have considerable market value. We use 'allocation factors' to determine the share of a given crop's energy that makes it into biofuels versus the co-products; these are calculated from values in BioGrace I & II (Institut für Energie- und Umweltforschung, 2015; Netherlands Enterprise Agency, 2021). For instance, only 27% of land area used for soybeans is attributed to soybean-oil-based biofuel.

Table 10 Indicative cropland area required for producing a unit of biofuel in a year, showing gross and net area

Fuel	Feedstock	Cropland Footprint (ha/TJ)		Cropland Footprint (Mha/Mtoe)	
		Gross	Net	Gross	Net
Bio-based diesel	Palm oil	8.08	7.70	0.34	0.32
	Soybean oil	48.52	13.32	2.03	0.56
	Rapeseed oil	19.87	11.99	0.83	0.50
	UCO	--	--	--	--
	Animal fat	--	--	--	--
	Other	--	--	--	--
	Cellulosic residue	--	--	--	--
	Cellulosic crop	7.82	7.82	0.33	0.33
Bio-LNG	Manure	--	--	--	--
	Whole maize	13.33	13.33	0.56	0.56
	Cellulosic residue	--	--	--	--
	Cellulosic crop	7.30	7.30	0.31	0.31
Biomethanol	Manure	--	--	--	--
	Whole maize	19.51	19.51	0.82	0.82
	Cellulosic residue	--	--	--	--
	Cellulosic crop	13.98	13.98	0.59	0.59

B.3. Greenhouse gas emissions intensity

Recalling the distinctions drawn at the end of Annex B.1, the biofuel emissions intensities presented here are the ones used to estimate the lifecycle greenhouse gas emissions from biofuel use presented in Section 4.1 of the results. These have been chosen to follow as closely as possible the emission factors used for calculating regulatory compliance, but differ in a couple of key aspects.

As described in Section 1.2, the lifecycle greenhouse gas intensity for each fuel is comprised of a direct contribution and ILUC. First we consider the direct emissions from each biofuel type, and then provide some comments on the adopted ILUC factors.

B.3.1. Bio-based diesel

For lipid-based fuels, the direct lifecycle emissions follow the FuelEU Maritime methodology, which relies on RED II/III for the WtT component (European Union, 2018). As mentioned in Annex B.1, these emission intensities were used to derive the fuel demand volumes which were used as an input to the feedstock modelling. It is possible that average performance would improve over time as agricultural practices and biorefining technologies develop, and as the energy mix becomes increasingly renewable. For this analysis, however, we follow T&E modelling and assume that lipid-based biofuel emissions are fixed.

For cellulosic residues, we again follow RED II/III, and the emissions intensity of cellulosic crops follows that for cellulosic residues. except for the addition of some agricultural emissions (including fuel and fertiliser use[34]) and an assumed bonus from the superior cleanliness and homogeneity of the feedstock stream.

B.3.2. Bio-LNG

Emissions factors for biomethane from manure, whole maize, and cellulosic residues all follow RED II typical values. Again, it is possible that production processes will improve over time (e.g. a move from venting off-gases from digestate storage to flaring as standard practice); to be conservative, we adopt fixed factors based on closed digestate storage. In the case of manure-based methane, the RED II defaults assign a large negative emissions term to account for 'avoided methane' (between 112 and 124 gCO_2e/MJ). We exclude this term from our baseline emissions factors, and discuss avoided methane separately (Section 4.1). Cellulosic crops' emissions again follow those of cellulosic residues with the modifications noted above.

Biomethane is liquefied to bio-LNG before bunkering on ships. This is an energy-intensive process, and the LNG supply chain also incurs extra leaks that are not reflected in the RED II lifecycle analysis. Howarth (2024) estimated liquefaction emissions for LNG produced in the USA to be 9.8 gCO_2e/MJ[35]. Howarth (2024) also estimated up- and mid-stream leakage to be 35.4 gCO_2/MJ, while Bakkaloglu et al. (2022) puts the leakage number at 45.7 gCO_2e/MJ[36]. We use the average of these two.

34 Following the methodology and typical values in Annex VI of RED II/III.

35 Our values differ from those quoted in Howarth (2024) because we are using GWP-100 rather than GWP-20, and we also use the global warming potential values for biomethane rather than fossil methane (Intergovernmental Panel on Climate Change, 2023).

36 Our value differs from the one quoted in Bakkaloglu et al. (2022) because we use fuels' lower

B.3.3. Biomethanol

Biomethanol made through the reforming pathway again inherits the characteristics assumed for biomethane, discounted by an energy efficiency penalty (Prussi et al., 2020). There is no need to add the bio-LNG liquefaction and leakage terms; but we do add a (smaller) emissions contribution from leaks in the biomethane supply chain since the RED II lifecycle emissions factors do not include leaks during storage and transport other than emissions from digestate storage.

When biomethanol is made from cellulosic feedstocks, its overall emissions intensity must reflect both the reforming and the gasification pathways. We assume that the emissions savings from gasified methanol will be roughly the same as for bio-based diesel made from cellulosic feedstocks via Fischer-Tropsch synthesis.

B.3.4. ILUC factors

Section 1.2.2 of the main text introduced the ILUC factors used in this report. We identify cellulosic crops with perennial grasses in Valin et al. (2015), and cellulosic residues with straw. Other feedstocks can be straightforwardly mapped.

However, Valin et al. (2015) did not consider every fuel-feedstock combination, and so we adapt some values for use in this report. Specifically, ILUC factors for bio-LNG and biomethanol must be estimated. For instance, Valin et al. (2015) estimated that using cereal straw for cellulosic ethanol incurred ILUC emissions of 21 gCO_2e/MJ of ethanol. Producing 1 MJ of ethanol would require about 0.15 kg of straw; producing 1 MJ of biomethane would require only 0.12 kg, and so for straw-based biomethane it is appropriate to adjust the ILUC factor down by the ratio. We apply a similar logic to biomethane made from cellulosic crops, and to biomethanol made from whole maize, cellulosic residues, and cellulosic crops. The value adjustments for methanol use the same biomethane reforming and biomass gasification conversion efficiencies mentioned in Annex B.2.3.

B.4. Feedstock mix

B.4.1. Feedstocks in 2040

Figure 3 in the main text showed the evolving feedstock mix for bio-based diesel only. Figure 6 and Figure 7 shows a snapshot of the feedstocks used for all three types of biofuels in 2030 and 2040 respectively.

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heating value.

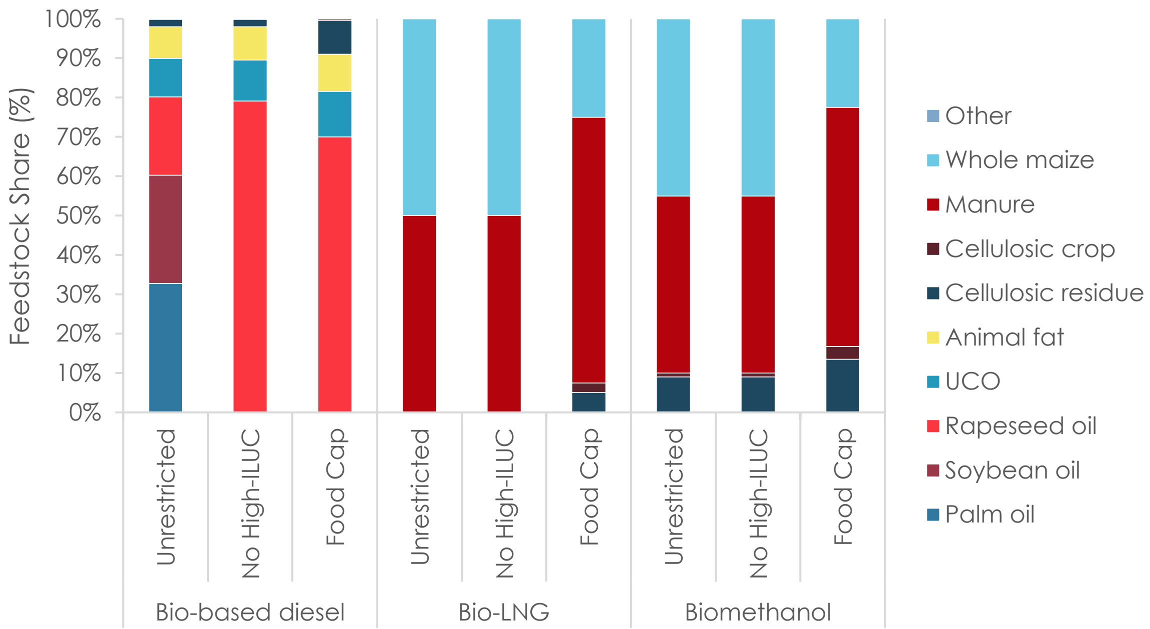

Figure 6 Biofuel feedstock mix in 2030 for the three scenarios

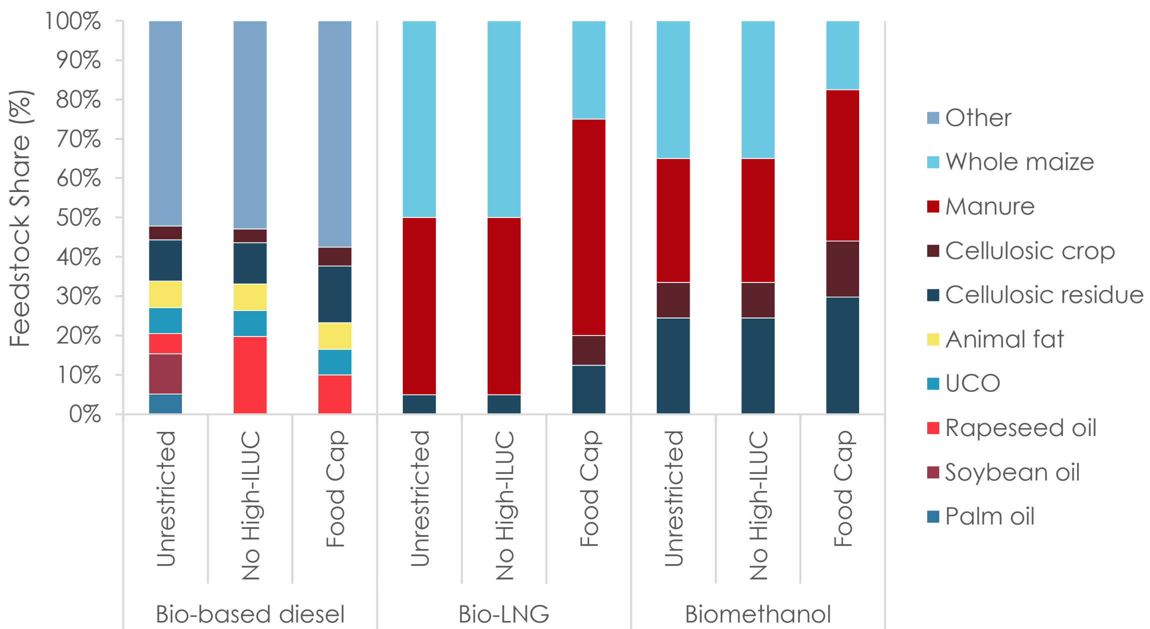

Figure 7 Biofuel feedstock mix in 2040 for the three scenarios

B.4.2. Bio-based diesel feedstock mix

To allocate the shares of vegetable oils in the '*Unrestricted*' scenario, we use the ratios implied by global biofuel consumption in 2023 for 2030[37]. By 2040, this transitions in 2040 to 25% of vegetable feedstock being palm oil, 50% soybean oil, and 25% rapeseed oil, based on our assessment of which oil markets will be most effectively able to meet growing biofuel feedstock demand.

At present, the split between UCO and animal fat biofuel produced in the EU (the world's biggest producer) strongly favours UCO (Flach et al., 2023). The ratio is similar for the UK (UK Department for Transport, 2024). Owing to the relative availability of the two resources (see Annex B.4.3), in the scenario modelling this re-balances to a more even split. Note that the contribution of 'Other' fuel (Section 3.2.3) is zero in 2030 – in early years of the system it is possible to achieve the targeted greenhouse gas reductions using known resources and fuel types.

Figure 3 in the main text presented bio-based diesel feedstock shares as percentages; Figure 8 translates these into absolute volumes. Note that this graph shows bio-based diesel fuel demand split by feedstock, and does not show feedstock demand (the latter, if expressed in energy units, would be higher due to fuel conversion losses).

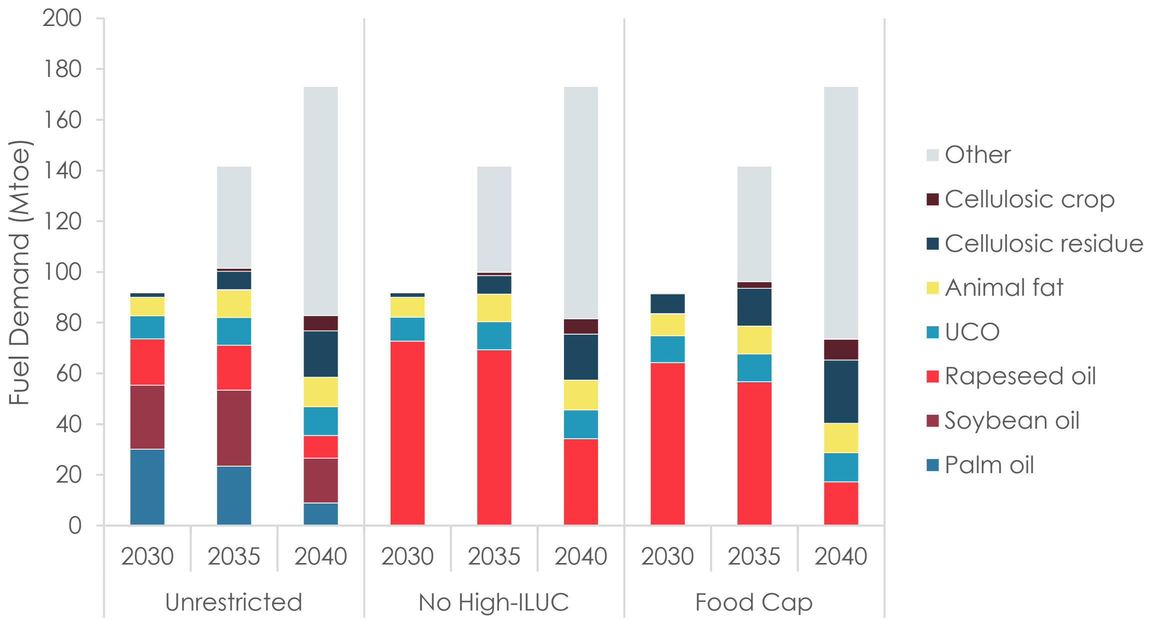

Figure 8 Bio-based diesel fuel demand by feedstock for the three scenarios

37 Using data from the U.S. Department of Agriculture's Global Agriculture Intelligence Network for the major global biofuel producers (Aradhey, 2015; Danielson, 2023; Das, 2024; Degreenia & Wynne, 2023; Demoss, 2024; Flach et al., 2023; Florence Mojica-Sevilla, 2024; Hayashi, 2024; Joseph, 2024; Prasertsri, 2024; Rahmanulloh, 2023).

B.4.3. Feedstock availability

Our modelling restricts the amount of UCO and animal fat that can be used for maritime bio-based diesel in any given year (Section 0). The actual limits used are intended to be indicative, and should not be considered a prediction of the quantities of material that will be available or used. Model limits are informed by sources quoted in Section 4.4 of the main text. We assume that global UCO supply increases over time in line with world population, and animal fat supply with expected growth in meat consumption (OECD & FAO, 2021).

Whatever the growth rates, a considerable fraction of the potential for both resources will have to be secured by the maritime fuel industry in order to satisfy IMO targets. As discussed in the main text, this means that the maritime sector will have to strenuously compete with the likes of aviation for the resource, implying high costs, the need for enforcement of significant non-compliance penalties, and rigorous monitoring to stamp out fraudulent supply.

For the purposes of the modelling, no other feedstock supply is explicitly limited.

Annex C Alcohol-to-liquid hydrocarbons

The industrial technology exists to chemically convert alcohols into hydrocarbons which are already compatible with existing engines and fuel supply infrastructure. This would avoid the technical issues with ethanol and allow for unlimited blending with conventional fuels. The conversion technology is of particular interest has been more thoroughly explored in the context of alcohol-to-jet fuel (AtJ) – particularly in the USA where the sizeable corn ethanol industry is keen to shore up demand in the face of road electrification. It could equally be used to produce maritime fuels, but at least in the near and medium term, production capacity will take time to scale up and the maritime segment would have to compete with aviation for limited fuel supply.