International Maritime Decarbonisation Transitions

The costs and impacts of different pathways for international shipping to achieve alignment to the 1.5°C temperature goal – Main Report

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Preface

This report has been written by a team of experts from UMAS, UCL and E4tech (now ERM) for the Department for Transport as part of the evidence base for maritime decarbonisation policies. The views expressed are those of the authors, not necessarily of the client.

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List of Abbreviations

AD	Anaerobic Digestion
AER	Annual Efficiency Ratio
AIS	Automatic Identification System
BAU	Business As Usual
BC	Black Carbon
BioLNG	Bio Liquefied Natural Gas
BioLSFO	Bio Low Sulphur Fuel Oil
BioMDO	Bio Marine Diesel Oil
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
capkm	Transport Demand Unit in Capacity Unit (e.g. Tonne, TEU) km
CCS	Carbon Capture and Storage
CH_4	Methane
CII	Carbon Intensity Indicator
CMP	Clean Maritime Plan
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
DAC	Direct Air Capture
DfT	Department for Transport
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EET	Energy Efficient Technology
EEXI	Energy Efficiency eXisting ship Index
EJ	Exajoules
EPC	Engineering, Procurement and Construction
ETC	Energy Transitions Commission
FAME	Fatty Acid Methyl Ester
FT	Fisher-Tropsch
FUSE	Fuel Use Statistics and Emissions
gCO_2	Grams of Carbon Dioxide
GloTraM	Global Transport Model
GHG	Greenhouse Gas
GWP	Global Warming Potential
H_2	Hydrogen
HTL	Hydrothermal Liquefaction
HTL-UPO	Hydrothermal Liquefaction and Upgraded Pyrolysis Oils
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
IEA	International Energy Agency
IMO	International Maritime Organization
IMO4	Fourth IMO GHG Study 2020
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
km	Kilometres
kW	Kilowatt
kWh	Kilowatt Hours

LH_2	Liquefied Hydrogen
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LSFO	Low Sulphur Fuel Oil
MARPOL	International Convention for Prevention of Marine Pollution for Ships
MDO	Marine Diesel Oil
MeOH	Methanol
Mt	Million tonnes
MTD	Methanol To Diesel
NH_3	Ammonia
NO_x	Nitrogen Oxides
N_2O	Nitrous Oxide
OECD	Organisation for Economic Co-operation and Development
OPEX	Operational Expenditure
Pax	Passenger
PEM	Polymer Electrolyte Membrane
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter 2.5 Microns
PTL	Power To Liquids
PTO	Power Take Off
RoPax	Roll-On/Roll-Off Passenger Ferry
RoRo	Roll-On/Roll-Off Ferry
SCR	Selective Catalytic Reduction
SNG	Synthetic Natural Gas
SVO	Straight Vegetable Oil
SZEF	Scalable Zero Emission Fuels
tn	Tonne
tn-capkm	Trillion Capacity Unit (e.g. Tonne, TEU) km
TEU	Twenty-Foot Equivalent Unit
TTW	Tank-To-Wake
UCO	Used Cooking Oil
UNCTAD	United Nations Conference on Trade and Development
UNFCCC	United National Framework Convention on Climate Change
USD	United States Dollar
WTT	Well-To-Tank
WTW	Well-To-Wake

The Glossary is located at the end of this report.

Executive summary

Key conclusions

- In all the core scenarios modelled, international shipping can reach zero or very near zero tank-to-wake (TTW) CO_2 emissions by 2050, on GHG emission reduction pathways aligned to a 1.5°C temperature goal. Overall well-to-wake (WTW) greenhouse gas (GHG) emissions fall at least 90% by 2050 compared to 2018 values, and therefore align with the 1.5°C temperature goal, but are assumed to remain non-zero due to emissions in upstream supply chains and residual use of pilot fuels.
- The dominant contribution to GHG reductions is the substitution of fossil fuels by fuels derived from renewable energy. Further improvements in vessel energy efficiency can reduce emissions, but the impact is limited compared to the overall reductions needed.
- All of the scenarios modelled result in a rapid shift away from fossil fuel use during the 2030s, with the transition starting in the mid to late 2020s.
- For each year of delay in the start of material reductions in absolute emissions, a further USD100bn is added to the total cost of decarbonisation. Delaying the start of shipping decarbonisation, even to 2030, results in a more disruptive and turbulent change in technology and a higher total cost of the transition.
- Costs of shipping peak during the transition, before reducing. In 2050, energy-related costs per unit of transport supply are 85% greater than energy-related costs in 2018. This magnitude of premium is within the range of cost increases experienced across 2021 and 2022 in several sectors of shipping due to supply chain disruption.
- Recently adopted policies risk increases in GHG emissions, particularly to 2030, as they only focus on tank-to-wake (TTW) CO_2 emissions. This incentivises solutions such as Liquefied Natural Gas (LNG), which has significant upstream and non-CO_2 GHG emissions. There is an urgent need to modify policy to include at least tank-to-wake (TTW) and well-to-wake (WTW) GHG emissions. There is also a clear need to increase stringency to drive the take-up of vessel efficiency measures at rates above those that would have been achieved without the policy.
- Further policy measures, both carbon pricing and command and control policy, can incentivise the transition. The two can complement each other. Revenues from carbon pricing can be deployed early in the transition to help reduce the level of carbon price needed and the size of the economic transfer.
- Early clarification of further policy measures can help unlock investment in scalable zero emission fuels and their associated infrastructure, reducing the potential disruption to the shipping industry.

Introduction

Since the International Maritime Organization (IMO) adopted its *Initial IMO Strategy on reduction of GHG emissions from ships* (Initial Strategy) in 2018[1], it has been clear that international shipping will phase out its use of fossil fuels and is on a pathway to zero GHG emissions. However, the specifics of when and how this will be achieved have yet to be agreed. The policy instruments that need to be adopted to incentivise the transition, as well as the timing of the transition, are guided by the Initial Strategy, but the language leaves room for interpretation.

This report describes a deep investigation into the technology pathways needed for a number of different 1.5°C aligned transitions to zero and near-zero GHG emissions in international shipping, in order to understand their relative costs and potential impacts, and to inform the revision of the IMO strategy and the adoption of further policy measures. The study focused on modelling three core scenarios, shown in Figure 0.1, ranging from scenarios that undertake rapid cuts in GHG emissions starting imminently, to scenarios that delay the initiation of absolute GHG reductions until the end of this decade[2].

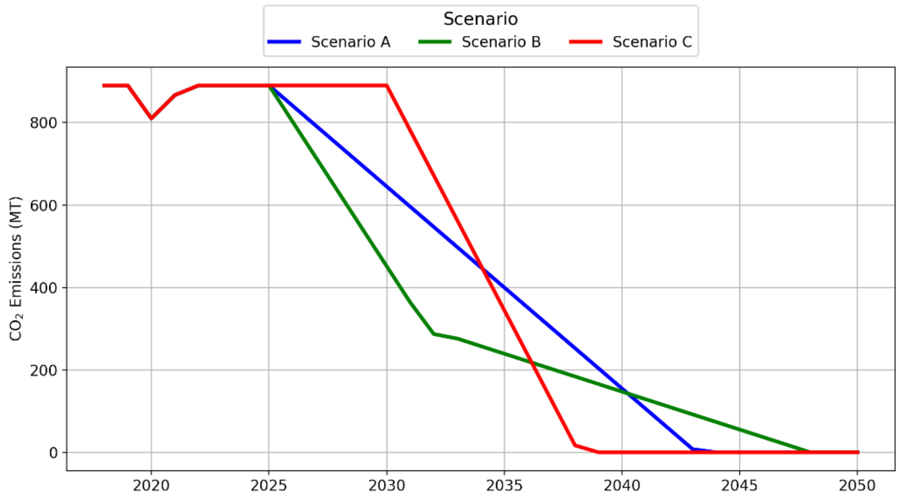

Figure 0.1 – TTW carbon budget[3] derived pathways in the core scenarios

In all core scenarios, the GHG emissions from international shipping are zero or near-zero by 2050 at the latest, and each trajectory aligns the operational (TTW) emissions of international shipping to the 1.5°C target set under the Paris Agreement. The core scenarios are all set against a backdrop of a growth in global population and wealth, and therefore a rising demand for trade and international shipping. A sensitivity scenario tests the consequences of a scenario that has lower demand growth – but still a steady increase in trade and international shipping demand in the period to 2050. In recognition of the

[1] See https://unfccc.int/sites/default/files/resource/250_IMO%20submission_Talanoa%20Dialogue_April%202018.pdf.

[2] The Initial Strategy framing is on GHG emissions. The modelling uses carbon dioxide (CO_2) targets because CO_2 is the dominant GHG emission from international shipping, and because current policy measures are framed on CO_2 emissions. The relationship between the modelled CO_2 targets and the capacity to achieve zero GHG emissions (on both a tank-to-wake (TTW) and well-to-wake basis (WTW)) is discussed within the report.

[3] A carbon budget refers to the cumulative/total operational CO_2 that can be emitted, whilst being consistent with achieving a given temperature goal. These carbon budgets and the study overall consider only international shipping (with international shipping emissions defined on a vessel-basis, as described in Faber, J. et al. (2020). *Fourth IMO Greenhouse Gas Study*) and its emissions. See Section 2.1.1 for clarification and definitions used.

uncertainty regarding many of the input parameters to these core scenarios, the study included sensitivity studies that explored how costs, technology choices and environmental impacts may vary as a function of assumptions such as transport demand growth, costs of fuels and availability of biofuels.

The body of this report uses detailed output data from modelling of the response of international shipping to those carbon budgets to focus on three questions:

- What are the differences in the transition, depending on the pathway taken?
- What are the overall differences between the pathways by which international shipping may achieve alignment to the 1.5°C temperature goal and zero GHG emissions by 2050?
- Can potential future supplies of new fuels and technology meet the demands created by these scenarios?

The results from the modelling show that any of the specified carbon budgets result in the international shipping sector experiencing a rapid shift away from fossil fuel use in the 2030s, with the slower initial phase of that shift starting this decade. This is against a backdrop of increasing use of the fossil fuel liquefied natural gas (LNG) this decade. Further improvements in the energy efficiency of international shipping, including reductions in operating speed, can reduce CO_2 and GHG emissions, but are ultimately only a small contribution to the overall reductions needed. The dominant contribution to long-term GHG reduction is the substitution of fossil fuels by Scalable Zero Emission Fuels (SZEFs) ultimately derived from renewable electricity, with a minor contribution from biofuels.

The key implications of this analysis are presented in this executive summary, focusing on those findings pertinent to the revision of the IMO Initial Strategy, and the findings pertinent to the adoption of mid-term measures (according to the IMO Initial Strategy, these could be finalised and agreed by the IMO between 2023 and 2030).

Findings pertinent to the revision of the strategy

Scenario B, which achieves approximately 10% lower cumulative CO_2 emissions than Scenario A and C, has a lower total cost by 2050 than Scenario C and a marginally higher total cost than Scenario A. When comparing two scenarios that achieve exactly the same cumulative CO_2 emission reduction (Scenario A and C), Scenario A, which starts reducing CO_2 earlier and enables a more gradual transition away from fossil fuel, has the lower total costs. Delaying the start of shipping's decarbonisation, even to 2030, results in a more disruptive and turbulent change in technology and a higher cost transition (Scenario C).

Can shipping achieve a 1.5°C aligned transition to zero GHG emissions by 2050?

In all the core scenarios, the modelling results in zero or very near zero tank-to-wake (TTW) CO_2 emissions by 2050. The GHG reduction pathways achieved over the period to 2050 are aligned to the 1.5°C global temperature goal. Small residual emissions of less than 3% of the 2018 baseline CO_2 emissions may remain by 2050. These residual CO_2 emissions come from fossil pilot fuels which are assumed to be needed for co-combusting with ammonia. These pilot fuel emissions could be minimised if there are sufficient biofuels to meet the pilot fuel demand, or through the use of new technology options that further reduce or remove the need for pilot fuels.

Fuel cell technology would remove the need for pilot fuel, as most existing fuel cells consume hydrogen (which could be stored onboard as hydrogen or ammonia), and fuel cells under development include those that can consume ammonia. Alternatively, spark ignition combustion engines could replace the compression ignition engines used in shipping today, and would be more likely to be able to co-combust hydrogen with ammonia without needing pilot fuels.

Tank-to-wake (TTW) and well-to-wake (WTW) GHG emissions are also non-zero in 2050, reducing at least 95% on 2018 baseline values. This is due to some remaining WTW CO_2 emissions from the combustion of pilot fuels, but additionally to N_2O and CH_4 emissions from combustion of pilot fuels, SZEFs and biofuels, as well as upstream (WTT) GHG emissions (which are assumed to fall to 2050, but remain non-zero).

Will recently adopted policy reduce GHG emissions in the near term?

Two Business-As-Usual (BAU) scenarios are modelled, one including the carbon intensity indicator (CII) and energy efficiency existing ship index (EEXI) policies that enter into force in 2023, and one without these policies included. The scenario including CII and EEXI implements these as adopted. CII targets are set to reduce only to 2026 and then held at these values for the period to 2050, even though these will need to be reviewed and are likely to be revised and extended in order to achieve the IMO's levels of ambition (or revised level of ambition) at least for 2030. The results for the BAU scenario without CII and EEXI included show higher TTW CO_2 and higher TTW and WTW GHG emissions over the period to 2026 than the scenario where those policies are modelled. From 2026 onwards, the emissions of both BAU scenarios converge, and there is negligible difference by 2050.

However, for both tank-to-wake (TTW) and well-to-wake (WTW) GHG emissions, the scenario that includes CII and EEXI policies achieves a smaller benefit than the TTW CO_2 results, particularly over the period to 2030, relative to the BAU scenario that does not include these policies. After 2030, the difference in GHG emissions between the two BAU scenarios reduce and by 2050 there are negligible differences.

The explanation for the differences between CO_2 and GHG emissions trajectories comes from the recently adopted policies being focused on tank-to-wake (TTW) CO_2 emissions only. This incentivises solutions such as LNG, even though LNG-use has significant non-CO_2 GHG emissions (on a tank-to-wake (TTW) and well-to-tank (WTW) basis). Per unit of energy, LNG has slightly lower WTW GHG emissions than LSFO in this modelling's assumptions. However, because the existing IMO policy measures (including EEXI and CII) act on CO_2 emissions, which are materially lower for LNG than LSFO, compliance can be achieved predominantly through the use of LNG as a fuel and there is comparatively weaker incentivisation of energy efficiency. When LNG use is less strongly incentivised by IMO policy (BAU scenario excluding CII and EEXI policies), the remaining regulation and market forces result in greater energy efficiency and one consequence is lower energy use than in the BAU scenario which includes CII and EEXI policies. The relatively smaller reductions in emissions seen in the BAU with CII/EEXI are partly due to the increased use of LNG as a fuel. Besides LNG use, energy efficiency improvements play a role in both BAU scenarios, but with the low level of stringency set in the recently adopted CII and EEXI policy, there is little policy incentive for levels of efficiency technology or operational intervention take-up above those that would be expected by market forces and that therefore occur in the BAU scenario which does not include CII and EEXI policy. The consequence of this finding is a need to modify CII/EEXI to increase stringency to drive efficiency take-up above rates that would have been achieved without the policy.

Different 1.5°C temperature goal aligned pathways have similar cost trends, and small differences in cost profiles

The cumulative energy-related costs[4] relative to a business-as-usual (BAU) scenario without significant CO_2 reductions are explained by the additional capital and operating expenditure for the technologies and fuel needed to achieve CO_2 reductions. These added costs are shown for Scenarios A, B and C in Figure 0.2. Scenario A starts deep CO_2 reductions sooner than Scenario C, and therefore achieves a more gradual transition for the global fleet. The costs for Scenario A are therefore slightly higher than Scenario C early on, but the gradual transition in Scenario A is less disruptive for the industry and avoids the high costs associated with high rates of machinery retrofit that occurs in Scenario C during the 2030s, when a large number of existing ships transition away from the use of fossil fuel. Scenario B has smaller overall cumulative emissions (compared to Scenarios A and C), and requires steep and early rates of CO_2 reduction, and therefore has a higher cost through the late 2020s and 2030s. However, the early start to the transition means Scenario B's total cumulative cost is higher than Scenario A by 2050, but lower than Scenario C.

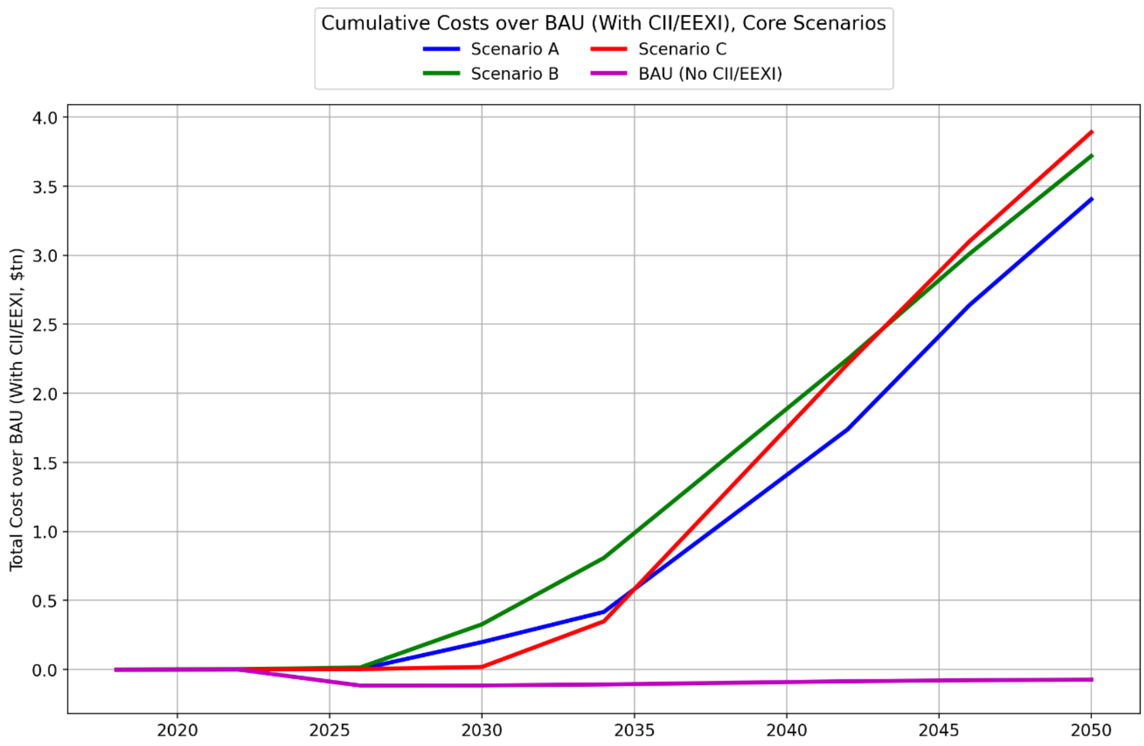

Figure 0.2 – Cumulative energy-related costs (without carbon costs) over BAU (with CII/EEXI) for core scenarios[5]

[4] Energy-related costs refers to the combination of energy/fuel costs, and capital and other operating costs associated with the equipment needed for the storage and conversion of energy/fuel onboard ships, and the costs associated with energy efficiency improvements. See Section 3.6 for clarification and definitions used.
[5] Two BAU scenarios are used, one including recently adopted policy option (with CII/EEXI) and one without these. The two scenarios allow comparison with earlier work produced prior to the adoption of the CII/EEXI policies. For further clarification of the BAU scenarios, see Section 2.1.1.

The costs of shipping peak during the decarbonisation transition before reducing.

International shipping's decarbonisation is expected to take place against a backdrop of growth in demand, and this was controlled for in the study by calculating energy-related costs per unit of transport supply. Figure 0.3 shows the energy-related costs per unit of transport supply[6] in Scenario A.

Decarbonising shipping is expected to increase energy-related costs per unit of transport work for shipping with a peak in annual transition costs around the middle of the transition away from fossil fuels (e.g. in the mid-2030s to early 2040s for these scenarios). The timing of the peak in annual energy-related costs per transport work varies as a function of the shape of the carbon budgets and the profile of technological change this induces. These annual costs are highest from the mid-2030s to early 2040s, because this is when retrofitting-related capital costs are highest, and also because new onboard technology and fuel production are both still expensive and are yet to benefit from cost reductions from full commercialisation. At this peak, Scenario A's per annum energy-related costs per transport work are 215% higher than the baseline (2018) costs. But by 2050, the per annum energy-related costs more than halve to approximately 85% higher than the 2018 costs. This is because energy efficiency improvements in combination with the cost reductions for technology and new fuels combine to result in a lower change relative to the baseline year (2018) transport costs. Of the three scenarios, Scenario C experiences the sharpest annual peak in energy-related costs.

Decisions made about how carbon revenues are used can create variations in the cost profile of the transition. To illustrate this, the energy-related costs per unit of transport supply for Scenario A are shown in Figure 0.3 for two cases: one in which carbon revenues are not fully invested into the sector's decarbonisation (50% of carbon revenues retained for other purposes); and one where the carbon revenues are fully invested back into the sector's decarbonisation. In addition, a third case is presented in Figure 3.16: one in which no carbon revenues are invested back into the sector's decarbonisation (100% of carbon revenues retained for other purposes). The results show that, whether carbon costs are excluded or included, the peak in energy-related costs per unit of transport supply is estimated to occur from the mid-2030s and in to the early 2040s.

[6] Energy-related costs per unit of transport supply relate to the energy-related cost to move 1 tonne of cargo or 1 passenger a distance of 1 km. Freight and passenger results are aggregated to produce a single trend by summing $/tkm (cargo/freight) with $/GTkm (passenger and other non-freight). The results therefore control for the fact that the demand for transport changes over time and provide a quantification for the indicative impacts over time on any given transport cost (the cost of moving a good or passenger on a given route). In addition to changes in costs, there are also changes to revenues which can arise due to the use of lower energy density fuels (use of lower energy density fuel reduces revenue) or changes in operating speeds. These are described in Section 2.5.6 and included in the modelling to ensure these are incorporated in selection of the technology pathway, but not the presentation of results of costs.

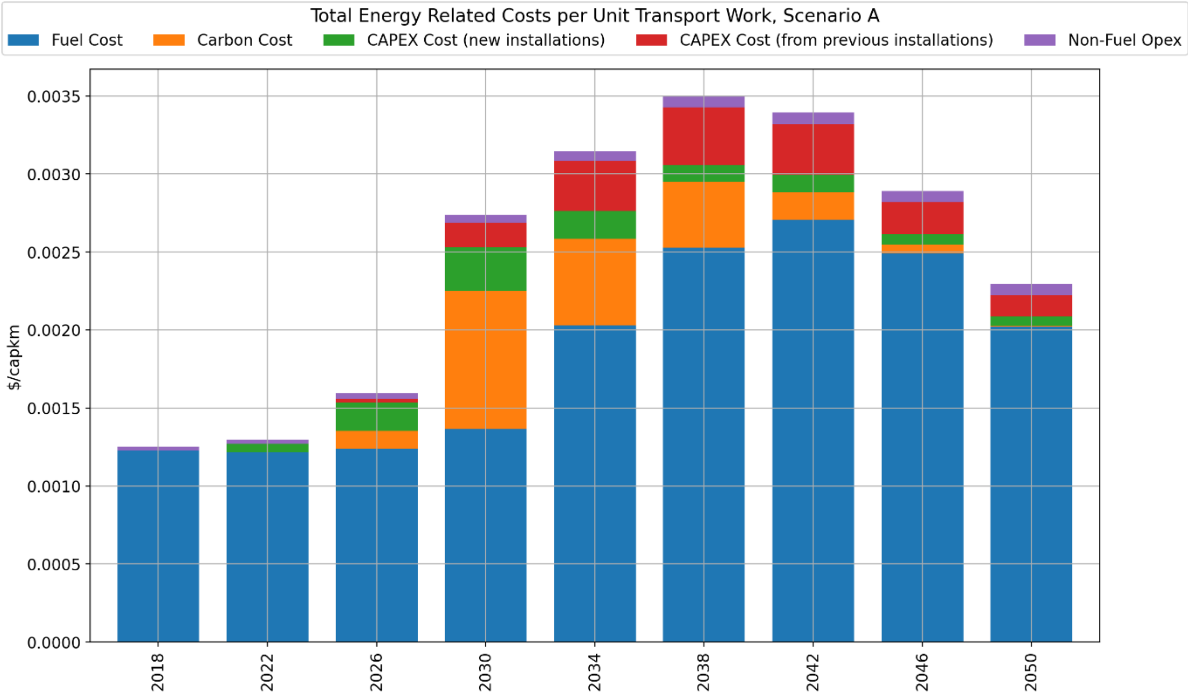

Figure 0.3 (a)

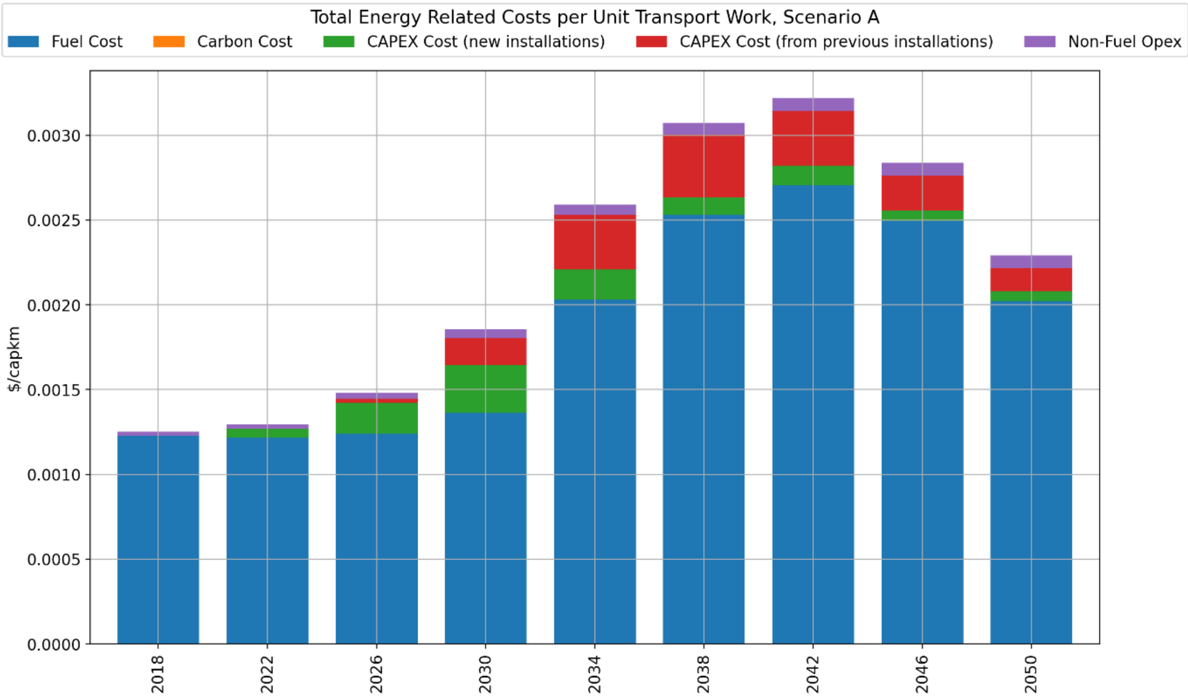

Figure 0.3 (b)

Figure 0.3 – Energy-related costs per unit of transport supply, Scenario A, with (a) 50% and (b) 100% of the carbon costs reinvested[7]

[7] 'CAPEX Cost (new installations)' is the amortised machinery CAPEX costs that have been incurred during the 4-year period represented by the bar of interest. The 'Capex Cost (from previous installations)' represents ongoing repayments on installations that have occurred prior to the 4-year period represented by the current bar.

What implications are there for the fleet?

The option for fleet decarbonisation with the lowest total cost involves the widespread use of low-carbon ammonia. There are other fuel options that could achieve a similar outcome, but do so at higher cost, such as low-carbon methanol and hydrogen. Collectively, these are fuels referred to as scalable zero emission fuels (SZEFs)[8]. The use of any SZEF requires changes in the technology on ships, including both equipment for fuel storage and handling, as well as changes to the machinery for converting the fuel into useful energy (energy for propulsion, heat or electricity). Of the two general types of conversion machinery considered (fuel cells and internal combustion engines), the least cost solution for the large majority of the fleet is the existing internal combustion engines. Use of SZEFs requires only slight modifications to the specifications of machinery in operation today, although larger changes to fuel storage, handling equipment and operating procedures will be required. Drop-in fuels, including biofuels, are also considered, but can be a more costly alternative due to the finite supply and high expected demand (across all sectors of the economy) relative to that finite supply. In all scenarios, including the sensitivity studies, biofuels face varying availability constraints. As a result, biofuels have limited impact on the overriding need for SZEFs.

Energy efficiency improvements, including the use of wind assistance for propulsion, have an important role to play in minimising the demand for SZEF and helping to reduce the cost of shipping's transition to zero emissions. But because ships already have well optimised and efficient systems, reductions in the demand for energy from efficiency measures make only small performance improvements and most of these improvements are enabled in the BAU scenario. Further energy efficiency therefore does not create significant absolute reductions in CO_2 or GHG emissions relative to the BAU scenario. All scenarios considered require absolute reductions in CO_2 and GHG to start by 2030 at the latest, and this can only be achieved if the switch to low-carbon fuels start by this date.

The model estimates ammonia and internal combustion engines (ICE) to be the least cost option for achieving the large majority of shipping's decarbonisation – given conservative but pragmatic estimates about how capital and fuel costs might evolve. There could be technology developments that mean other fuel/technology options become cheaper than ammonia and ICE. If that is the case, the transition costs should be lower than those estimated here.

Can fuel supplies ramp-up to meet these scenario demands?

Under all three core scenarios, demand for low-carbon ammonia grows rapidly from later this decade, and by the 2040s is the major fuel used in the shipping sector. Achieving this level of ammonia supply requires current global ammonia production capacity to quadruple by the 2040s, with year-on-year growth rates close to or exceeding historical record growth rates, as shown in Figure 0.4. This can only happen if action to unlock investment is taken urgently, which relies on rapid agreement of the underpinning policy frameworks. These will primarily be set at the IMO, in particular in the specification of any further policy including mid-term measures, but also in its adoption of lifecycle guidelines that clarify the way tank-to-wake (TTW) and well-to-wake (WTW) GHG emissions are considered. However, they are also set at the national and regional level, for example in EU policy, and through the steps

[8] SZEF refers to the fact that these fuels have zero or close to zero GHG emissions on a lifecycle (well-to-wake) basis, as well as being able to be produced competitively at scales appropriate for shipping's overall demand for energy.

taken by national governments to incentivise the development of SZEF production and supply chains.

Most ammonia production today is ‘high carbon’ (with high GHG emissions). Production that meets existing demands for ammonia needs to be retrofitted or substituted with ‘low-carbon’ production by 2050, even before the demands of shipping are added. This low carbon production could be through ‘green’ production pathways (i.e. using electrolytic hydrogen with renewable energy as the power source), or ‘blue’ production pathways (applying carbon capture and storage (CCS) to fossil-based production pathways). The fleet technology pathways findings indicate that the most significant consideration for new SZEF supply ramp-up is likely to be focused on low-carbon ammonia. However, the amount of investment and growth required in low-carbon hydrogen production is similar regardless of which SZEF (ammonia, methanol or liquid hydrogen) becomes dominant in practice.

In Scenario B, ammonia demand increases substantially beginning in 2025, and this demand profile exceeds the current project pipeline of announced green/blue ammonia production capacity by 2027 (indicated by the green and blue columns in Figure 0.4). Green ammonia capacity announcements currently far exceed those for blue ammonia (the blue columns to 2030 in Figure 0.4 are extremely small). Given the rapid growth in announcements for green/blue hydrogen and ammonia projects, it is reasonable to expect that more projects will be announced in coming years that can increase capacity still further above that estimated in this analysis before 2030, even if some projects are delayed or cancelled. However, because the typical project development timeframe is 3–5 years for new-build ammonia projects, Scenario B will not be feasible unless there is a sharp increase in development activity between 2022-2024, with a focus on projects supplying ammonia for maritime uses (rather than only as a hydrogen vector). Meeting the more gradual Scenario A still requires the ammonia industry to grow at an above historical average rate, with investment in new ammonia projects required within the next few years. If the start of growth in the low-carbon ammonia industry is delayed to 2030, the required 18% year-on-year growth rate for the industry during the 2030s in Scenario C would far exceed the highest sustained historical annual growth rates in ammonia production (~10% year-on-year) and may not be feasible.

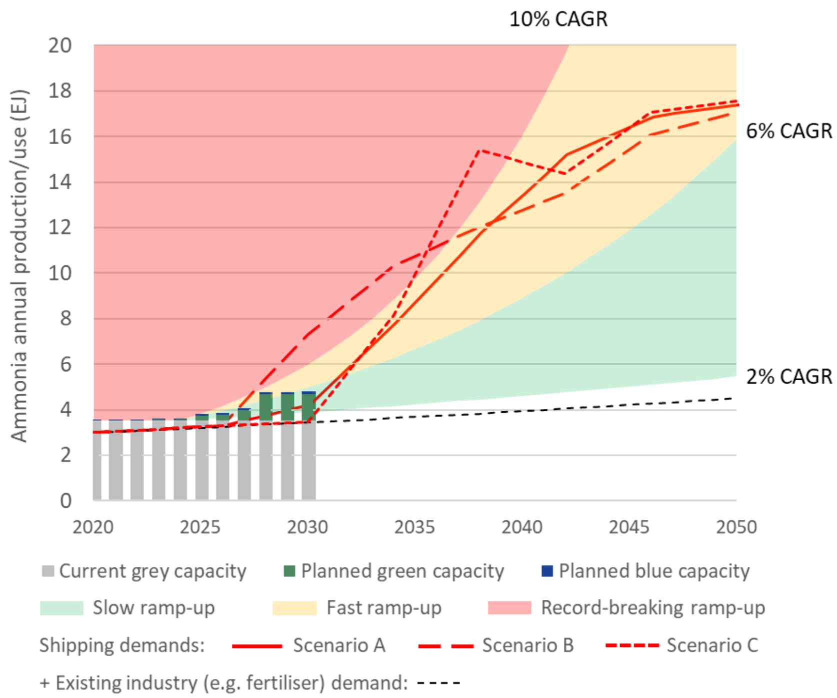

Figure 0.4 – Comparison between current and planned global ammonia capacity (columns), projected industrial and maritime demands (lines) and required growth rates from 2025 (shaded regions)

Low carbon hydrogen is the key feedstock for blue/green ammonia production. Low carbon hydrogen is also the key feedstock for other SZEFs, so the equivalent project pipeline data for hydrogen supply is also relevant to examine. Results in Section 5 show nearly twice as much low carbon hydrogen supply relative to low carbon ammonia supply by 2025 on an energy basis, and more than twice as much by 2030. However, announced projects in renewable synthetic methanol (non-biogenic) are far less significant to 2030. Aggregating across the production of these three SZEFs (hydrogen, ammonia and methanol), the total supply from already announced SZEF projects is 4.1EJ a year in 2030. This supply could be significantly larger by 2030 when further projects are launched, assuming most known projects are successful. While many end users will compete for this total supply of SZEFs, it shows currently announced projects (as of early 2022) just exceeding Scenario B's 2030 total maritime demand for SZEFs, and far exceeding Scenario A and C's 2030 demands. This highlights the importance of future work to understand competing demands for hydrogen, ammonia and methanol across other end-users/sectors, the sensitivities of these demands to volatile global energy and fuel prices, and a need for governments to ensure demands for all end-users, including international shipping, are built into national hydrogen and energy strategies.

As well as the rapid demand growth required of SZEF, the scenarios also consider the role of biofuels. Biofuels refer to any fuel produced via the conversion of biomass. In the modelling, the overall supply of biofuels is constrained in recognition of the finite supply and multiple end-users, but even with these constraints applied, meeting the demands for biofuel would be stretching for several pathways. However, biofuel is not forecast to be a dominant source of energy in any of the scenarios, and excluding the use of biofuels (in a 'zero biofuel' sensitivity scenario) does not materially impact the ability of international shipping to achieve the CO_2 reduction goals of the core scenarios. Some additional biofuel supply beyond the conversative central scenario limits used in the study may also be feasible, to replace the small amount of remaining pilot fuel, which could then ensure shipping's emissions do reach zero by 2050.

Maritime demands for biodiesel fuels in the 2040s will require development of multiple pathways. Biofuels produced from waste oils and fats are likely to be constrained by the limited availability of these feedstocks and competing demands from road and aviation sectors. Commercialisation of less mature 'advanced biofuels' based on new technologies using solid biomass or waste feedstocks will be required, including investment in gasification pathways this decade, and development of alternative routes such as power-to-liquids or upgrading of bio-alcohols before 2040. Sustainable aviation fuel developers should also optimise their projects to make co-products suitable for use in the maritime sector.

Findings pertinent to the design and adoption of further policy measures

Early adoption of stringent mid-term measures is key to reducing the cost of decarbonising shipping. In line with the findings on the cost of the different transition pathways, the sooner a mid-term measure is implemented, the less disruptive the transition. Entry into force of a strong and effective mid-term measure by 2025 is critical to minimising the overall cost of any 1.5°C temperature goal aligned pathway.

Every year's delay to the start of deep decarbonisation this decade adds approximately USD100bn to the total cost of decarbonisation

The technology pathways show that the later absolute reductions in international shipping are incentivised through mid-term measures, the more disruptive and higher the cost of transition. This is clearly evidenced in the comparison between Scenarios A and C, in which a 5-year delay in the onset of deep-decarbonisation from 2025 to 2030, increases the cumulative costs of transition by ~USD0.5tn (i.e. every year of delay this decade adds approximately USD100bn to the total cost of the transition). Thus, early clarification of policy measures can help to reduce the cost of transition and reduce the risk of SZEF availability and production capacity being insufficient for the scale of demand for new fuels. Another solution to build support for SZEF production is to focus on policy that can immediately incentivise a small volume of deep decarbonisation through the early use of SZEF, alongside a fleet retaining BAU fuel technology – in preference to policy that incentivises all ships to decarbonise similarly and incrementally.

The transition of international shipping benefits from carefully designed policies. A combination of measures and the use of carbon revenues may be important.

Incentivisation of the decarbonisation and technology pathways in the core scenarios A, B and C could be achieved through market-based policy measures (that include some form of carbon pricing), command and control policy measures (such as fuel or GHG-intensity standards), or a combination of both types of policy. Whilst the modelling incorporates a carbon price to enable the solutions to follow the prescribed CO_2 trajectory, the analysis remains agnostic on the specifications or combination of policy that could be most appropriate.

Even if the analysis is policy agnostic, some insights pertinent to policy design to incentivise transition are revealed in the results.

- One challenge of carbon pricing policy can be found in the resulting carbon price trajectories, shown in Section 4. From initially low values at the point of policy implementation, carbon price rapidly increases as a function of the Scenario CO_2 trajectory (Scenario A and B carbon price levels exceed USD200/tCO_2 by 2028, whereas Scenario C's carbon price is below USD50/tCO_2 and only exceeds USD200/tCO_2 after 2032). Within the sensitivity scenarios (particularly those associated with the price of fuel), the carbon price and emission reductions are highly variable. The issue is therefore that there is high uncertainty in what carbon price will be needed to incentivise the use of SZEF, and a challenge in calculating that carbon price in advance.
- This also suggests that there needs to be regular review of any policy that relies on price or subsidy (using carbon revenues) in order to ensure that the necessary investment and change is being incentivised.
- If carbon price is the only policy instrument used to incentivise a shift away from fossil fuel use, the modelling suggests that transition may only be completed if the carbon price is set at levels around USD600/tCO_2 (and possibly higher)[9]. For all other assets, the incentive required to enable their contribution to the reduction target is lower and, in many cases, significantly lower that this price indicates. If a carbon price is used as the only mechanism to incentivise the transition, it creates a much larger economic transfer than if it is used in combination with command and control policy. Because of this, the modelled carbon prices should not be read as a proxy for a change in transport cost or the 'cost' to industry. The way that any carbon price influences costs to states or industry stakeholders can only be determined once revenue uses are determined and defined.
- In some circumstances, the model-derived carbon price reduces over time. For example, Scenario B has an initial peak value in 2034, with carbon pricing levels falling until the last time-step in 2050. In case a falling carbon price risks incentivising the transition to be a temporary change (with some switching back to fossil fuels opportunistically), a carbon price can be complemented by command and control policy measures that can more simply and unambiguously lock-in a transition to new technology. This may also help to achieve a similar transition but with a lower carbon price trajectory.
- A common feature of all scenarios is that the transition is characterised by an initially small take-up of SZEF and associated technology (this decade in Scenario A and B, from 2030 in Scenario C). This small volume of SZEF requires a high carbon price to incentivise its use. Whilst there is only a small volume of SZEF with most of the fleet still using conventional fuels, that carbon price can impose high costs on the rest of the fleet and create high carbon revenues as a result. As the fleet's take-up of SZEF increases, even if carbon prices increase, total collected revenues may not. Therefore, careful design of how revenues are used, in particular how some share of revenues support/subsidise the early-stage SZEF use, should enable a lowering of the carbon price needed to achieve the transition.

[9] This is due to the modelling's calculation of a carbon price at the margin – e.g. representing the price signal needed to incentivise the most expensive intervention that is required to achieve the reduction target at that specific point in time.

Using policy that incentivises change through a well-to-wake GHG emission framing is key to avoiding unintended increases in GHG emissions

A key assumption behind the modelling is that international shipping will be incentivised to use energy/fuel that has low and reducing WTT GHG emissions, or that countries will adopt policies that will decarbonise the upstream emissions of fuel production. If the currently dominant ‘high carbon’ production of hydrogen and ammonia persists, this would negate any GHG reductions achieved from onboard use, and could even increase lifecycle (WTW) GHG emissions of international shipping relative to the level of emissions in BAU scenarios. This risk that well-to-wake (WTW) emissions will increase if shipping adopts SZEF which are produced through high GHG emissions pathways can be managed if existing and further policy is framed on incentivising reduction of lifecycle (WTW) GHG emissions, and not its current framing on operational (TTW) CO_2 emissions.

Early clarification of policy measures can help unlock investment in SZEF and reduces the potential for disruption to the industry

Because all scenarios require some amount of retrofitting of existing ships, clarity on future policy is important for helping the sector to anticipate the need for retrofitting to a new fuel technology, and to build ships that have the least cost for retrofitting. Earliest possible notification of the timing and future stringency of policy is therefore as important in helping to minimise the cost of shipping’s transition as the implementation of progressive stringency in the policy.

Early clarification of policy measures that would clearly incentivise SZEF use is also critical to sending a signal that can enable investment in fuel production and infrastructure, and reducing the pressure on the sector that would be created if rapid growth in capacity of SZEF production only starts at the end of this decade.

Recently adopted and further policy measures risk incentivising the fossil fuel LNG. As well as increasing GHG emissions this would also increase the overall cost of shipping’s transition.

The study shows that the recent adoption of policy measures[10] at the IMO has little additional effect (over BAU) on the energy efficiency and CO_2 emissions of the fleet. However, this policy, in combination with further policy measures (carbon pricing or command and control measures) during the 2020s, is the driver of a rapid growth in adoption of the fossil fuel LNG this decade. In both the BAU scenario inclusive of recent policy (CII and EEXI), and the core decarbonisation scenarios, this rapid growth in LNG lasts to 2030, after which the demand for LNG as a marine fuel contracts. In the BAU scenario which did not include recent policy (CII and EEXI) the growth in demand for LNG is much lower to 2030, and energy efficiency improvement is similar. The contraction of LNG as a marine fuel is rapid, in order to enable the necessary substitution of SZEF that can achieve the CO_2 reduction objective. That contraction therefore results in large retrofitting of LNG-fuelled ships, and/or premature scrapping of LNG-fuelled assets. The rate of retrofit or scrapping of LNG-fuelled ships varies depending on the scenarios, but in all cases adds significant capital cost to the transition.

[10] Energy Efficiency eXisting ship Index (EEXI) and Carbon Intensity Indicator (CII) policies adopted by IMO in 2021.

1 Introduction

1.1 Aims and objectives

This report is the primary output of a study commissioned by the United Kingdom Department for Transport (DfT) as part of work to build evidence and understanding on the technology pathway and viability for international shipping to reach a 1.5°C temperature goal aligned transition to zero greenhouse gas (GHG) emissions on a 'lifecycle' basis by 2050[11].

The report is aimed at policymakers considering further regulation of international shipping, as well as stakeholders throughout the value chain of international shipping (including ship owners and financiers, ship operators and charterers, crewing agencies, fuel producers, and operators of ports and harbours).

The content is relevant to a broad readership because the decarbonisation of international shipping will change the sector fundamentally.

In particular, the report shows that changes will occur not just to the technology on board ships, but also to the fuels used by shipping, leading to direct changes to the energy system and energy supply chains, and the port and land-side infrastructure associated with production, distribution, storage and bunkering of energy for shipping.

International efforts to reach net zero GHG emissions often aim for 2050[12], but focusing on the target year risks overlooking the cumulative emissions between now and that target. This is because any increase in temperatures above pre-industrial levels is a function of the total GHG emissions in the atmosphere (i.e. the sum of GHG emissions to date and expected future emissions). In other words, the sooner deep reductions in GHG emissions are achieved the easier it will be to reach the 1.5°C temperature goal that is associated with the global net zero emissions target. For the international shipping sector, decisions taken now about the optimum pathway to GHG emission reductions – and therefore the cumulative GHG emissions resulting from that pathway – are critical decisions for reducing the contribution made by international shipping to dangerous climate change.

The Intergovernmental Panel on Climate Change (IPCC) defines sources and sinks of GHG emissions[13]. Simply put, sinks reduce GHGs in the atmosphere and sources increase GHG emissions. National emissions inventories collate data on both sources and sinks of GHG emissions and, in order to limit emissions in line with international targets, national inventories need to reach a point of 'net zero GHG emissions'. However, in GHG inventory terms which account only for operational terms from ships, international shipping is only a *source* of GHG emissions and not a sink, so for this sector the term 'net' can be misleading. Instead, the target for the international shipping sector is to neutralise its contribution to dangerous climate change by achieving 'zero GHG emissions on a lifecycle (WTW) basis'.

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[11] 'Lifecycle' refers to the assessment of GHG emissions from fuel production through to the use onboard ship, known as well-to-wake (WTW) emissions, which is a combination of 'upstream' emissions from primary production to carriage of the fuel in a ship's tank (i.e. well-to-tank or WTT) and 'downstream' emissions from the ship's fuel tank to the exhaust (i.e. tank-to-wake or TTW).
[12] See United Nations Framework Convention on Climate Change (UNFCCC) 'Race to Zero' https://unfccc.int/climate-action/race-to-zero-campaign.
[13] IPCC (1992) *Climate Change: The 1990 and 1992 IPCC Assessments*. Working Group 1. https://www.ipcc.ch/report/climate-change-the-ipcc-1990-and-1992-assessments/.

Thus, in order to achieve GHG reductions in line with these aims, all changes need to take place over a short period of time and this directly affects the commercial viability of existing assets as well as those being specified and built today.

This study therefore looked at the trade-offs between different pathways for GHG reductions that might be adopted by the International Maritime Organization (IMO) and incentivised by its subsequent policies. This involved addressing the following key questions:

- What are the differences in the transition, depending on the pathway taken?
- What are the overall differences between the pathways by which international shipping may achieve alignment to the 1.5°C temperature goal and zero GHG emissions by 2050?
- Can potential future supplies of new fuels and technology meet the demands created by these scenarios?

1.2 Modelling shipping's decarbonisation pathways

The study used a robust modelling technique that takes into account a particular series of questions that are relevant to decisions to be debated and taken at the IMO over the next 2–3 years.

The analysis represents the state-of-the-art in combining all the different considerations about the decarbonisation of international shipping – its least cost pathway, and the possible limits to shipping's decarbonisation that may arise if new fuels do not become available in time for their supply to develop in line with expected demand from the shipping sector.

This study builds on the underpinning evidence for the UK DfT's 2019 Clean Maritime Plan (CMP)[14], and shares many modelling assumptions and output structures. However, it also includes a number of key updates following lessons learned during further analysis of the previous report's results, as well as developments in policy and technology that have occurred since that earlier work.

The modelling performed for this study was carried out using the UMAS Global Transport Model (GloTraM)[15]. GloTraM is a state-of-the-art tool that has been used and developed for over a decade. It is designed to simulate the investment and operating choices made by owners and operators in international shipping, and aggregates those choices into forecasts of fleet-level technology change (including costs, emissions of GHGs and air pollutants, and demand for different fuels). To represent these changes with a high level of accuracy, the global fleet of international shipping is broken down into 53 ship type and size categories, in line with the categorisation used in the *Fourth IMO GHG Study* in 2020 (IMO4)[16].

The model steps forward in time from a baseline year in 2018 to 2050, and represents profit-maximising decision-making for each cohort and each ship type and size category.

[14] Frontier Economics, UMAS, E4tech and CE Delft (2019). *Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution: Scenario Analysis*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/816018/scenario-analysis-take-up-of-emissions-reduction-options-impacts-on-emissions-costs.pdf

[15] Frontier Economics, UMAS, E4tech and CE Delft (2019). *Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution: Scenario Analysis - Technical Annex. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/816019/scenario-analysis-take-up-of-emissions-reduction-options-impacts-on-emissions-costs-technical-annexes.pdf*

[16] Faber, J. et al. (2020). *Fourth IMO Greenhouse Gas Study*.

Decisions take into account a combination of capital costs, operational costs (including fuel price), and regulatory compliance factors. This ensures that the technology selections are appropriate for the age and type of ship. Disaggregated results are then summated so that the overall trends at the macro level for international shipping can be presented to test the total cost and effectiveness and implications for different scenarios. Further details on the method can be found in the Technical Annex and spreadsheets that accompany this report. See the Appendix for a full list of the scenarios modelled using GloTraM.

1.3 Context and structure of this report

The IMO adopted its *Initial IMO Strategy on reduction of GHG emissions from ships* (hereinafter, Initial Strategy) in 2018[17]. Since then it has been clear that international shipping will phase out its GHG emissions, but the details of how this will be achieved have yet to be agreed. The policy instruments that need to be adopted to incentivise the transition, as well as the timing of the transition, are described in the Initial Strategy, but the language leaves room for interpretation.

In the same year that the Initial Strategy was adopted, the IPCC published a special report[18], *Global Warming of 1.5°C*, which reviews the impacts that are likely to arise if temperatures exceed 1.5 degrees above pre-industrial levels. The predicted severity of these impacts – including the existential and severe economic and biodiversity threats to many – have resulted in a growing number of UNFCCC Member States adopting commitments to reach net zero GHG emissions by 2050 at the latest.

In 2021 Member States of the IMO put forward a resolution at its 77th meeting of the Marine Environment Protection Committee (MEPC 77) that would commit the IMO to reach zero GHG emissions no later than 2050[19]. However, although there was broad support for the concept, the resolution was not adopted.

In addition to the strengthening of political ambition at both the UNFCCC and the IMO to address dangerous climate change, significant steps are underway to progress the technological solutions that the shipping sector would need in order to phase out its use of fossil fuels. For example, hydrogen and hydrogen-derived fuel production using renewable energy is rapidly increasing[20]. This is already reducing uncertainty in the costs of new fuels and machinery, as well as providing insights into the viability of scaling up production in order to meet the forecasts of demand.

[17] Available at https://unfccc.int/sites/default/files/resource/250_IMO%20submission_Talanoa%20Dialogue_April%202018.pdf.
[18] IPCC (2018) *Global Warming of 1.5°C*. Available at https://www.ipcc.ch/sr15/.
[19] Draft Resolution on Zero Emission Shipping by 2050 (2021) available at https://imoarcticsummit.org/wp-content/uploads/2021/11/MEPC-77-7-3-Resolution-on-zero-emissions-no-later-than-2050-Kiribati-Marshall-Island....pdf.
[20] IEA (2021), Global Hydrogen Review 2021, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2021

1.3.1 Chapter summary

The remainder of this report is structured in the following way:

- Chapter 2 provides an overview of the method, and details specific modifications to the GloTraM method made for this study
- Chapter 3 presents the key findings of the fleet modelling results, and describes aspects of the decarbonisation of shipping that are common to all three core decarbonisation scenarios. It also integrates findings from the sensitivity scenarios in order to derive the consequence of uncertainty in input assumptions for these key findings
- Chapter 4 provides detailed results of the fleet modelling for the two business-as-usual (BAU) scenarios and the three core decarbonisation scenarios. The air emissions, fuel mix, technology change and costs are presented in full to enable direct comparison
- Chapter 5 compares the forecast of demand for new fuel estimated by GloTraM with the historical and forecast supply of new fuels, in order to explore the viability of the modelled decarbonisation scenarios
- Finally, Chapter 6 compares the forecast demand for shipbuilding, including retrofitting, with the capacity to build and modify ships. This assesses whether there may be shipbuilding capacity constraints related to the modelled decarbonisation scenarios.

The study is underpinned by extensive work developing input data and assumptions for use in the modelling and derivation of fuel availability/supply forecasts. The accompanying Technical Annex and spreadsheets provide the detailed derivation, justification and description of the key assumptions used. It also describes the quality assurance and quality control undertaken to validate the results, including comparison with other similar studies in the literature.

It is important to note that throughout the rest of this report, and in the Technical Annex, GHG emissions when expressed as a total across all GHG emissions species are quantified in tonnes of carbon dioxide equivalent (tCO_2e). The terms GHG emissions and CO_2e emissions are used interchangeably.

1.4 Key findings about the nature of shipping's transition

Chapters 3, 4 and 5 all contain analysis results and findings. Chapter 3 focuses on the key findings and sub-findings about the nature of shipping's transition, listed below. Chapter 4 and 5 contain further detailed findings that are summarised in the executive summary, alongside the findings of Chapter 3, which are as follows:

1. Without further intervention, under recently adopted regulations, international shipping is expected to see increasing GHG emissions to 2050.
    - The transition needs to take place over a period shorter than the economic life of a ship, and the way new fuels and technology enter the fleet is key to the nature of the transition.
2. All scenarios require a rapid transition away from fossil fuels, but the start point and duration of this transition varies depending on the scenario.

3. Adopting SZEFs will be the main driver of decarbonisation. Technology pathway, rate of adoption of new fuel, and cost of decarbonisation are not highly sensitive to the future demand for international shipping.
   - Lower transport demand does lead to a lower rate of growth in demand for new fuels, but there are no significant differences in the fuel mix as a consequence of variations in the transport demand scenario.
   - In both scenario variations, a high rate of growth in the use of liquefied natural gas can be seen until 2030.
   - Ammonia use grows rapidly to become the dominant fuel by 2040.
   - Biofuels are not used in large volumes in the transitions, but do play a role as pilot fuels in the 2040s.
   - Direct electricity use becomes only a small share of international shipping's total energy demand.
4. Lower transport demand reduces the CO_2 emissions, if the carbon price is held constant
5. Profit-maximising decision-making in decarbonisation scenarios leads to significant amounts of retrofitting, including double retrofitting.
6. There is a significant change in the profile over time of energy-related costs of international shipping, as a function of the shape of decarbonisation.
   - Operating international shipping with zero GHG emissions can be expected to increase energy-related costs.
   - Enabling the transition creates a peak in costs during the transition, but the choice of target CO_2 trajectory changes the timing of that peak.
   - Decisions made about how carbon revenues are used can create variations in the cost profile of the transition.
   - There is a potential for premature scrapping to be an alternative to retrofitting.
   - Energy-related costs per unit of transport supply reduce if there is some premature scrapping of ships (although other capital costs for newbuildings may increase because a greater number of newbuildings are likely to be required, and the overall cost/benefit taking this into account is not calculated).
7. The price forecasts for fossil fuel and SZEF are a key uncertainty and a key influence on which policy intervention is needed. Unless the chosen policy is robust to this uncertainty, it may result in a failure to achieve a 1.5°C temperature goal aligned transition to zero emissions by 2050.
   - The CO_2 reduction outcome of a fixed levy has high uncertainty given the uncertainty in fuel price, it will therefore be hard to know what value to use for the levy and frequent adjustment to the levy may be required.
8. A high availability of biofuel supply reduces the level of retrofitting, but is not material to the CO_2 pathway or the costs of decarbonisation.
   - Biofuels do not exert a significant influence on the normalised[21] energy-related costs of international shipping's decarbonisation.
9. Uncertainty around the costs of SZEF machinery onboard vessels does not have a large influence on the cost of the energy transition.

[21] Normalisation is applied to enable scenarios to be compared purely on the basis of the parameter of interest (in this case biofuel availability). Controls for other sources of variation are applied to isolate the sensitivity to the parameter of interest.

2 Data and method

2.1 Approach to addressing aims and answering key questions

2.1.1 Question 1: What are the differences in the transition, depending on the pathway taken?

In order to answer question 1, this study modelled three core scenarios (A, B and C), each of which aligns with IMO4 in terms of the composition and definition of the baseline fleet (the fleet in 2018). International shipping is defined by IMO4 Option 1 (vessel based) emissions, see Section 2.4 for justification and details.

The modelling produces projections of how the given emissions target for each scenario might be achieved in practice. The three core scenarios are:

A. Decarbonise fully by 2050, with the bulk of emission reductions made between 2025 and 2050 (i.e. a slow and steady transition with costs spread out over time)
B. Decarbonise fully by 2050, with the bulk of emission reductions made between 2025 and 2035 (i.e. an early, steep decarbonisation trajectory)
C. Decarbonise fully by 2050, but the bulk of emissions reductions are left until the 2030s (i.e. a longer BAU period with a later, steep decarbonisation trajectory).

Target GHG emissions pathways for scenarios A and C were based on decarbonisation trajectories that were derived in a study commissioned by the United Kingdom Department for Business, Energy and Industrial Strategy as part of the Climate Services for a Net Zero Resilient World (CS-N0W) programme[22]. Each trajectory aligns the operational (TTW) emissions of international shipping to the 1.5°C target set under the Paris Agreement[23], representing a more stringent commitment to reducing emissions than current IMO ambitions imply. The target emissions pathways for scenarios A and C have the same cumulative emissions.

Scenario B is aligned with the guidance in the summary to policymakers of the IPCC AR6 WP1 report[24]. This guidance recommends a rapid reduction in absolute GHG emissions to 2030, followed by a less rapid reduction to reach zero GHG emissions around 2050. The steeper earlier emissions pathway results in 11% lower cumulative emissions relative to Scenario A and C, representing a lower risk of dangerous climate change, and is broadly representative of a pathway aligned to the guidance from IPCC across all sectors on what is required to avoid temperatures rising above 1.5°C. Figure 2.1 shows the resulting CO_2 budgets for the three core scenarios.

[22] See https://www.gov.uk/government/publications/climate-services-for-a-net-zero-resilient-world/cs-n0w-overview.
[23] Available at https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.
[24] Available at https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf.

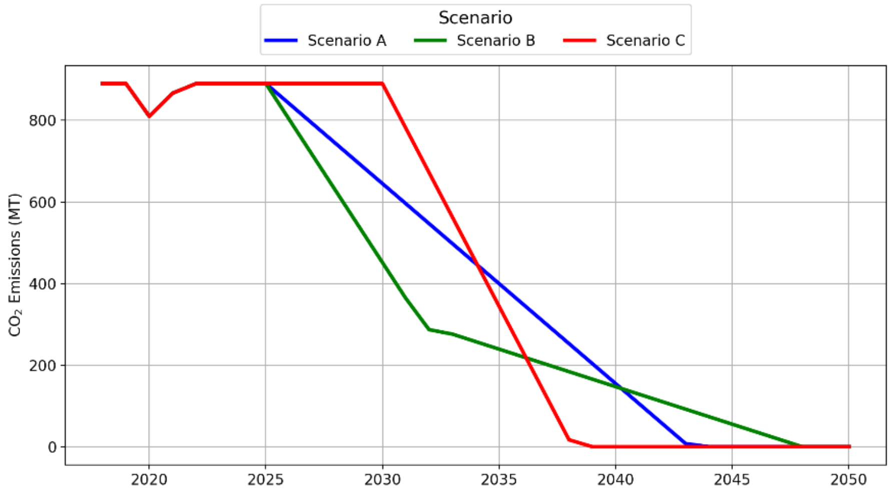


Figure 2.1 – TTW carbon budget derived pathways per scenario

GloTraM was used to predict the level of GHG emissions under each scenario. All three scenarios have targets set on operational (TTW) CO_2 emissions, and the modelling tool was configured to match that target as closely as possible. The most significant GHG in emissions from international shipping, by far, is CO_2, so the modelled scenarios mostly result in zero operational (TTW) GHG emissions by 2050. In addition, the modelling tool was also configured to assume that the wider energy system is also decarbonising. This results in international shipping achieving close to zero GHG emissions on a lifecycle (WTW) basis. Whether zero GHG emissions is achieved in practice for both the operational (TTW) and lifecycle (WTW) bases is discussed in Chapter 4.

The modelling was carried out to test and then understand the difference between the decarbonisation scenarios and two reference scenarios. The reason for two reference scenarios is that two BAU variations are considered. Both BAU scenarios reflect existing air pollution regulations under the International Convention for Prevention of Marine Pollution for Ships (MARPOL), which includes emission control areas for certain air pollutants, without any carbon budgets or prices, as follows:

- **BAU (existing policies)** follows the 2019 CMP evidence-based definitions of existing policy from the 2018 baseline year, such as the Energy Efficiency Design Index (EEDI), a design standard requiring newbuildings to achieve a minimum CO_2 performance in ideal conditions[25]. The modelling also includes existing IMO air pollution policies relating to SO_2 and NO_x emissions[26].
- **BAU (additional policies)** as above, plus the policies agreed following the completion of the 2019 CMP, such as the Energy Efficiency eXisting ship Index (EEXI) and Carbon Intensity Indicator (CII) reference trajectories. EEXI is a variant of EEDI that is applied to the existing ships so that even ships built before the entry into force of EEDI meet a minimum CO_2 performance in ideal conditions. CII is a policy measure that grades a ship's operational (TTW) CO_2 performance (e.g. actual CO_2

[25] Greater detail on the EEDI regulation and the different minimum requirements for different ship types is available here https://www.imo.org/en/OurWork/Environment/Pages/Technical-and-Operational-Measures.aspx
[26] Greater detail on air pollutant regulation is available here: https://www.imo.org/en/OurWork/Environment/Pages/Air-Pollution.aspx

emissions and distance travelled, not idealised performance), and requires remedial action for ships failing to reach a minimum performance.

In each case, comparisons between these two BAU scenarios and the core (A–C) scenarios have made it possible to separate the effect of direct carbon pricing from the impacts of the upcoming EEXI and CII regulatory frameworks on the take-up of alternative fuels[27] and emissions abatement technologies.

Question 1 is also answered by analysing sensitivities of some of the key assumptions, which makes it possible to discuss the robustness and features of the scenario findings. The key uncertainties considered include:

- Transport demand forecast – an additional variation of Scenario A is modelled using the OECD RCP2.6 G transport demand forecast, with a lower overall growth model than SSP2.
- Availability of biofuel (for use in international shipping) – two additional variations of each core scenario with an increased availability of biofuel (2 EJ) and no available biofuel.
- Fuel prices – two additional variations of each core scenarios with an increased SZEF/decreased fossil fuel price, and a decreased SZEF/increased fossil fuel price.
- Cost of decarbonisation technologies – an additional variation of Scenario A where the cost of SZEF machinery and efficiency technologies is increased, with a reduced rate of learning through the modelling period.
- Premature scrappage – an additional variation of Scenario C, where rather than scrapping all vessels 30 years after construction, vessels are scrapped if retrofitting their main engine past the age of 20 becomes the most profitable choice.

2.1.2 Question 2: What are the overall differences between the pathways by which international shipping may achieve alignment to the 1.5°C temperature goal and zero GHG emissions by 2050?

Building on the same three core scenarios, Chapter 4 of this report provides a detailed comparison of the three core scenarios, but without the sensitivity parameters.

2.1.3 Question 3: Can potential future supplies of new fuels and technology meet the demands created by these scenarios?

The results discussed in Chapter 4 were used to quantify demand for new fuels, which were then compared with the existing and projected supply of new fuels in Chapter 5. Constraints on the supply and rate of growth in supply are also discussed qualitatively. In Chapter 6, potential for constraints on the supply of new technology in the fleet are analysed quantitatively and qualitatively.

2.2 Description of the model and data used and produced

GloTraM was built to make holistic analyses of the global shipping system, including how shipping activity, costs and emissions might change in response to developments in economic drivers such as fuel prices and to changing environmental regulations.

[27] Alternative fuels are fuels that can displace the incumbent crude oil-derived fuels (such as LSFO).

The tool combines multi-disciplinary analysis and modelling techniques to explore foreseeable futures of the shipping industry using computational simulations of the evolution of the shipping fleet from a baseline year to a projected future year. Figure 2.2 is a conceptualisation of the modelling framework: each box represents a component within the model. The feedbacks and interconnections are complex and only a few are displayed on this diagram for the sake of clarity. This conceptualisation shows how the modelling framework breaks down the shipping system into manageable analysis tasks, ensuring that the analysis and any algorithms used are robust, and then connects everything together to consider the dynamics at a whole-system level.

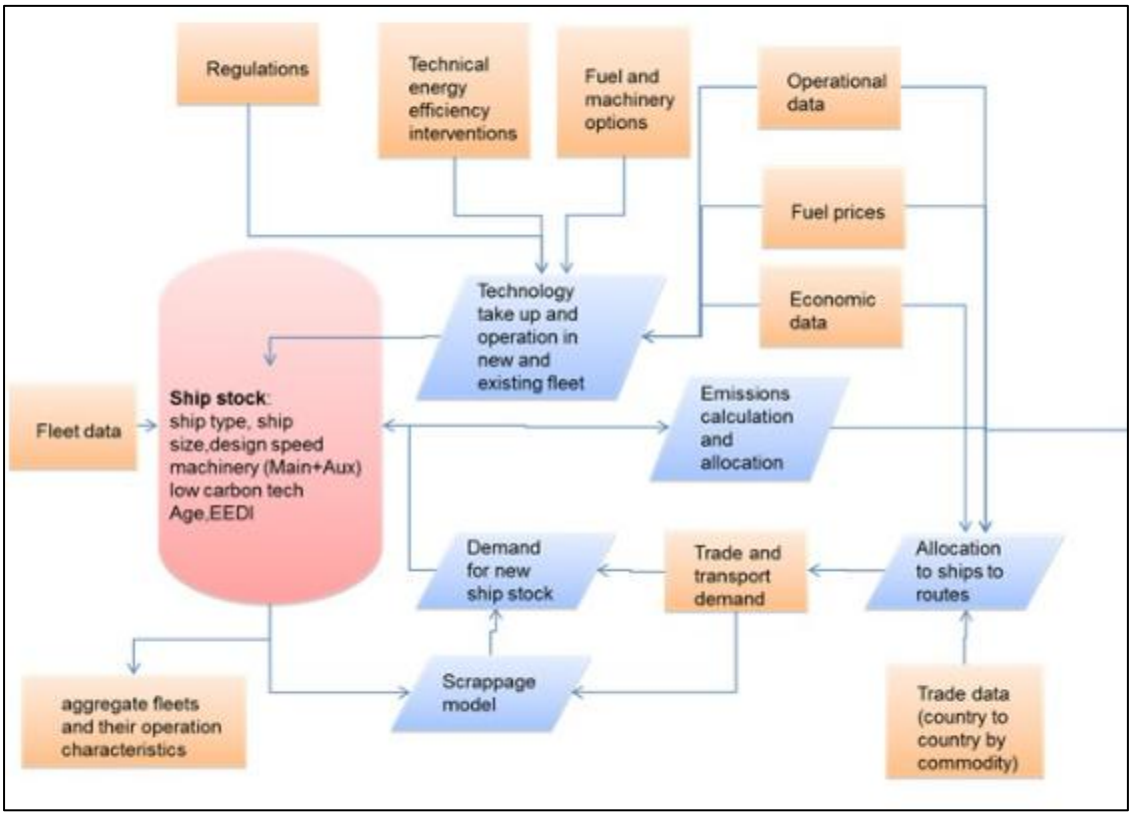


Figure 2.2 – Conceptual diagram of GloTraM operation

To make the GloTraM calculation process manageable, the global fleet is divided up into a set of 'vessel cohorts' that are groupings of vessels based upon their type (e.g. tanker or container vessel), size and generation (i.e. the time period when the vessels are introduced to the fleet). GloTraM then models a 'base ship' for each vessel cohort, which represents the average technical and operational characteristics of that cohort. The objective set within the model is for the operator of this base ship to maximise its discounted profit (including, where appropriate, any carbon pricing) while adhering to regulatory constraints thus incentivising the take-up of energy efficiency technology, emissions abatement options and alternative fuels. The resulting 'average' base ship costs and performance characteristics are then applied to the population of vessels within that cohort. There is also a mechanism to retire vessels once they reach the end of their economic life. New vessels are introduced at each 4-year time-step to meet the fixed input transport demand, and their characteristics are, in turn, determined by the regulatory constraints and commercial competitiveness of the technology options available to them in that year. Using a predetermined and fixed input transport demand simplifies the modelling approach by assuming there is no form of demand response. This both improves computational tractability (i.e. the capacity of the computer to run the model at a reasonable speed – allowing the model to maintain a runtime of approximately 24hrs) and enables direct comparisons to be made between scenarios on the basis of the technical and operational variations of technology alone.

Long-term systems forecasting requires compromises to be made (e.g. by naturally introducing limitations into the interpretation of results), for the sake of simplification such as:

- Decision-making behaviour of ship owners is driven only by simple profit maximisation; there is therefore no mechanisms to represent, for example, political and marketing gains from being a first-mover in a particular technology class
- The modelling inputs (specifically the estimated fuel and technology price trajectories, abatement option effectiveness and transport demand) are the most significant driver of variations in the modelling output. As such, the accuracy of these inputs has a direct influence on the 'accuracy' of the forecast outputs, but this is inherently limited by the uncertainty of estimating whole systems over long periods of time
- The characterisation of the global fleet, including its technical and operational specifications, is also subject to inaccuracy. However, significant effort has been made in both this and preceding studies to gather reputable and verifiable representations of the state of the maritime fleet in the 2018 baseline year.

These sources of inherent uncertainty cannot be removed, but their influence on the modelling forecasts can be tested using sensitivity scenarios, each of which varies an element of the input data while other conditions remain the same. The Technical Annex and accompanying spreadsheets contain further details on the definition and results of these scenarios.

A key aspect of the GloTraM model is its ability to use a carbon price to coerce the global fleet to meet a user-specified decarbonisation trajectory, which is a key requirement for this work. Due to the highly non-linear and dynamic interactions between the economic decisions of ship owners in the global fleet, an iterative approach is deployed. The carbon price iteration function is designed to generate the cheapest possible carbon price in each year that incentivises the fleet to meet the operational (TTW) CO_2 emissions required to align with the specified decarbonisation trajectory. This function works by automatically adjusting the carbon price in each year and re-running the model over each time-step repeatedly until a stable carbon price converges that maximises global fleet profit while meeting the required decarbonisation target.

2.2.1 Data produced

The output data for GloTraM includes a number of parameters that can be used to interrogate how the CO_2 target was achieved in practice and gain understanding of the practicalities and viability of a projected pathway.

Output data are available at each time-step, and therefore can be used to present trends over each projection from 2018 to 2050. Key outputs include:

- Actual GHG and air pollutant emissions: TTW CO_2 pathway emissions are calculated, including the quantities of other GHG emissions (operational (TTW) and lifecycle (WTW)), and estimates of quantities of a number of air pollutant species, including when the vessel is at berth and at sea

- Technology pathway: the mix of machinery and fuels used by international shipping
- Fuel consumption: the quantity of different fuels used
- Take-up of energy efficiency technologies: the level of penetration of different energy efficiency technologies in the international fleet
- Carbon price and costs: the values of the carbon price and the carbon costs (synonymous with the carbon revenues)
- Machinery, fuel and operating costs: a breakdown of different capital and operating costs.

Results in subsequent chapters make use of all of these different types of data in order to discuss the results and their implications.

2.3 Characterisation of the global fleet

The baseline year for this study is 2018, which was chosen in order to align with the latest year of reported results in the IMO4. Two data sources were used for building the characteristics of the baseline fleet to be modelled: a set of global vessel technical specifications compiled and maintained by IHS Markit[28]; and a combination of terrestrial and satellite automatic identification system (AIS) data that tracks the operational activity of all vessels that have an AIS transponder. These two data sets are linked by each vessel's IMO number and the Maritime Mobile Service Identity number (a unique identifier) of its AIS transponder, so that the fuel consumption and emissions for each vessel could be estimated by a series of calculations using the vessel's reported speed and engine configuration. The full methodology of this approach is detailed in the IMO4.

The baseline fleet was defined in GloTraM by its composition in 2018 for which reliable AIS messages were observed; and this fleet data was allocated into cohorts by type, size and age. Figure 2.3 shows these 2018 cohorts organised by type and size and provided as a pareto histogram based upon their CO_2 emissions. It is important to note that the emissions of the baseline fleet attributed to each cohort, as shown in Figure 2.3, differ slightly from the figures published in the IMO4. This is because of differences in the emissions calculation methodology between FUSE (the platform designed by UMAS to estimate the fuel consumption of the global fleet in the IMO4) and GloTraM. These differences are necessary to make the computations tractable. For example, FUSE estimates fuel consumption and emissions for each observed vessel according to its hourly instantaneous engine state and location, whereas GloTraM must use cohort averages aggregated over the entirety of 2018. This is a necessary compromise to ensure that the modelling can capture global transition trends in reasonable computational time frames.

The modelling undertaken to inform the DfT's 2019 CMP modelled only a subset of the global fleet, leaving out various vessel types such as liquefied gas tankers, which meant that a scaling factor had to be applied to the resulting fuel consumption, emissions and cost figures to account for the non-modelled fleet. In the current study, all vessel types that are defined in the IMO4 are included in the modelling, eliminating the need for any scaling of the costs and emissions to account for the non-modelled fleet. As described under the next

[28] https://ihsmarkit.com/products/maritime-data-index.html

section of this report, Section 2.4, this set of vessel types is then reduced according to the types described in Option 1 of the IMO4 to account for those that participate in international shipping.

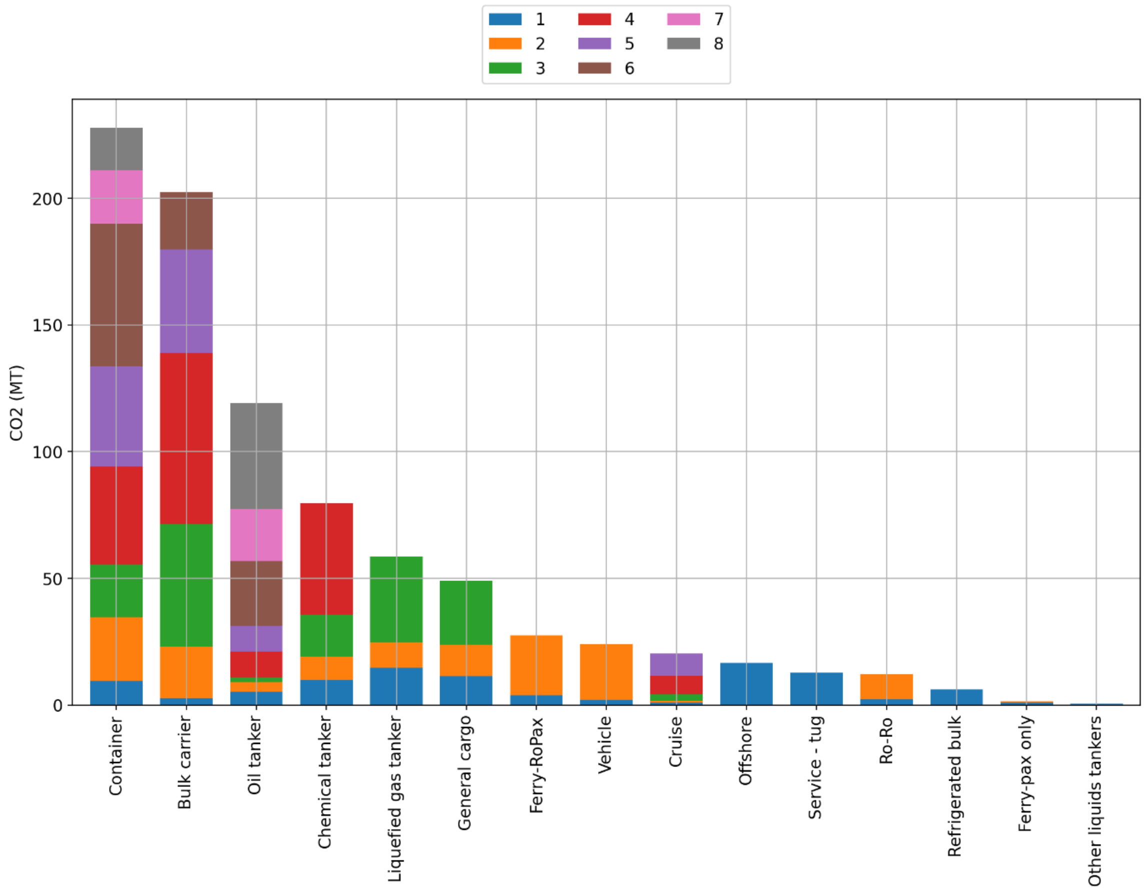


Figure 2.3 – Baseline year (2018) fleet TTW CO_2 emissions by vessel type and size category

2.4 Allocating emissions to the international and domestic fleet

The principal question of this study concerns the influence of IMO-led market-based measures on the international fleet, and how they might influence the cost and technology take-up trends as the fleet approaches decarbonisation.

There is little consensus on defining which emissions should be allocated to the international fleet and which to the domestic fleet. The IMO4 presented two possibilities:

- **Option 1:** Define *a priori* the vessel types[29] that constitute the international fleet, and allocate all emissions from those vessel types accordingly. This is the approach adopted in the *Third IMO GHG Study*[30] and the details for each ship type (including the minimum size for each ship type for classification as international shipping) are included in that study, it was modelled in the IMO4 alongside Option 2 for comparative purposes

[29] The vessels included in Option 1 are Bulk carriers, Containers, Chemical tankers, General cargo, Liquefied gas tankers, Oil tankers, Other liquids tankers, Ferry-pax only, Ferry-RoPax, Cruise, Ro-Ro, Vehicle carriers, and Refrigerated bulk.
[30] Smith, T. et al. (2014). *Third IMO Greenhouse Gas Study*.

- **Option 2:** Allocate emissions on a ‘voyage basis’ (i.e. allocate emissions from each vessel to either international or domestic based on whether each voyage is between ports of the same country or between ports of different countries). This approach is more complex because it results in many vessels being neither fully ‘international’ nor ‘domestic’. However, it gives a clearer aggregate picture of where emissions are produced. The IMO4 concluded by recommending this option for the allocation of international and domestic emissions for future studies.

Although there is a recommendation in the IMO4 to adopt Option 2 as the preferred emissions allocation method, there was no decision taken by IMO on this and there is still considerable uncertainty concerning which approach the IMO will adopt for its future policy mechanisms.

This study selected Option 1, vessel based emissions allocation, even though this can encompass emissions that by UNFCCC/IPCC accounting will also appear in domestic GHG emissions inventories. This is because the objective is to understand emissions reductions and costs of technology pathways, which are determined by assets (e.g. vessels) not by voyages. Until now, existing IMO regulations relating to GHG emissions have not discriminated by voyage (domestic/international), so use of this definition also provides a conservative but representative estimate for the implications of further GHG policy.

2.5 Key improvements and developments made to GloTraM for this study

2.5.1 Alignment to Fourth IMO GHG Study assumptions

GloTraM represents international shipping by simulating the evolution of the global fleet starting in a baseline year. To ensure the most accurate starting point for the modelling, the most recent year in the IMO4, 2018, was used as the baseline year. As described above, the input data for GloTraM was then aligned with IMO4 results for that baseline year. This includes ensuring consistency with:

- Fleet composition (number of ships in different types and size categories)
- Fleet technical characteristics
- Emissions inventory (breakdown of emissions across the fleet)
- Operational parameters (including speed and utilisation).

The transport demand forecasts for all scenarios are the same as those used for IMO4, apart from two modifications. Chapter 4 of the IMO4 included a range of scenarios that were extrapolated from the AIS-derived historical results to attempt to show possible emissions and carbon intensity trajectories, but there were no assumptions on additional regulatory mechanisms to induce decarbonisation. To further align with the assumptions of the IMO4, the current study utilises the ‘SSP2 RCP2.6 L’ transport demand scenario. This scenario employs the same underlying logistics model used in the *Third IMO GHG Study*, but with updated input data to account for observed changes in the world economy between 2014 and 2018.

Two key changes have been made to the transport demand scenario as used in the current study:

- The effect of the Covid-19 pandemic on international trade has been factored in, amounting to a 4% drop in the demand of all commodity transport work in 2020, followed by a 4.8% rebound in 2021, with the original relative increase between years continuing to 2050. This approach follows the recommendations of the United Nations Conference on Trade and Development (UNCTAD) *Review of Maritime Transport 2020*[31].
- The magnitudes of transport demand in the baseline year are not derived from a comprehensive inventory of the global fleet. The decision was made as part of this study to give preference to the composition of the baseline fleet as defined in the IMO4 through AIS observations, rather than to modify that composition to match the magnitude of trade defined in the transport demand scenario. As such, the transport demand scenario is scaled to match the supply observed in the baseline fleet, and then evolved through to 2050 using the relative year-on-year increase observed in the original transport demand scenario.

The resulting transport demand scenario is shown in Figure 2.4, using an annual resolution (e.g. there is transport demand data shown for 2018, 2019, 2020 etc.). In the presentation of modelling results in subsequent sections, because the model runs with a 4-year time-step, the per annum variations in output parameters caused by the contraction of demand in 2020 are not captured. Only the longer-run consequences of this demand contraction are captured.

[31] UNCTAD (2020). *Review of Maritime Transport 2020*, November 2020. Available at https://unctad.org/webflyer/review-maritime-transport-2020. Please note, after this input was set, in November 2021, a newer version of the report was released with a 3.8% percent drop in international trade for 2020 followed by a 4.3% rebound in 2021. These updated trade numbers are similar to the previous numbers used in this study and therefore would not materially change the outcomes presented in this report.

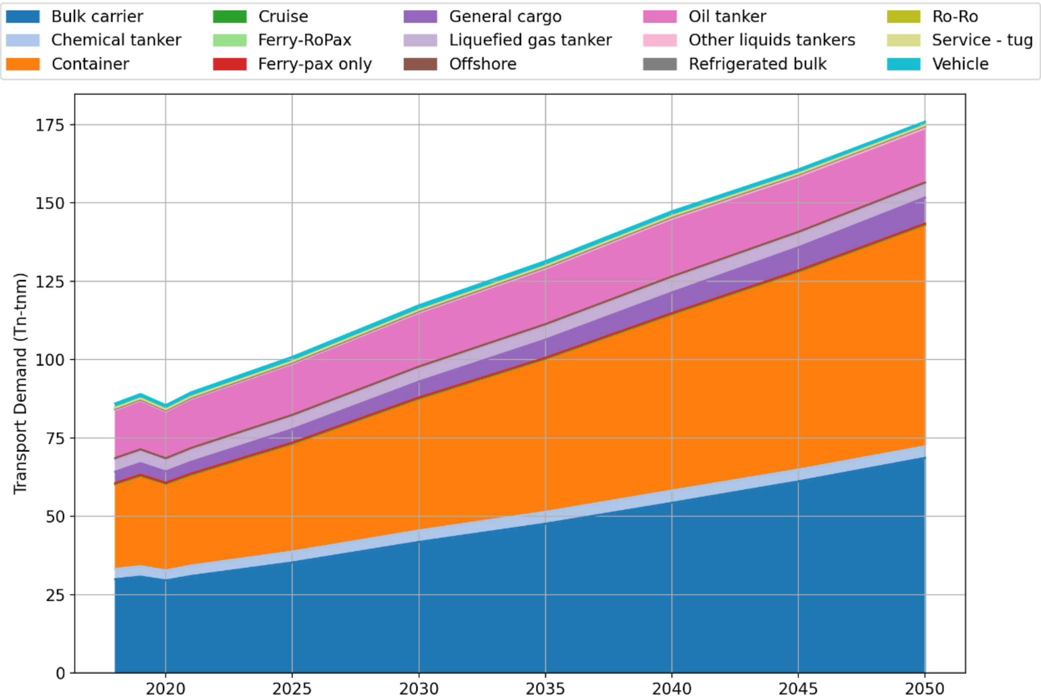


Figure 2.4 – Transport demand by vessel type from SSP2 RCP2.6 L

To estimate the change in technology and operating parameters of the fleet over the period to 2050 (including changes in operating speeds of ships), we updated earlier work on the evidence base for CMP[32], rather than using the IMO4 data on cost and performance of technology and fuels. This ensured that the forecasts were performed with the most up-to-date data on technology and fuels. The derivation of key assumptions, and the values used, are provided in the Technical Annex. The Technical Annex (Section 2.2) also includes a mapping of vessel types to transport demand types, allowing the comparison of Figure 2.4 with Figure 3.1.

2.5.2 Representation of the latest policy developments, including the short-term measures CII/EEXI

The EEDI, a carbon intensity estimation framework that stipulates a minimum threshold for the design efficiency of new-build vessels, has already been implemented in GloTraM as part of the 2019 CMP modelling. The EEXI and CII, both due to be enforced from 2023 onwards, are new features that have been integrated for this study.

The EEXI is defined by a scaling factor applied to the baseline EEDI value for a vessel. It requires existing ships to meet technical efficiency standards equal to the EEDI targets for that ship type in 2022[33]. New-build ships are therefore by definition adhering to EEXI if they have passed their requisite EEDI. The scaling factors applied to the baseline EEDI values are included in the input spreadsheets provided with this report.

[32] Frontier Economics, UMAS, E4tech and CE Delft (2019). *Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution: Scenario Analysis.*
[33] Rutherford, D. et al. (2020). *Potential CO_2 Reductions under the Energy Efficiency Existing Ship Index*. Available at https://theicct.org/sites/default/files/publications/Marine-EEXI-nov2020.pdf.

Implementing the CII is more complicated because it is an operational efficiency standard that varies by ship type, size and year of enforcement.

Each year, all vessels with a gross tonnage of 5,000 or greater that are in the list of qualifying ship types receive a rating from A to E based on their annual efficiency ratio (AER), defined as their annual CO_2 emissions (in grammes) divided by their annual transport supply. The rating they receive is dictated by which band the vessel's AER falls into relative to the required (i.e. target) CII for the specific year, vessel type and size.

$$Reference\ CII = a \cdot Capacity^{-c}$$

Equation 1

The required CII is itself derived from a 'reference' CII given by Equation 1 above. The coefficients *a* and *c* are taken from tables that assign values to vessels based on their type and size range. For most vessel types, *Capacity* takes the deadweight tonnage, except for roll-on roll-off (Ro-Ro) ferries and cruise vessels, which take gross tonnage instead. The reference CII is then modified by a reduction factor that represents the tightening of the carbon efficiency requirements over time, starting with 5% in 2023 then increasing by 2 percentage points annually. The reduction factor is fixed by the CII regulation and is due to be reviewed in 2027. The outcome of that review cannot be predicted, so for this study the reduction factor was set at the 2026 level then held it constant out to 2050. This is conservative because these will need to be reviewed and are likely to be revised and extended in order to achieve the IMO's levels of ambition (or revised level of ambition) at least for 2030.

The calculated values of attained CII of a vessel for a given year are then allocated a rating according to which band the attained CII falls into relative to the required CII. An example of this allocation is illustrated in Figure 2.5. The four values of *d* are also taken from tabular data that varies by vessel type and size range, and is also included in the spreadsheets that accompany the Technical Annex.

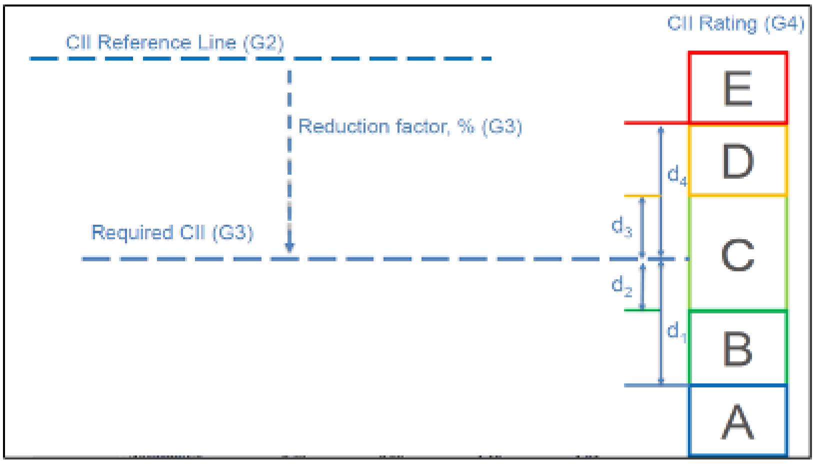


Figure 2.5 – Example derivation of CII rating bands

In practice, a vessel is deemed to have failed if it acquires three consecutive D ratings or a single E rating, at which point the vessel owner would need to submit to their flag administration a formal plan of technical and operational improvements to ensure that the vessel returns to compliance. In GloTraM, if a certain vessel configuration will fail the CII, then it is not considered for any new-build or retrofit options, even if it results in greater profit. The point at which a vessel would fail the CII is calculated independent of number of years between each time step of the model, but changes to vessel configuration that result from enforcement of the CII measure will be reflected at the next time-step following the year of failure.

2.5.3 Bioenergy availability

In the 2019 CMP modelling, only one scenario included biofuels, and biofuels were applied exogenously as a fixed proportion of total take-up per year. In the current study, with a global rather than UK-centric focus, the approach to modelling biofuel take-up has been modified to allow for more dynamic behaviour to emerge, as follows.

At each time-step, the penetration of biofuel is modelled by assuming the same percentage substitution in each fossil fuel such that the total biofuel energy does not exceed the total availability of biofuels. The price and emission factors for each fuel combination are then determined by the linear combination of the fossil fuel-derived component and the biofuel component (i.e. the blended fuel cost and emission factors are a ratio of the cost and emission factors of the combination of fuels based upon the relative proportion of each fuel in the blend). In the 2019 CMP modelling, the price of the biofuel blend was not altered to account for the percentage penetration, and so the competitiveness did not vary beyond the existing fossil fuel price trajectory. With this new approach, the take-up of each biofuel blend is directly influenced by both the increased price and the lower emissions, as the penetration of biofuel in the blend increases.

2.5.4 Representation of a mechanism to achieve the targeted CO_2/GHG reductions

For Scenarios A, B and C, GloTraM is run in order to achieve the CO_2 trajectories defined in Figure 2.1. In addition to representing the situation under existing policies, the model simulates the imposition of a CO_2 policy lever and calculates the necessary stringency of that policy lever that will achieve the prescribed environmental (CO_2) outcome. The simulated CO_2 policy level used is a carbon price, and it is calculated iteratively for each time-step until the required level of absolute CO_2 emission is reached for that time-step. However, it should be emphasised that carbon pricing is used for modelling purposes, not as a presumption that this is the policy mechanism that will be selected by the IMO in order to enable the achievement of a given level of ambition.

The use of a carbon price in the modelling means that the subsections within international shipping undertake decarbonisation where it is most profitable to do so first. This would also be similar to how decisions are made under an emissions trading scheme, or by a fuel standard policy that allows for compliance through fleet average performance. In this respect, the results produced are generic and relevant to all the policy concepts being expressed in the most recent IMO debates on mid- to long-term measures.

In practice, there are significant revenues generated by any carbon pricing policy applied to international shipping. However, for the modelling, no specific assumption was made on the use/redeployment of revenues arising from the simulated carbon price, so in most results the revenues are factored in as a cost but remain ‘unspent’. The implications of this assumption and consequences of its relaxation on the costs are discussed in Section 3.

The modelling sets targets on operational (TTW) CO_2 emissions, and therefore the simulation involves a price set on those CO_2 emissions only (not the lifecycle (WTW) CO_2 or GHG emissions, or the wider operational (TTW) GHG emissions). The upstream (WTT) CO_2 and GHG emissions are forecast (see Technical Annex for detailed derivations), and are assumed to change over time in line with decarbonisation of the wider energy system and economy. Therefore, although there are no targets set for wider GHG emissions, both the operational (TTW) GHG emissions and the WTW GHG emissions of international shipping are estimated and included in the results.

2.5.5 Sensitivity studies assume the stringency of simulated policy to be constant, and compare the difference in environmental effectiveness

In addition to modelling the two BAU variations and the three core scenarios (A, B, C), a number of sensitivity studies were undertaken. For the core scenarios A, B and C, the scenarios were targeted to achieve the prescribed CO_2 trajectory. For the sensitivity studies, the output carbon price trajectory of each core scenario was used as an input to the sensitivity scenario, and the resultant change in the scenarios (including any change in CO_2 trajectory and cost) was then available for discussion. In each case the calculations are provided that normalise the cost of decarbonisation on a per tCO_2e basis (i.e. normalising for any variation in CO_2 emissions relative to the core scenario) so that the respective cost implications of the sensitivity scenario could be discussed, as well as any sensitivity to environmental effectiveness.

2.5.6 Focus on energy-related costs

International shipping's costs can be categorised and broken down in a number of ways, including capital costs associated with the assets (e.g. ships) and their operating costs (which for example can be broken down into port dues, crew/manning, fuel, insurance etc.). These costs all vary over time. Characterising and modelling each component of cost adds significantly to the overall complexity of modelling, and also adds complexity to interpreting outputs because the effects of these costs on trends need to be separated out from those that are occurring because of the imposed CO_2 constraints. Please note that within this report all capital costs are amortised unless specifically referred to as absolute.

Therefore, the modelling incorporates only the costs which are primarily affected by the transition, and therefore producing the most important changes between the scenarios. This includes:

- The capital costs of energy conversion machinery (e.g. internal combustion machinery, fuel cells, motors, whether conventional or SZEF fuelled)
- The capital costs of storage and energy handling equipment (e.g. fuel tanks)
- The maintenance costs of energy conversion machinery
- The costs of energy/fuel (fuel and electricity prices)
- The capital costs of energy efficiency and wind assistance machinery
- The maintenance and/or operating costs of energy efficiency machinery

Landside infrastructure costs, such as those associated with fuel production, are not explicitly included. However, these capital costs are included in the estimates for energy/fuel prices.

In order to calculate the overall profitability of a given technical and operational specification, changes in costs are combined with changes in revenue. Changes in revenue arise from two sources:

- The reduction in usable space (including cargo carrying space) due to the use of a lower energy density fuel. This incorporates the fact that many SZEFs have a lower energy density than the fossil fuels used today and will need more space on board for their storage. The reduction in space is calculated assuming that the range/endurance (the distance a vessel can travel with a maximum use of fuel storage) is maintained regardless of the fuel specification. The revenue reduction is proportionate to the reduction in usable space.
- The reduction in operating speeds. This reduces the amount of transport work that a ship produces in a given time period (e.g. year) and therefore the amount of revenue that is earned.

Many of the results show comparisons between BAU scenarios and decarbonisation scenarios, which provides further justification for this focus. The underlying non energy-related costs will otherwise be common and can be expected to cancel out, leaving the above list as the explanation for the difference in costs. This includes the non-energy capital cost of the fleet servicing international trade e.g. the cost associated with the construction of ships. If a higher trade scenario is considered then if all else is held equal, the number of ships needed will increase and the non-energy capital cost of the fleet will increase. That cost increase will need to be met by increased revenues which are obtained from greater levels of international trade. If ship speeds vary between scenarios, there can be changes to the size of the fleet and therefore the non-energy capital cost of the fleet. These are not incorporated in the modelling because earlier modelling showed only small changes in operating speeds[34] between scenarios and this cost is therefore considered of lower significance than the core energy-related costs for equipment, fuels and maintenance.

[34] Frontier Economics, UMAS, E4tech and CE Delft (2019). *Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution: Scenario Analysis - Technical Annex*

3 Key findings on the nature of international shipping's transition

3.1 Without further intervention, under recently adopted regulations, international shipping is expected to see increasing GHG emissions to 2050

Without further intervention GHG emissions from international shipping are expected to rise by approximately 30% over the period from 2018 to 2050. This is because there is strong underlying growth in demand for shipping and the existing regulations driving any improvement in energy efficiency or reduction in carbon intensity are not sufficient to result in any reduction in absolute emissions.

Due to alignment with the 'SSP2 RCP2.6 L' transport demand scenario from IMO4 (as discussed in Section 2.5.1), transport demand input for the current study exhibits a much slower increase in demand than in earlier modelling for the 2019 CMP, as shown in Figure 3.1(a) and (b). A slower increase in transport demand is important because shipping's energy demand is directly proportional to transport demand. If all else is held constant and shipping energy demand doubles, then GHG emissions from shipping would also be expected to approximately double. Thus, the reduction in forecast transport demand also reduces the forecast increase in emissions, as well as reducing the level of intervention needed to achieve deep reductions in emissions.

A further development that has been captured in this study, and which changes the BAU scenario relative to earlier analysis, is the adoption at IMO in 2021 of short-term policy measures CII and EEXI. These policies enter into force in 2023 and set increased stringency until 2026. That means they stimulate a change in the energy efficiency and carbon intensity of the fleet which, for a given scenario of transport demand, can reduce the forecast CO_2 emissions relative to the forecast had the policies not been adopted.

Figure 3.1(a) shows the forecast CO_2 BAU emissions trajectory from earlier CMP modelling (i.e. BAU with existing policies) , and Figure 3.1(b) shows the implications of the transport demand forecast and the adoption of short-term policy measures CII and EEXI (i.e. BAU with additional policies); while Figure 3.2 compares the two charts in Figure 3.1, making it possible to see the relative changes to CO_2 emissions of these modifications in isolation (e.g. just the change in transport demand) and in combination (e.g. both the change in transport demand and regulation). It is clear from the charts that, even with additional policies taken into account, international shipping is expected to experience an increase in CO_2 emissions over the period to 2050, indicating a need for a significant policy intervention. It is also clear from this analysis that little deviation has occurred to the forecast CO_2 emissions as a result of the adoption of CII and EEXI. In their current form, these policies are not sufficiently stringent to materially reduce the intervention needed to achieve a significant reduction in GHG emissions from international shipping.

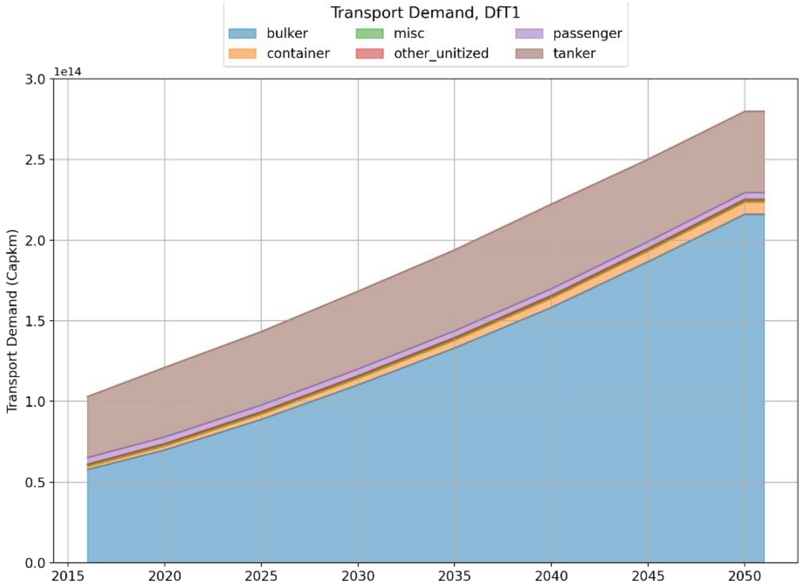


Figure 3.1(a)

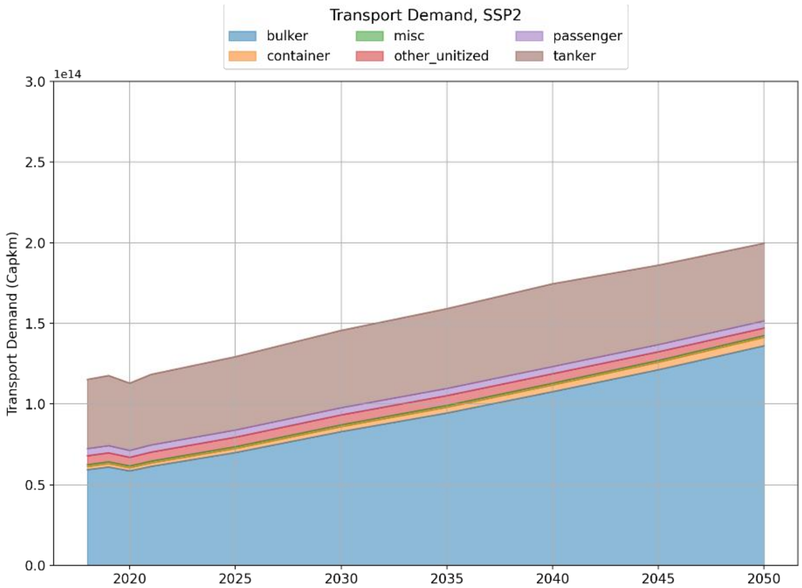


Figure 3.1(b)

Figure 3.1 – International shipping transport demand scenarios: 2019 DfT CMP modelling referred to as DfT1[35] (a); and current study (b)

For the purposes of comparison against the 2019 CMP results, transport demand has been rendered here in units of capacity-kilometres. The underlying data are equivalent for SSP2 as presented in Figure 2.4.

35 Frontier Economics, UMAS, E4tech and CE Delft (2019). *Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution: Scenario Analysis - Technical Annex*

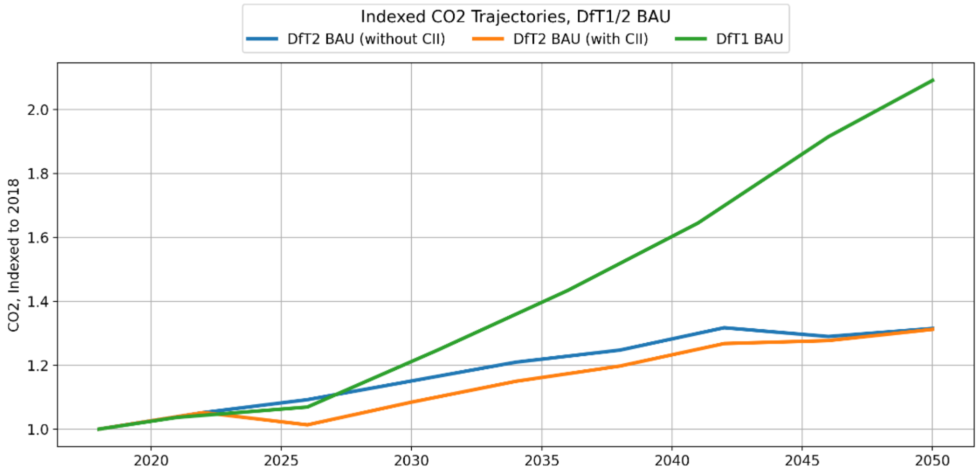


Figure 3.2 – Indexed international shipping TTW CO_2 trajectories. 'DfT1' denotes 2019 DfT CMP modelling and 'DfT2' the BAU CO_2 trajectories from this study, indexed to 2018

The rest of this chapter discusses the levels of decarbonisation that could be achieved by following each scenario rather than the BAU. Results are presented as a comparison relative to the BAU that includes the application of EEXI and CII (i.e. Figure 3.1 (b)).

3.1.1 The transition needs to take place over a period shorter than the economic life of a ship, and the way new fuels and technology enter the fleet is key to the nature of the transition

In order to achieve any of the transition pathways identified in Section 2.1.1, where the slowest decarbonisation transition takes approximately 23 years, the fleet will have to substitute all its fossil fuel use within less time than the conventional economic life of a ship (approximately 30 years). Furthermore, due to current IMO policy development timescales, the assumption applied for these scenarios is that the earliest point at which a policy mechanism could drive the deep decarbonisation and fuel substitution of international shipping is 2025. In other words, decarbonisation does not start instantaneously; consequently there is even less time to achieve fuel substitution.

Fuel substitution requires both the development of the new fuel supply chain (to meet demand), and the development of a fleet compatible with the new fuel. This chapter focuses on understanding the 'least cost pathway' for the fleet, on the assumption that supply can grow to meet the scenario of energy demand; the feasibility of a fuel supply developing as required by these scenarios is explored further in Chapter 5.

For the fleet, fuel substitution can be achieved in three ways:

- New-build scalable zero emission fuels (SZEF) ships entering into the fleet
- Using a drop-in fuel that is compatible with a fleet designed to use fossil fuel
- Retrofitting the existing fleet to be SZEF-compatible.

Figure 3.3 shows that for the example of one of the decarbonisation scenarios, scenario A, the fleet composition in the 2030s retains a significant portion of the fleet built before 2020. For the fleet in the 2040s – a point at which the energy mix has switched to >80% SZEF – there remain a significant number of ships that have been built before 2025 (i.e. before the implementation of any fuel transition policy). For the lower rate of demand growth than that in Figure 3.3, considered in the sensitivity study, there would be an even larger percentage of older ships active in any given year, because the lower demand growth would correspond to lower rates of new ship building.

One implication of these findings is that there is an opportunity to design ships to be built in the 2020s such that they will be resilient to the developments in policy and escalating stringency, and can be adapted to use SZEFs competitively (i.e. retaining competitiveness against the new-builds they will have to compete with during the 2030s). This also emphasises the importance of having policy clarity as early as possible in the transition.

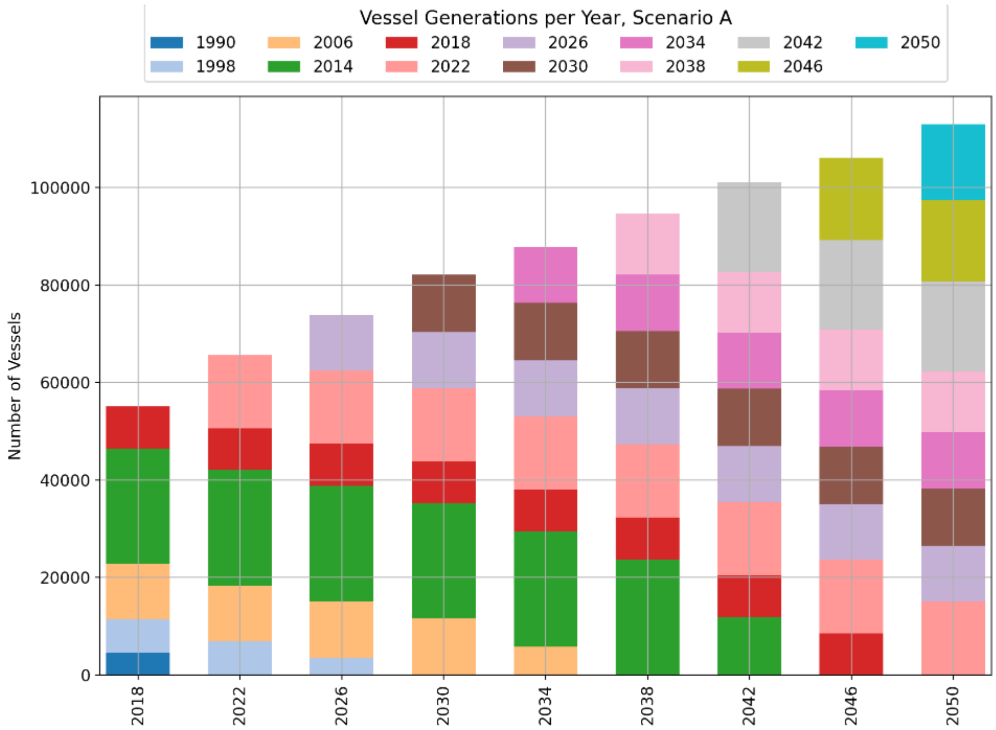


Figure 3.3 – Vessel generations per year, Scenario A

This positions the way the fleet transitions to new fuel, particularly the existing fleet, as a key consideration in understanding the nature and cost of the transition of international shipping.

Subsequent sections therefore focus on exploring the sensitivity to the fuel transition of different target CO_2 trajectories (Scenario A, B and C), as well as some of the key fuel-related sensitivities (both the price of fuels and the availability of biofuels), and considering whether scrapping ships before their normal economic life could be a lower cost alternative way to achieve a high rate of fossil fuel substitution.

3.2 All scenarios require a rapid transition away from fossil fuels, but the start point and duration of this transition varies depending on the scenario

Modelling conducted to support the 2019 CMP found that achieving deep decarbonisation of international shipping could be partly assisted by further increases in energy efficiency, but adopting new fuels would be more significant. That is also the case in the current study.

Calculating the least cost pathway to decarbonising shipping, even with the reductions in demand growth relative to earlier modelling, shows that further take-up of energy-efficient technology (EET) achieves only modest absolute reductions in emissions. Consistent with the earlier analysis, it is the transition from fossil fuels to new fuels that has the greatest impact on reducing GHG emissions (i.e. abatement); and in all scenarios, this requires a transition away from fossil fuels that starts in the 2020s and then grows rapidly during the 2030s. Figure 3.4 to Figure 3.6 highlight the difference in contributing factors[36] for each of the core scenarios. In these breakdowns of abatement contributions, fuel transition includes both full electrification and shore power, while EET and operational measures include wind- and solar-based efficiency interventions.

The important differences between the scenarios are related to how the magnitude and timing of emission reductions from fuel substitution occur. This is found because EET and operational efficiency CO_2e savings are consistently small and similar between Scenarios A, B and C. The differences in CO_2 abatement per scenario therefore predominantly have a direct impact on the timing and volume of take-up of new fuels. For example, achieving the CO_2 target in Scenario B requires rapid take-up of new fuels over the latter part of the 2020s; conversely, Scenario C has much slower initial take-up of new fuels and fuel substitution starts in significant volume from 2030.

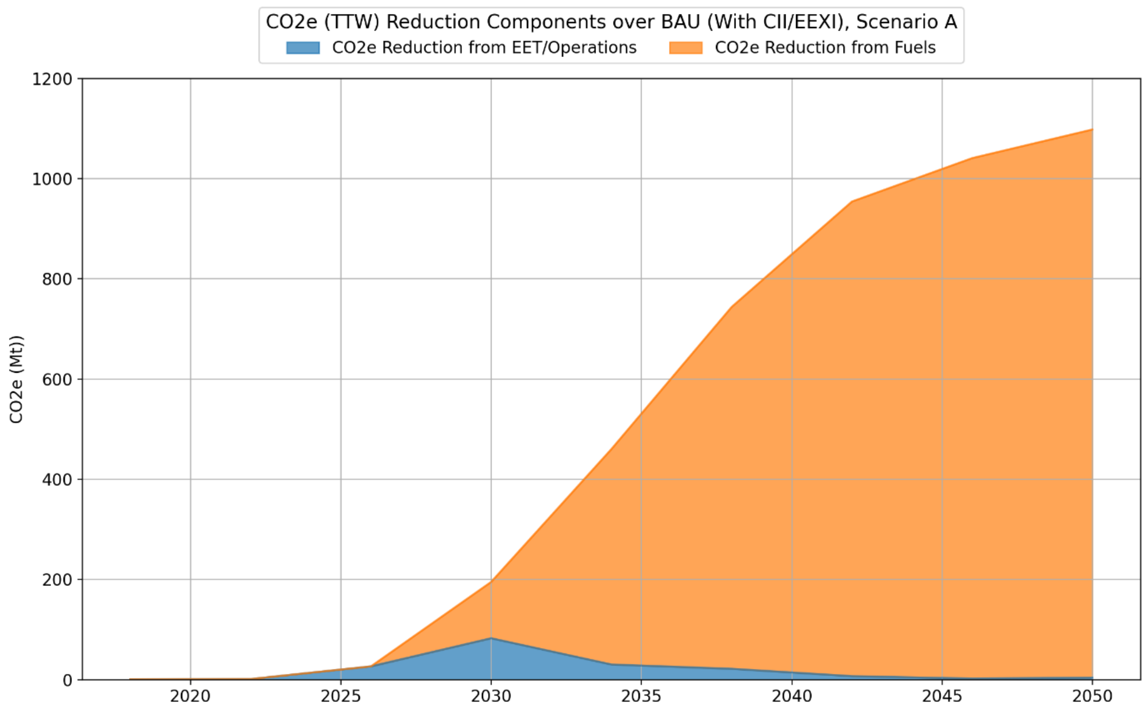


Figure 3.4 – CO_2e (TTW) reduction over BAU (with CII/EEXI) by reduction source (fuels or EET/Operations), Scenario A

[36] It is assumed that if a vessel in a given year uses, for example, an SZEF in Scenario A and low sulphur fuel oil (LSFO) in the BAU (with CII/EEXI) scenario, CO_2e reductions are attributed (in this case to "CO_2e reduction from fuels") based on the CO_2e differences that are found from that fuel substitution (e.g. the differences between LSFO and SZEF). EET and operational reductions include both EET impacts as well as slow steaming.

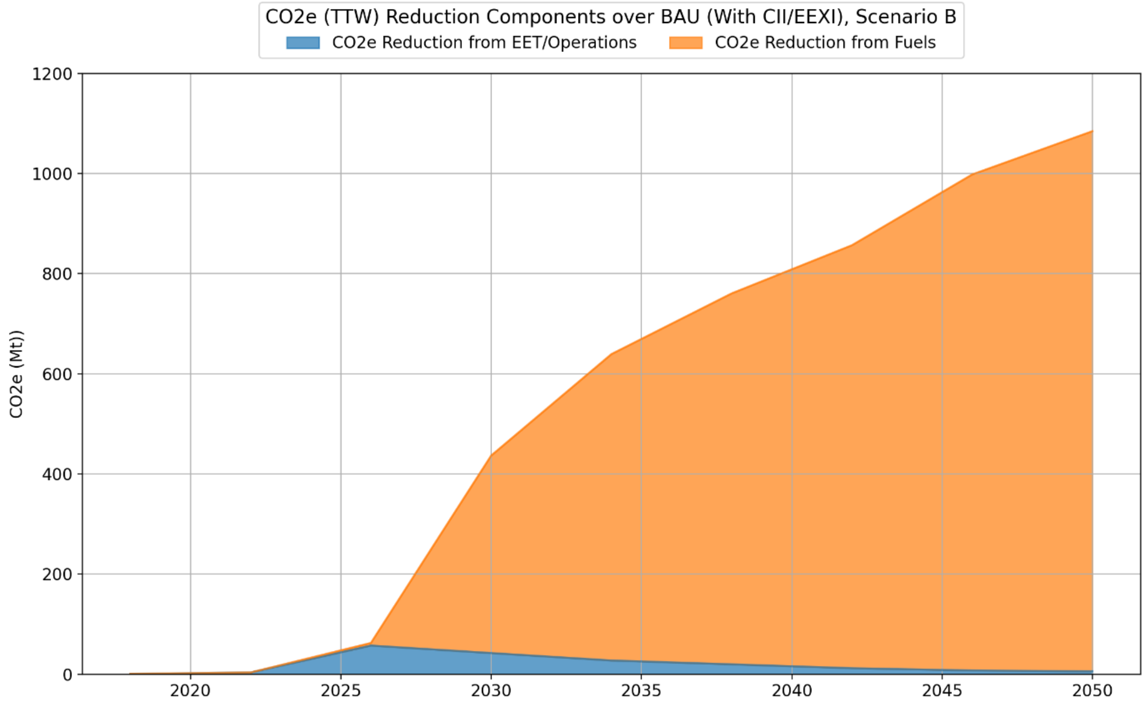


Figure 3.5 – CO_2e (TTW) reduction over BAU (with CII/EEXI) by reduction source (fuels or EET/Operations), Scenario B

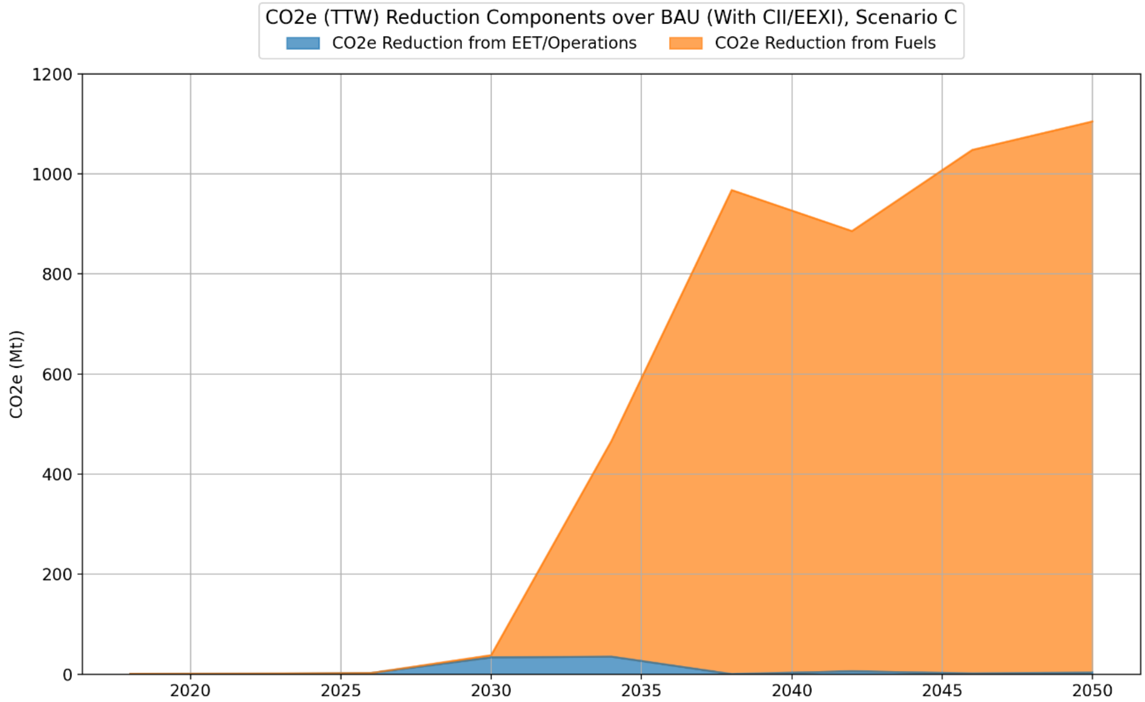


Figure 3.6 – CO_2e (TTW) reduction over BAU (with CII/EEXI) by reduction source (fuels or EET/Operations), Scenario C

3.3 Adopting SZEFs will be the main driver of decarbonisation. Technology pathway, rate of adoption of new fuel, and cost of decarbonisation are not highly sensitive to the future demand for international shipping

IMO4 recognised the uncertainty in the forecast of transport demand by estimating four different trajectories that were all labelled 'BAU'. In order to simplify the current study, the three core scenarios used to explore the different pathways to achieve both 1.5°C alignment and zero GHG emissions by 2050 all have the same transport demand forecast.

However, before further discussion on the differences between Scenarios A, B and C, this section describes a test of the sensitivity of results to the chosen transport demand forecast by considering the differences between Scenario A and a variation with lower transport demand[37]:

- Scenario A (with core transport demand) – approximately constant reduction in operational (TTW) CO_2 emissions from 2025 until 2042, using the transport demand forecast SSP2 RCP2.6 L
- Scenario A (with lower transport demand) – applies the carbon price trajectory from Scenario A and the transport demand scenario OECD RCP2.6 G

The two transport demand scenarios represent the upper bound (SSP2 RCP2.6 L) and lower bound (OECD RCP2.6 G) of the transport demand forecasts used in the BAU scenario of IMO4. Both scenario variations were corrected to account for the effect of the Covid-19 pandemic[38]. The key results are presented in Figure 3.7 to Figure 3.9; and the similarities and differences of the two scenario versions are discussed in Sections 3.3.1 and 3.3.2, along with an explanation of the general features of the transition common to both scenario versions.

3.3.1 Lower transport demand does lead to a lower rate of growth in demand for new fuels, but there are no significant differences in the fuel mix as a consequence of variations in the transport demand scenario

Figure 3.7 shows that, irrespective of the transport demand scenario, there is a similar transition in the fuel mix. In both scenario variations, the incumbent fossil fuels (LSFO and MDO) were substituted first by liquefied natural gas (LNG), before the rapid growth in the use of ammonia (NH_3) as a fuel, from 2026. The consequence of the lower transport demand is that a smaller volume of ammonia is taken up by 2030. Over the 2030s and 2040s the rapid continued substitution of all fossil fuels (low sulphur fuel oil (LSFO), MDO and LNG) by ammonia is common to both scenario variations, with the resulting fuel mix in the 2040s containing a diminishing portion of residual fossil fuels and small volumes of biofuels.

Beyond the observed small differences in the fuel mix, a key difference between the fuel mix in the two scenario versions is the difference in total energy demand, with the lower transport demand scenario displaying a reduction in the total energy needed for 2018–2050 (total demand of approximately 10EJ by 2050), compared with the core transport demand

[37] This transport demand scenario is described in the IMO4.

[38] A 4% drop in all commodity transport work in 2020, followed by a 4.8% rebound in 2021, with the original trajectory growth rates resuming the following year, as suggested in UNCTAD (2020) *Review of Maritime Transport 2020*.

scenario, displaying a small increase in the total energy needed over the same period (total demand of approximately 14EJ by 2050). Therefore, a lower transport demand scenario reduces the absolute volumes of new fuels that would be needed to achieve the sector's decarbonisation, and therefore also a lower rate of growth in supply of new fuels would be needed to achieve the sector's decarbonisation.

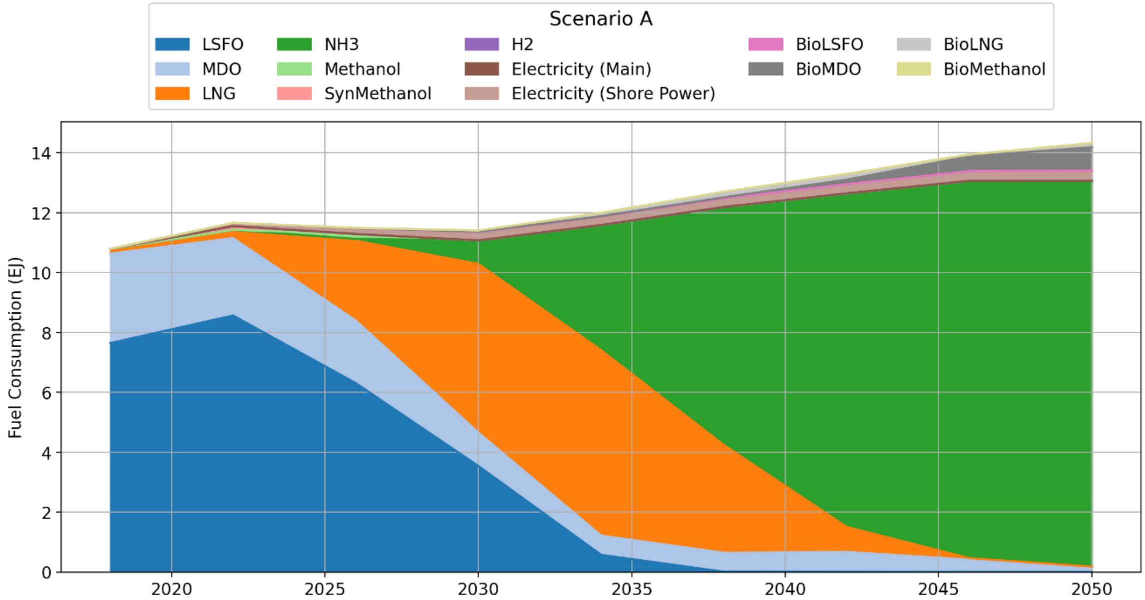


Figure 3.7(a)

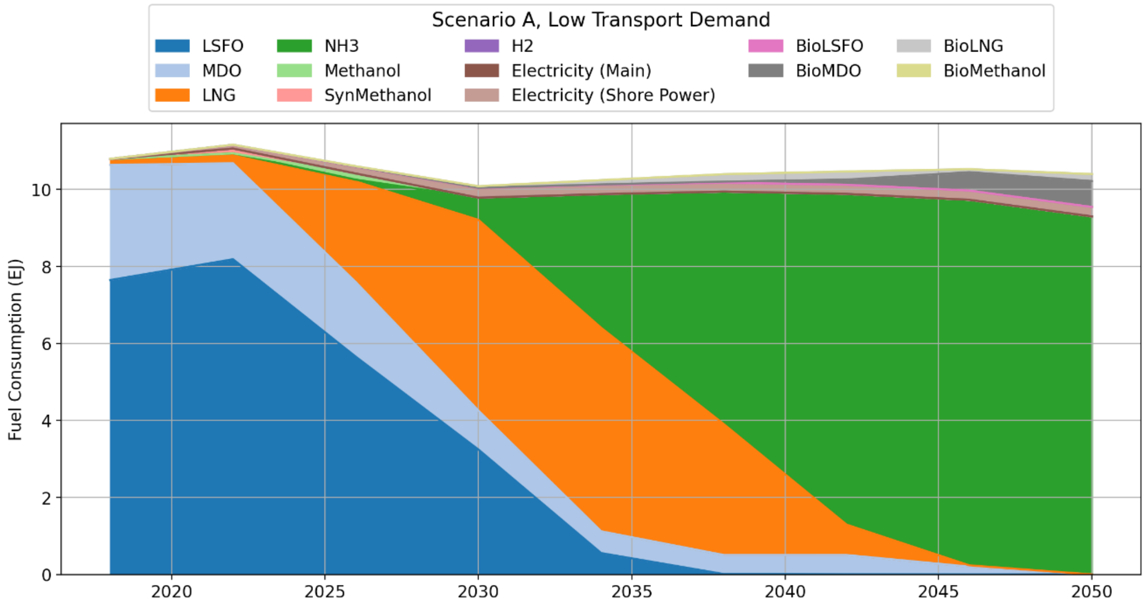


Figure 3.7(b)

Figure 3.7 – Scenario A (a) and Scenario A with low transport demand (b) fuel mix

3.3.2 In both scenario variations, a high rate of growth in the use of liquefied natural gas can be seen until 2030

Both scenario variations show rapid substitution to LNG during the 2020s, resulting in it becoming the dominant fuel (by energy) by 2030. Demand for LNG in the fuel mix peaks in

2030, but it rapidly loses its dominance, reducing to very low levels by 2040. This contrasts with the finding when modelling for the CMP, which did not forecast a significant take-up of LNG. One explanation for the differences between the two studies relates to assumptions used around the relative pricing of different fuels and machinery; however, these do not fully explain the difference. The current study takes into account the application of a regulation adopted since the earlier work; namely, CII. CII incentivises lower carbon intensity in operation. LNG is superior to LSFO/MDO in terms of its operational CO_2 (TTW) emissions (approximately 20% lower), and it is therefore attractive as a means of compliance with the CII targets. During the 2020s, the carbon price needed to achieve the targeted reduction in CO_2 emissions in Scenario A is low. At these low levels of carbon price, the relatively lower operational (TTW) CO_2 emissions of LNG receive a competitive advantage over LSFO/MDO. And although the zero CO_2 emissions of hydrogen-derived fuels such as ammonia results in an even greater advantage than LNG in terms of carbon pricing, for most ships in the fleet the carbon price in the 2020s is not yet great enough to close the gap in their relative competitiveness.

The competitive advantage of LNG arising from both the CII regulation and this lower level of carbon pricing explains this high take-up of LNG in the results. However, the results obtained for the current study's scenario do not mean that this outcome is preferable to the transition shown in the CMP modelling, which did not see large take-up of LNG, but a transition predominantly from the incumbent fossil fuels (LSFO and MDO) directly to ammonia. Further discussion of these differences, and the consequences of high take-up of LNG to methane (CH_4) and CO_2e emissions are included in Section 4.3.1.

3.3.3 Ammonia use grows rapidly to become the dominant fuel by 2040

Under both variations of Scenario A the 2020s see initial use of a number of alternatives to fossil fuels, which are categorised into two groups: the SZEFs, which include hydrogen (H_2), ammonia (NH_3) and synthetic methanol (SynMethanol); and the biofuels, which are constrained in supply and therefore do not have the same scalability. The different fuels can be used with different combinations of machinery. Both internal combustion engines (the incumbent technology) and fuel cells (a potential new technology) are considered as options during the modelling.

By 2030 the most dominant alternative to fossil fuels is the SZEF ammonia which, in both variations of Scenario A, accounts for approximately 10–20% of the fuel mix by 2030, but then grows rapidly to a share of 80% or more from 2042.

The finding that ammonia is the dominant SZEF is consistent with the CMP study. It can be explained by the relative competitiveness of the different SZEFs, which results from both the differences in price (relating to differences in the cost of production per SZEF) and the differences in the machinery and equipment associated with use of each SZEF on ships. The assumptions and their derivation are detailed in the Technical Annex. In summary, ammonia has a higher cost of production than hydrogen, but a lower cost of production than synthetic methanol. Hydrogen, however, has higher costs associated with storage onboard ships (and on land) than either ammonia or synthetic methanol. The lower onboard costs of ammonia compensate for its higher production costs relative to hydrogen.

3.3.4 Biofuels are not used in large volumes in the transitions, but do play a role as pilot fuels in the 2040s

Constraints assumed about the availability of biofuels limit their take-up in both scenario variations (see Technical Annex for detail on these assumptions). The constraints assumed are the same in both scenarios. Lower transport demand also reduces the total demand for energy, so the share of the total energy that is biofuel is slightly different in the two scenario variations. Biofuels (predominantly bioLNG and bioMDO) constitute approximately 10% of the energy mix by 2050 in the lower demand scenario, and approximately 7% of the energy mix in the higher demand scenario.

The volume of biofuels available increases over time[39], so their role during the transition from fossil fuels to SZEFs during the 2020s and 2030s is minimal: biofuels do not enable a significant portion of the fleet to avoid needing to move to SZEF during this period. However, biofuels do have an important role in substituting the remainder of fossil fuels in the 2040s. This role is important because the identified use of SZEFs still relies on a volume of hydrocarbon fuel to be available for use as a pilot fuel (a small amount is injected with ammonia to enable the ammonia's combustion). The model identifies ammonia use in internal combustion engines as the least-cost way to achieve the target CO_2 trajectory (as opposed to use of ammonia in fuel cells). Therefore, the constrained supply of biofuels, while not large relative to the scale of SZEF use, has value as a competitive solution for the decarbonisation of that pilot fuel.

3.3.5 Direct electricity use becomes only a small share of international shipping's total energy demand

The modelling of the two scenario variations included several different ways that the fossil fuel currently used on ships could be substituted by direct use of electricity, including:

- Using shore power (also known as cold ironing) whereby the ship is connected to an electricity supply when in port and alongside a berth, so that any electricity needs normally supplied by an onboard electricity generator powered by fossil fuels, is substituted by the port's electricity supply
- Using batteries on the ships to store electricity, with battery charging occurring when alongside in port.

Although both options are needed in the period to 2050 (Section 3.3.1), in total electricity accounts for only a small share of the total energy mix used in international shipping (2.3% by 2050). This is because the two sources of electricity are used for different purposes:

- The role of shore power is fundamentally limited. It can only replace the energy consumption in the auxiliary machinery, and only for the time that a ship is alongside a berth, whereas the majority of a ship's fuel and energy consumption occurs at sea and in main machinery
- The modelling shows that the option of storing energy in batteries (including for use in propulsion) is not cost competitive relative to SZEFs for much of international shipping because of the cost of batteries and the low frequency at which they could be recharged. This does not mean that there will not be some ship types/sizes for

[39] In the central and high biofuel availability trajectories, see Figure 3.31. For further detail refer to the Technical Annex, Section 3.3.1.

which battery electrification is the most competitive solution; rather battery power is better suited to smaller ships operating on shorter routes, more commonly found in domestic shipping than international shipping. The earlier modelling work for CMP included analysis of domestic shipping and showed significantly greater opportunity for battery electrification in that fleet.

3.4 Lower transport demand reduces the CO_2 emissions, if the carbon price is held constant

The CO_2 emissions trajectories for the two variations of Scenario A can be seen in Figure 3.8. Both profiles reach approximately zero CO_2 emissions by 2050, as prescribed by the target. Small residual emissions in 2050 are associated with the use of some fossil fuel as a pilot fuel (see Section 4.3). As described in Section 2.5, the 4-year time-step does not capture the CO_2 emissions implications of the short-term contraction in demand in 2020 due to Covid-19. This transport demand sensitivity results in a very similar profile, consistent with the target trajectory specified for Scenario A. However, there is a small reduction in magnitude for the emissions at any given point in time for the lower transport demand scenario. This is consistent with Figure 3.7, and the lower energy demand in the scenario with lower transport demand.

One implication of this finding is that if decarbonisation of shipping is primarily driven by a carbon price and that carbon price is held constant, there will be a sensitivity to the absolute reduction in CO_2 (and GHG) emissions achieved at interim points throughout the transition (e.g. 2030, 2040), as a function of how transport demand evolves relative to the forecast. However, as long as the overall target is zero GHG emissions no later than 2050, the outcome for a specific scenario is not affected by the demand (lower or higher), because by that point 100% of the fossil fuel should have been substituted irrespective of the demand scenario.

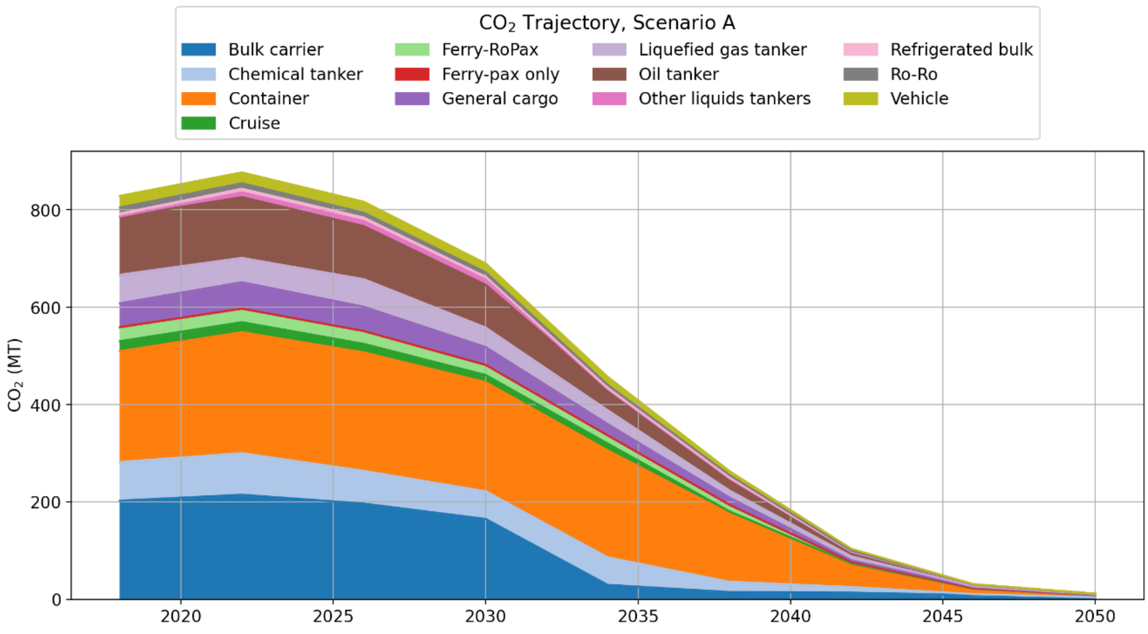


Figure 3.8(a)

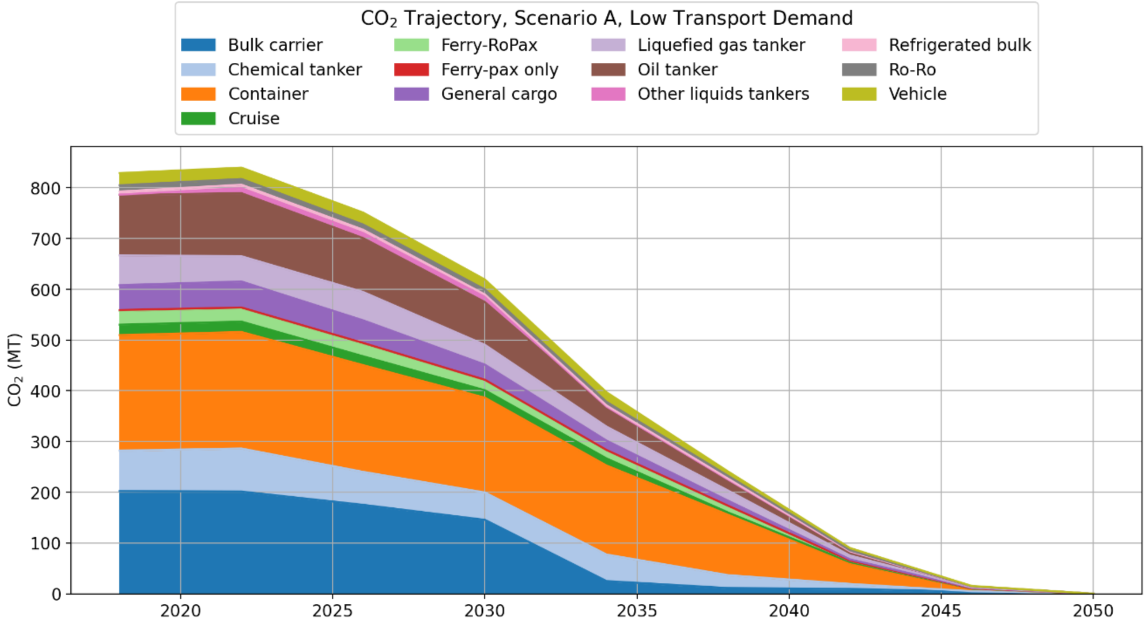


Figure 3.8(b)

Figure 3.8 – TTW CO_2 emission trajectories, Scenario A (a) and Scenario A with low transport demand (b)

Figure 3.9 presents the normalised energy-related cost per tonne of CO_2e abated in Scenario A and Scenario A with low transport demand. The normalisation is applied because the two scenarios have different transport demands, and result in different absolute and therefore cumulative CO_2 emissions. This normalisation controls for these exogenously imposed causes of variation in order to isolate the sensitivity to unit cost of transport created by different rates of demand growth.

In order to fairly compare the results of each sensitivity scenario, it was necessary to control for both the different transport demand scenarios used, as well as the different degrees of decarbonisation achieved in each. For instance, sensitivity scenarios where the price of SZEFs is high do not achieve complete operational decarbonisation within the modelling timeframe (i.e. by 2050); as such, the absolute abatement results simulated in each scenario must be accounted for in the comparisons. Therefore, both transport demand and CO_2e abatement are included in the denominator of cost for these figures.

The lower transport demand results in a small reduction in the CO_2e normalised energy-related costs (relative to the BAU with CII/EEXI[40]) when compared to the core Scenario A transition. This is because the lower transport demand growth reduces the quantity of SZEFs needed to achieve the same level of carbon emissions. This raises a potential role for demand-side policy (e.g. policy to reduce demand for transport) for helping to reduce the cost of shipping's transition away from fossil fuel.

[40] Please note that all of the CO_2e normalized energy-related cost plots are relative to the BAU with CII/EEXI. These plots show the difference in costs in fuel OPEX, non-fuel OPEX and CAPEX costs for the indicated scenario vs BAU with CII/EEXI scenario divided by the difference between the BAU (with CII/EEXI) CO_2e and the indicated scenario divided by the total transport work of that scenario. For example, the fuel OPEX bar is calculated for a **given scenario and year** by subtracting the fuel OPEX from the BAU (with CII/EEXI) fuel OPEX, then dividing that by the difference between the BAU (with CII/EEXI) CO_2e and the CO_2e of the indicated scenario. This is then divided by the transport supply for the indicated scenario and year. This process is repeated for all cost categories, scenarios and years.

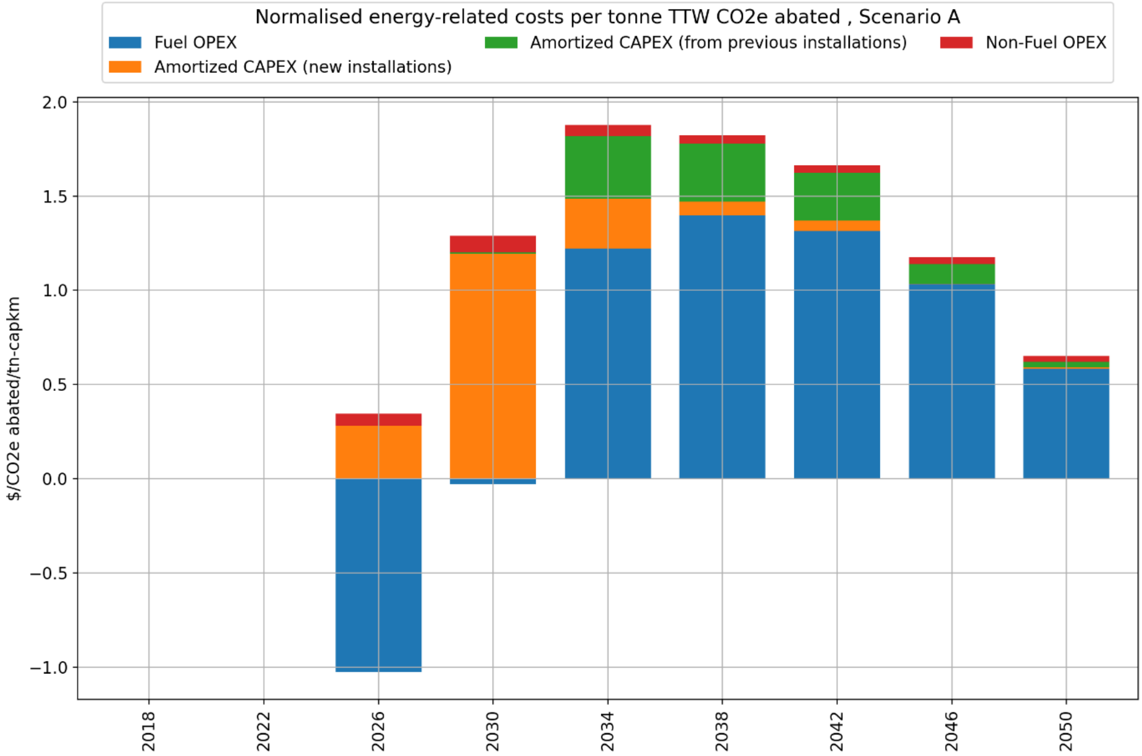


Figure 3.9(a)

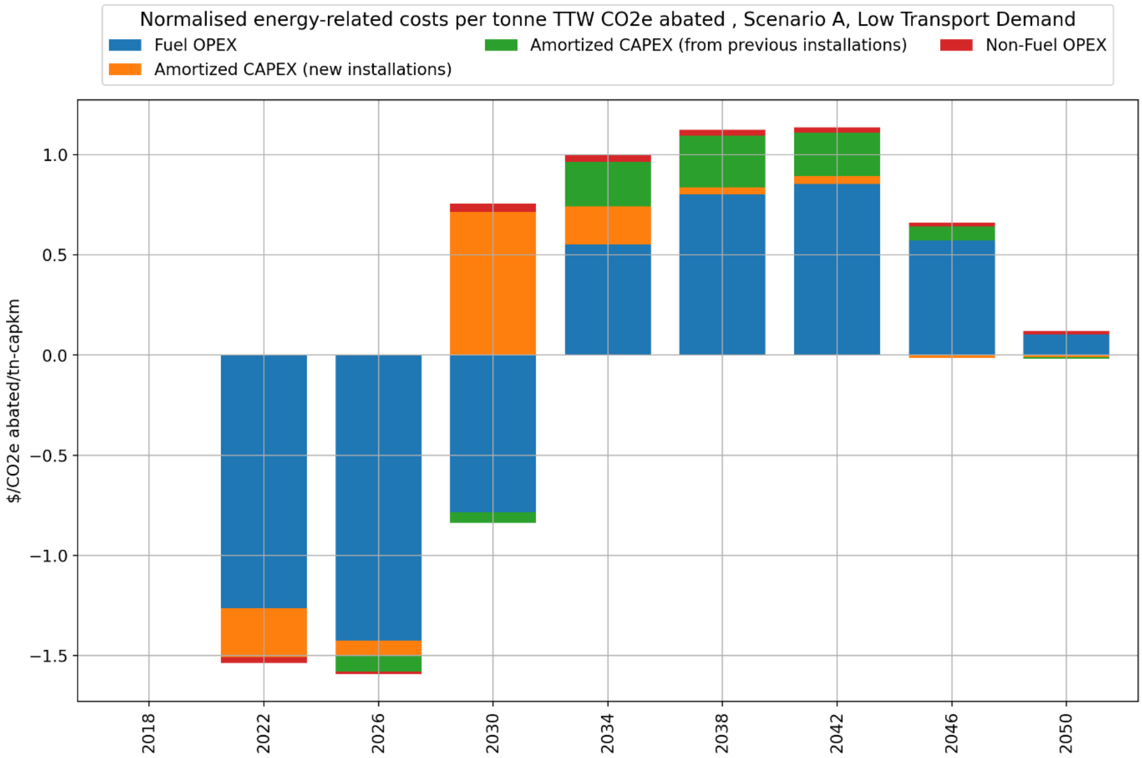


Figure 3.9(b)

Figure 3.9 – Normalised energy-related costs per tonne TTW CO_2e abated, Scenario A (a) and Scenario A with low transport demand (b), relative to BAU with CII/EEXI

3.5 Profit-maximising decision-making in decarbonisation scenarios leads to significant amounts of retrofitting, including double retrofitting

Figure 3.10, Figure 3.11 and Figure 3.12 compare the number of vessels in each year that have retrofitted machinery (to enable use of a different fuel) in each of the core scenarios. There are two types of retrofit that dominate the scenarios: retrofits to LNG (from LSFO) and retrofits to ammonia (from LSFO and LNG). To place the results in context, the fleet size is approximately 60,000 ships in 2018 rising to approximately 100,000 by 2050 (the growth in the size of fleet is approximately the same in each of Scenario A, B and C).

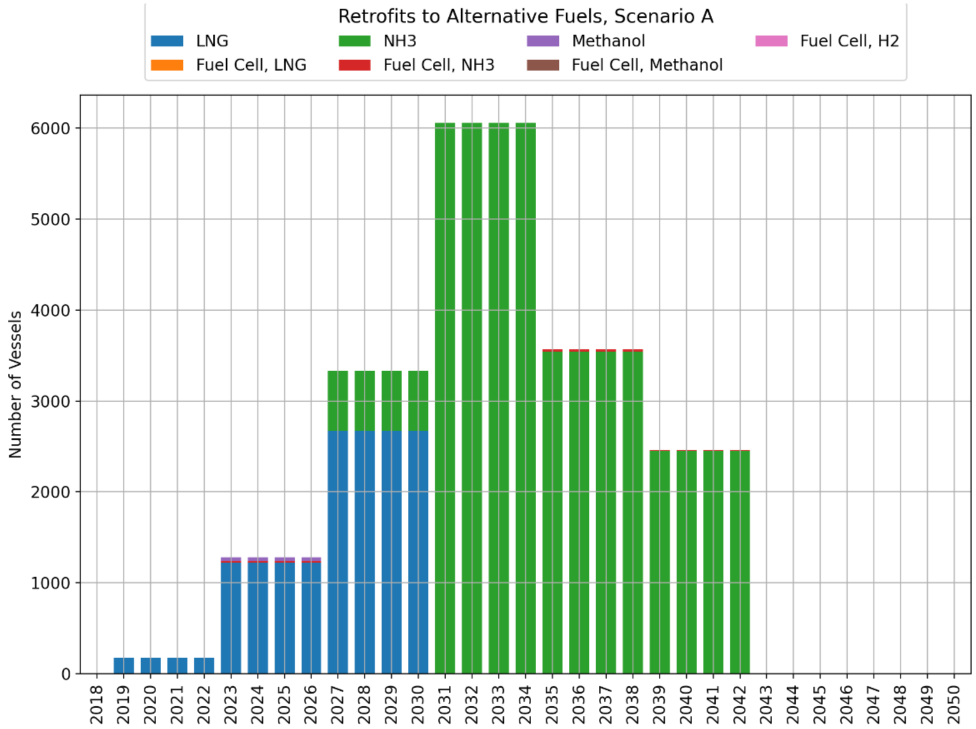


Figure 3.10 – Rate of retrofit to alternative fuels, Scenario A

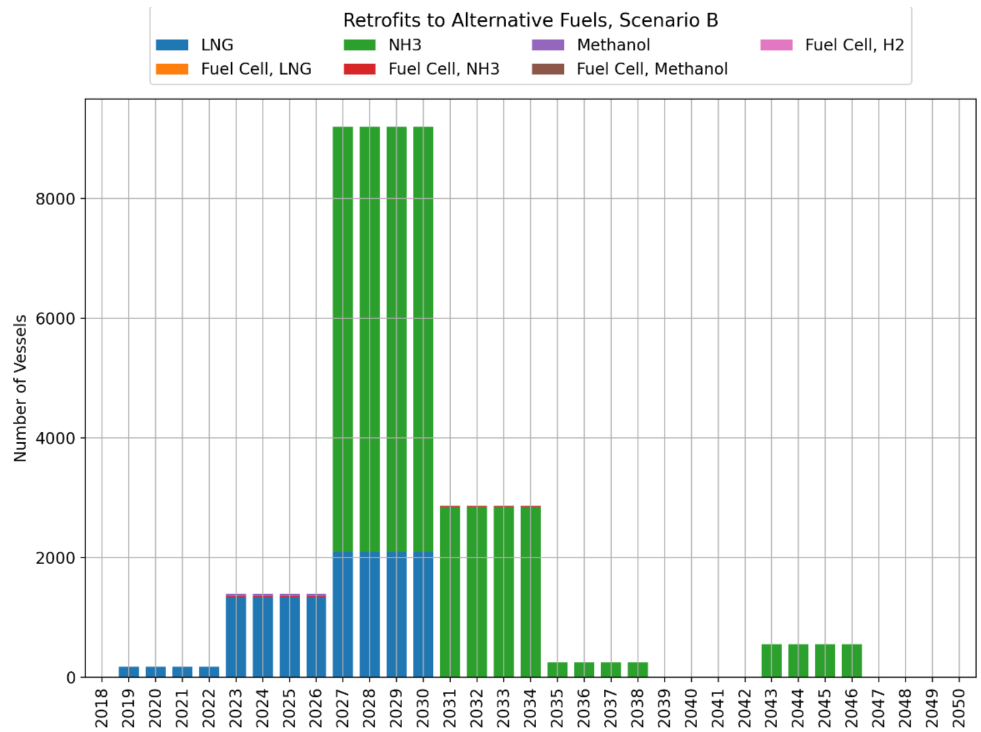


Figure 3.11 – Rate of retrofit to alternative fuels, Scenario B

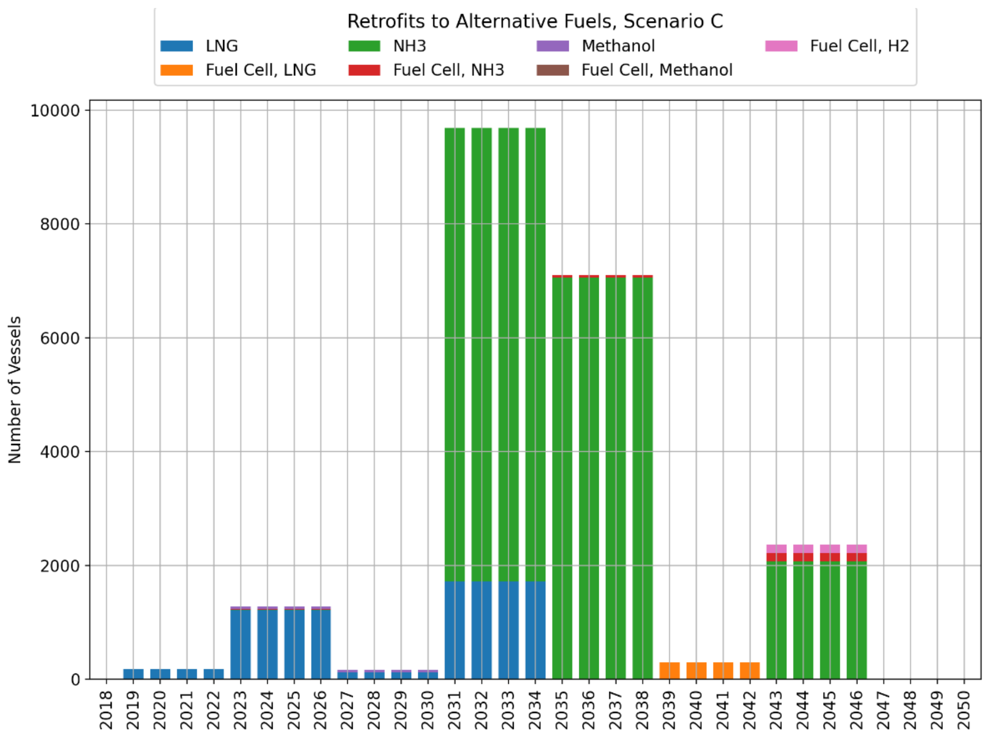


Figure 3.12 – Rate of retrofit to alternative fuels, Scenario C

As discussed in Section 3.3.1, Scenario A experiences a strong growth in demand for LNG in the period to 2030. That growth in demand is associated with new-building, but also with a significant amount of retrofitting (a total of approximately 15,000 ships would have been retrofitted to run on LNG by 2030). In addition to that retrofitting, there would also be a large amount of retrofitting to ammonia, which happens in two periods – first in the late 2020s and early 2030s and then in the late 2030s and early 2040s.

This latter demand for ammonia retrofitting is associated with substituting the remainder of the LNG fuel use before 2042, and affects ships that were built in the 2020s to run on LNG, as well as some ships that were originally built to run on LSFO, retrofitted to LNG in the 2020s and then retrofitted to ammonia. To illustrate this phenomenon of 'double retrofitting', which occurs in all three core scenarios, Figure 3.13 to Figure 3.15 below illustrate the rate of double retrofitting, counting only those vessels that incurred more than one main machinery retrofit during the modelling period. In the figures, each colour indicates a specific machinery transition pair, so each of the double retrofitted ships appears twice in the plot. The dominant double retrofit sequence is an initial retrofit from LSFO to LNG followed by a second retrofit from LNG to ammonia.

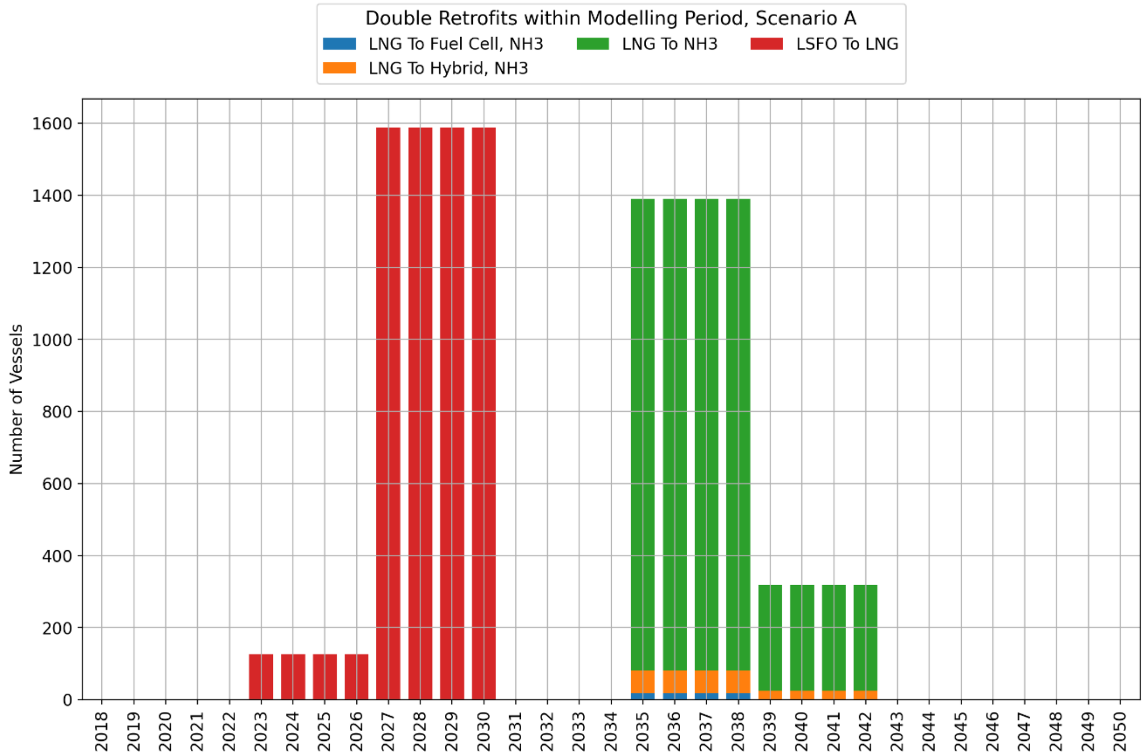


Figure 3.13 – Rate of double retrofits, Scenario A

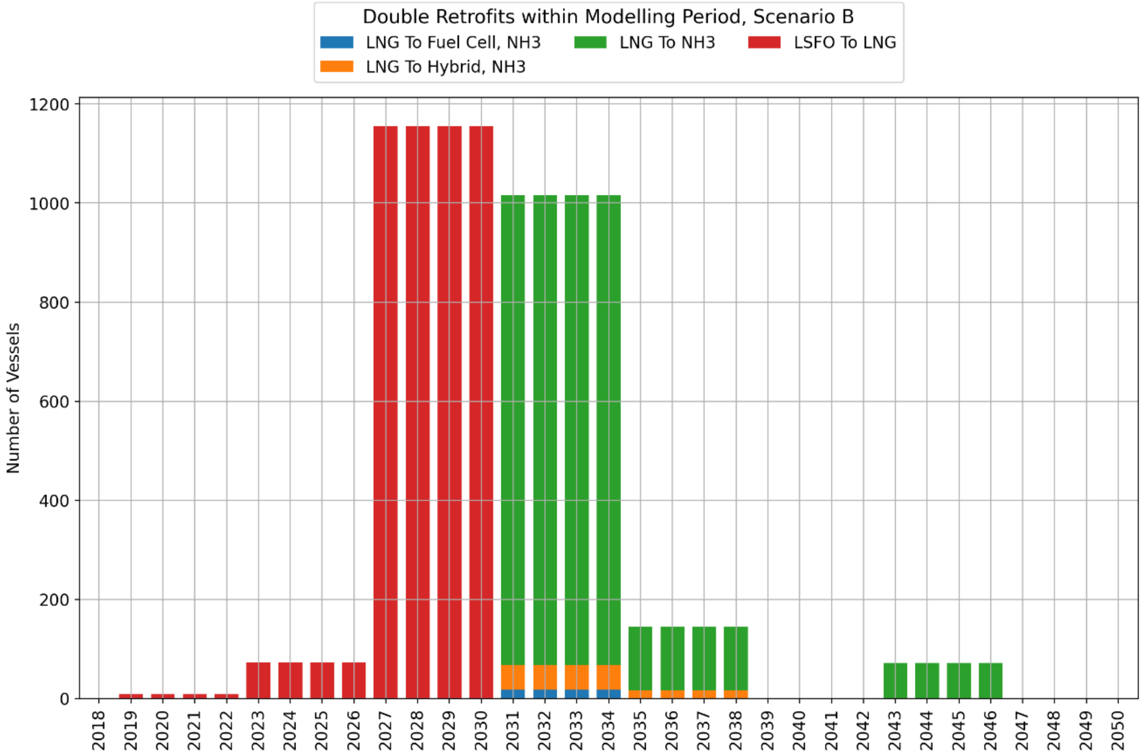


Figure 3.14 – Rate of double retrofits, Scenario B

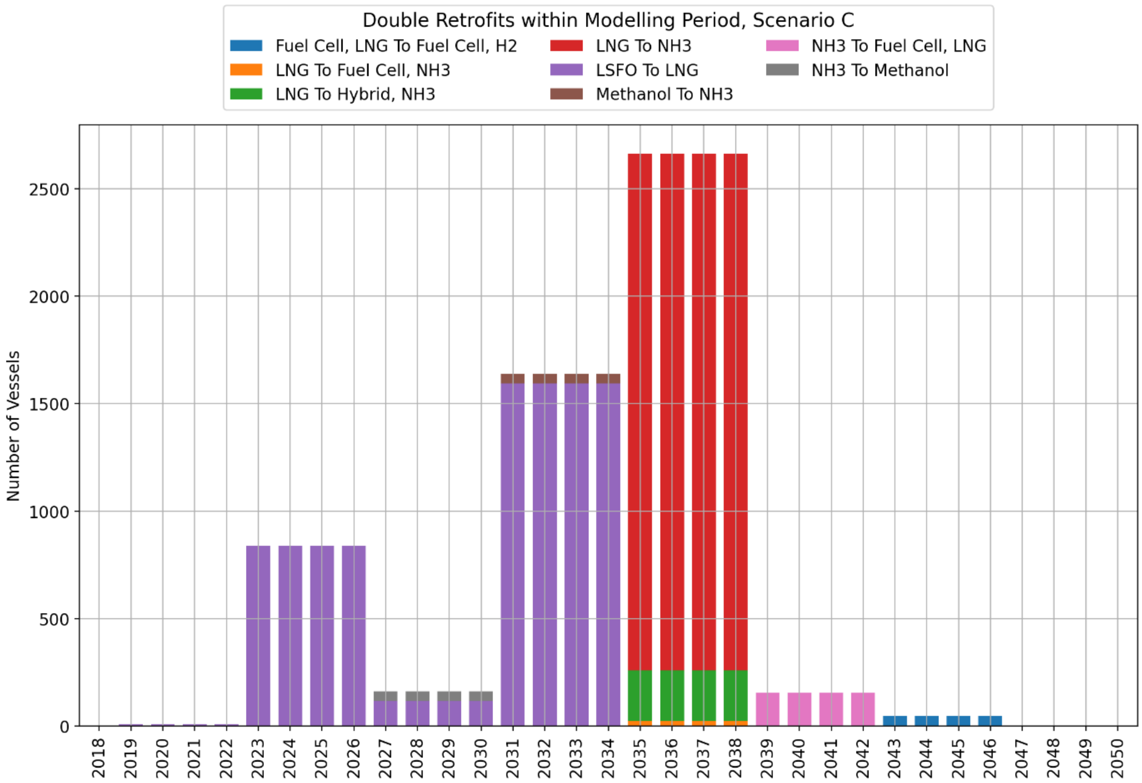


Figure 3.15 – Rate of double retrofits, Scenario C

The results for Scenario A can be contrasted with the results for Scenario C, which experiences only a shorter but more condensed period of retrofitting to ammonia. The period of retrofitting to ammonia is focused in the 2030s: a rate of retrofitting of approximately 5,000 ships per year is sustained through the decade. Relative to the other scenarios, Scenario C sees the highest retrofitting rates, which is consistent with the shape of the target CO_2 profile, which starts late and then, in order to sustain consistency with the targeted cumulative emissions, needs to reach very low absolute GHG emissions by 2040.

Scenario C also sees approximately 15,000 ships retrofitted to use LNG (similar to the number in Scenario A), but over a longer period of time and with the rates of retrofitting not exceeding 1,500 ships per year. Scenario C also experiences the largest rates of double retrofitting (LSFO to LNG then LNG to ammonia).

Scenario B sees the period of retrofitting to ammonia condensed into the period 2026–2034; approximately five years earlier than in Scenario C. However, the rates of retrofitting required in this period are lower than in Scenario C because the transition to full substitution to SZEF can happen more gradually, relying more on substitution through the delivery of SZEF-compatible new-builds than other scenarios. Even in Scenario B, there are conditions that incentivise retrofitting to LNG during the 2020s; however, with the longer period over which LNG is used as a marine fuel (see Section 4.4.2), these ships are less likely to need to be retrofitted a second time (from LNG to ammonia).

The modelling generated a number of examples where fuel cells are being retrofitted in each of the three scenarios, including early on in the transition. Although this does not constitute a large number of retrofits and therefore is not likely to be significant to the overall cost of the transition, it does include a small number of retrofits to LNG, ammonia and hydrogen fuel cells. In Scenario C, the retrofit from ammonia ICE to LNG fuel cell is due to a small rebound (or increase) in CO_2 emissions during the 2040s. These LNG fuel cell vessels then convert to lower carbon alternatives in 2050. Converting to either hydrogen fuels cells or back into their original form of ammonia ICEs. This is an artefact of the model's iterative solver approach combined with the rapid carbon reductions of Scenario C, and not considered a true market response.

3.6 There is a significant change in the profile over time of energy-related costs of international shipping, as a function of the shape of decarbonisation

Figure 3.16 to Figure 3.18 present the normalised total energy-related modelled cost profiles for scenarios A to C. These results include the amortised capital expenditure (CAPEX) costs (machinery, and energy efficiency and wind-assistance technology), as well as the total fuel and non-fuel operating costs. To differentiate between newly amortised CAPEX - i.e., purchases made within the current 4-year simulation period - and previously amortised CAPEX, which refers to the debt still owed on purchases made in previous modelling periods, the amortised CAPEX has been categorised into "new installations" and "from previous installations” in the plots below.

The carbon cost represents the amount spent paying a carbon levy (e.g. if using a fossil fuel during a period when there is a non-zero carbon price): in these figures there is no assumption applied around redistribution of that revenue (it just accrues). Section 3.6.3 discusses scenarios of redistribution that reduce the magnitude of the carbon cost.

To produce the charts for Figure 3.16 to Figure 3.18 the costs are totalled for all ships in the international shipping fleet, and then divided by the total transport work done by international shipping (the quantification of demand) in order to normalise the costs per unit of transport work done. This controls for the fact that, during the period from 2018 to 2050, there was a growth in the demand for transport (shipping). The other components of the cost of owning and operating ships (e.g. the cost of building the hull and superstructure, the cost of technology/equipment that is not related to the storage and use of energy on the ship, port costs, crewing) are not included in those figures. The total costs shown in the figures therefore represent the normalised cost premium for the energy and energy-machinery costs of the fleet and how these vary over time as these costs adjust to accommodate the target CO_2 trajectory. This is referred to as 'normalised energy-related costs'.

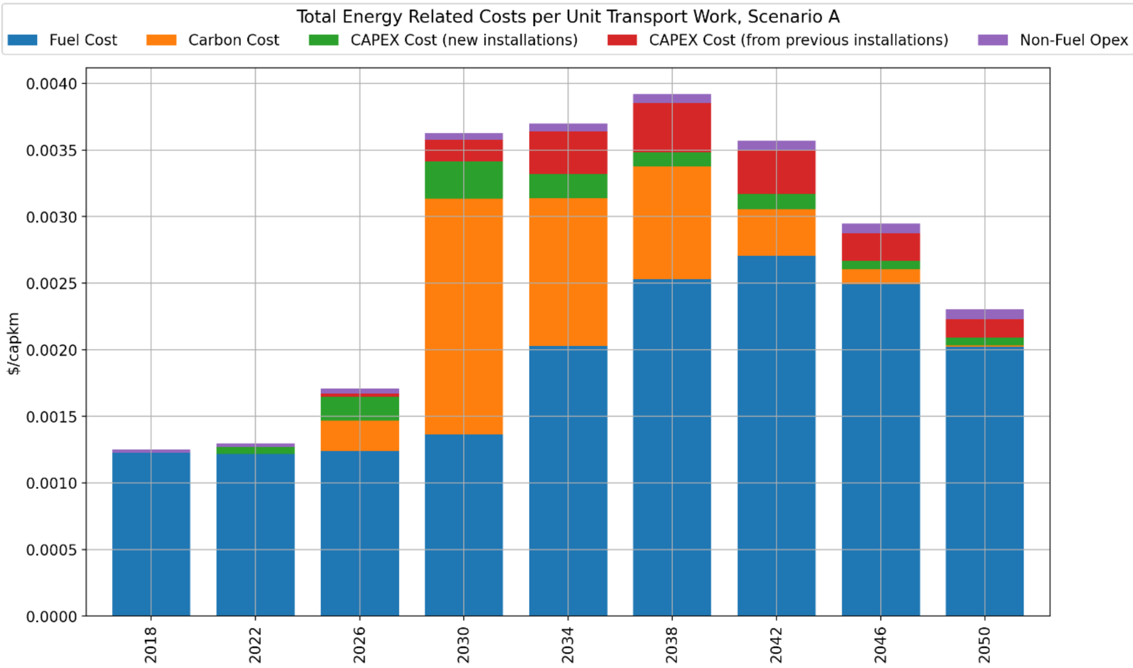


Figure 3.16 – Total energy-related costs per unit of transport work, Scenario A

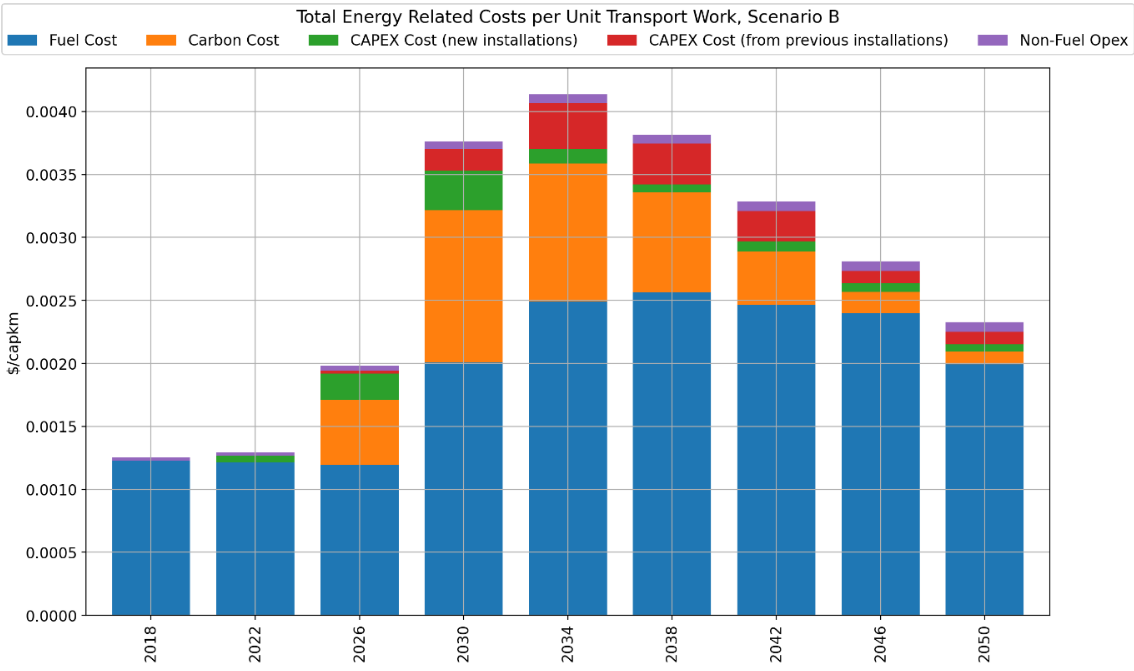


Figure 3.17 – Total energy-related costs per unit of transport work, Scenario B

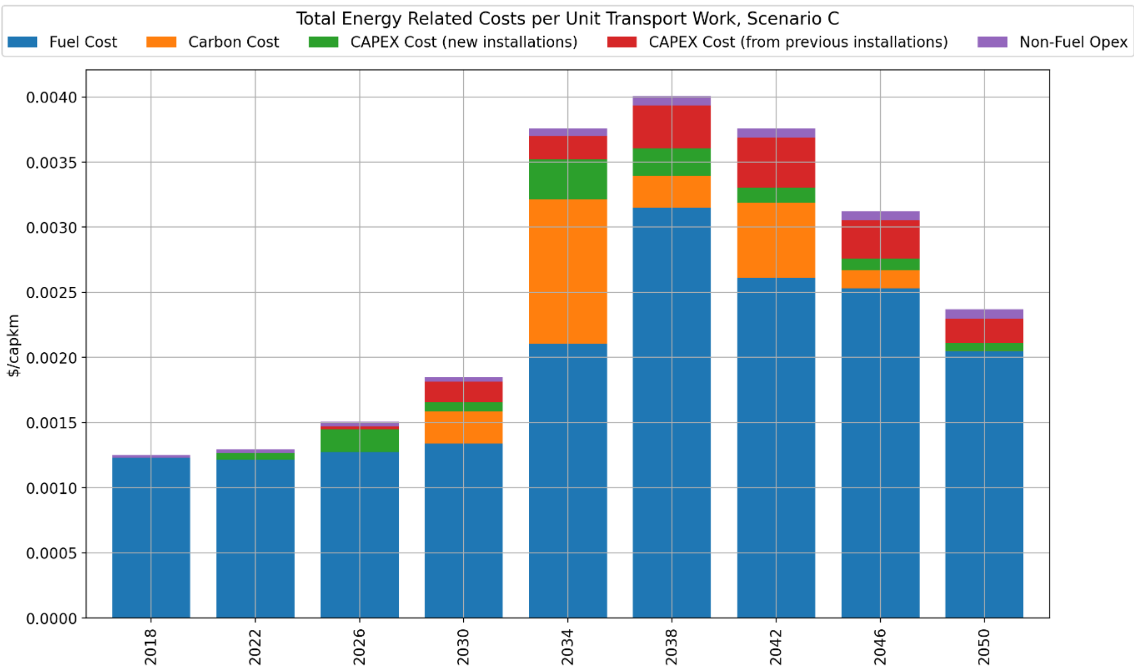


Figure 3.18 – Total energy-related costs per unit of transport work, Scenario C

3.6.1 Operating international shipping with zero GHG emissions can be expected to increase energy-related costs

In all three scenarios the normalised energy-related costs increase between 2018 and 2050. This is the result of a combination of the following:

- A transition away from fossil fuels to SZEF, which means that by 2050 in all three scenarios there is near full substitution to SZEF
- The relative higher price of SZEF, when compared with the fossil fuels in use today

- The take-up of energy efficiency and wind-assistance technology across the global fleet reducing the energy needed per unit of transport work
- The reduction in technology costs (CAPEX) over the period to 2050
- The reduction in cost of SZEF over time, as both the feedstock cost, especially renewable electricity, and the cost of its production technology reduces over the period.

In all three scenarios the costs reduce significantly over the period 2040–2050, predominantly driven by the forecast SZEF prices, which sees the cost of SZEF reduce as a consequence of 'learning effects' relating to learning in the maritime sector as well as in the wider energy system, and which are also expected to increase learning on renewable electricity and low/zero GHG hydrogen production during this period.

In total, by 2050, the normalised energy-related costs have increased by approximately 85% relative to 2018. However, those costs represent only part of the total costs of owning and operating ships, so if all else stays unchanged the increase in the total cost of international shipping as a service will be less than 85%.

The carbon cost forms a significant and varying component of the normalised energy-related cost in all three scenarios. Scenario C, which has the shortest transition period, sees the lowest cumulative carbon cost over the period. Scenarios A and B both have an extended period over which a high carbon price is incentivising the transition to new fuels, but during which there remain many ships still using fossil fuels.

3.6.2 Enabling the transition creates a peak in costs during the transition, but the choice of target CO_2 trajectory changes the timing of that peak

All three scenarios see a peak in the normalised energy-related costs in the 2030s. This decade sees a high carbon cost, high capital costs (because of retrofitting activities) and rapid growth in fuel costs driven by the substitution to SZEF. The fuel cost increase during this period is also driven by the comparatively higher price of SZEF during the period.

Unsurprisingly, the different target CO_2 trajectories change the point in time at which a peak in normalised energy-related costs occur. Scenario B sees a large increase in this cost in the mid- to late 2020s (approximate doubling), and then continued growth in that cost to the highest levels of all scenarios by the mid-2030s. Scenario C sees the normalised energy-related costs remain approximately constant until around the middle of the 2030s. In Scenario A, the sudden cost increase occurs in the early 2030s.

Therefore, although the end point in 2050 is the same for all three scenarios, the shape of the target CO_2 trajectory creates different profiles in Figure 3.16 to Figure 3.18 for the timing of the peak in cost, and the shape of the peak.

3.6.3 Decisions made about how carbon revenues are used can create variations in the cost profile of the transition

The carbon cost shown in Section 4.2 is an artefact of the modelling method (see Technical Annex for full description). The carbon cost is used to incentivise a switch away from fossil fuel in the model, and to provide a way to ensure the target CO_2 trajectory is achieved.

In practice, this cost is only present if it is a feature of the policy designed to achieve the transition. There are multiple conceivable scenarios for that policy design, including the following:

- If a carbon price is applied as a tax in which there is no hypothecation of the revenues (i.e. the revenues are simply returned to governments), then the carbon cost would manifest as a cost as shown in Figure 3.16 to Figure 3.18
- If a command-and-control policy (e.g. a fuel standard) is used instead of a carbon price, then there is no carbon cost and only the CAPEX and fuel costs are shown
- If a carbon price is applied as a levy, there can be choices to be made about revenue use. If the revenue is efficiently reinvested into the sector's decarbonisation, this cost will be reimbursed to the sector overall. If revenue use comprises a mix of efficient reinvestment into the sector's decarbonisation, and use out of sector, then some of the cost will be reimbursed to the sector, some cost will remain for the sector.

Figure 3.19 to Figure 3.21 show the change in normalised energy-related costs if the revenue is deployed in order to reduce costs of the transition (e.g. through direct subsidy of energy-related technology, fuels or fuel production). Two cases are considered: 50% of the carbon revenue being reinvested in energy-related costs; and 100% of carbon revenue being reinvested in energy-related costs. The latter represents the case of command-and-control policy or a levy with 100% of revenue reinvested in energy-related costs. The former (50%) represents a levy in which 50% of the costs are reserved for use outside of shipping's energy-related costs and 50% of the costs are reinvested in energy-related costs.

These plots all assume that the revenue is deployed for the chosen use at the same time as it is generated. In practice, revenue uses enabled by a levy could be phased to provide infinite variations in the profile of normalised energy-related cost premium over time than those shown here. Furthermore, revenue uses include the potential to reduce transport costs other than those that are energy-related (e.g. those associated with ports and infrastructure in which efficiency improvements could reduce cost).

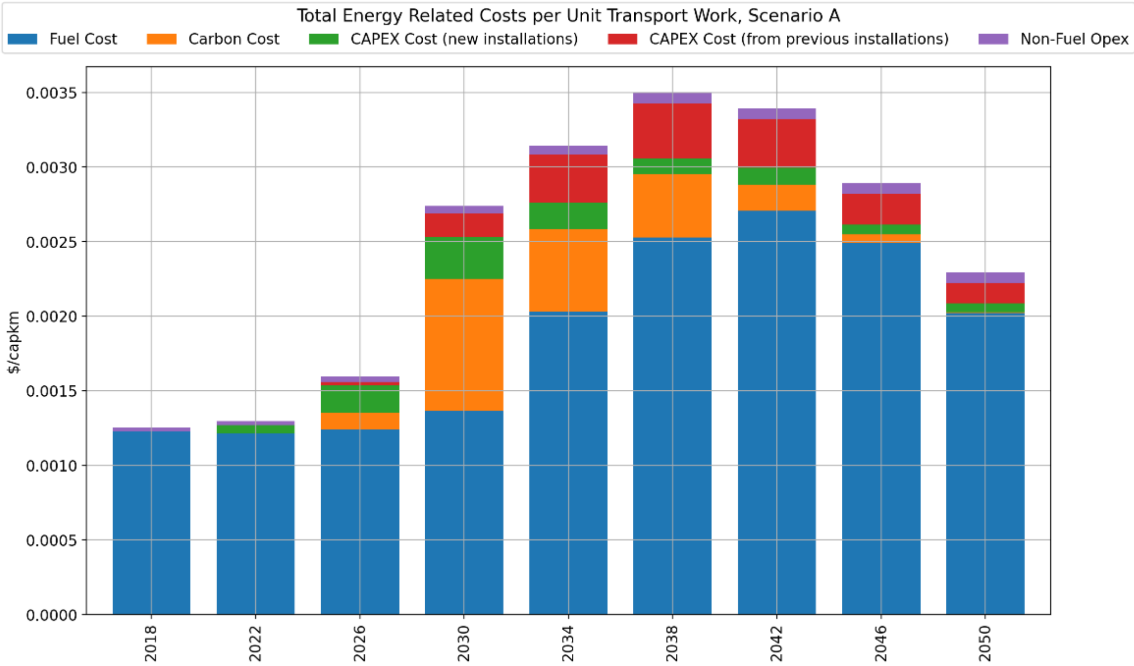


Figure 3.19(a)

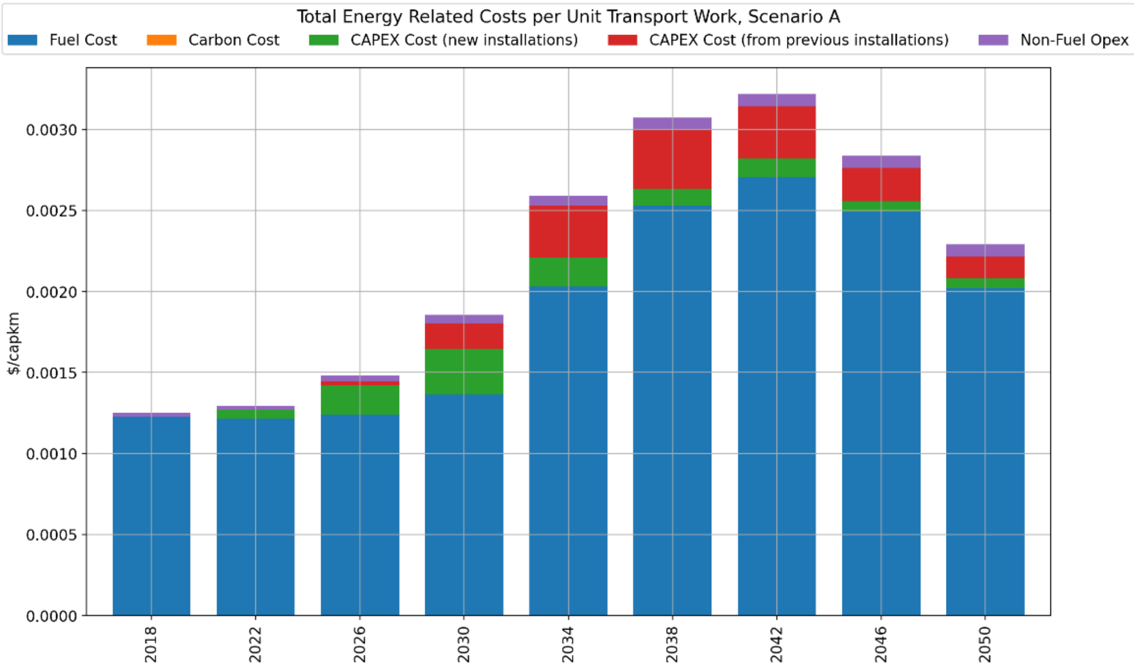


Figure 3.19(b)

Figure 3.19 – Total energy-related costs per unit of transport work, Scenario A, with 50% (a) and 100% (b) of the carbon costs reinvested

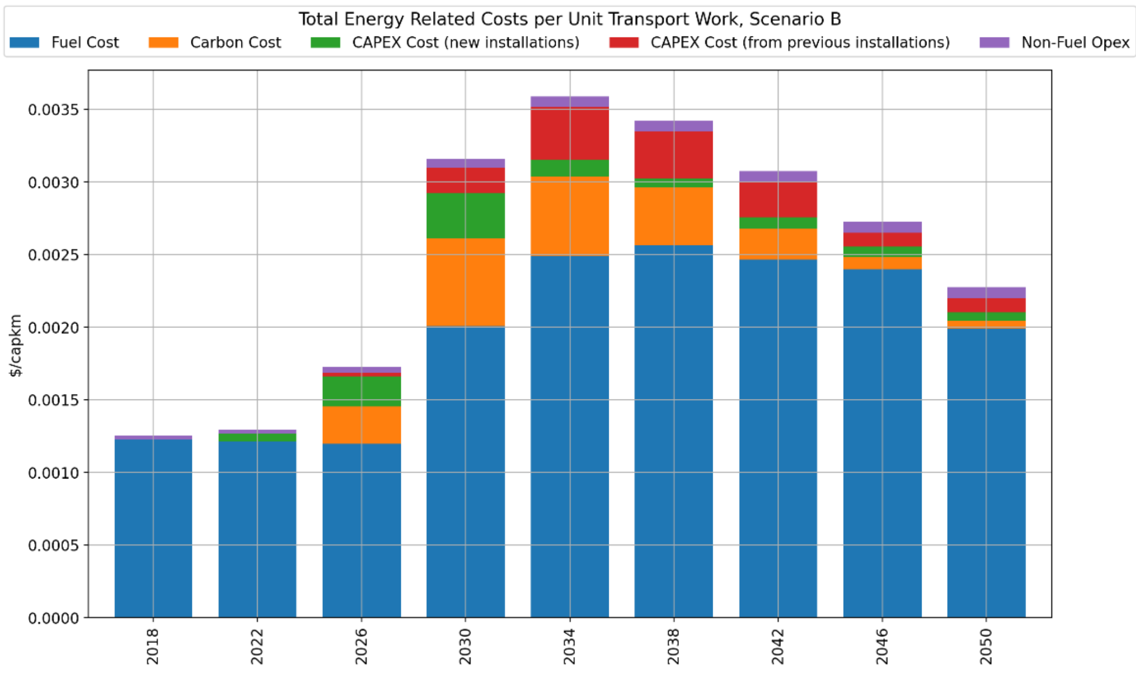


Figure 3.20(a)

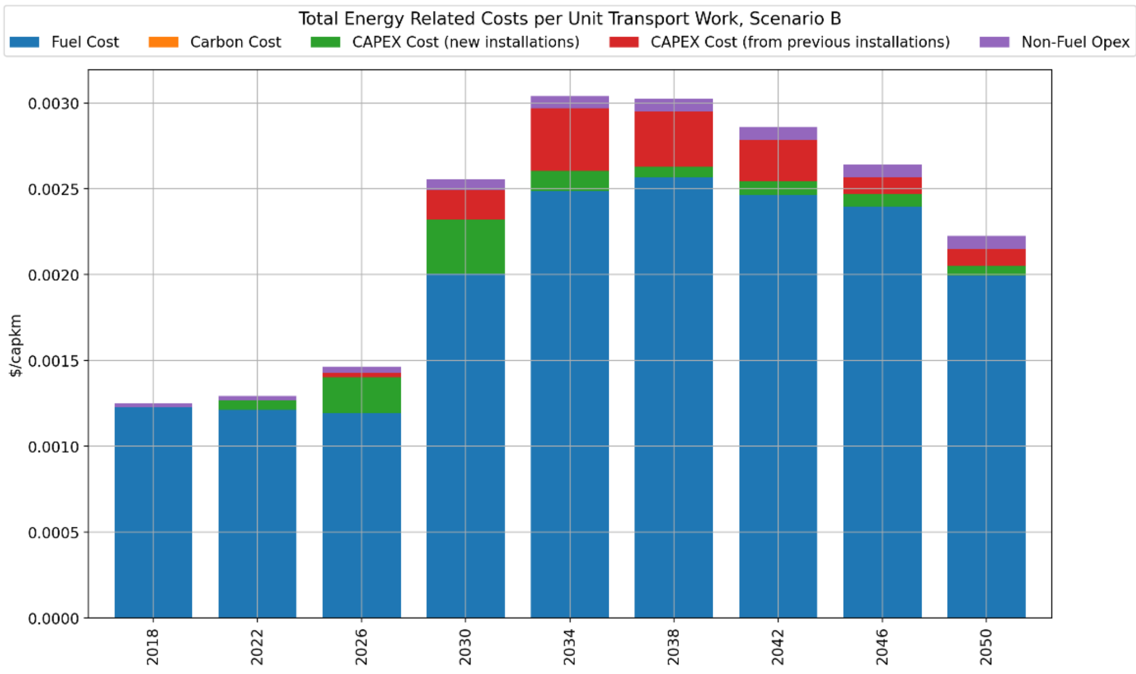


Figure 3.20(b)

Figure 3.20 – Total energy-related costs per unit of transport work, Scenario B, with 50% (a) and 100% (b) of the carbon costs reinvested

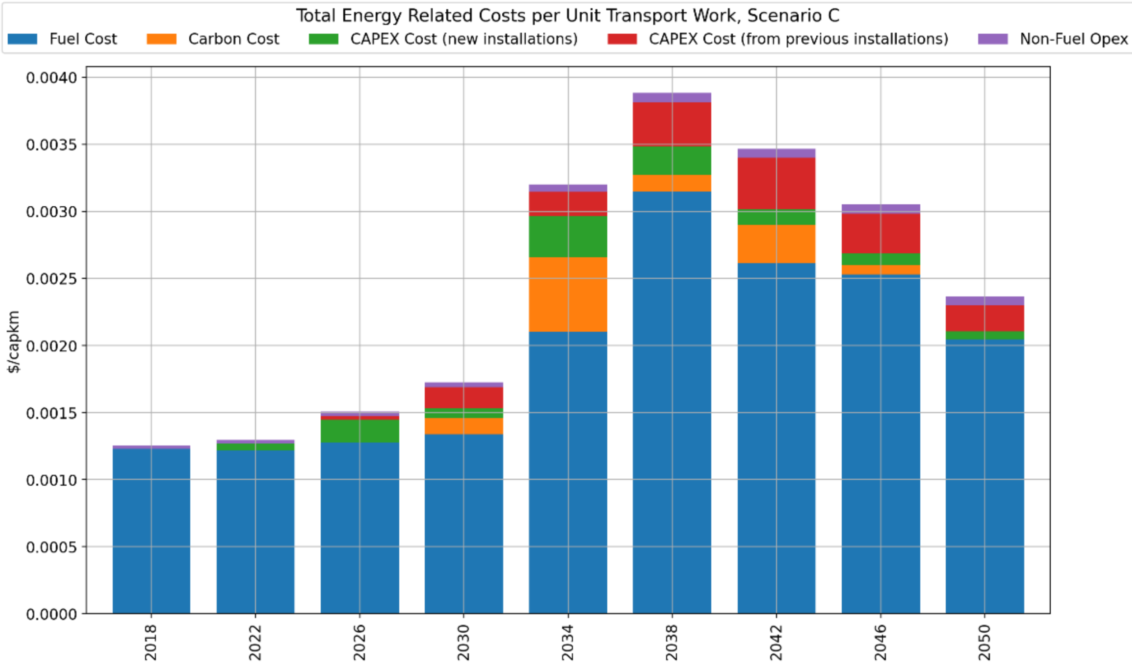


Figure 3.21(a)

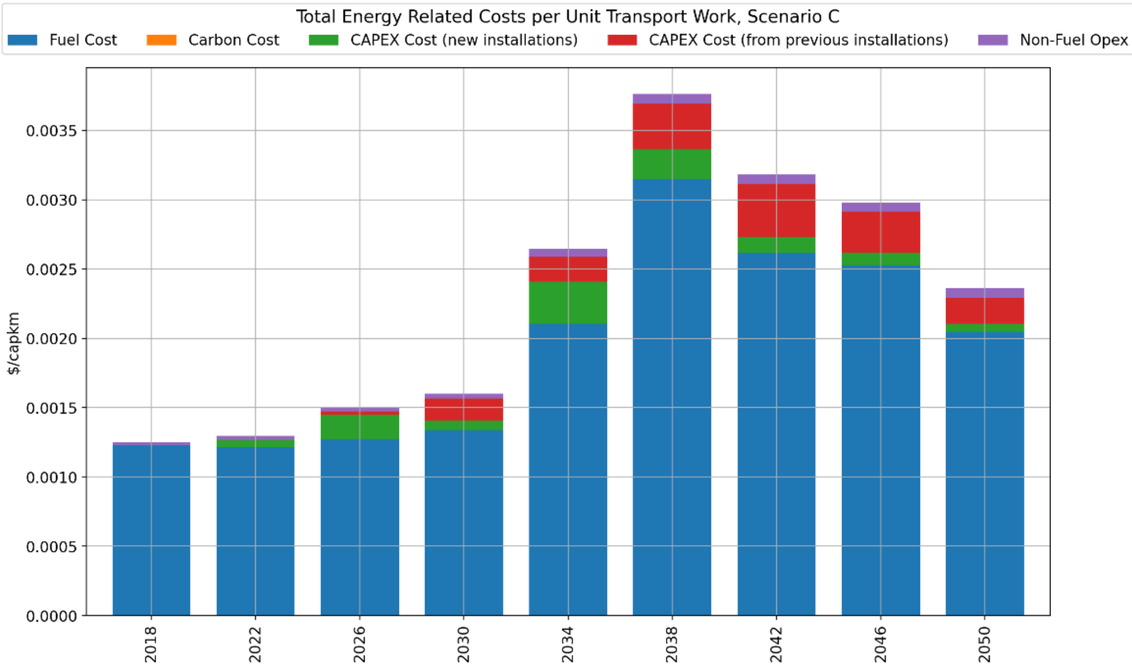


Figure 3.21(b)

Figure 3.21 –Total energy-related costs per unit of transport work, Scenario C, with 50% (a) and 100% (b) of the carbon costs reinvested

The results show that, with carbon costs excluded or partially included, the peak in the normalised energy-related costs moves later, towards the end of the 2030s and early 2040s.

3.6.4 There is a potential for premature scrapping to be an alternative to retrofitting

The alternative to using retrofits to enable the necessary steep rates of change in emissions and switch to SZEF is for vessels to be scrapped prematurely and new-build SZEF vessels used to replenish the fleet. Alongside the standard modelling assumption that all vessels are scrapped after 30 years, a second modelling approach was implemented that explores the role of premature scrapping in the transition, and quantifies the number of new-builds, retrofitted and prematurely scrapped ships for each of the three core scenarios. The two different approaches modelled to estimate scrapping behaviour are[41]:

- Conventional – ships are retrofitted as deemed cost effective, and are only scrapped at the end of their expected life (assumed to be 30 years based on expert judgment[42]).
- Premature scrapping – ships are retrofitted as deemed cost effective until they reach 20 years of operation. After that point, if at any subsequent point in time further retrofit is identified as the most profitable way to operate, the ship is scrapped. Furthermore, premature 20-year scrapping was implemented in two separate sub-analyses:
    - 'Retroactive premature scrappage': premature scrapping was retroactively applied as a post GloTraM analysis with the results of the premature scrappage having no effect on costs or simulated fleet decision-making.
    - 'Advanced premature scrappage': a single GloTraM run was implemented ('Scenario C Advanced Scrappage') where the impact of premature scrappage on the fleet evolution and therefore costs was modelled and estimated.

Figure 3.22 to Figure 3.24 present the results for Scenarios A to C in which the 'retroactive premature scrapping' method has been applied. The retrofit values in these plots can be compared with Figure 3.10 to Figure 3.12, which assume conventional 30-year scrapping. See Section 3.6.5 for the 'advanced premature scrappage' results.

Applying the assumption of retroactive premature scrapping, the level of retrofitting in Scenario A is reduced relative to the original level of retrofitting shown in the results that do not allow premature scrapping, Figure 3.10. The relative reduction in retrofitting is particularly observable in the early and late 2030s periods. This is due to a combination of fleet age profile and the pressure to further abate carbon through technology retrofits resulting in scrappages as per the 'retroactive premature scrappage' approach. The largest amount of premature scrapping occurs in the period 2031–2038 (depending on the scenario).

Scenario B also sees reduction in the amount of retrofitting, particularly in the mid-2030s, if a small number of ships are prematurely scrapped at the same point in time. Premature scrapping in 2050 also significantly reduces the retrofitting that was expected in this period in the version of results that modelled conventional scrapping (see Figure 3.11).

The use of retroactive premature scrapping in Scenario C makes a significant reduction in the peak rate of retrofitting in the early to mid-2030s, relative to the version of this scenario's results that modelled conventional scrapping (Figure 3.12). This results in a near halving of the rate of retrofitting that was estimated to otherwise be required. This is associated with a peak in premature scrapping that occurs in the mid- to late 2030s, and is of much greater

[41] This assumption is in line with UMAS' experience from broker and chartering stakeholders.
[42] Frontier Economics, UMAS, E4tech and CE Delft (2019). *Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution: Scenario Analysis - Technical Annex*

peak magnitude (premature scrapping rates of over 2000 ships per year) than in the other scenarios.

In all scenarios, introducing premature scrapping reduces the amount of retrofitting needed, but also increases the rates of new-building. It is assumed in these scenarios that prematurely scrapped vessels are directly replaced with new-build vessels, with no time lag in replacement. Therefore, regardless of which decision is chosen in practice, there will still need to be a significant supply and installation of new machinery and equipment. In addition to considering costs, it may also be important to consider emissions associated with shipbuilding and disposal relative to those associated with the operation of ships, as these may counteract out some of the economic or shipping emissions benefits of premature scrapping. Depending on whether or not retrofitting needs to be carried out in a dry dock, this can also be considered as a significant pressure on the global capacity for dry docking.

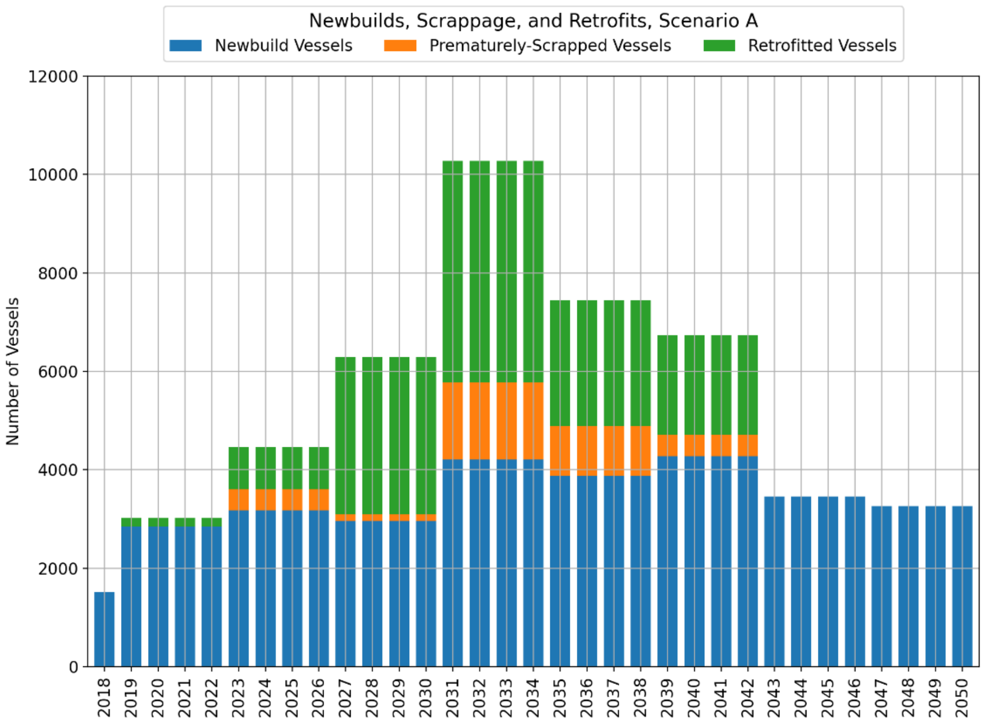


Figure 3.22 – Numbers of new-builds, prematurely scrapped vessels and retrofits for Scenario A (retroactively applied)

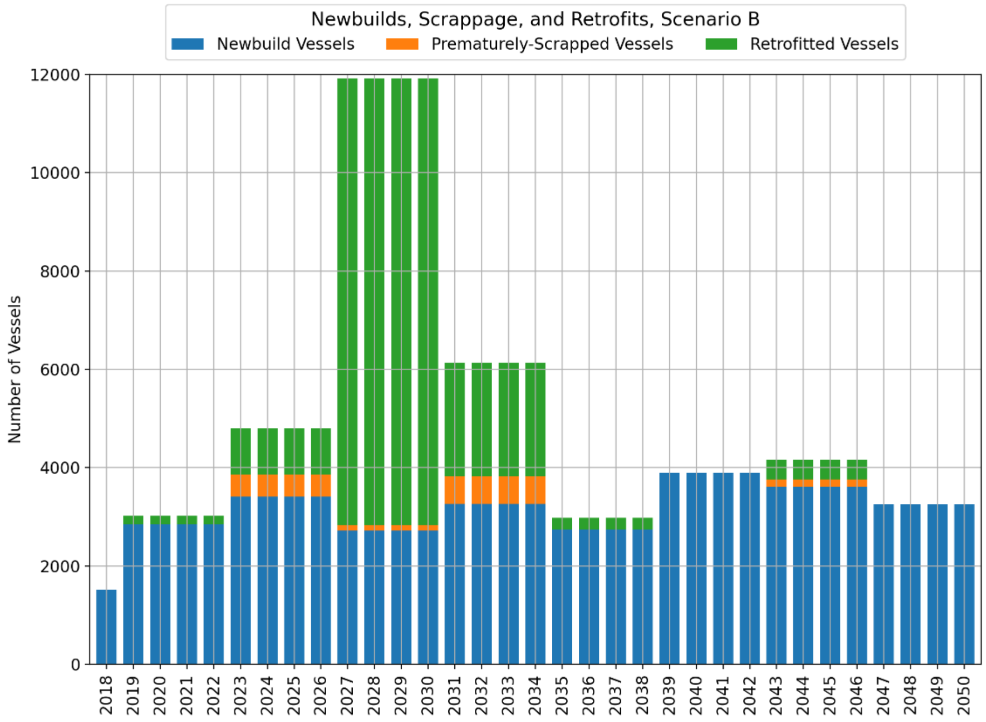


Figure 3.23 – Numbers of new-builds, prematurely scrapped vessels and retrofits for Scenario B (retroactively applied)

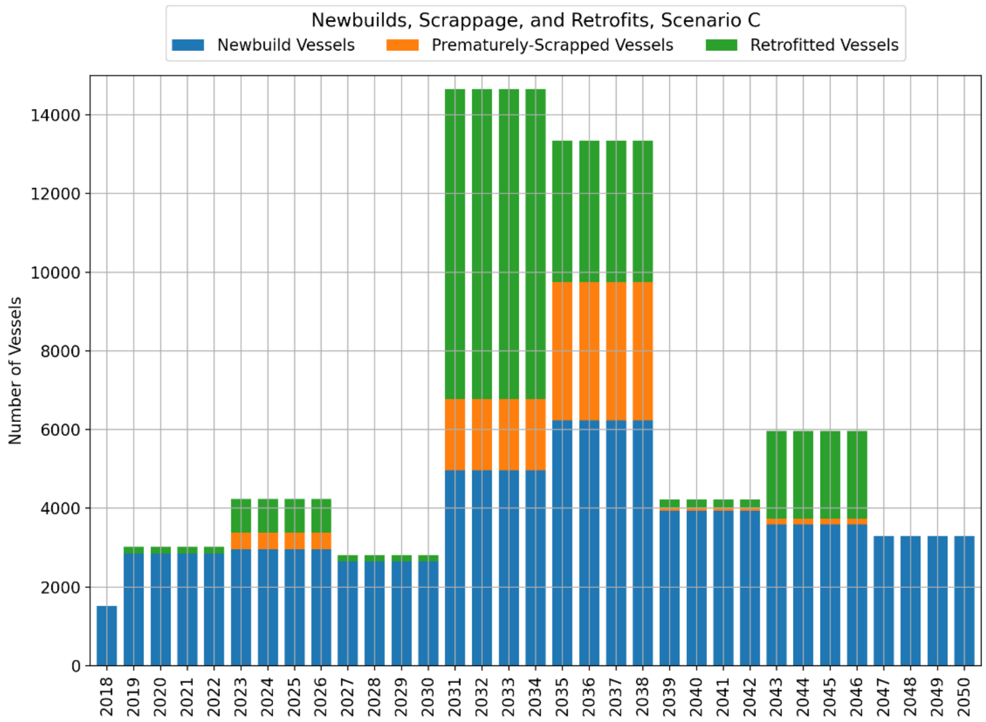


Figure 3.24 – Numbers of new-builds, prematurely scrapped vessels and retrofits for Scenario C (retroactively applied)

3.6.5 Normalised energy-related costs reduce if there is some premature scrapping of ships

Using the advanced premature scrappage approach, Figure 3.25 shows that there are some differences in the CO_2e normalised energy-related costs for the scenario where ships are eligible for premature scrapping. On the one hand, premature scrapping reduces the quantity of retrofits, and therefore their capital costs. However, on the other hand, during any period of premature scrapping, higher quantities of new-building are needed in order to meet the demand for transport, and this increases energy-related capital costs. The level of overall energy-related cost reduction depends on the relative costs of new-build and retrofit solutions, and because the new-building machinery solution is cheaper than the equivalent retrofit (see Technical Annex for details), this scenario overall will have proportionately lower normalised energy-related cost. However, omitted from this simplified calculation are other elements of capital costs. This includes omitting the capital cost of the non-energy-related components making up the remainder of the vessel (e.g. the hull and superstructure). Premature scrapping will mean a higher turnover of the fleet and therefore an overall greater number of newbuildings to meet the given transport demand in a given period of time. Whether or not the increases in these components of capital cost outweigh the savings in energy-related costs would require further evaluation.

As in the scenario with lower transport demand, in the 2040s once there is widespread adoption of SZEF, the normalised energy-related costs are very similar to those of the core Scenario A.

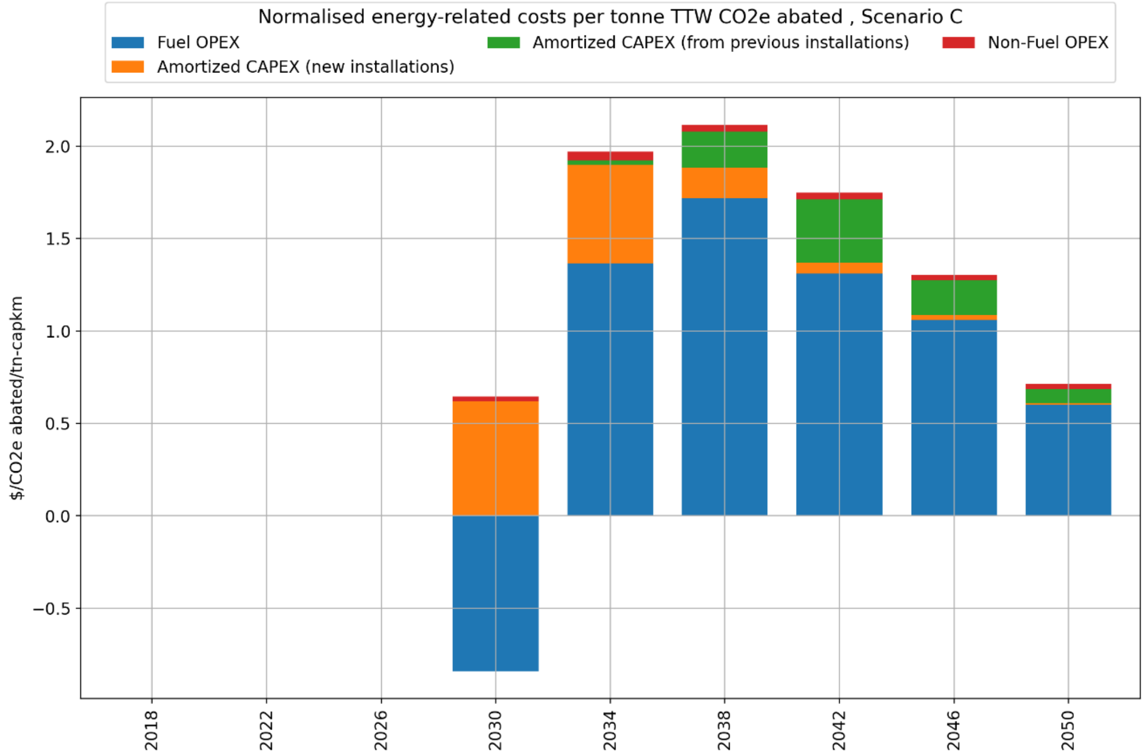


Figure 3.25(a)

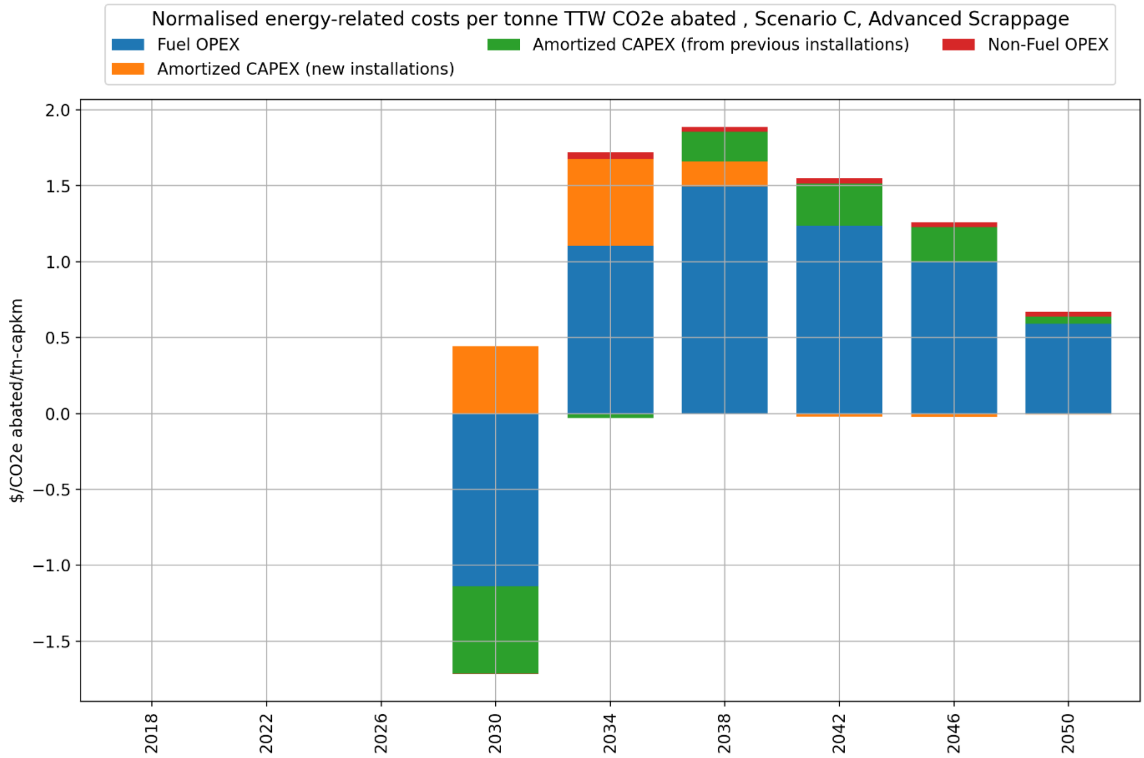


Figure 3.25(b)

Figure 3.25 – Normalised energy-related costs per tonne TTW CO_2e abated for (a) Scenario C and (b) Scenario C with advanced premature scrapping, both relative to BAU with CII/EEXI

3.7 The price forecasts for fossil fuel and SZEF are a key uncertainty and a key influence on which policy intervention is needed. Unless the chosen policy is robust to this uncertainty, it may result in a failure to achieve a 1.5°C temperature goal aligned transition to zero emissions by 2050

The forecasts for the prices of the incumbent fossil fuels and of biofuels and SZEF have an inherent level of uncertainty. The uncertainties are all considered to be exogenous to the modelling carried out in the current study, in that they are the product of patterns of supply and demand in the energy system and wider economy. In order to understand the sensitivity of the results to these uncertainties, two variations to the core scenario assumptions have been investigated: a 'high SZEF fuel price' case using high SZEF and low fossil/bio blend fuel prices relative to the core scenario prices; and a 'low SZEF fuel price' case with low SZEF and high fossil/bio blend fuel prices relative to the core scenario prices. These additional fuel price trajectories are illustrated in Figure 3.26. Details on how fossil fuels, biofuels and synthetic fuels were derived are available in Section 3 of the technical annex, and the "*Fuel price input assumptions.xlsx*" spreadsheet. The fuel price assumptions used in this modelling were finalised in January 2022 and therefore do not reflect recent market developments.

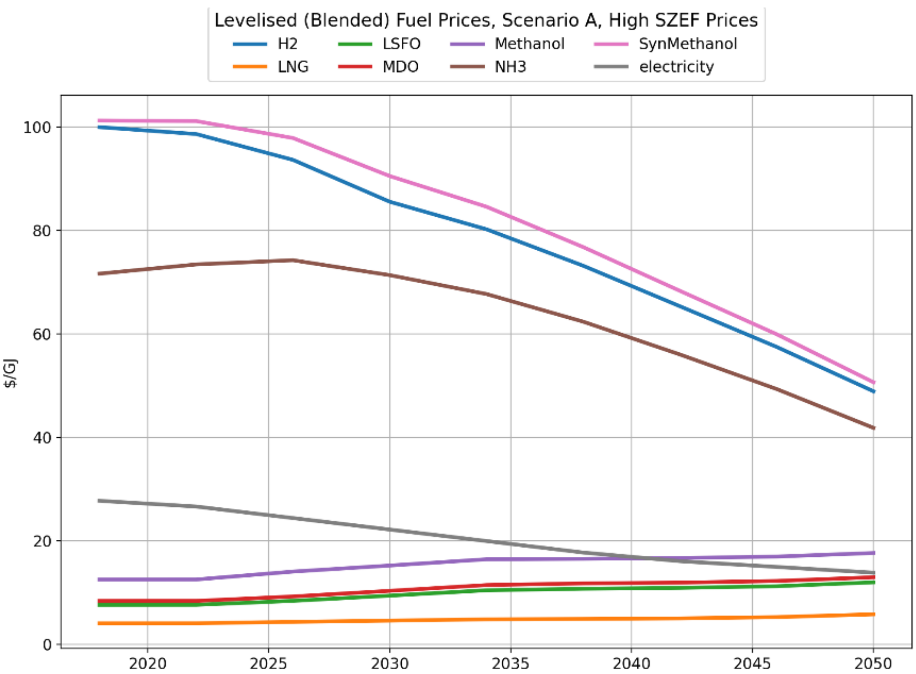


Figure 3.26(a)

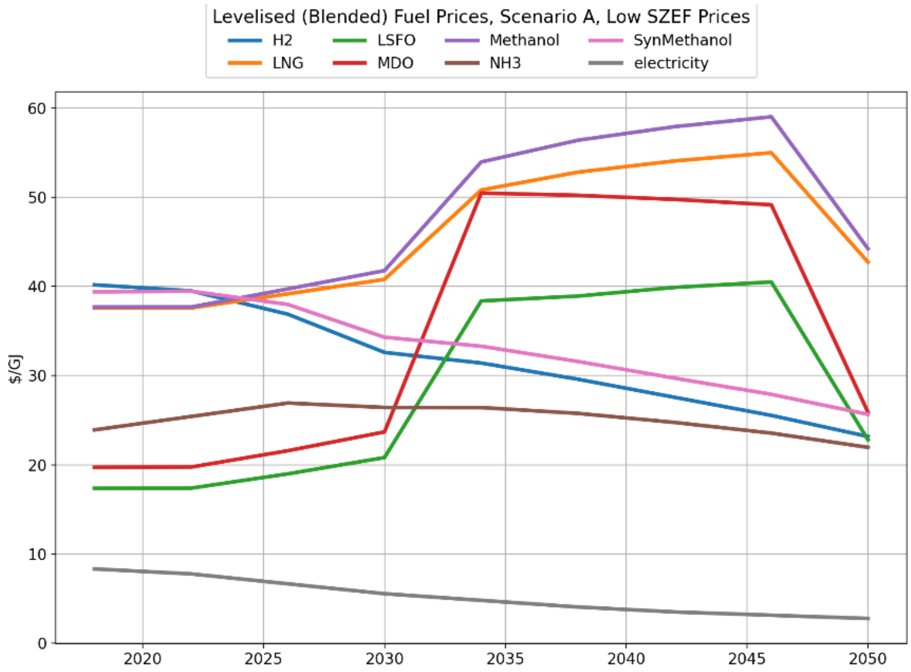


Figure 3.26(b)

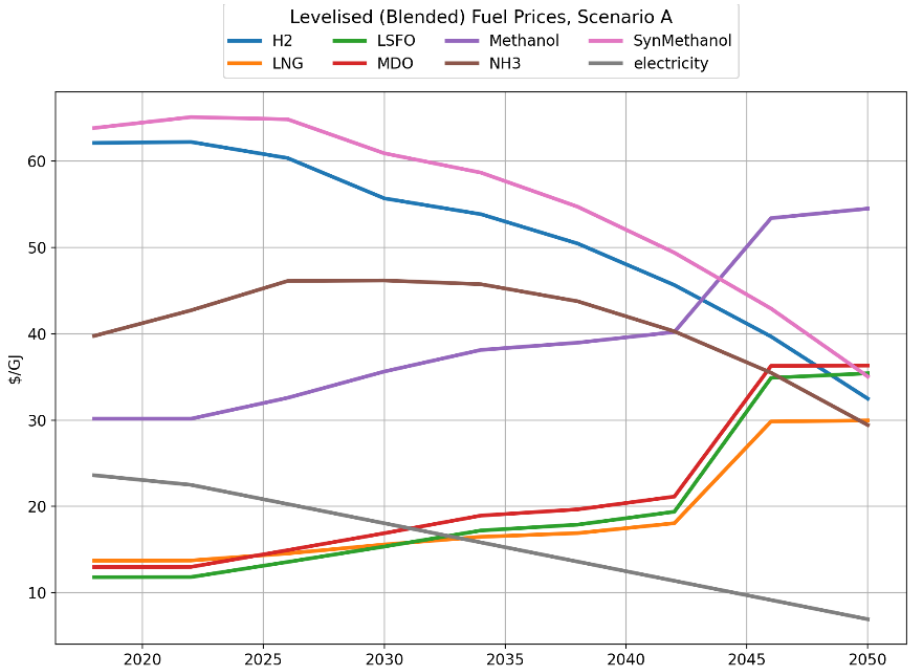


Figure 3.26(c)

Figure 3.26 – Fuel price trajectories by year for (a) high SZEF and (b) low SZEF price sensitivities, and (c) central trajectory for Scenario A

The consequences of the fuel price sensitivities on the CO_2 emissions are shown in Figure 3.27. Figure 3.27 shows that this high SZEF price version of Scenario A sees much lower CO_2 reduction than the core Scenario A result, and misses the CO_2 reduction target set for that scenario, significantly exceeding the target in terms of emissions throughout the period and resulting in both higher absolute and cumulative emissions. Conversely, the low SZEF price version of Scenario A outperforms relative to the target, achieving reductions that reach close to zero emissions by 2030.

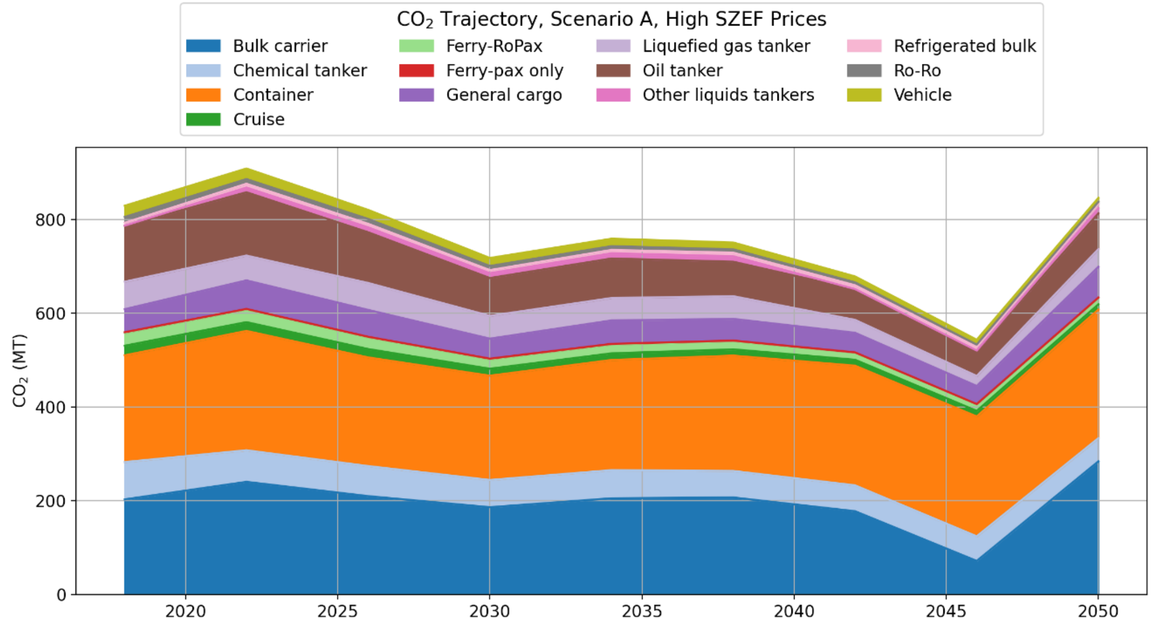


Figure 3.27(a)

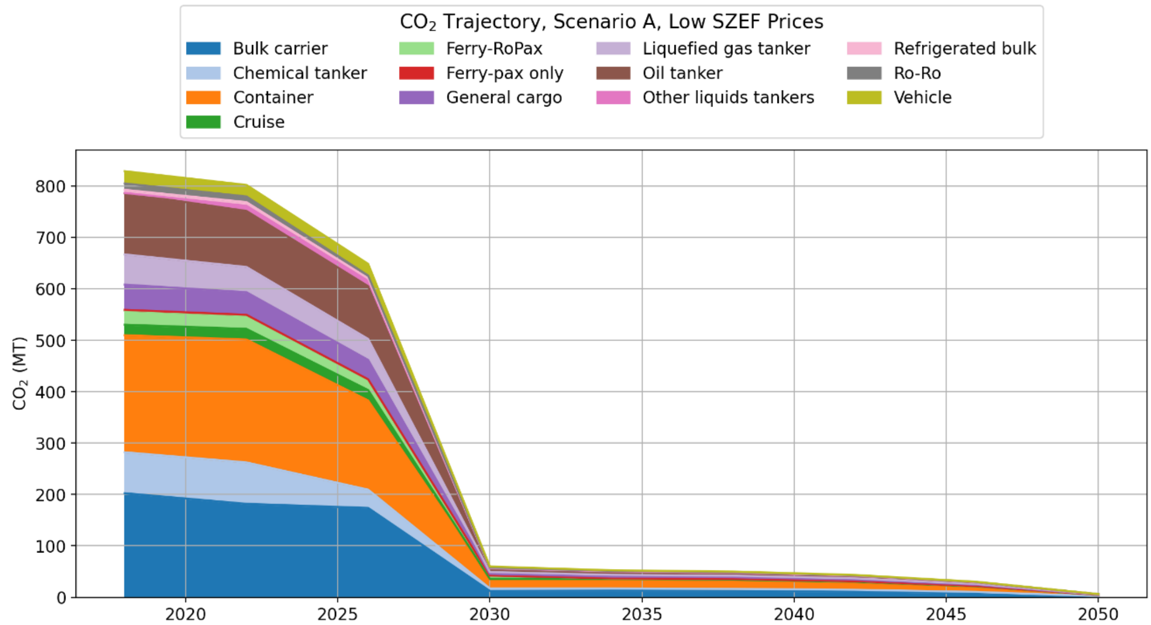


Figure 3.27(b)

Figure 3.27 – TTW CO_2 emission trajectories for Scenario A with (a) high SZEF and (b) low SZEF price sensitivities

Figure 3.28 and Figure 3.29 show that the two fuel price variations (high and low, shown in Figure 3.26(a) and (b)) lead to radically different fuel mixes. In the scenario using high SZEF prices (Figure 3.28), there is no use of ammonia/SZEF until much later in the transition. The results for that scenario also show a stronger advantage for LNG over the incumbent fossil fuels (LSFO and MDO). Fossil-derived methanol, a high GHG emitting fuel that can be derived from natural gas, is also shown to become more competitive. Together, methanol and (predominantly) LNG substitute nearly all of the incumbent fossil fuel use by 2030 in this scenario. However, with the higher SZEF prices, there is then much less onwards substitution because the carbon prices are not high enough to close the price spread and it is therefore preferable to pay the carbon price than convert to a technology/fuel that would incur lower carbon costs.

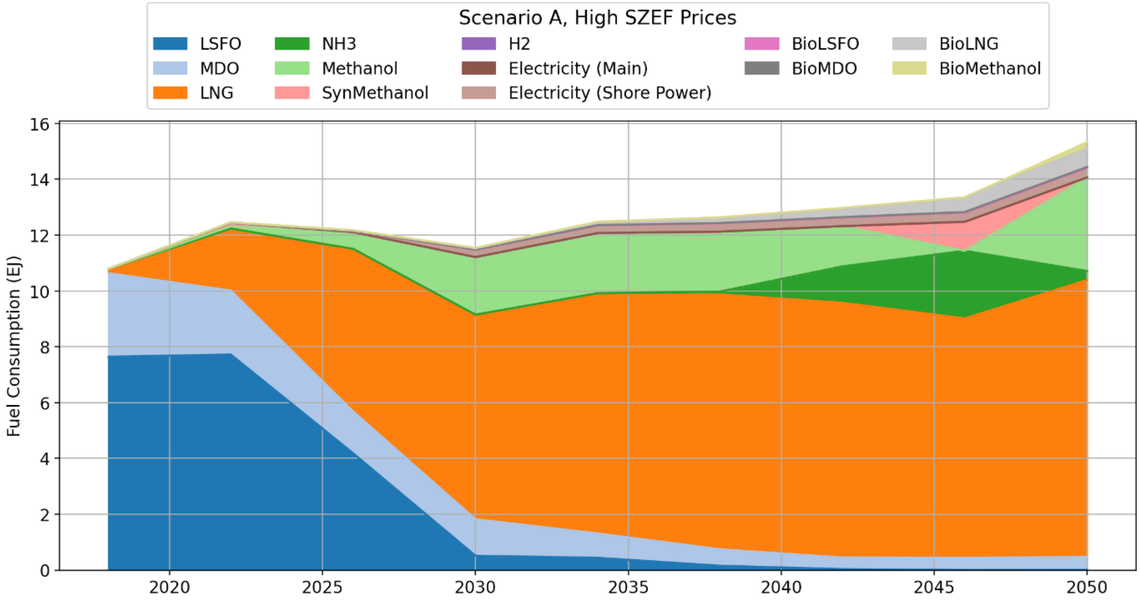


Figure 3.28 – Fuel mix, Scenario A with high SZEF prices

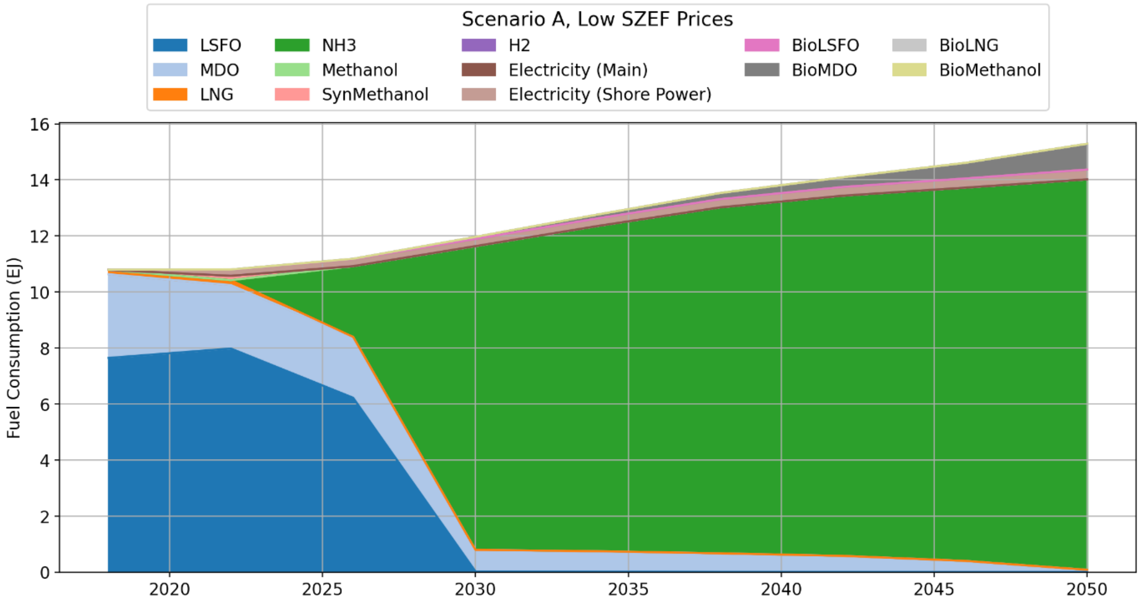


Figure 3.29 – Fuel mix, Scenario A with low SZEF prices

In the low SZEF price scenario, Figure 3.29, the reverse is the case. The spread between fossil and SZEF pricing results in a rapid substitution to SZEF, given the high carbon prices that are reached for the core fuel price version of Scenario A (see Figure 4.1). In this scenario there is almost no use of LNG, and the incumbent fossil fuels are directly substituted by ammonia.

3.7.1 The CO_2 reduction outcome of a fixed levy has high uncertainty given the uncertainty in fuel price

The results of the sensitivity studies for SZEF price show that if the price of a carbon levy is fixed, and the variations in the price and price spread of fuels are of similar magnitude to those assumptions, the resultant CO_2 and GHG reductions could be highly uncertain. Those results were interrogated further (as discussed in the Technical Annex), from which it can be concluded that the design of policy that can ensure a given CO_2/GHG reduction outcome would need to include the following considerations:

- If a carbon levy is used to incentivise the transition to new fuel, the levy price will need to be reviewed periodically and to be adjustable, so that the CO_2/GHG outcome can be ensured in spite of fluctuations to prices and price spreads.
- A carbon levy can be usefully complemented by command-and-control policy measures including CII and fuel standards, because if values for their stringency are specified sufficiently far into the future those measures help to ensure there is a predictable long-run expectation of demand for SZEF. This can also help to increase the likelihood that the corresponding supply of SZEF will be available.

Furthermore, Figure 3.30 shows that varying the fuel prices creates large departures to the core Scenario A normalised energy-related costs. Variations in take-up of technology and fuels relative to BAU can create both positive and negative costs. It should be noted that the high SZEF price scenario coincides with a reduction in the fossil fuel costs (e.g. an increase in the spread between the fossil and SZEF price), whereas the low SZEF price scenario coincides with an increase in the fossil fuel costs (a reduction in the spread between the fossil and SZEF price). Because fossil fuel prices remain an important part of the overall energy costs in the high SZEF price scenario (which achieves much lower penetration of SZEF and lower emission reduction), the high SZEF price normalised energy-related costs are significantly lower for most of the transition, than the core scenario. If the emission reduction had been forced in this sensitivity study to be equivalent to the core Scenario A, the higher fuel prices would have resulted in a similar fuel mix, and an increase in the normalised energy-related cost relative to the core Scenario A.

In the sensitivity with low SZEF prices, the normalised energy-related costs are initially higher (while the fleet is still dependent on large amounts of fossil fuel). However, the lower prices result in a more rapid adoption of SZEF, and the lower price of SZEF then starts to contribute to a significant overall reduction in normalised energy-related cost.

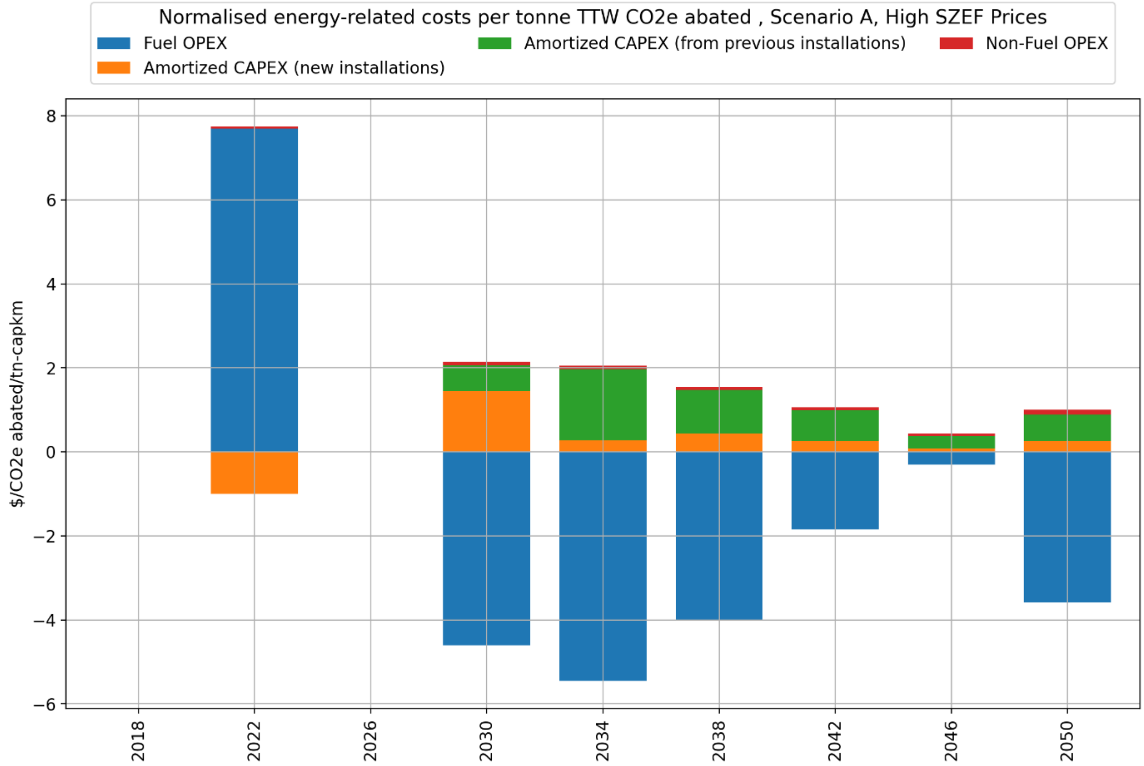


Figure 3.30(a)

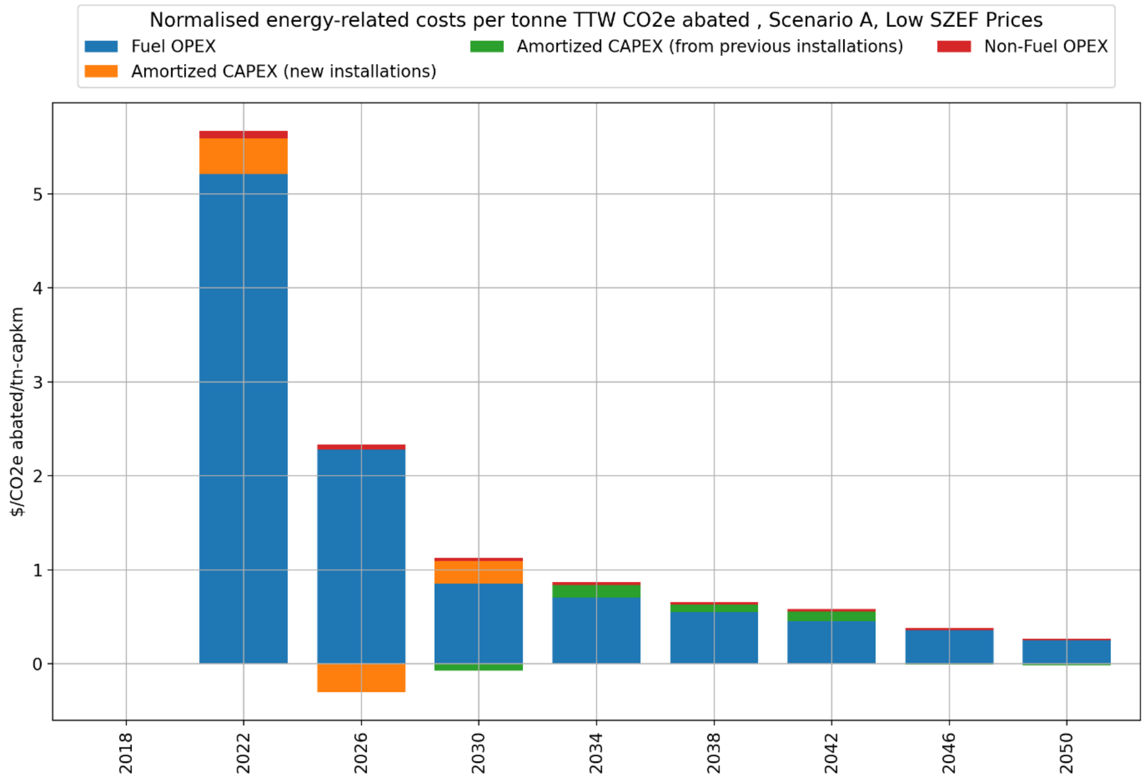


Figure 3.30(b)

Figure 3.30 – Total energy-related costs normalised to transport work per tonne TTW CO_2e abated, Scenario A with (a) high SZEF prices and (b) low SZEF prices, relative to BAU with CII/EEXI

3.8 A high availability of biofuel supply reduces the level of retrofitting, but is not material to the CO_2 pathway or the costs of decarbonisation

Biofuel may have a role to play in shipping's decarbonisation, given that it can be directly substituted as a replacement for existing fossil and fossil-derived fuels (sometimes referred to as drop-in fuels), including methanol. However, uncertainty exists surrounding the role of biofuel in the maritime sector because of the current low levels of biofuel production and the low levels of sustainable supply (given the constraints and competition for sustainable biofuel feedstocks). The price dynamics of biofuel will be a function of how supply and demand develop not just in shipping but the wider economy.

The role of biofuel was investigated using simplified assumptions to model three different sensitivities to the available biofuel. Figure 3.31 shows the assumed biofuel availabilities, and the accompanying price trajectories are shown in Figure 3.32. The detail of the derivation of these availabilities and prices is discussed in the Technical Annex.

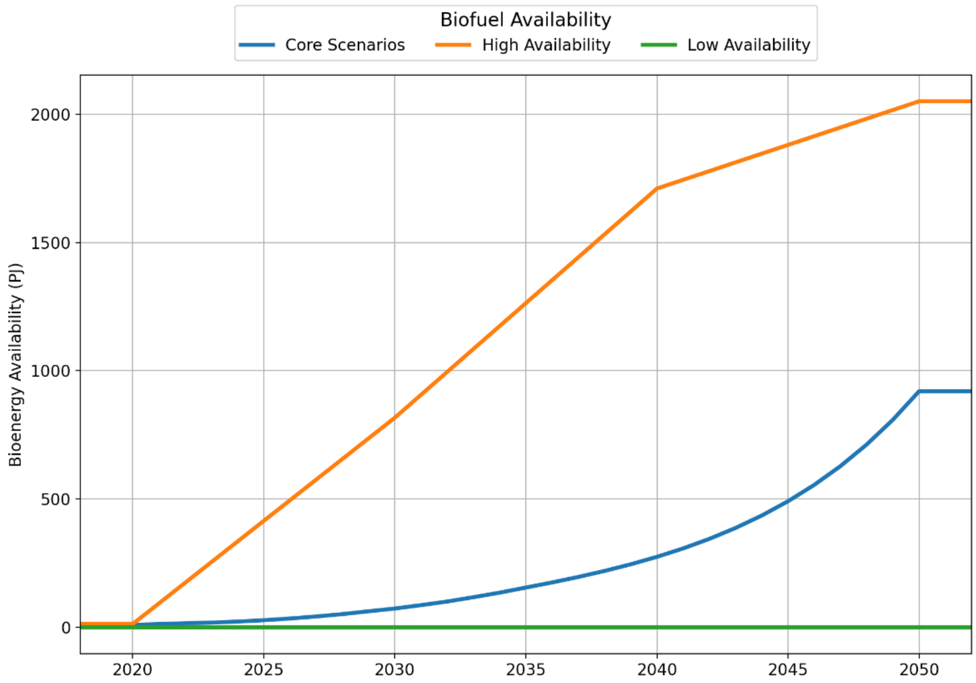


Figure 3.31 – Bioenergy availabilities for core and sensitivity scenarios

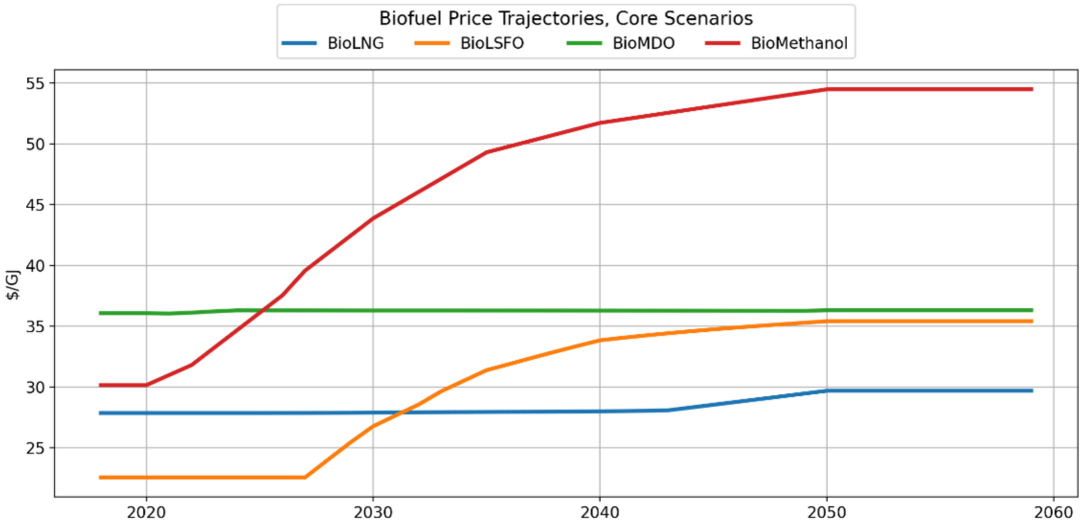


Figure 3.32 – Biofuel price trajectories (pre-blend[43]), core scenarios

Figure 3.33 and Figure 3.34 present the resulting fuel mix for the high and low biofuel availability sensitivity assumptions, respectively. These results can be compared with the fuel mix for Scenario A with the core biofuel availability assumption (shown in Figure 3.7). The consequences of the different biofuel availabilities to the rate of new-building, retrofitting and premature scrapping are shown in Figure 3.35, which can be compared and contrasted with Figure 3.22.

One key difference between these sensitivity scenarios is in the take-up of SZEF. In the high biofuel availability scenario, biofuel availability reduces the rate of growth in SZEF take-up and the volumes of SZEF use, at least until the mid-2030s. By 2050, biofuels constitute approximately 15% of the total energy used in international shipping. However, the low volumes of biofuel available even in the 'high availability' scenario are still not sufficient to delay the initial use of SZEF. Therefore, using biofuels does not obviate the need for policies that can stimulate a switch using SZEF starting in the 2020s. By the mid- to late 2030s, the rate of CO_2/GHG emission reductions is much higher than the rate of growth in supply of biofuel and, over this period, there remains a growth in SZEF demand similar to the core scenario. In the high biofuel availability scenario, the fuels used are bioLNG for substitution (drop-in) for the LNG-powered ships built earlier in the period, and bioMDO used to substitute the remainder of MDO use (including its use as a pilot fuel for combustion of ammonia).

The high biofuel availability scenario has the advantage of reducing the amount of retrofitting relative to the core and low biofuel availability versions of Scenario A. This is expected, given that the take-up of biofuel reduces CO_2 emissions without the need for retrofitting. One consequence of this situation would be an increase in the premature scrapping of ships in the late 2030s relative to the core assumptions for Scenario A (based upon retroactively inferring the rate of premature scrappage post the main GloTraM model). The higher availability of biofuels postpones – but ultimately does not remove – the need for the large majority of the fleet to substitute to SZEF, and the late 2030s is the point when this can no

[43] 'Pre-blend' refers to the biofuel input prices before they are blended with their fossil equivalents within the GloTraM model. For further information please see the Technical Annex.

longer be avoided. However, at that point in time, it is possible to achieve this substitution by scrapping ships older than 20 years, rather than retrofitting younger ships.

The low biofuel availability scenario assumes that there is effectively no biofuel use in shipping. Some vessels are therefore forced to switch to SZEF use sooner than they would otherwise have done, avoiding a carbon cost but incurring a higher fuel cost.

Because of the assumed need for a pilot fuel for the combustion of ammonia, in this scenario there is sustained use of MDO even in 2050 when the target CO_2 emission is zero. For this scenario to reach zero emissions, an alternative technology for ammonia combustion would be needed (e.g. its use in fuel cells instead of internal combustion machinery). Alternatively, instead of the compression ignition internal combustion engines assumed as the default for the use of ammonia (see Technical Annex), a small volume of ammonia could be used as a pilot fuel in spark-ignition internal combustion engines in which it is cracked into hydrogen to aid the combustion[44]. The assumptions around the pilot fuel and machinery specifics are discussed in greater detail in Section 4.3.

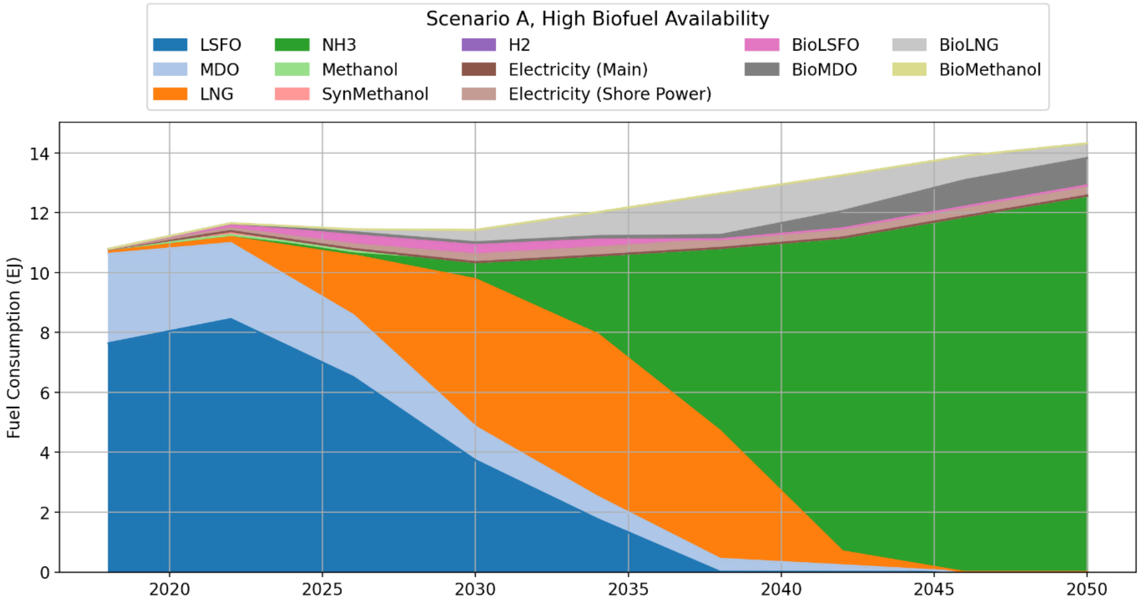


Figure 3.33 – Fuel mix, Scenario A with high biofuel availability

[44] Lhuillier, C. et al. (2020). 'Experimental study on ammonia/hydrogen/air combustion in spark ignition engine conditions'. *Fuel*. https://doi.org/10.1016/j.fuel.2020.117448.

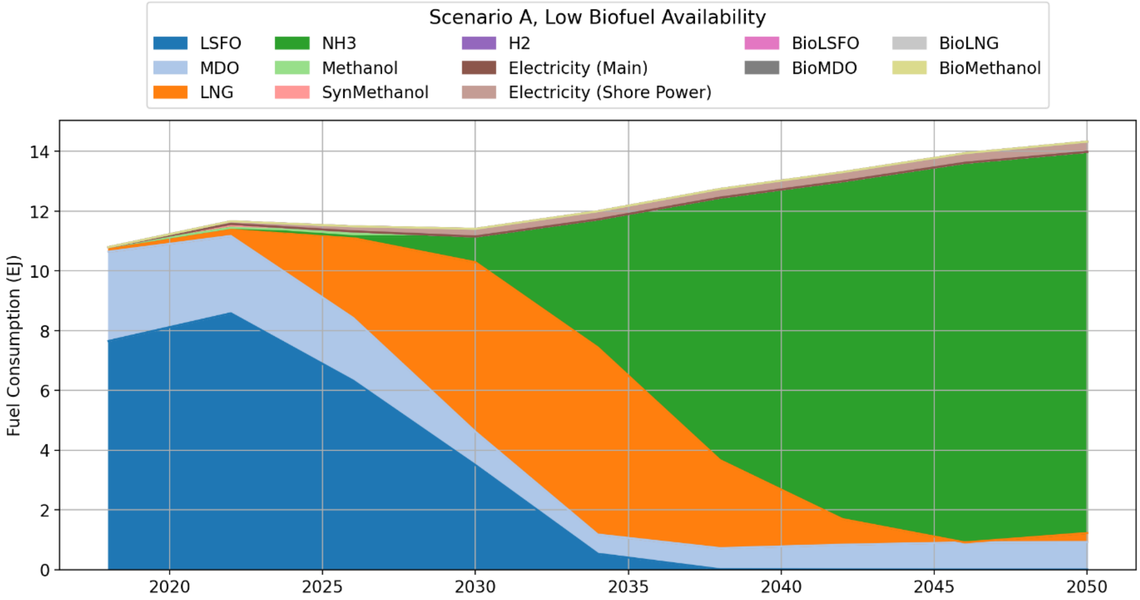


Figure 3.34 – Fuel mix, Scenario A with low biofuel availability

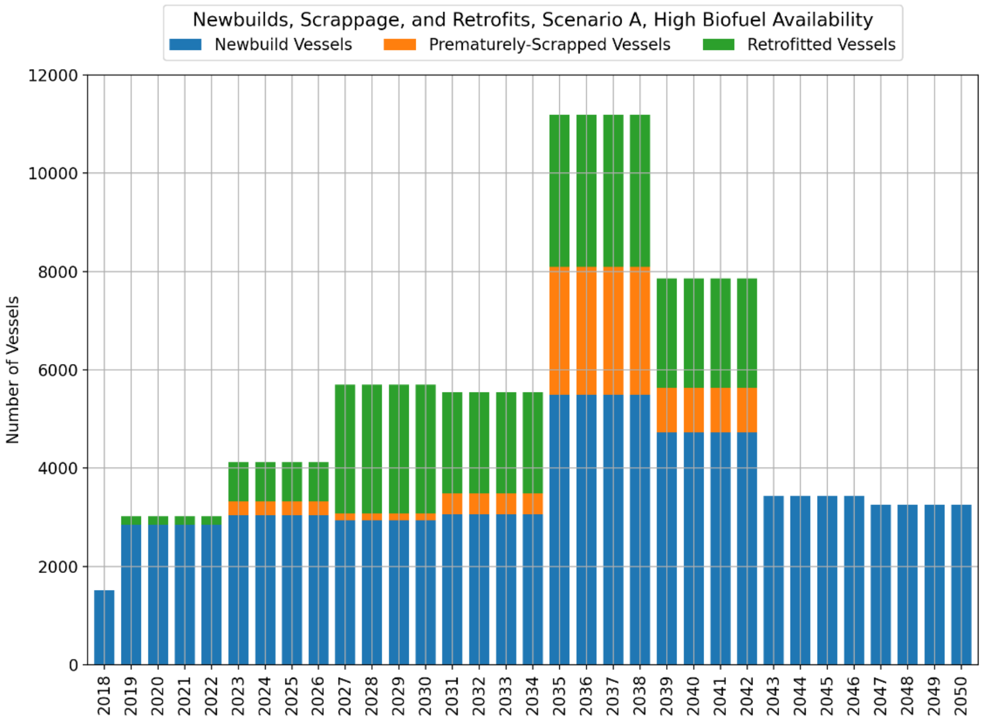


Figure 3.35(a)

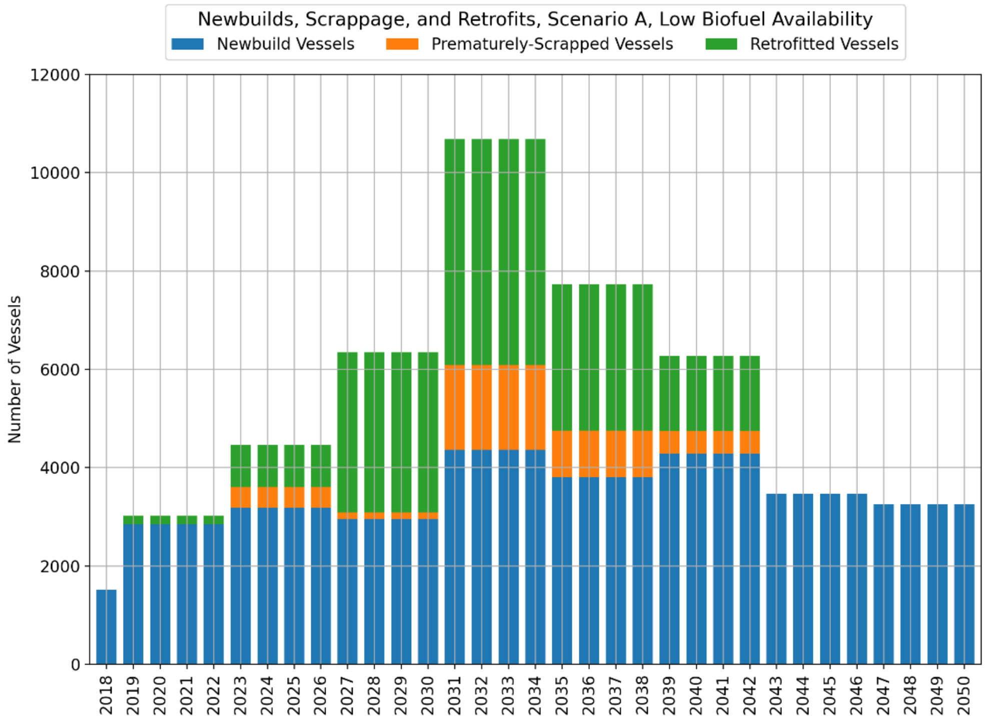


Figure 3.35(b)

Figure 3.35 – New-builds, retrofits and premature scrappage, Scenario A with high (a) and low (b) biofuel availability

3.8.1 Biofuels do not exert a significant influence on the normalised energy-related costs of international shipping's decarbonisation

Overall, at a maximum level of approximately 15% of the fuel mix (in the high biofuel availability scenario), biofuels do not exert a significant influence on the normalised energy-related costs of decarbonising international shipping. Figure 3.36 shows that the overall effect of higher biofuel availability does not result in a reduction in the normalised energy-related costs. That is because variations in take-up of technology and fuels relative to BAU create both positive and negative costs. Also, because the modelling assumes a price of bioenergy that increases over time, there is no clear benefit of higher biofuel availability in terms of fuel OPEX.

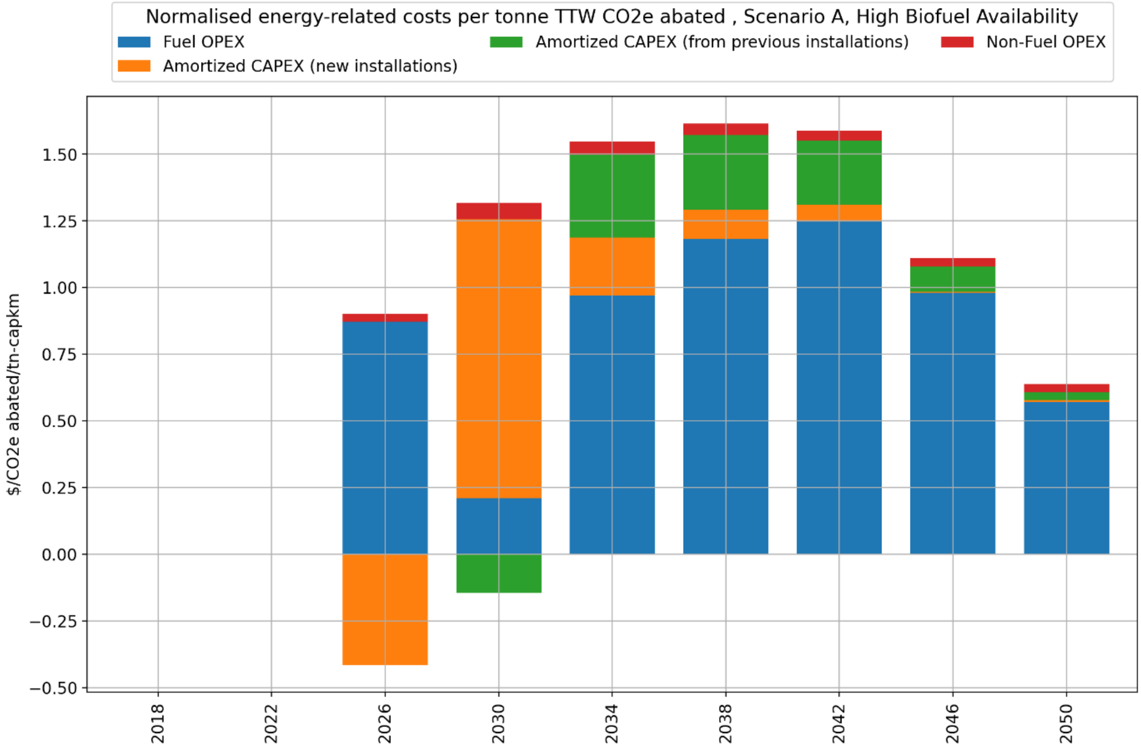


Figure 3.36(a)

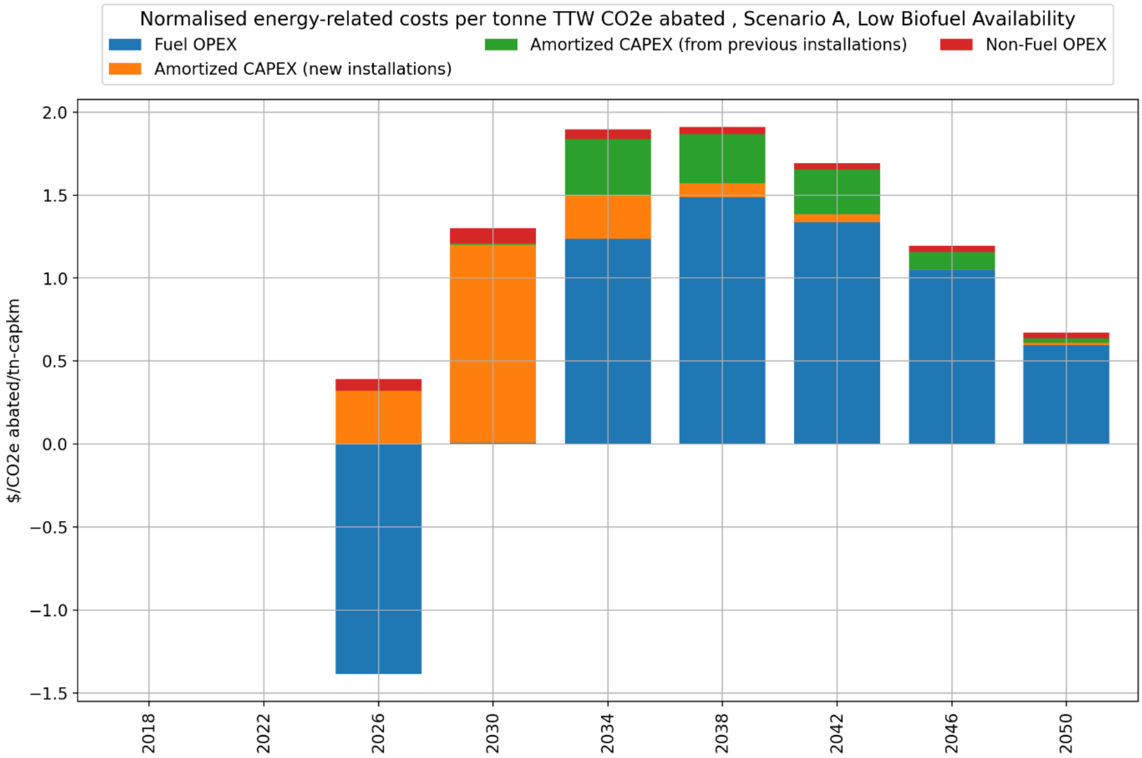


Figure 3.36(b)

Figure 3.36 – Normalised energy-related cost per tonne TTW CO_2e abated, Scenario A biofuel availability: (a) high and (b) low (zero), relative to BAU with CII/EEXI

3.9 Uncertainty around the costs of SZEF machinery onboard vessels does not have a large influence on the cost of the energy transition

A final sensitivity check of Scenario A was run that modelled the potential for higher-than-expected capital costs for SZEF machinery, and reduced learning effects and cost reductions over the modelling period. The results are presented in Figure 3.37. As is to be expected for a sensitivity study with increased costs, there is an increase in the normalised energy-related costs. This is most noticeable at earlier points in the transition when capital expenditure is higher than the fuel expenditure. By the 2040s, once the transition of the fleet is broadly complete, there is less observable difference between this sensitivity and the core Scenario A. Overall the effect on the energy-related costs is small. This result, in combination with the SZEF sensitivity scenario presented in Section 3.7, suggests that the uncertainty around future fuel prices will play a considerably greater role in the cost of the energy transition than uncertainty around the costs of machinery installed on vessels.

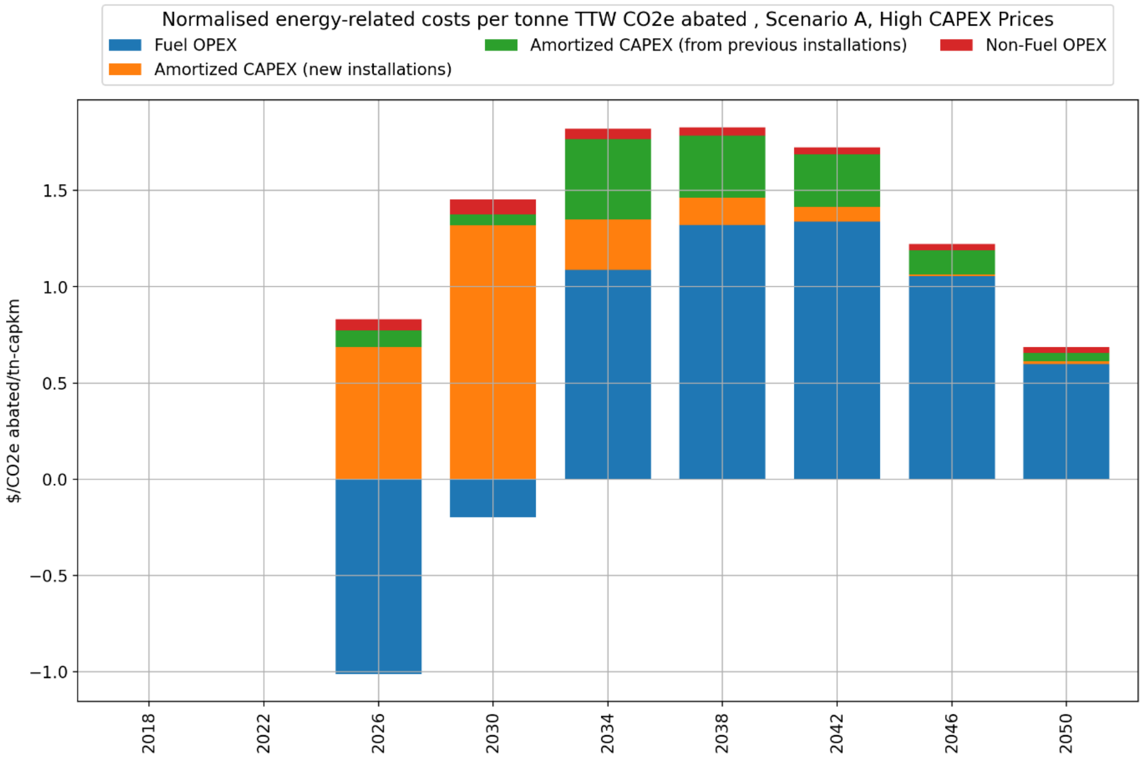


Figure 3.37 – Normalised total abatement cost per tonne TTW CO_2e abated, Scenario A high CAPEX prices, relative to BAU with CII/EEXI

4 Detailed results for core modelling scenarios

This chapter provides additional details on the results of the modelling for the three core scenarios A, B and C, as well as both BAU scenarios that include:

- Implementation of the EEXI/CII regulatory measure to be introduced in 2023. This implementation follows the guidance in MARPOL annex VI applying increments of stringency to 2026, and then holding that stringency constant to 2050
- A BAU scenario that does not include any application of EEXI/CII.

For the three core scenarios, which all reach approximately zero CO_2 emissions by no later than 2050, for the purpose of modelling the change in technology and emissions is incentivised by a carbon price. The carbon price is determined by GloTraM, which works from the input conditions and iterates its calculations to find the price level needed in order to achieve the specified CO_2 pathway. The values calculated by the model are illustrated in Figure 4.1 below for each core scenario. These carbon prices are used for the sensitivity variations of each core scenario modelled, to ensure that only a single degree of freedom is varied in each instance.

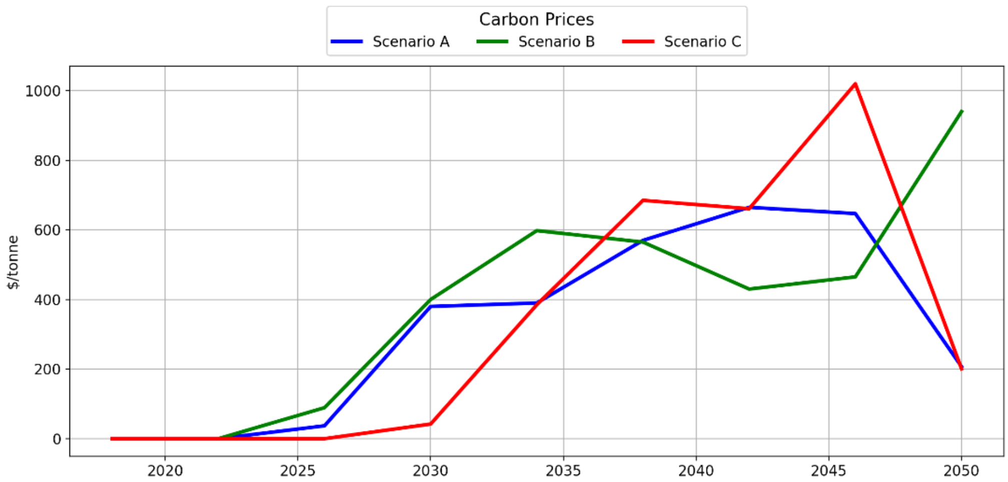


Figure 4.1 – Carbon price results for core scenarios

GloTraM iterates to find the lowest possible carbon price that can satisfy the required carbon budget each year, given the configuration of the fleet in the previous time-step. As such, the carbon price can fluctuate in both directions. For example, Scenario B sees an initial peak price in 2034, which then falls in 2042 before climbing again to peak in 2050. This coincides with the shape of the target CO_2 emissions trajectory for Scenario B, which delineates the initially early and steep emission reductions and the gentler slope to zero emissions by 2046. This emphasises the dual purpose of the carbon price market-based measure: to control the rapidity of decarbonisation; and to achieve a given level of decarbonisation as the marginal abatement cost increases. This can be seen in the later years of each scenario as the last sources of emissions can become the most expensive to abate (for example in Scenario C, which has largely decarbonised in 2040, the model still needs a large carbon price after this date to incentivise the minimisation of the small residual carbon emission). It can also be seen that once the fleet has been decarbonised, the modelled carbon price can reduce. In Scenario A and C, which need to make deeper reductions earlier than the more gradual

Scenario B, in 2050, the carbon price reduces to a much lower value than at their peak modelled carbon price a few years previously. With SZEF compatible technology on all ships, and with the price of SZEF falling over time, there is less incentive required from the carbon price.

The level of carbon price in a given scenario and a given year is variable depending on all the assumptions used as inputs, and the rate of emission reductions achieved. A critical input assumption for driving the level of carbon price needed to achieve a given CO_2 target is the price of SZEF, as shown in the sensitivity study in Section 3.7. Therefore, the carbon price scenarios presented here should be interpreted as modelling trends rather than precise values, and interpreted within the context of the assumptions made about the core scenario SZEF pricing, presented in the Technical Annex. Because the carbon price represents the marginal cost e.g. the cost of the most expensive tonne of CO_2 abated, it is higher than, and not indicative of, the cumulative costs of decarbonisation presented elsewhere (e.g. the sum of the capital, operational and fuel costs).

Scenarios that see a large reduction in emissions over short periods of time required a high carbon price to achieve this, relative to those scenarios that have a more gradual rate of emission reduction. That is why Scenario B has the highest carbon prices pre-2035, in order to actualise an early and rapid decarbonisation. Similarly, the carbon price in Scenario C quickly escalates in the early 2030s because the reduction there is also very abrupt. Overall, carbon prices range from USD400–700/tonne during the period in the 2030s when the fuel mix is experiencing the highest rate of change. The USD/tonne carbon price in 2042 for Scenario C is an artefact of the iteration process used in GloTraM. That is, because near-zero operational (TTW) CO_2 emissions are achieved in 2038, the iterator finds that the minimum carbon price needed to *further* decarbonise in the following time-step is zero, as the budget has already been achieved. This results in a ‘whiplash’ effect (in the models) where a small amount of fossil fuel take-up in 2042, in response to the removal of the carbon price, is then rejected in 2046 once the carbon price rebounds to an even higher price to force these components out. In reality, it is likely that the carbon price will be maintained at the level at which total decarbonisation is achieved, in this case around the USD700/tonne mark attained in 2038.

4.1 Interpreting the modelled carbon prices for the design of policy to incentivise shipping’s transition

Incentivisation of the decarbonisation and technology pathways in the core scenarios A, B and C could be achieved through market-based policy measures (that include some form of carbon pricing), command and control policy measures (such as fuel or GHG-intensity standards), or a combination of both types of policy. Whilst the modelling incorporates a carbon price to enable the solutions to follow the prescribed CO_2 trajectory, the analysis remains agnostic on the specifications or combination of policy that could be most appropriate.

Even if the analysis is agnostic, some insights pertinent to policy design to incentivise transition are revealed in the results.

- One challenge of carbon pricing policy can be found in the resulting carbon price trajectories, shown in Section 4. From initially low values at the point of policy implementation, carbon price rapidly increases as a function of the Scenario CO_2 trajectory (Scenario A and B carbon price levels exceed USD200/tCO_2 by 2028, whereas Scenario C's carbon price is below USD50/tCO_2 and only exceeds USD200/tCO_2 after 2032). Within sensitivity scenarios (particularly those associated with the price of fuel), the carbon price and emission reductions are highly variable. The issue is therefore that there is high uncertainty in what carbon price will be needed to incentivise the use of SZEF, and a challenge in calculating that carbon price in advance. This suggests that there needs to be regular review of any policy that relies on price or subsidy (using carbon revenues) in order to ensure that the necessary investment and change is being incentivised.

- If carbon price is the only policy instrument used to incentivise a shift away from fossil fuel use, the modelling suggests that transition may only be completed if the carbon price is set at levels around USD600/tCO_2 (and possibly higher). This is due to the modelling's calculation of a carbon price at the margin – e.g. representing the price signal needed to incentivise the most expensive intervention that is required to achieve the reduction target at that specific point in time. For all other assets, the incentive required to enable their contribution to the reduction target is lower and in many cases significantly lower that this price indicates. If carbon price is used as the only mechanism to incentivise transition, it creates a much larger economic transfer than if it is used in combination with command and control policy. Because of this, the modelled carbon prices should not be read as a proxy for a change in transport cost or the 'cost' to industry. The way that any carbon price influences costs to states or industry stakeholders, can only be determined once revenue uses are determined and defined.
- In some circumstances, the model-derived carbon price reduces over time. For example, Scenario B has an initial peak value in 2034, with carbon pricing levels falling until the last time-step in 2050. In case a falling carbon price risks incentivising the transition to be a temporary change (with some switching back to fossil fuels opportunistically), a carbon price can be complemented by command and control policy measures that can more simply and unambiguously lock-in a transition to new technology. This may also help to achieve a similar transition but with a lower carbon price trajectory.
- A common feature of all scenarios is that the transition is characterised by an initially small take-up of SZEF and associated technology (this decade in Scenario A and B, from 2030 in Scenario C). This small volume of SZEF requires a high carbon price to incentivise its use. Whilst there is only a small volume of SZEF with most of the fleet still using conventional fuels, that carbon price can impose high costs on the rest of the fleet and create high carbon revenues as a result. As the fleet's take-up of SZEF increases, even if carbon prices increase, total collected revenues may not. Therefore, careful design of how revenues are used, in particular how some share of revenues support/subsidise the early-stage SZEF use, should enable a lowering of the carbon price needed to achieve the transition.

4.2 Summary results of metrics relative to 2008 for core scenarios

The IMO Initial Strategy (see Section 1.3) contains both a carbon intensity objective (for 2030 and 2050) and a GHG objective (in 2050). It was further suggested in IMO submission

MEPC 77/7/15[45] that the IMO's revised strategy should include further metrics at a number of dates (including 2030 and 2050, and also 2040). The Initial Strategy presents metrics relative to 2008; however, IMO4 quantifies emissions to 2018 and provides a more recent baseline against which to present quantifications of targets and changes. Taking this context from the policy discussion into account, Table 4.1 to Table 4.4 list a number of different potential metrics that can be used to characterise shipping's decarbonisation and transition, as reductions relative to two potential baseline years: 2008 and 2018. Results are presented for the three core decarbonisation scenarios and for the BAU scenario that includes the estimated impact of EEXI/CII, showing the trends that can be expected based on existing regulations in combination with market forces. The different metrics and their application to the scenario output data are described below.

Carbon intensity metrics represent a quantity of emissions relative to the delivered transport work of the global fleet. They help to separate out the absolute emissions from the backdrop of increasing demand for shipping, and provide useful insight into the level of emission reductions that will need to be achieved for an 'average' ship over a period of time.

- AER – This metric is a proxy for carbon intensity of transport work, using the capacity of shipping as a proxy for the actual cargo carried by shipping. In practice, ships do not operate fully loaded on every voyage, so the 'capacity' proxy overestimates the actual transport work and therefore under-reports the carbon intensity of the fleet. In this calculation, the metric is calculated using operational (TTW) CO_2 emissions (ignoring wider GHG and any upstream (WTT) emissions). There are two versions of the metric: one for ships that are carrying cargo, which uses their deadweight displacement to represent their cargo capacity (in grammes of CO_2 per deadweight tonnage per nautical mile; gCO_2/dwtnm); and the other, AER cgDist, for ships that do not predominantly carry cargo (passenger and service/work vessels) and uses the gross tonnage (gtnm, the product of gross tonnage and distance travelled in nautical miles) to represent their cargo capacity
- Energy efficiency operational indicator (EEOI) – This metric uses the actual transport work done, and combines the distance travelled with estimates of the actual cargo carried (gCO_2/tnm). This is done using estimates of utilisation produced in IMO4. It is a metric that can be measured for individual ships, but the data on cargo mass derived transport work is not currently reported to the IMO's Data Collection System, so for use with official data, less accurate proxies such as AER remain necessary. In this calculation, the metric is calculated using operational (TTW) CO_2 emissions (ignoring wider GHG and any upstream (WTT) emissions).
- Energy efficiency – This is not a carbon intensity metric because it is in energy units (joules, as J/(deadweight tonnes x distance travelled), but it provides a useful comparison for the carbon intensity metrics because it isolates the improvements in the average ship's energy efficiency from changes in carbon content of fuel/emissions. This metric is only applied for the ship types that carry cargo.

The following emissions metrics[46] relate to the absolute emissions in a given year:

[45] MEPC 77/7/15 Revision of the Initial IMO Strategy on Reduction of GHG emissions from ships. Costa Rica, Norway, United Kingdom and United States.
[46] In this report, GHG emissions are expressed as CO_2e by applying global warming potential (GWP) values to the non CO_2 GHG emissions (AR4 100-year GWP values, IPCC 2007.)

- CO_2 TTW – This metric is the change in operational (TTW) CO_2 emissions for international shipping (measured in tonnes, t). It excludes any change in other operational GHG emissions (CH_4 and N_2O), and it excludes any change in upstream (WTT) CO_2 or wider GHG emissions
- CO_2e TTW – This metric is the change in operational (TTW) GHG emissions for international shipping CO_2e
- CO_2e WTW – This metric is the change in lifecycle (WTW) GHG emissions for international shipping CO_2e.

The following fuel/energy metrics[47] track the change in the composition of the energy used by international shipping over time:

- Energy intensity TTW – This metric represents the operational (TTW) GHG emissions per unit of energy used (tCO_2e/MJ) in international shipping CO_2e
- Energy intensity WTW – This metric represents the lifecycle (WTW) GHG emissions per unit of energy used in international shipping CO_2e
- SZEF energy % – This metric represents the share of SZEF (%) in the total energy mix used by international shipping. It includes both direct use of electricity (including shore power) and the use of hydrogen and hydrogen-derived renewable fuels (ammonia and synthetic methanol). It does not include biofuels or lower CO_2 fossil or fossil-derived fuel (e.g. methanol and LNG).

The results shown in Table 4.1 to Table 4.4 are a summary of results that are discussed in detail in Sections 4.3 and 4.4, and are included here to illustrate the scale of changes and provide values that can guide the revision of the strategy. All items are percentage changes relative to the baseline year in question, except for SZEF Energy, which represents a percentage of the total fuel mix. Therefore, for the percentages, negative numbers represent a percentage reduction relative to 2008/2018, and positive numbers represent a percentage increase relative to 2008/2018.

Table 4.1 – Summary results for BAU (with CII/EEXI) scenario, change relative to 2008 and 2018 (except for SZEF Energy, which is % of fuel mix)

BAU with CII/EEXI Results	% relative to 2008			% relative to 2018		
	2030	2040	2050	2030	2040	2050
AER ($gCO_2/dwtnm$)	-35.8	-41.1	-46.8	-23.7	-30.0	-36.8
AER cgDist ($gCO_2/gtnm$)	-73.1	-75.2	-77.4	-24.3	-30.0	-36.3
CO_2 TTW (t)	-2.6	10.1	17.4	9.1	23.2	31.5
EEOI (gCO_2/tnm)	-41.8	-46.7	-52.1	-23.8	-30.2	-37.3
Energy efficiency (J/dwtnm)	-19.9	-25.6	-31.2	-16.5	-22.4	-28.3
Energy intensity, TTW (tCO_2e/MJ)	-3.5	-4.9	-7.4	-6.0	-7.3	-9.8
Energy intensity, WTW (tCO_2e/MJ)	-3.7	-12.7	-18.8	-12.5	-20.7	-26.2
CO_2e TTW (t)	0.1	12.8	20.0	12.3	26.5	34.6
CO_2e WTW (t)	2.0	5.7	7.5	4.5	8.3	10.2
SZEF energy (% of fuel mix)	0.3	1.0	3.9	0.3	1.0	3.9

[47] Ibid.

Table 4.2 – Summary results for Scenario A, change relative to 2008 and 2018 (except for SZEF Energy, which is % of fuel mix)

Scenario A Results	% relative to 2008			% relative to 2018		
	2030	2040	2050	2030	2040	2050
AER (gCO_2/dwtnm)	-51.6	-89.8	-99.5	-42.5	-87.9	-99.4
AER cgDist (gCO_2/gtnm)	-79.7	-95.7	-99.8	-42.9	-87.9	-99.4
CO_2 TTW (t)	-26.5	-81.3	-98.9	-17.7	-79.1	-98.7
EEOI (gCO_2/tnm)	-56.1	-90.8	-99.5	-42.5	-88.0	-99.4
Energy efficiency (J/dwtnm)	-27.5	-32.8	-37.2	-24.4	-29.9	-34.5
Energy intensity, TTW (tCO_2e/MJ)	-15.5	-78.8	-97.3	-17.7	-79.3	-97.3
Energy intensity, WTW (tCO_2e/MJ)	-14.2	-77.8	-97.6	-22.0	-79.8	-97.8
CO_2e TTW (t)	-20.7	-77.5	-96.8	-11.0	-74.8	-96.4
CO_2e WTW (t)	-17.7	-76.0	-97.1	-15.6	-75.4	-97.0
SZEF energy (% of fuel mix)	6.8	71.8	88.1	6.8	71.8	88.1

Table 4.3 – Summary results for Scenario B, change relative to 2008 and 2018 (except for SZEF Energy, which is % of fuel mix)

Scenario B Results	% relative to 2008			% relative to 2018		
	2030	2040	2050	2030	2040	2050
AER (gCO_2/dwtnm)	-68.6	-87.9	-98.9	-62.6	-85.7	-98.7
AER cgDist (gCO_2/gtnm)	-86.8	-94.9	-99.5	-62.9	-85.7	-98.7
CO_2 TTW (t)	-52.3	-77.6	-97.6	-46.6	-74.9	-97.3
EEOI (gCO_2/tnm)	-71.5	-89.1	-99.0	-62.7	-85.7	-98.7
Energy efficiency (J/dwtnm)	-28.1	-33.3	-37.7	-25.0	-30.5	-35.0
Energy intensity, TTW (tCO_2e/MJ)	-42.4	-74.7	-96.0	-43.9	-75.4	-96.1
Energy intensity, WTW (tCO_2e/MJ)	-37.8	-74.0	-96.4	-43.5	-76.4	-96.7
CO_2e TTW (t)	-46.4	-73.2	-95.3	-39.8	-69.9	-94.8
CO_2e WTW (t)	-40.9	-71.9	-95.7	-39.4	-71.2	-95.6
SZEF energy (% of fuel mix)	33.6	67.1	86.7	33.6	67.1	86.7

Table 4.4 – Summary results for Scenario C, change relative to 2008 and 2018 (except for SZEF Energy, which is % of fuel mix)

Scenario C Results	% relative to 2008			% relative to 2018		
	2030	2042	2050	2030	2042	2050
AER (gCO_2/dwtnm)	-38.7	-93.8	-99.8	-27.1	-92.7	-99.7
AER cgDist (gCO_2/gtnm)	-74.3	-97.4	-99.9	-27.7	-92.7	-99.7
CO_2 TTW (t)	-6.9	-88.3	-99.5	4.2	-86.9	-99.5
EEOI (gCO_2/tnm)	-44.4	-94.4	-99.8	-27.2	-92.7	-99.7
Energy efficiency (J/dwtnm)	-22.1	-31.7	-36.7	-18.8	-28.8	-34.0
Energy intensity, TTW (tCO_2e/MJ)	-4.8	-87.0	-97.9	-7.2	-87.3	-97.9
Energy intensity, WTW (tCO_2e/MJ)	-4.8	-85.6	-98.1	-13.5	-86.9	-98.3
CO_2e TTW (t)	-4.0	-85.7	-97.5	7.7	-84.0	-97.2
CO_2e WTW (t)	-2.0	-83.9	-97.7	0.4	-83.5	-97.7
SZEF energy (% of fuel mix)	0.3	81.5	88.9	0.3	81.5	88.9

4.3 GHG and air pollutant emissions

Figure 4.2, Figure 4.3 and Figure 4.4 below illustrate the trends of each major emissions species for the core modelling scenarios, including WTW CO_2e, which is inclusive of upstream (WTT) emissions. Results are discussed first for GHG emissions (including black carbon), and then for air pollutant emissions.

4.3.1 CO_2 and GHG emissions, including black carbon

Figure 4.2 (a), (b), and (c) show that Scenarios A, B, and C are observed to reach a 98.7%, 97.3%, and 99.5% reduction in tank-to-wake (TTW) CO_2 emissions respectively, and a 96.4%, 94.8%, and 97.2% reduction in tank-to-wake (TTW) GHG emissions by 2050.

In all the core scenarios, the modelling results in zero or very near zero tank-to-wake (TTW) CO_2 emissions by 2050. Small residual emissions in 2050 are shown in Figure 4.2(c) of less than 5% of the 2018 baseline emissions. The residual CO_2 emissions shown in Figure 4.2(c) are due to the use of MDO as a pilot fuel which is important for the combustion of SZEFs. These pilot fuel emissions could be minimised if biofuels or SZEFs were used, and the pilot fuel demand is broadly compatible with the small volumes of biofuel that are estimated to be available. However, where/if demand cannot be fully met by biofuel supply (which is finite in the modelling), some fossil use may remain. Because this finding is primarily a function of the use of a certain type of internal combustion, the need for pilot fuels may be further reduced or completely eliminated as a function of technology development. Several fuel cell and alternative internal combustion technologies are under development, but have not been used as the default assumption for machinery specifications in order to be conservative and test the viability of these decarbonisation objectives using the currently most mature technologies only.

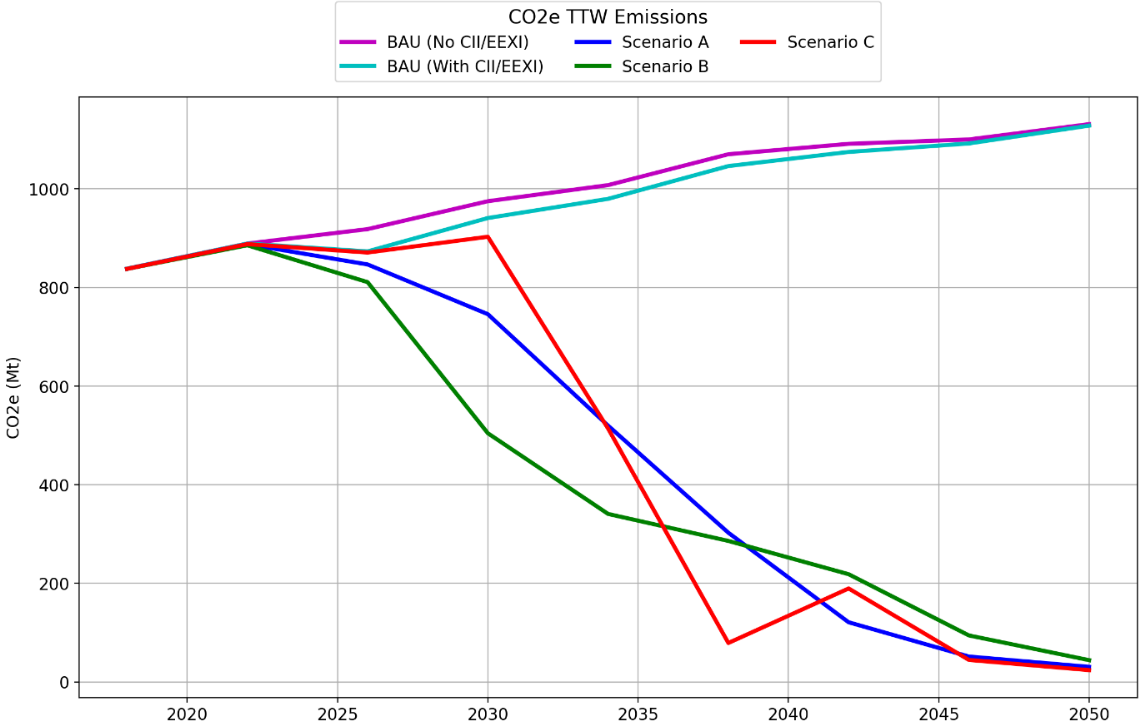


Figure 4.2(a)

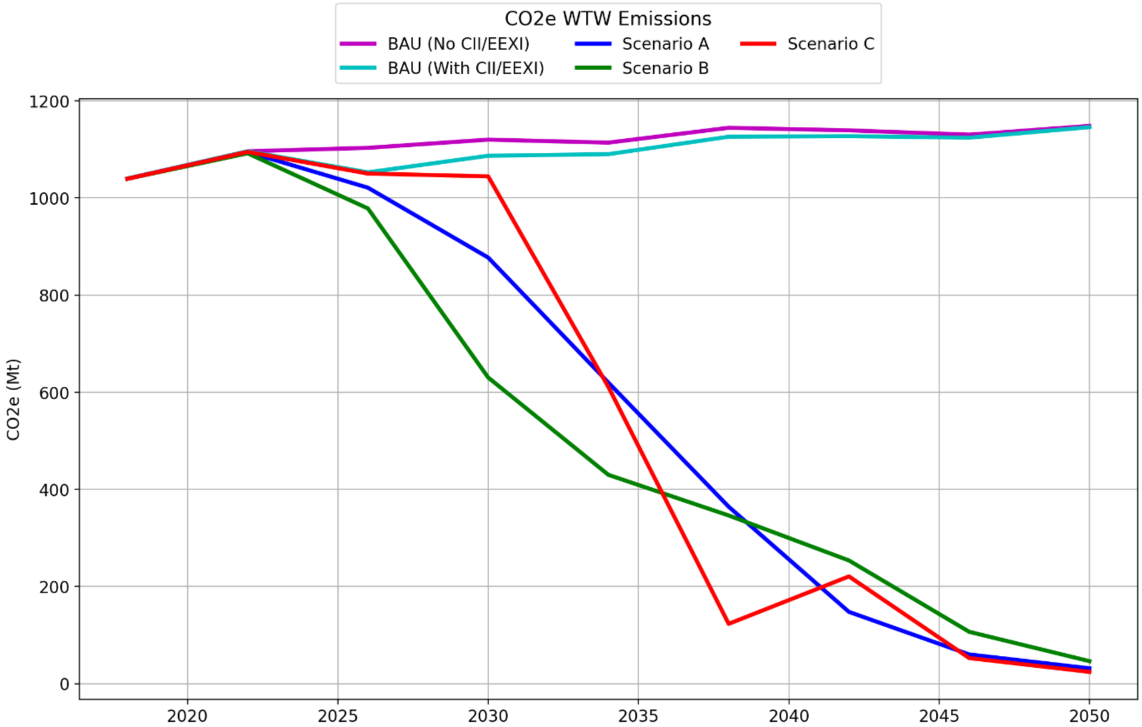


Figure 4.2(b)

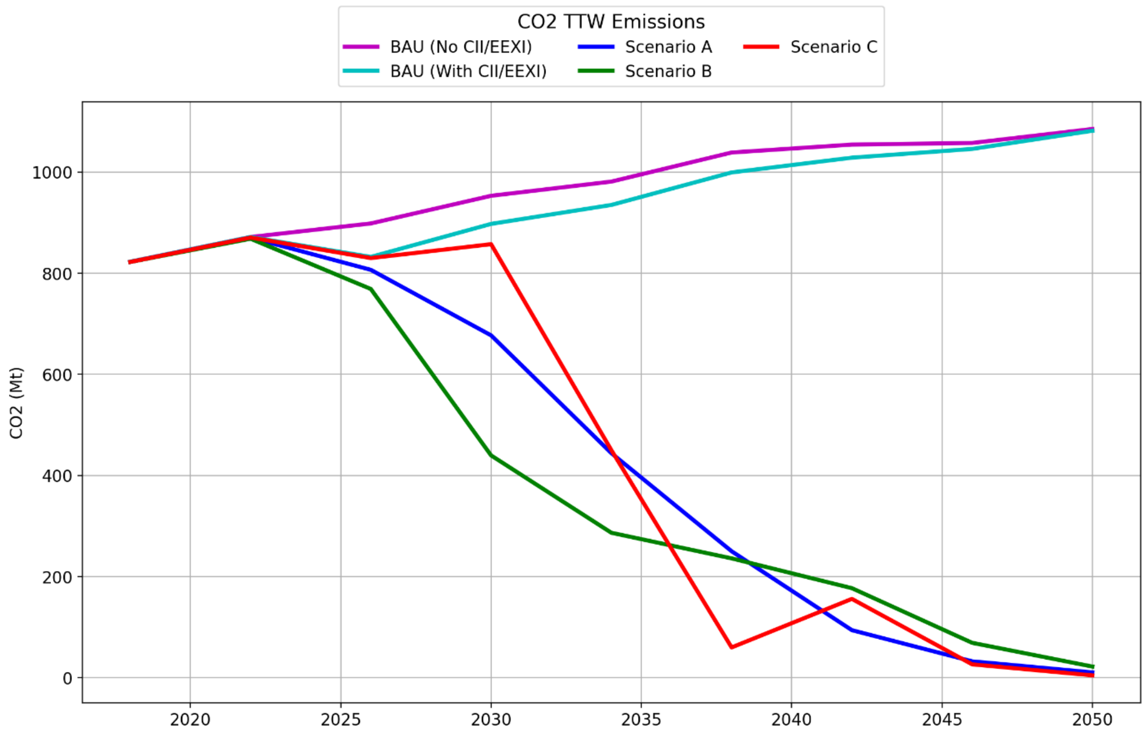


Figure 4.2(c)

Figure 4.2 – Trends in TTW CO_2, TTW and WTW CO_2e, Core and BAU Scenarios

The residual operational (TTW) GHG emissions (shown in Figure 4.2(a)) are due to a combination of both the residual operational CO_2 emissions and the residual operational nitrous oxide (N_2O) and methane (CH_4) emissions shown in Figure 4.3(a) and (b). Of the GHG emissions species, N_2O is the most potent GHG and so even small absolute quantities of this species have a significant impact on the overall operational GHG reduction.

Nitrous oxide emissions do not show significant absolute reductions relative to other emissions species (see Figure 4.3(b)). The combustion of any fuel in air, and the use of selective catalytic reduction (SCR) as a way of converting nitrogen oxides (NO_X), is expected to result in some level of N_2O emissions. There may also be material emissions of N_2O for ammonia combustion, given this is a nitrogen-rich fuel. The result is a function of the assumptions made about the emission factors of this GHG species (see Technical Annex for derivation). For all combustion machinery it is assumed to be limited to the level of the existing fuel and machinery combination. Relative to CO_2 and CH_4, N_2O currently receives little attention, so this finding that N_2O cannot be assumed to reduce to zero as the sector takes up SZEF implies that more thought is needed on how this emissions species will be controlled, in terms of both guidelines and technology pathways.

The black carbon (BC) emissions (Figure 4.3(c)) follow similar trends to the air pollutant emissions sulphur dioxide (SO_2) and particulate matter ($PM_{2.5}$), which are shown in Figure 4.4. The BAU (with the additional policies CII/EEXI) makes initial reductions in these emissions, driven by the substitution to LNG in the 2020s, before the emissions increase again, in line with growth in transport demand. The decarbonisation scenarios A–C show significant absolute reductions in these emissions sustained to 2050. By 2050, there remain some BC emissions due to the use of biofuels including as pilot fuel, but because the large majority of fuel has switched to an SZEF without any carbon content (ammonia), the main source of BC has been removed.

The BAU with CII/EEXI and the three core scenarios all include high rates of take-up of LNG as a marine fuel during the period to 2030. The result of this is a rapid increase in the level of CH_4 emissions in all of these scenarios (shown in Figure 4.3 (a)), at least until 2030, continuing a trend of high growth in CH_4 emissions first observed in IMO4 during 2012–2018. When considering the BAU with CII/EEXI scenario, the evolution in fuel mix in combination with the energy efficiency take-up results in a small reduction in the operational and lifecycle GHG emissions when compared to the BAU without CII/EEXI applied. For the core scenarios substitution from LNG to ammonia during the 2030s acts to reduce both CH_4 and CO_2 operational emissions and enables significant GHG reduction relative to both BAU scenarios. All of these results were produced under the 100-year GWP.

The profile of the lifecycle (WTW) GHG emissions, Figure 4.2(b) is very similar to the profiles of operational (TTW) GHG emissions, Figure 4.2(a). In 2018, Scenario A upstream (WTT) emissions constitute roughly 19% of total CO_2e WTW emissions, falling to 15% in 2030, and approximately 3% in 2050. Over the period to 2050, the input assumptions assume that actions taken on land and in national emissions inventories have removed significant sources of GHG emission (as part of wider efforts to decarbonise the global economy), including in the production pathways of SZEF. As a result, lifecycle GHG emissions reduce to a similar absolute level in 2050 as the operational GHG emissions. This means that the lifecycle GHG emissions undertake a steeper rate of reduction than operational GHG emissions. This indicates that although upstream (WTT) emissions remain material to the overall GHG output of the international fleet, the choice of trajectory taken to decarbonise is immaterial. Instead, the results show that the input assumptions made in this study (i.e. the implicit reduction of upstream (WTT) emissions as production processes mature) are more important than the ultimate composition of the fuel mix. This finding also shows the importance of efforts to achieve the reduction in GHG emissions associated with the production of fuels, especially of SZEF.

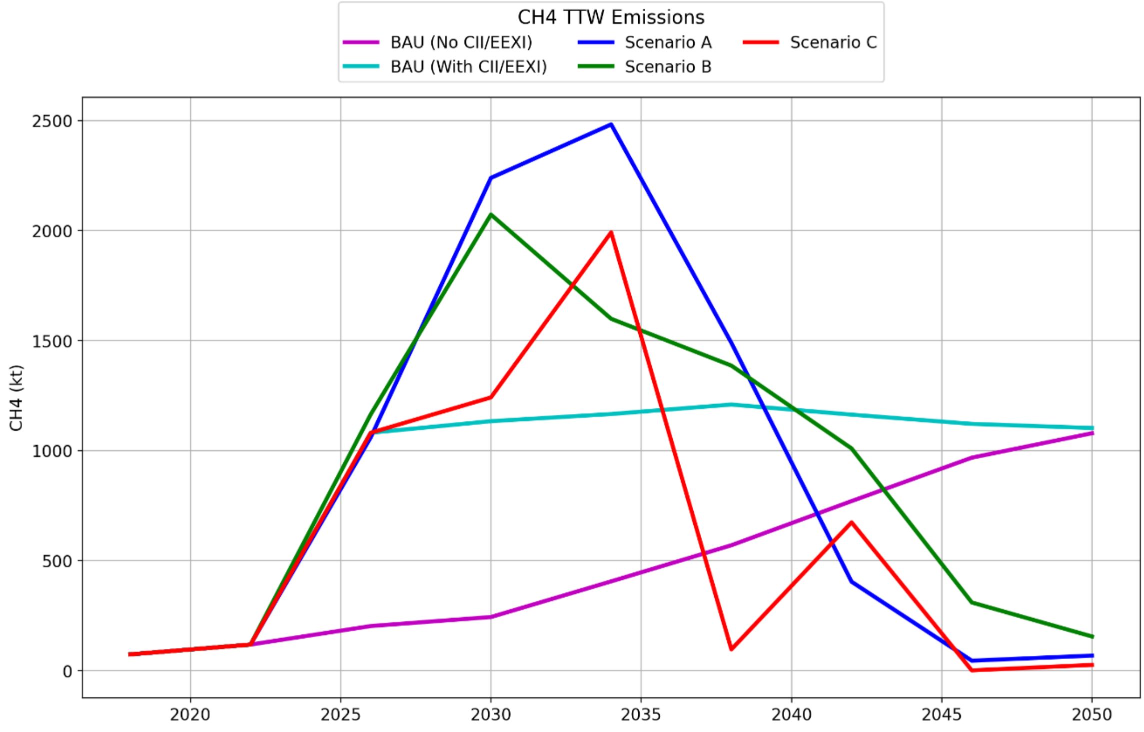


Figure 4.3(a)

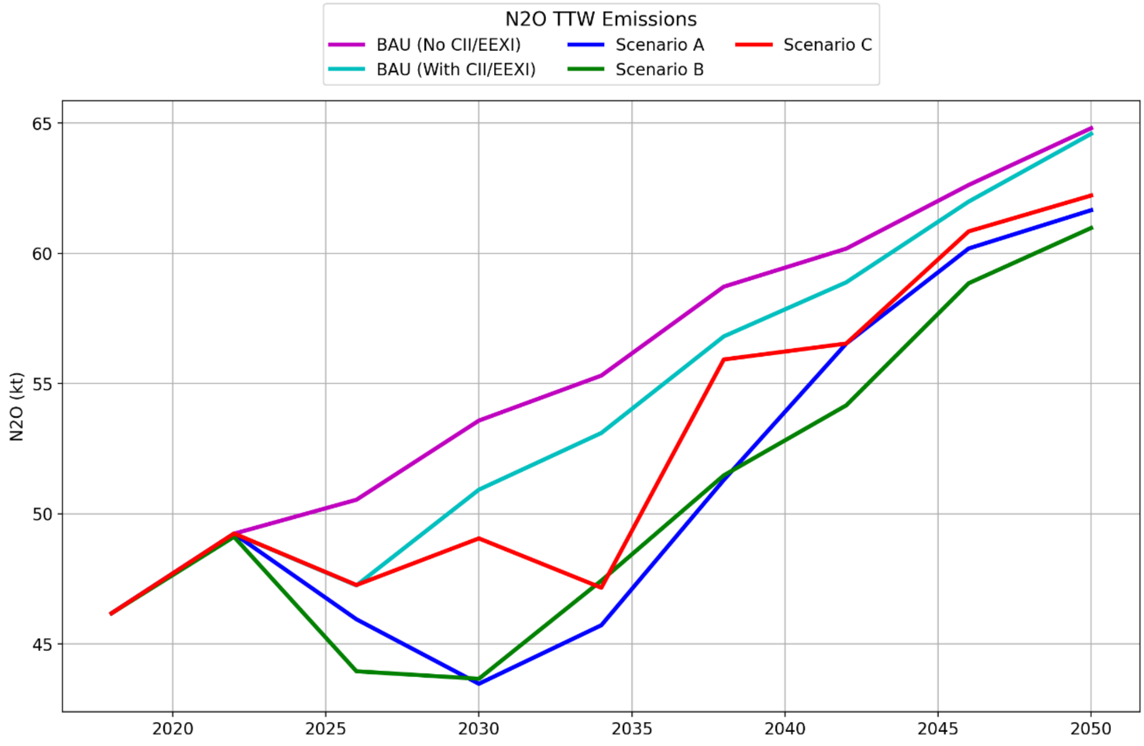


Figure 4.3(b) – please note non-zero y axis

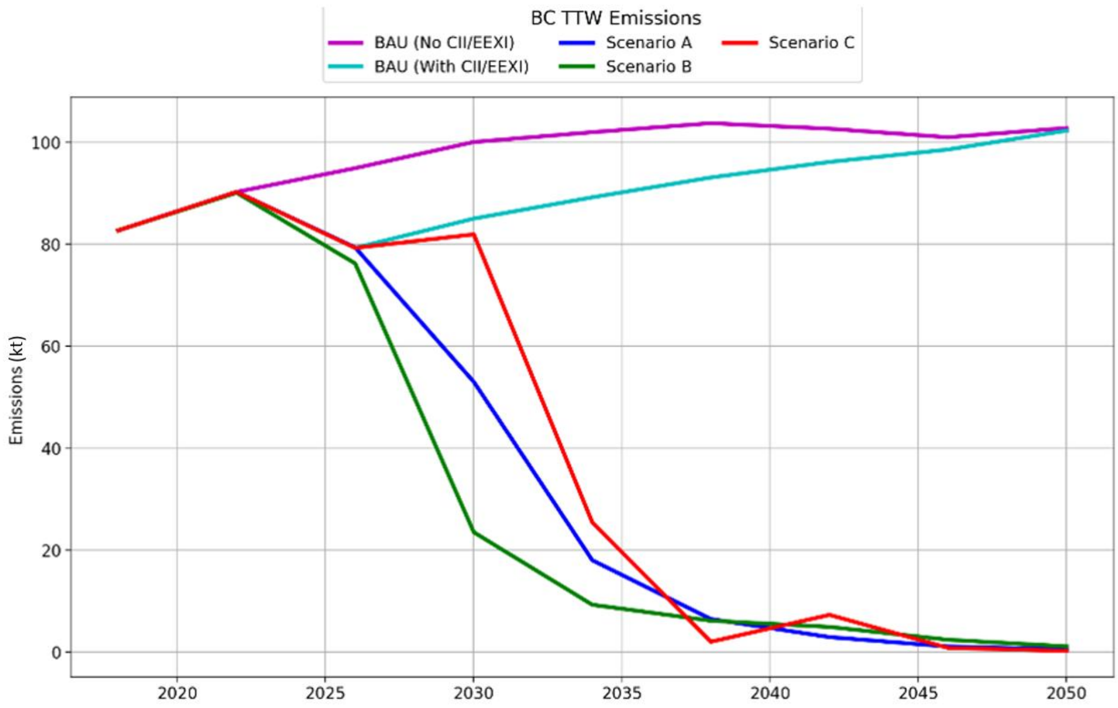


Figure 4.3(c)

Figure 4.3 – Non-CO_2 TTW GHG emissions species and black carbon for core and BAU scenarios

4.3.2 Air pollutant emissions

A clear co-benefit of such a rapid transition to SZEF is the complete elimination of SO_2 emissions by the late 2030s in all decarbonisation scenarios (Scenarios A, B and C), Figure 4.4(a). There is also a significant reduction in SO_2 for the BAU (with CII/EEXI) scenario until 2026, following the introduction of the CII regulatory mechanism, almost to the extent of the core decarbonisation scenarios. This is caused by a number of pre-2018 vessels retrofitting to LNG during this period. This trend does not continue and these emissions then start growing again, with the absolute reductions in these air pollutant emissions reversed as the growth in demand for transport and energy use takes over. The same co-benefit and trend can be seen for $PM_{2.5}$ emissions, Figure 4.4(b) and BC emissions, Figure 4.3(c), both because of the differences in the fuel mix for each of these scenarios (presented in Section 4.4).

During the period 2030-2035, differences between Scenario A, B and C occur in the timescales of the large reduction in air pollutant emissions SO_2, $PM_{2.5}$ and BC. Scenario B achieves the fastest rate of reductions in these air pollutants. These differences are all explained by the differences in rate of adoption of SZEF during this period, as this changes the rate at which fossil fuel use is reduced, and with it the associated air pollution its use causes.

The emissions of the air pollutant NO_X (Figure 4.4(c)) do not show a similar level of reduction to SO_2 and $PM_{2.5}$ emissions. More so than for other air pollutant species, NO_x emissions are affected by both the fuel and the machinery, not just the fuel's specifications. NO_X emissions result from the combustion of any fuel, whether biofuel, fossil or SZEF. In both the BAU scenarios and Scenarios A, B and C, internal combustion remains the dominant technology in the fleet and differences are primarily in the fuel composition (mix between fossil fuel and

SZEF). Whilst there are small differences between fuels on their specific NO_x emissions levels (see Technical Annex), NO_x emission reduction is generally limited to the level of Tier II compliance, regardless of the fuel. As a result, material NO_x emissions remain in all scenarios over the period to 2050.

Regulation on NO_x emissions, requires the use of machinery with lower NO_x emissions levels (Tier II and III compatible machinery), and is applied at the point of newbuilding or major retrofit. This contributes to a lowering of specific NO_x emissions (e.g. NO_x emissions per unit of energy used) over time. However, the reduction driven by adoption of Tier II and III compatible machinery is not significant enough to result in absolute reduction in NO_x emissions once transport demand growth and by association energy use growth has been factored in. This results in NO_x emissions in all scenarios being slightly higher in 2050 than in the baseline year 2018.

The main driver of the variation in NO_x between scenarios comes from the way retrofitting and newbuilding rates are stimulated by GHG regulation. The BAU (no CII/EEXI) scenario sees no sudden change in NO_x emissions, just steady growth over the period to 2050. This scenario does not see any significant pressure on retrofitting. The other four scenarios all incentivise a significant amount of LNG and ammonia retrofitting (see Section 3.6.4), which accelerates the take-up of Tier II compliant machinery and creates a reduction in the NO_x emissions level. This acceleration of take-up only temporarily relieves the pressure on NO_x emissions – the take-up would have happened eventually by 2050 due to natural turnover of the fleet as ships reached the end of their economic life. This is why the emissions then return to a similar level as the BAU scenario, by 2050.

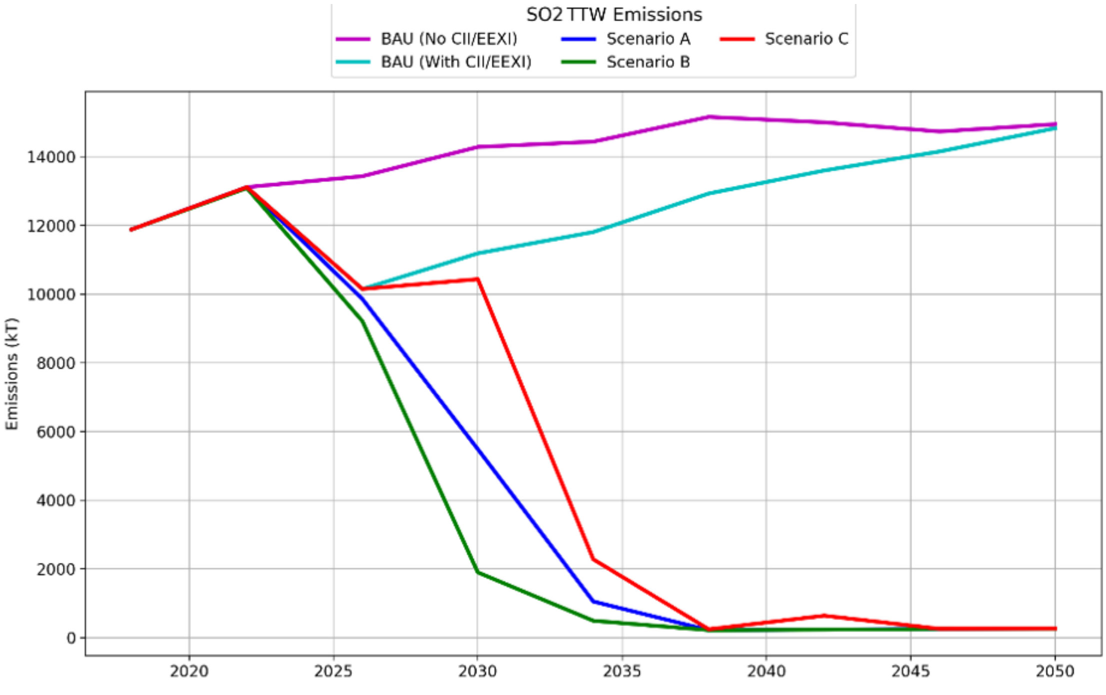


Figure 4.4(a)

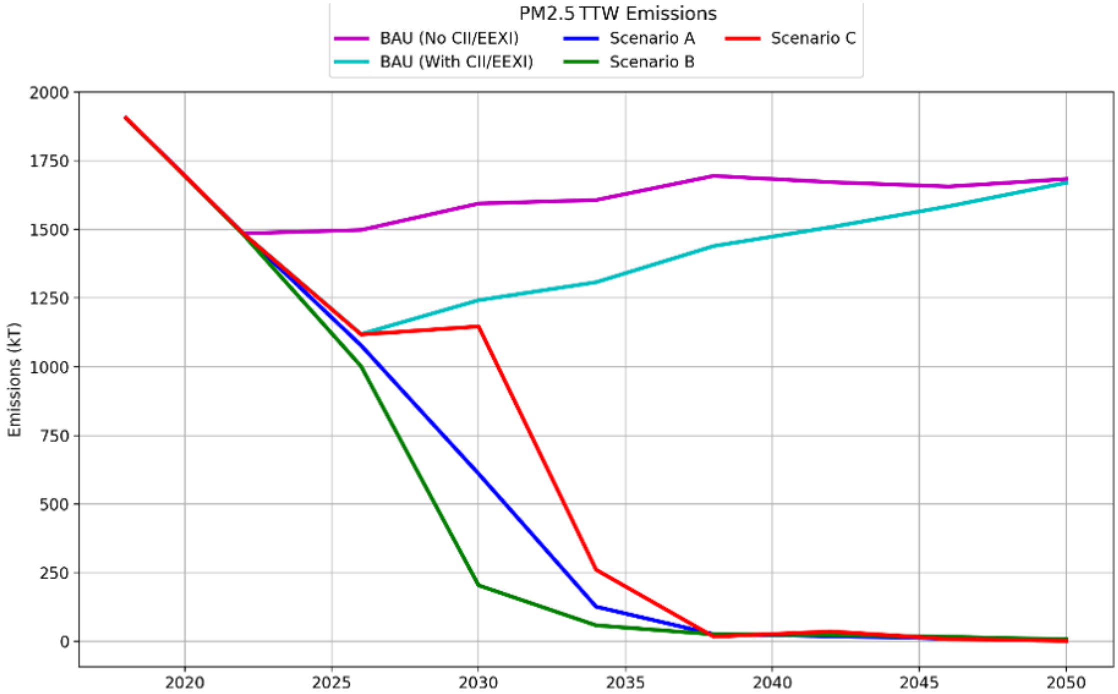


Figure 4.4(b)

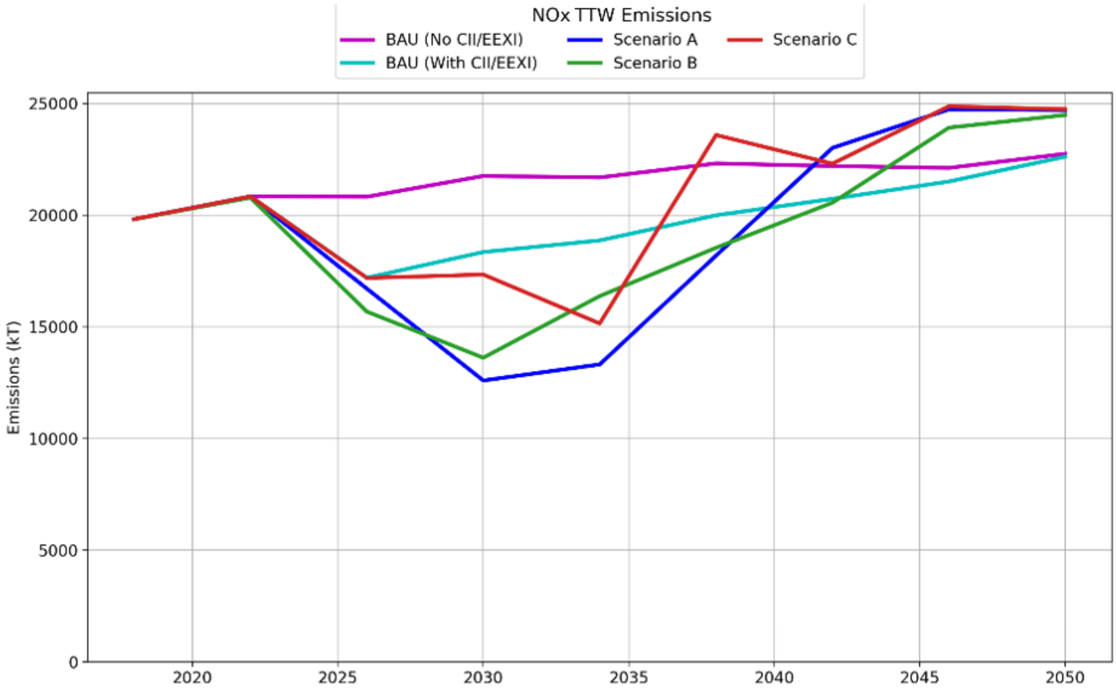


Figure 4.4(c)

Figure 4.4 – TTW air pollutant emissions for core and BAU scenarios[48]

[48] Please see Figure 4.3(c) for BC emissions. BC is both climate forcing as well as a local air pollutant.

4.4 Fuel mix

Figure 4.5 (a)–(e) shows the fuel mix plots for the core and BAU scenarios. These plots show both the composition (by energy) over the period to 2050, and therefore also the absolute energy input needed (total energy demand) by international shipping.

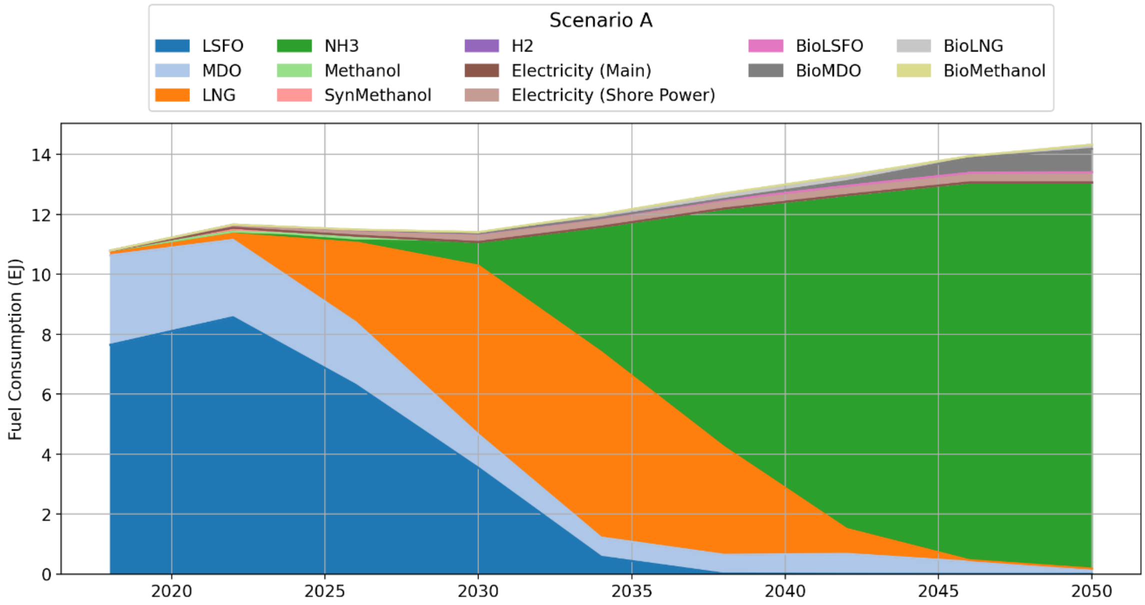


Figure 4.5(a)

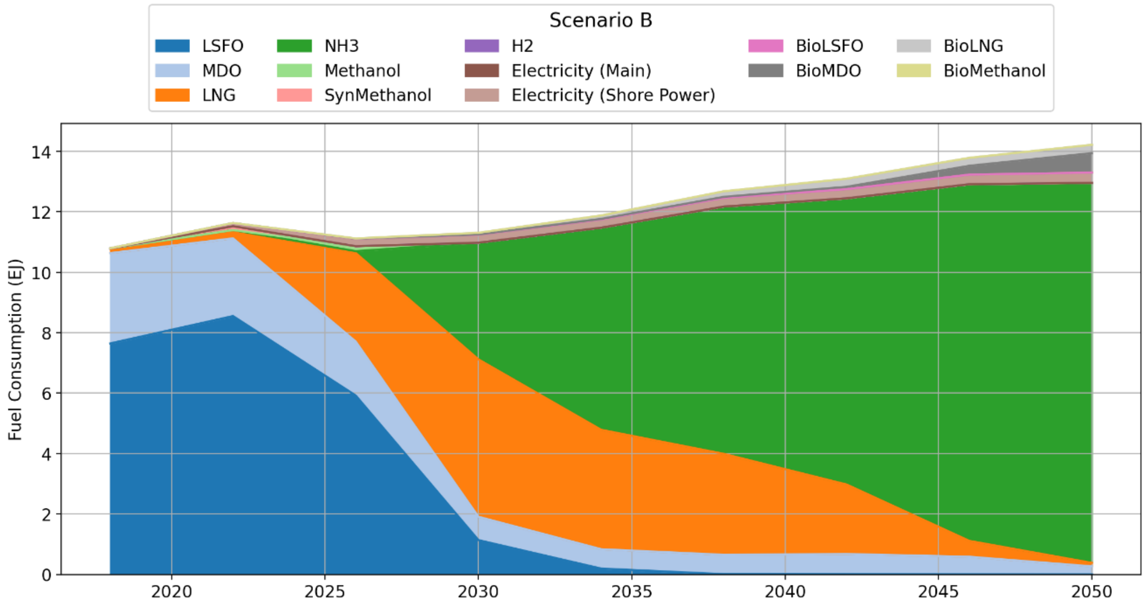


Figure 4.5(b)

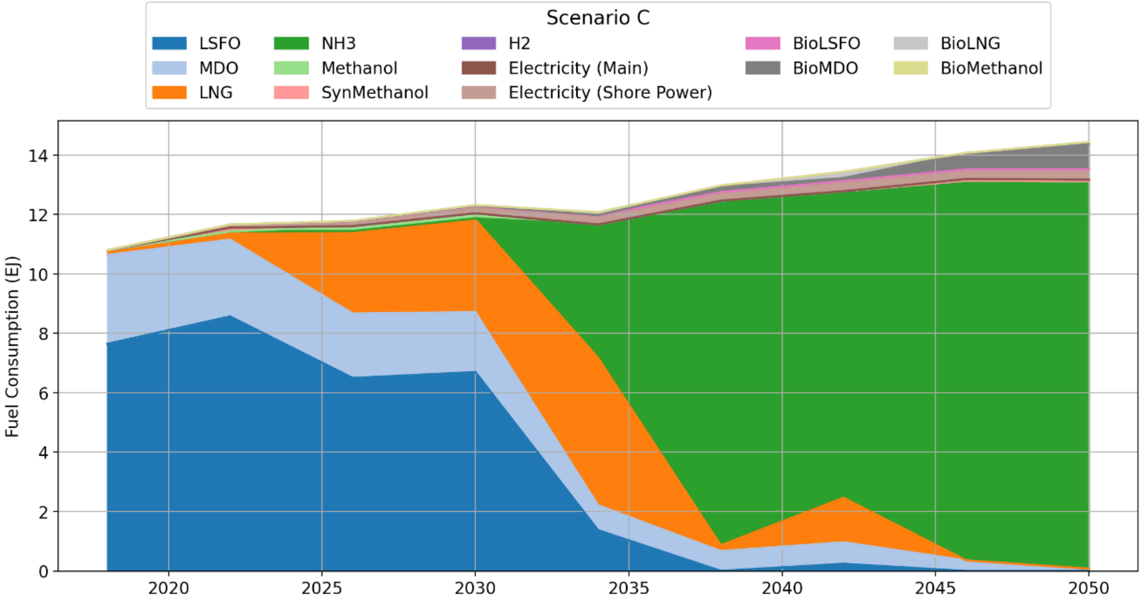


Figure 4.5(c)

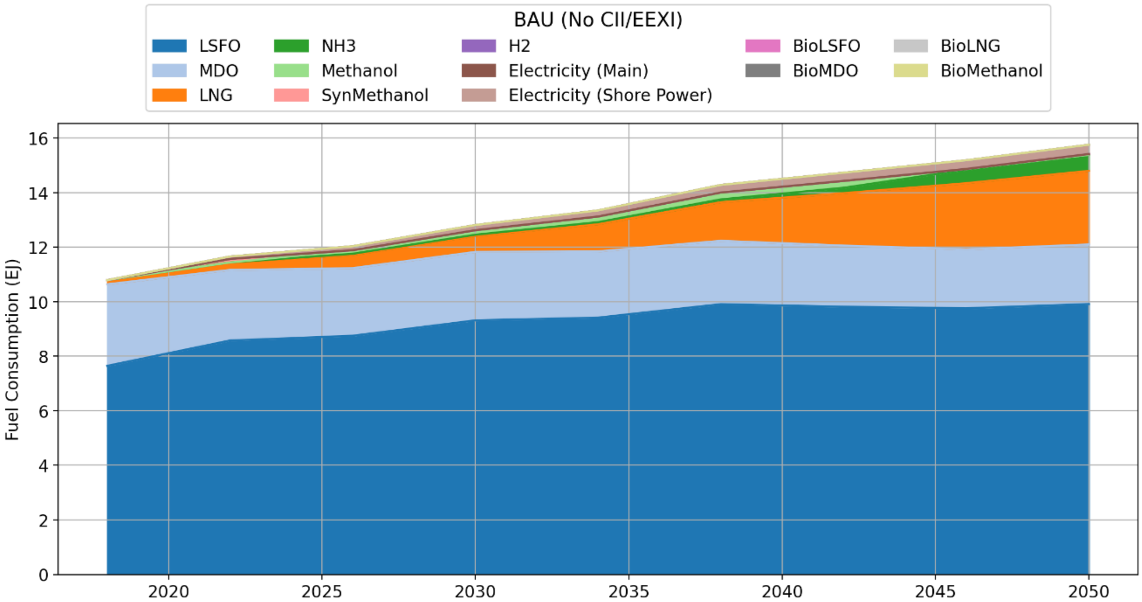


Figure 4.5(d)

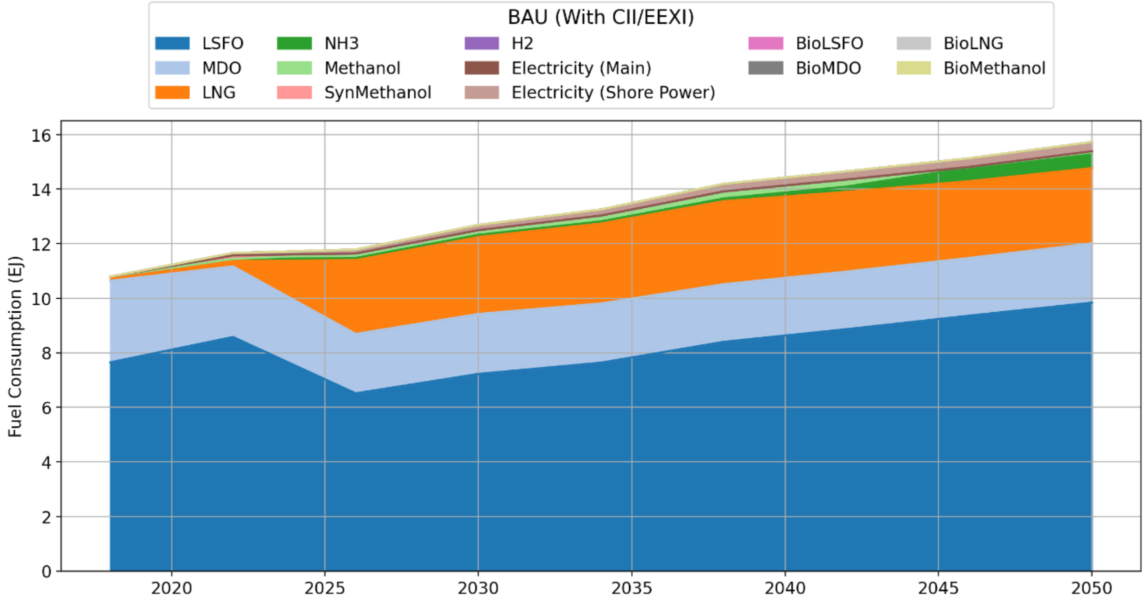


Figure 4.5(e)

Figure 4.5 – Fuel mixes (energy demanded) by year for core and BAU scenarios

4.4.1 Total energy demand

As Figure 4.5(d) and (e) shows, the absolute energy demand increases to approximately 16EJ by 2050 in both of the BAU scenarios, in line with the growth in transport demand and the relatively limited further potential for energy efficiency.

The decarbonisation scenarios (A–C) each reach a total energy demand of slightly over 14EJ, despite meeting the same level of transport demand. This 12% reduction in overall demand is driven by the increased EET take-up and slower operating speeds[49], incentivised by the higher fuel/carbon price of the three core scenarios relative to the BAU (with existing policies). This is particularly marked in Scenario B where, in 2026, the energy demand reduces below the 2018 level due to a high take-up of EETs. The model's carbon price is particularly high at this point because of the steep reductions in the target CO_2 trajectory and the high price for SZEF early in the transition.

The introduction of EEXI/CII (i.e. BAU with additional policies) is estimated to have only a small impact on the total energy demand by 2030, relative to the BAU without those. By 2050 the level of energy demand is also similar in both BAUs. This is because of the very low stringency at which EEXI/CII has currently been applied – a stringency that is very close to the level of energy efficiency improvement that is expected due to market forces and fleet turnover (replacing older less-efficient ships with new more efficient ships). Comparing the energy demand in BAU (Figure 4.5 (d) and (e)) with the energy demand in the decarbonisation scenarios (Figure 4.5 (a), (b) and (c)) shows that there is potential for higher stringency and that, if applied, this would complement the efforts to reduce the CO_2 emissions of the fleet, and help reduce the quantity of SZEF needed in order to achieve any absolute GHG reduction target.

[49] For further information, see discussion on the generally small variation in operating speeds between scenarios in Section 2.5.6

4.4.2 Changes in fuel composition

In all decarbonisation scenarios (Figure 4.5(a)–(c)), a marked shift to LNG in the 2020s and early 2030s can be seen, followed by a rapid substitution to ammonia. The substitution to ammonia is most rapid in Scenario C and more drawn out in Scenario B, consistent with their difference in CO_2 target trajectories. In Scenarios A and B, all of the LNG energy demand growth occurs through to the late 2020s; from then, no new LNG engines are installed on new or existing vessels, which is indicated by the thickness of the orange wedge in Figure 4.5 (a) and (b) reaching a maximum in the late 2020s and declining through to 2050. During the 2030s and early 2040s, the majority of these LNG-powered vessels are retrofitted to use ammonia, with very few continuing with LNG use to the late 2040s when they would expect to be scrapped. This transition to and from LNG has serious implications in terms of stranded LNG assets on both the supply side and the demand side. While this study has not considered the geographic distribution of LNG supply and demand, it is plausible that there could be a natural concentration of the remaining supply of LNG to a limited number of locations as demand drops in the 2030s, and this could force vessels to be scrapped or retrofitted even faster than is indicated by these results.

Without the additional incentive to achieve CO_2 reductions, as applied in core decarbonisation scenarios A, B and C, comparing the two BAU scenarios shows that LNG appears to be the initial preferred route for vessels to adhere to the EEXI/CII requirements. In the BAU without this recent regulation, a more modest and gradual penetration of LNG occurs. However, in both scenarios there remains a significant role for incumbent marine fuels LSFO and MDO.

Other than the BAU scenarios, where no biofuel take-up has been assumed, all decarbonisation scenarios see maximum take-up of available biofuels, although this still constitutes a small proportion of the overall energy demand. By 2050 biofuels are overwhelmingly used to substitute the MDO pilot fuel required by SZEF and LNG, with the remainder substituting some of what little LNG remains as a primary fuel. This is, however, not the case for Scenario B, where a heavier early take-up of LNG causes an earlier full transition to ammonia, leaving no LNG to be substituted for bioLNG in 2050.

Overall, ammonia attains a competitive advantage over alternative SZEFs in all decarbonisation scenarios, becoming the predominant maritime fuel by the mid-2030s, and taking nearly all the energy demand in 2050. The prevalence of LNG up to that point is the most variable component of the transition, and results in significant impacts to the cost of transition (discussed in Section 3.5), as well as the risk of perverse unintended consequences to GHG emissions (discussed in Section 4.3.1). In particular, for Scenario C (Figure 4.5 (c)), it can be seen that by 2030 the fleet has roughly 75% of the LNG demand compared with Scenarios A and B, but that demand is wiped out within 8 years. This would represent a financially traumatic transition for the international maritime fleet if it had not been fully anticipated and priced in. Scenario B, despite having a lower carbon budget than Scenarios A and C, maintains a steady decoupling from LNG through to 2050, suggesting that an early push for decarbonisation could result in a more sustainable transition between primary energy sources and result in fewer stranded assets.

4.5 Total and normalised fleet energy-related costs

The operation of international shipping involves a number of component costs, both capital costs and operational costs. The growth in transport demand means that there are underlying drivers of the growth in these costs regardless of any technology change. This section presents energy-related costs in a variety of ways, in order to provide insight to how costs might change and how those changes are driven by a combination of growth in demand for transport, and different target CO_2 trajectories and technology changes. Energy-related costs include the following:

- Energy-related capital costs of the vessel fleet, such as:
    - EETs, including wind-assistance technology
    - Onboard energy-conversion machinery (engines, fuel cells, motors) and energy storage and handling equipment (tanks, fuel handling)
- Energy-related operational costs of the vessel fleet, such as:
    - Fuel costs
    - Carbon costs (associated with fuels with operational CO_2 emissions)
    - Maintenance costs of EETs and energy-conversion machinery.

There are a number of other areas of cost which are therefore not included, many of which are also expected to increase over the period due to the increase in demand for transport. See Section 2.5.6 for further details.

4.5.1 Cumulative total and normalised energy-related costs (excluding carbon costs)

Figure 4.6 presents the total energy-related costs for each core and BAU scenario, both in absolute terms, plot (a), and as a cost above each BAU scenario variation, plots (b) and (c).

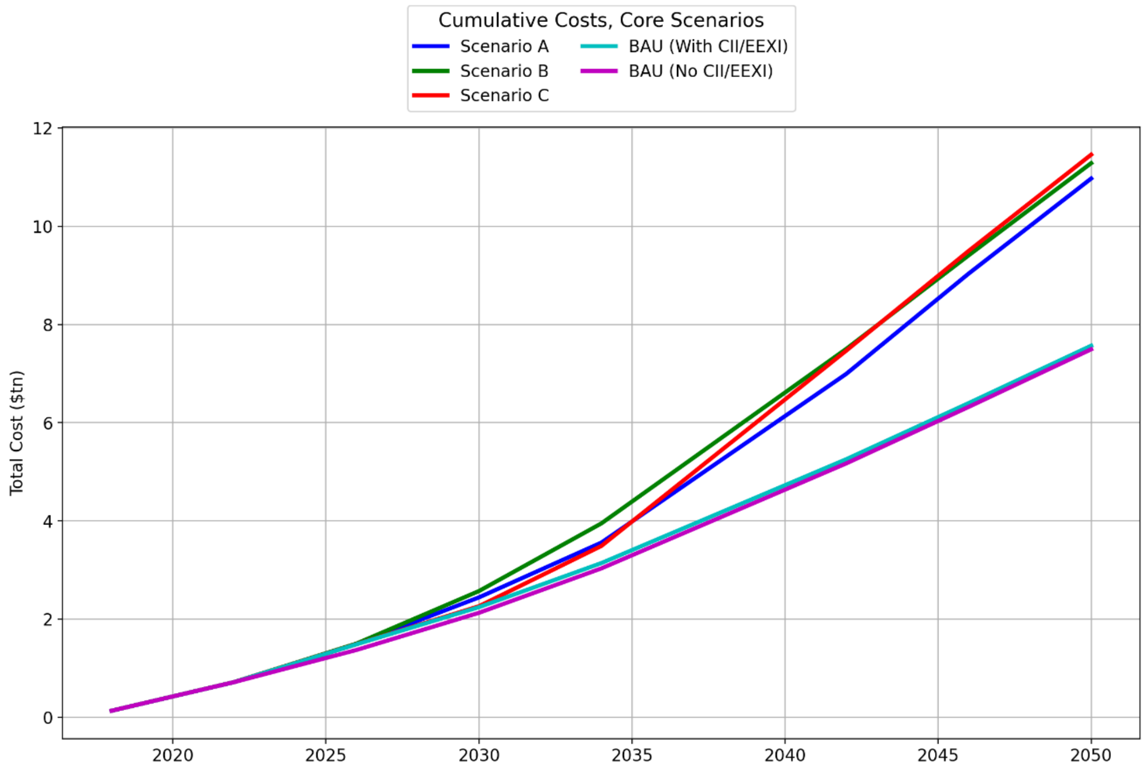


Figure 4.6(a)

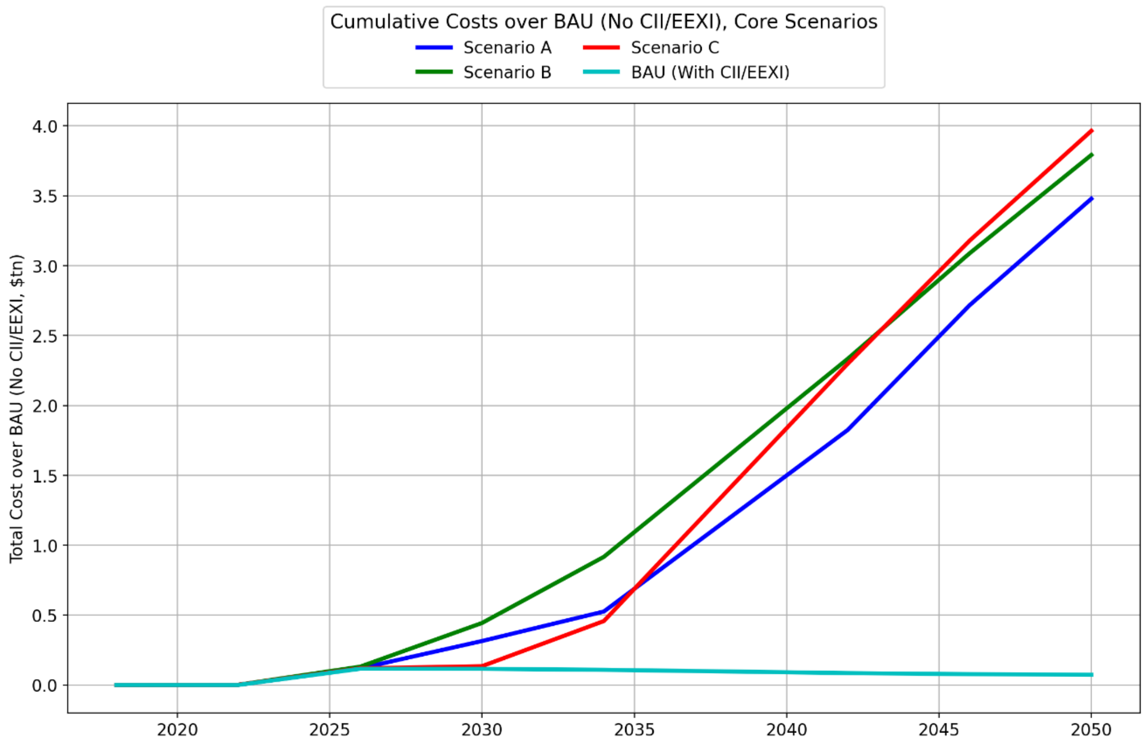


Figure 4.6(b)

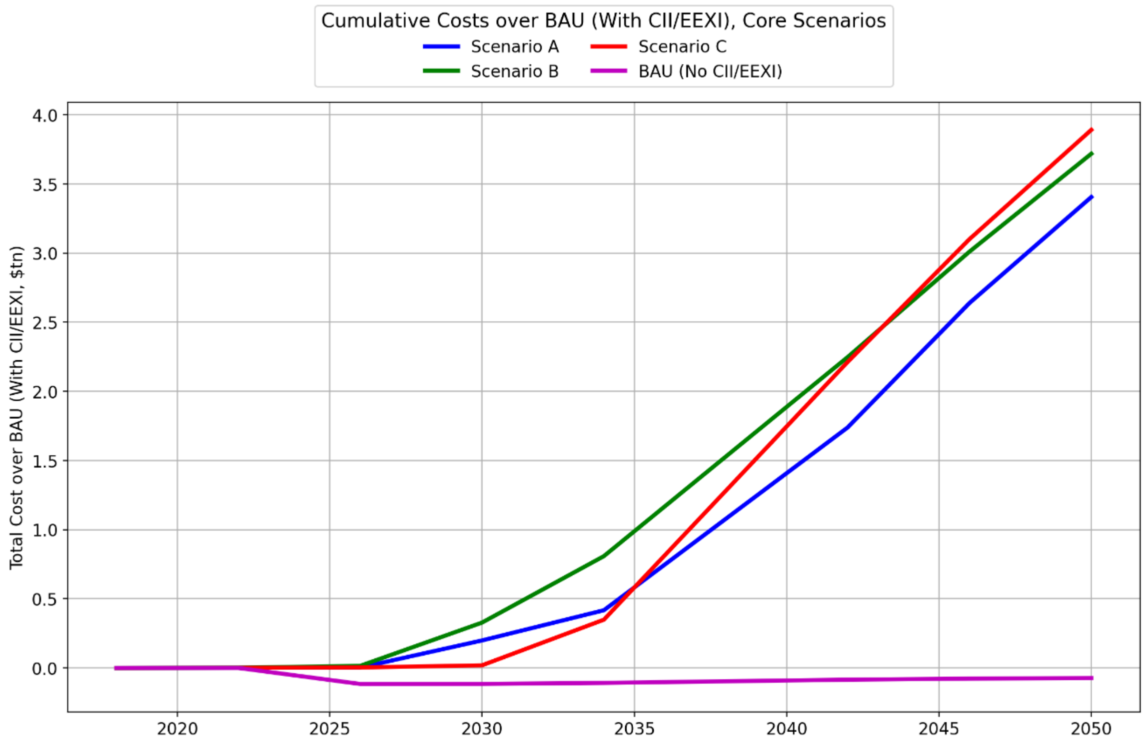


Figure 4.6(c)

Figure 4.6 – Cumulative energy-related total costs, and costs over BAU (with and without CII/EEXI), excludes carbon cost

Comparing the results in Figure 4.6 (b) and (c) for the two BAU scenarios shows that the EEXI/CII regulation has a negligible difference in the total costs. The BAU with EEXI/CII has a slightly higher cost than the BAU which does not include this regulation.

For the three core decarbonisation scenarios in all their presentations in Figure 4.6, the cumulative costs follow a similar trajectory – divergence from the BAU scenario's total costs occurs in the late 2020s, with the onset of the substitution away from fossil fuels to higher (capital and operating cost) SZEF use, there are increases in the rate of cumulative cost growth.

Setting cumulative costs relative to each of the two BAU scenarios, Figure 4.6 (b) and (c), makes it possible to see more clearly the relative cumulative cost of the three decarbonisation scenarios. Beginning the decarbonisation transition earlier (Scenario B) incurs an initially higher total cost as learning effects from the wider global economy have not yet had the chance to percolate into the maritime sector. It is also clear that Scenario B, with a lower carbon budget than Scenarios A and C, sustains a higher cumulative cost through much of the transition. However, because Scenario B enables the most gradual transition away from fossil fuel use (because it allows the longest period between initiation of substitution away from fossil fuel to SZEF use), it experiences less cost in the 2040s. The result is that by 2050 the cumulative cost of this lower cumulative GHG scenario is marginally higher than Scenario A. Scenario C, which experiences decarbonisation over the shortest period of time, sees a lower cumulative cost initially, but then cumulative costs increase faster than Scenarios A and B such that by 2050 there is a cumulative cost increase relative to those scenarios.

In all three decarbonisation scenarios, the gradient of the cumulative costs reduces over the period 2030–2050. This indicates that the transition/decarbonisation of shipping involves a period of heightened cost, but that in the longer run it can be expected to return to trends that are more aligned with the BAU.

4.5.2 Normalised energy-related costs (including carbon cost)

Figure 4.7 (a)–(e) presents the total energy-related costs (i.e. just those costs that are associated with energy use of international shipping), normalised against the total transport demand so this can be presented independently of the underlying growth in transport demand.

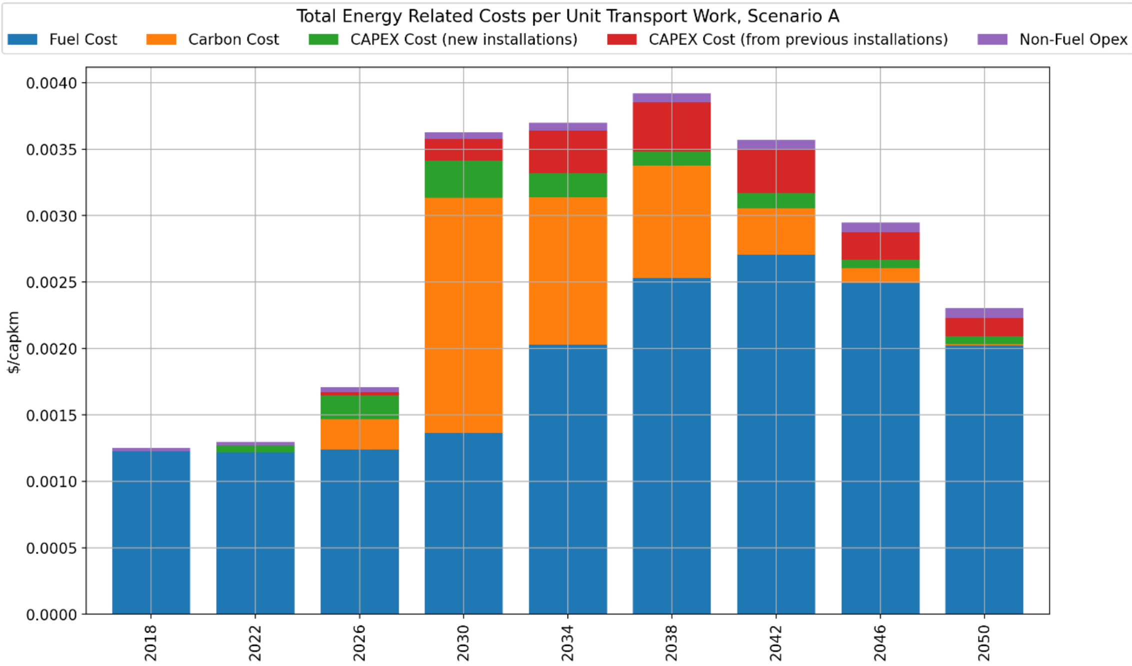


Figure 4.7(a)

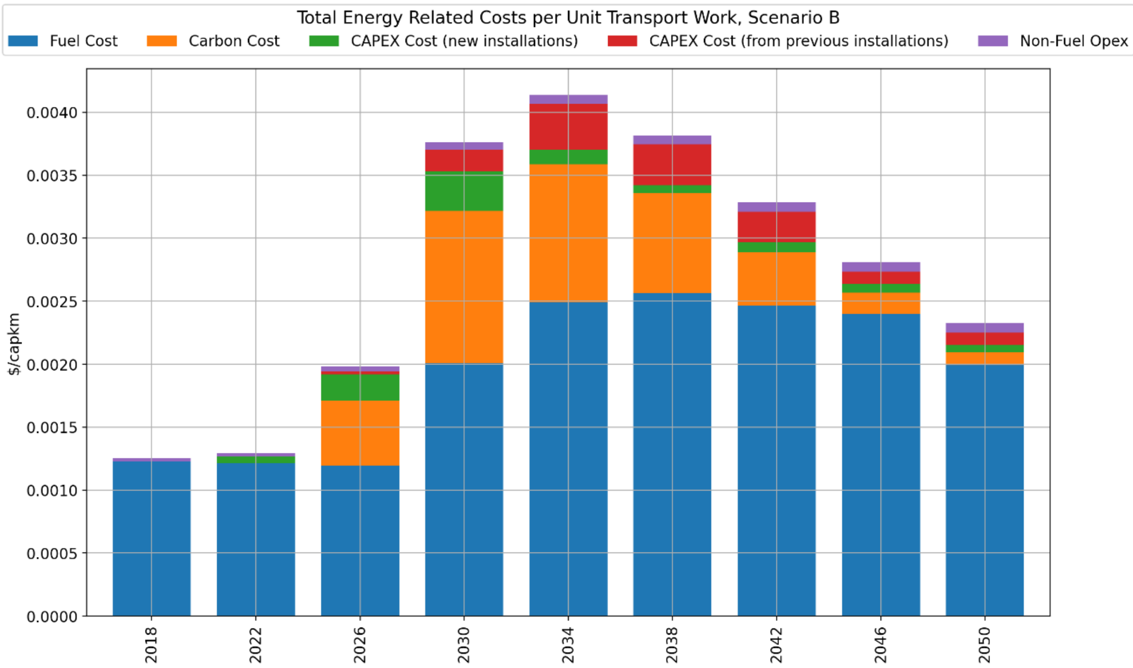


Figure 4.7(b)

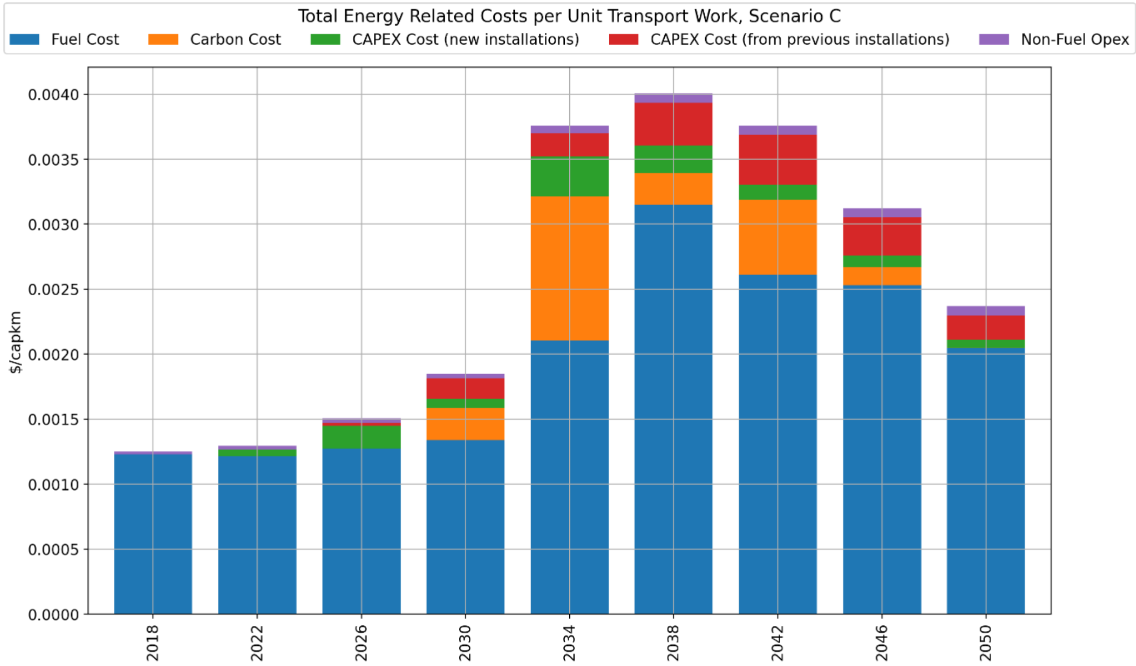


Figure 4.7(c)

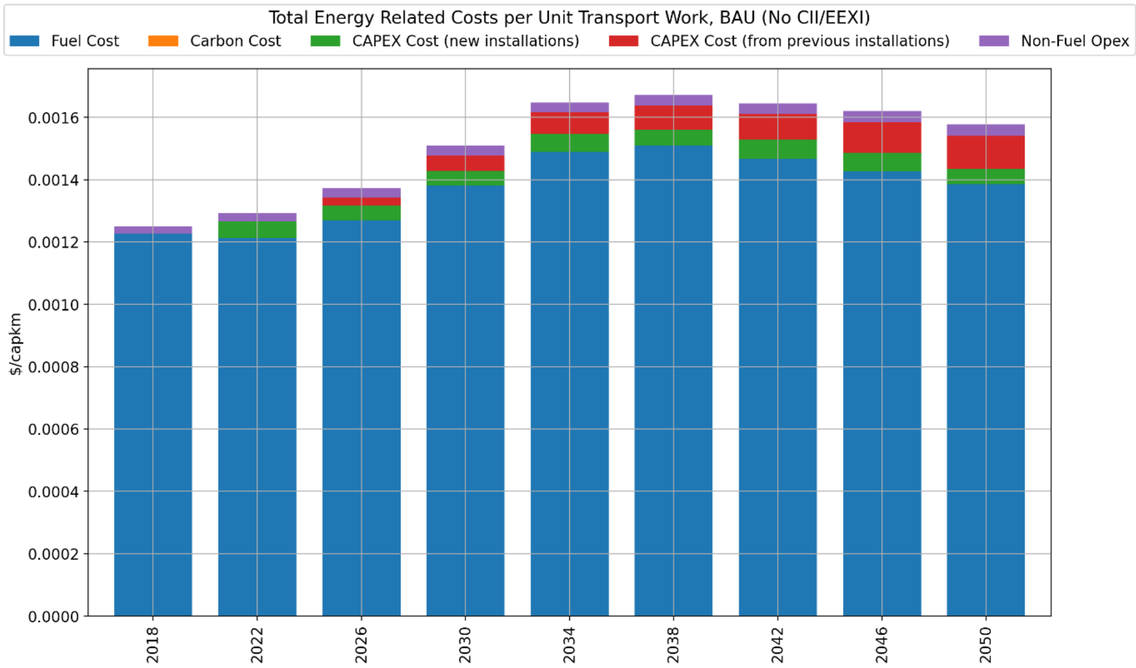


Figure 4.7(d)

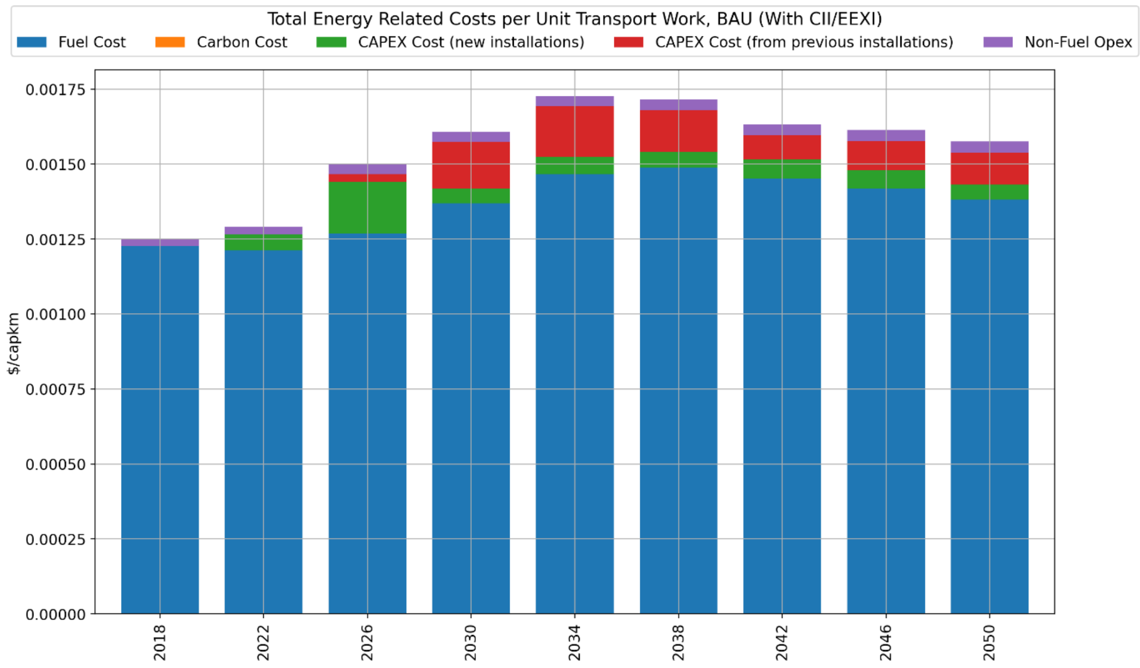


Figure 4.7(e)

Figure 4.7 – Total energy-related costs per unit of transport work for core and BAU scenarios

Normalising energy-related costs against the underlying growth in transport demand, Figure 4.7 clearly shows the transient cost increases of decarbonisation. In these results, the carbon cost is included and there is no assumption about any use of the amassed revenues (either in-sector or out-of-sector).

Comparing the two BAU scenarios in Figure 4.7 (d) and (e), there is a higher CAPEX cost per unit of transport work in 2026 for the BAU with CII/EEXI scenario relative to the BAU scenario without. This represents the retrofitting to LNG by older vessels as discussed earlier in Section 3.5. In other aspects these two cost trajectories follow similar and unremarkable trends.

While it initially appears that the cumulative cost of Scenario C by 2050, Figure 4.7 (c), is lower than in Scenarios A and B, Figure 4.7 (a) and (b), this does not imply that deferring the transition is the least-cost pathway. The differential visible between the normalised costs of these three scenarios is significantly driven by the carbon cost. Carbon cost represents an economic transfer, so depending on where the transfer is made to can be considered cost neutral. Once that cost is removed (as it would be in certain policy designs, including fuel standards and carbon levies that reinvest revenues into the sector's decarbonisation), the underlying capital and operating costs for Scenario C are greater than those of Scenarios A and B.

In total, Scenario C accrues 46% less carbon cost than Scenario B, as well as exhibiting a much higher fuel cost per unit of transport work than the other scenarios in the late 2030s. Another issue that is not accounted for in this model is that although Scenario C demands a considerable rate of retrofits in the mid-2030s, GloTraM does not exclude these vessels from servicing transport demand while they are retrofitted. It may, however, be challenging to fit 30,000 vessels (Figure 3.12), or around 40% of the international fleet, in the same four-year period unless the retrofit could be done simply and within the period of planned maintenance, see analysis and discussion in Section 6.2.

All decarbonisation scenarios show very sharp increases in total energy-related cost per unit of transport work of approximately 215% in 2038 for Scenario A, 230% in 2034 for Scenario B, and 220% in 2038 for Scenario C. These costs all decrease from the late 2030s to settle in 2050 at roughly the same value regardless of the decarbonisation scenario chosen.

4.6 Technology take-up and capital expenditure breakdown

4.6.1 Energy efficiency technology take-up

Figure 4.8 to Figure 4.12 below outline the take-up of key EETs at 2030 and 2050 for the core scenarios, for the highest CO_2-emitting subsectors of international shipping; namely, oil tankers, containers and bulk carriers (Figure 3.8 evidences this selection).

There is a clear increase in the take-up of a number of technologies in the BAU with CII/EEXI scenario relative to the BAU without CII/EEXI, indicating that EETs play a role alongside fuel/machinery take-up in meeting the CII requirements in the 2020s. There is also a notably higher take-up of EETs in 2030 for Scenario B relative to Scenario A, and likewise for Scenario A relative to Scenario C. This is in line with the expected effect of implementing carbon pricing earlier in the modelling period. By 2050, all of the decarbonisation scenarios have settled on a roughly similar penetration of technologies. In these plots, ‘wind’ includes kites, Flettner rotors and sails.

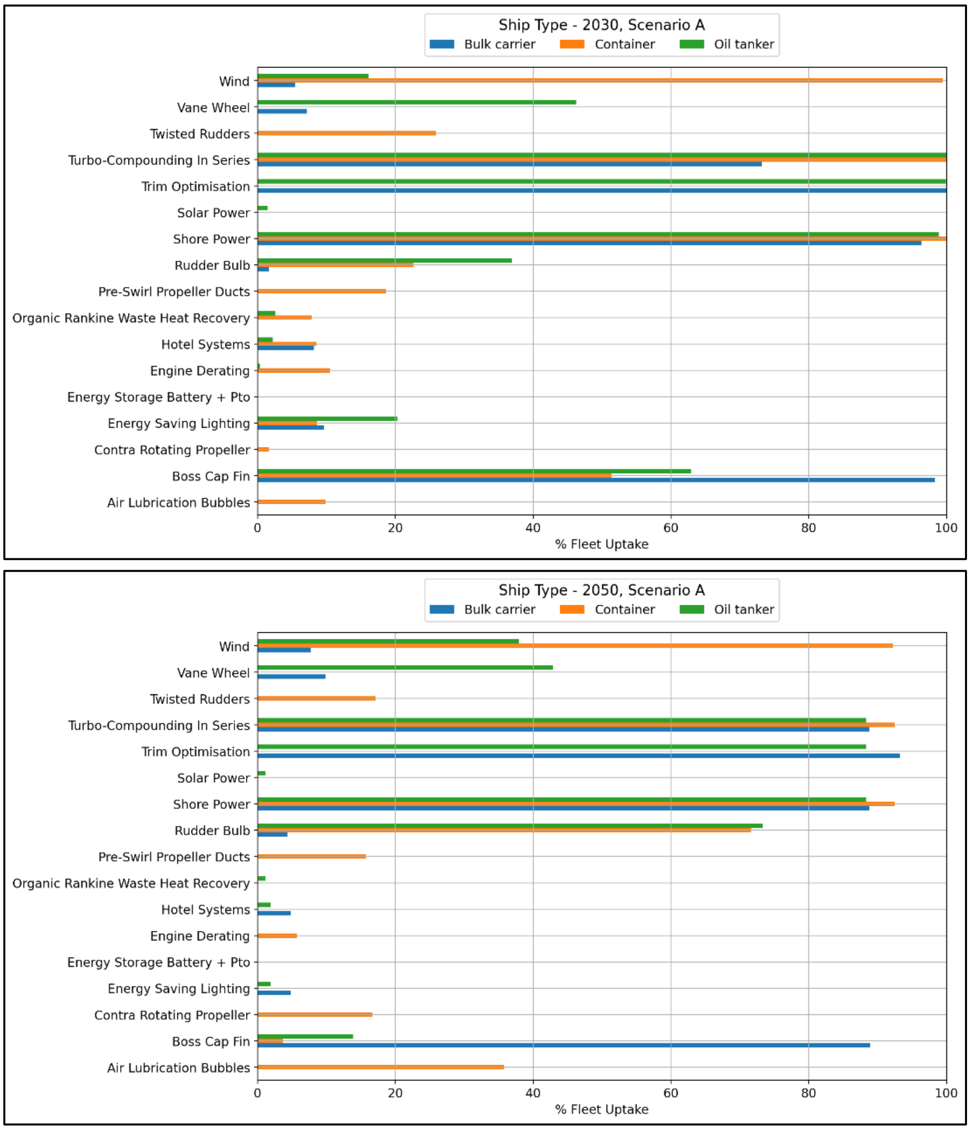
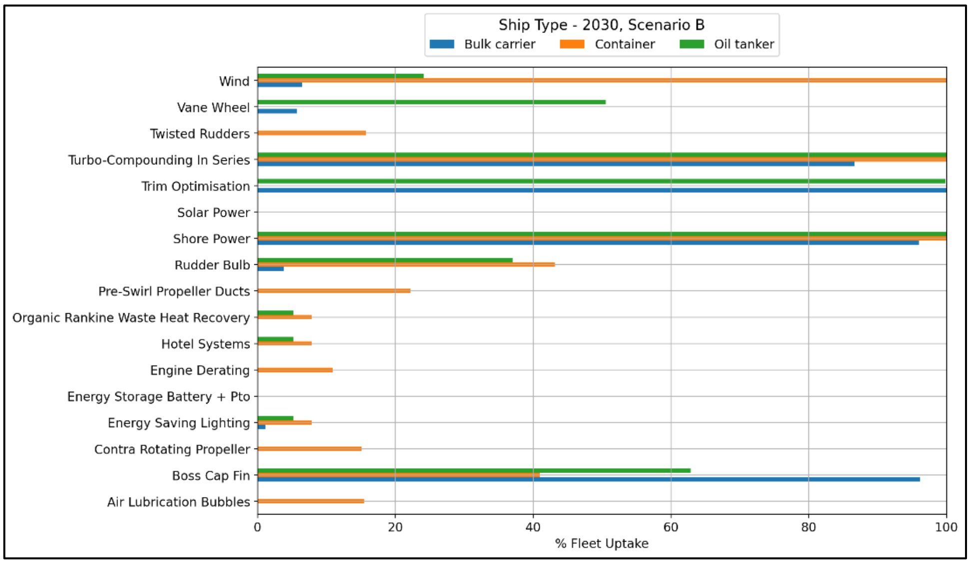


Figure 4.8 – EET take-up for 2030 and 2050 by ship type, Scenario A



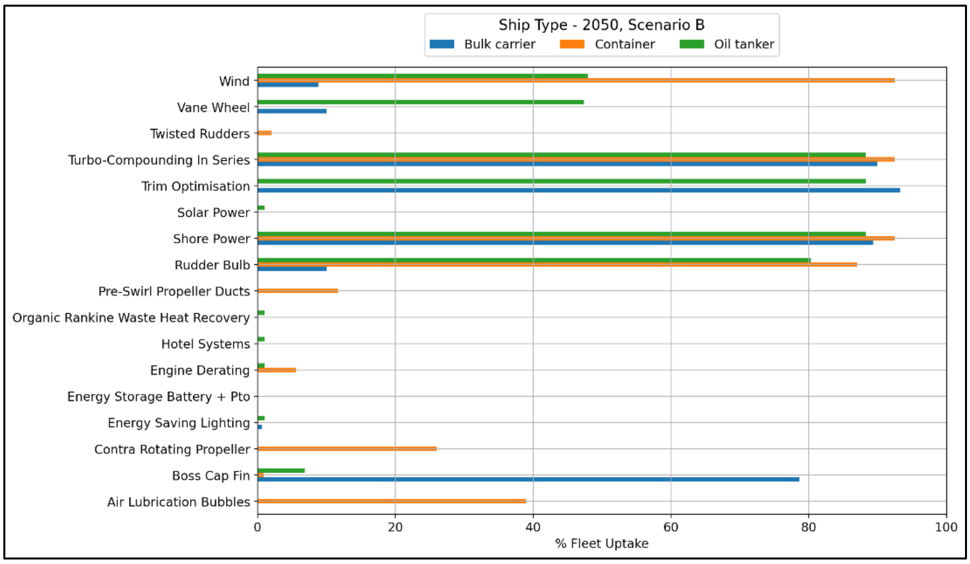


Figure 4.9 – EET take-up for 2030 and 2050 by ship type, Scenario B

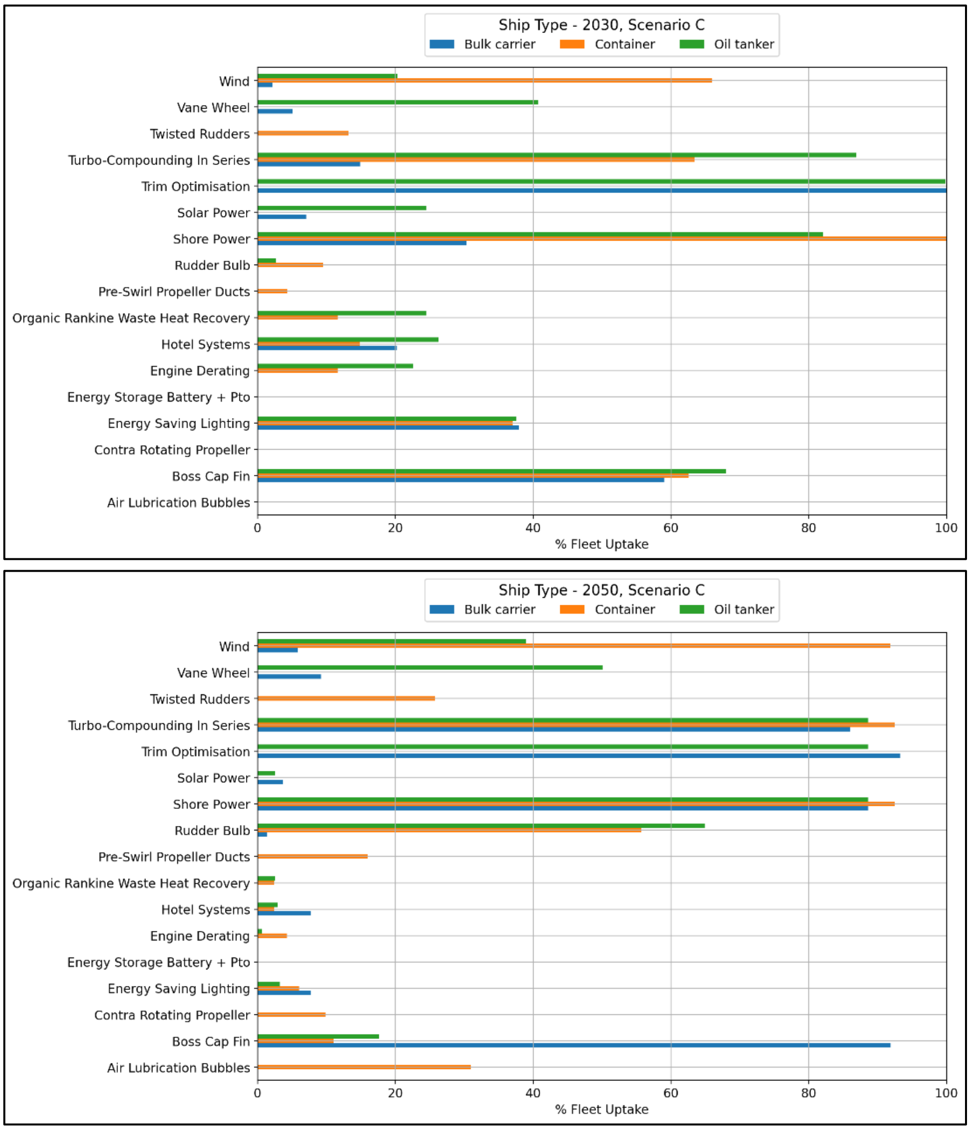
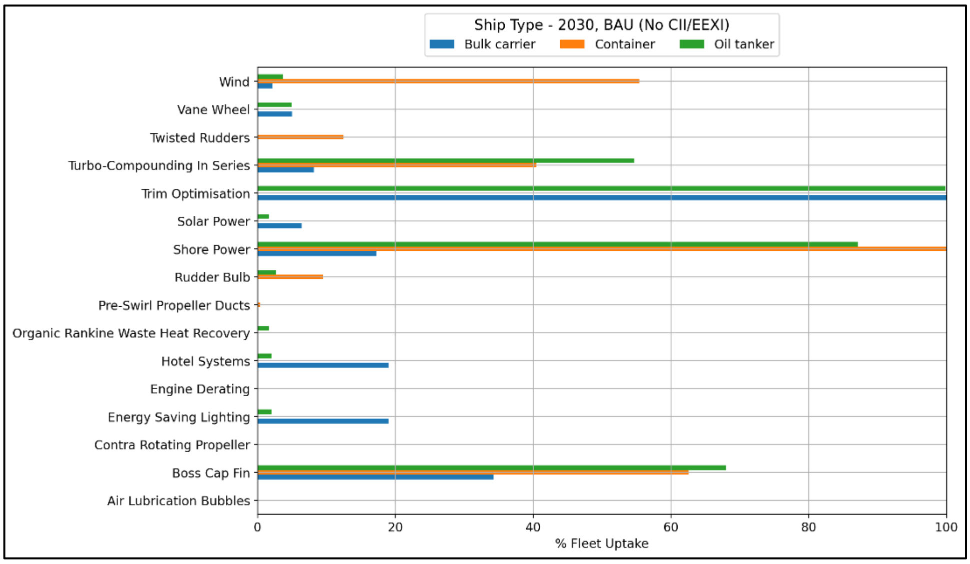


Figure 4.10 – EET take-up for 2030 and 2050 by ship type, Scenario C



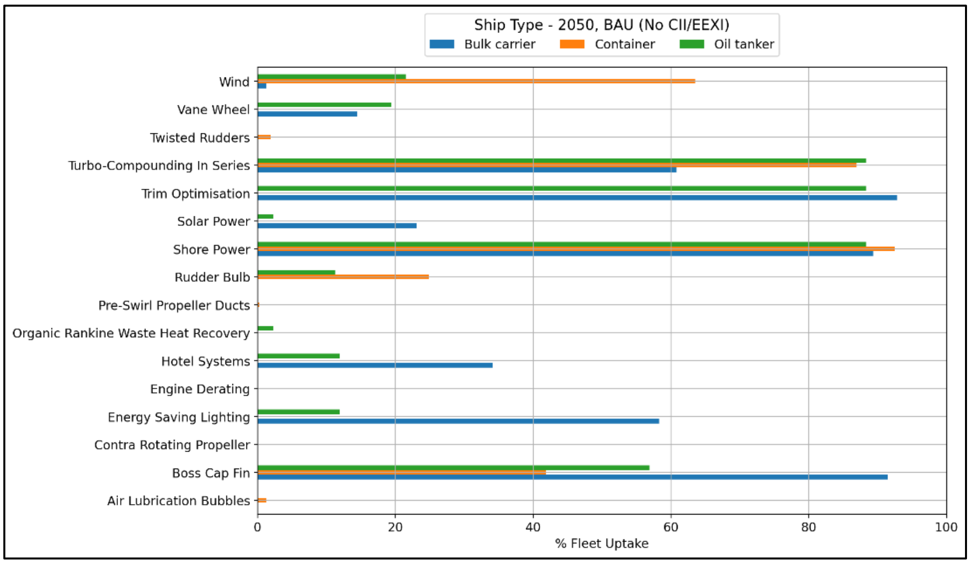


Figure 4.11 – EET take-up for 2030 and 2050 by ship type, Scenario BAU (no CII/EEXI)

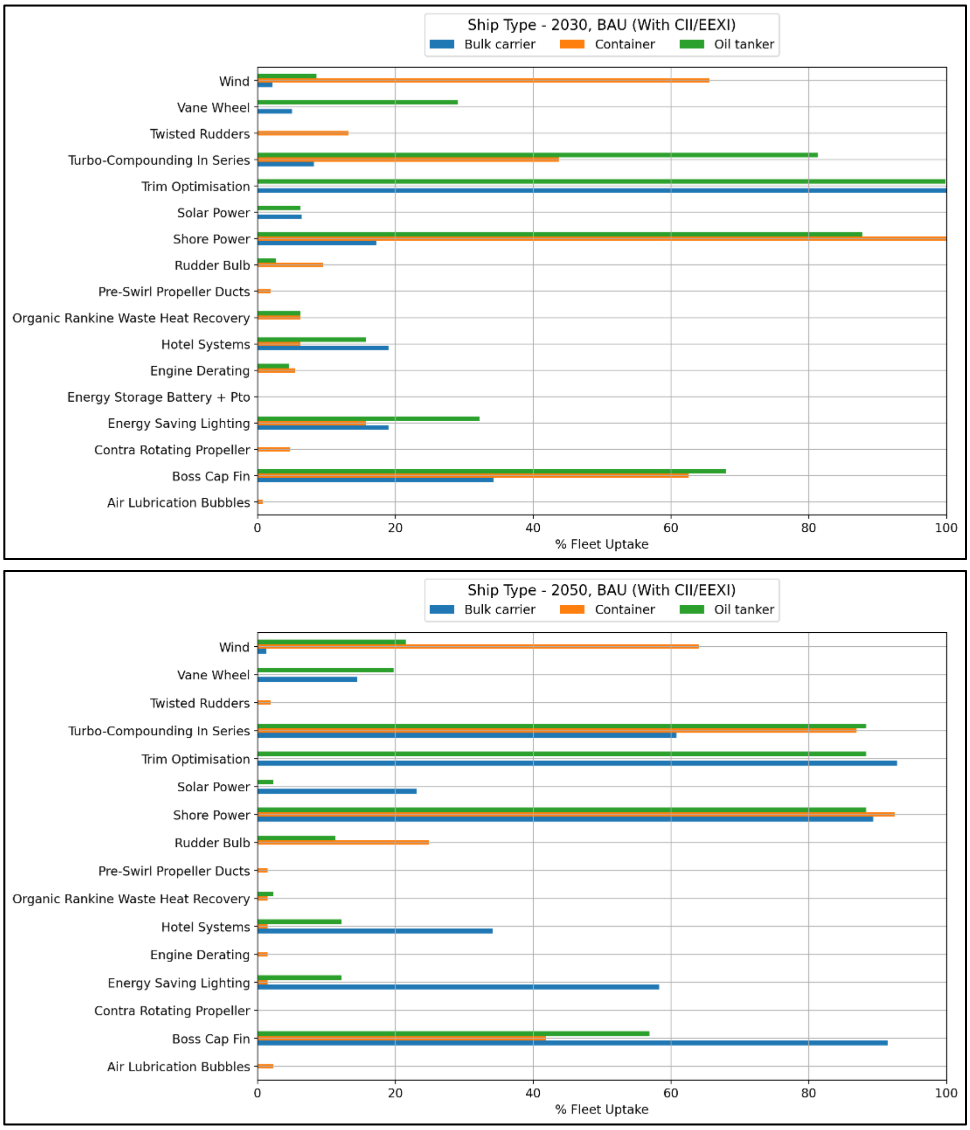


Figure 4.12 – EET take-up for 2030 and 2050 by ship type, Scenario BAU (CII/EEXI)

4.6.2 Energy-conversion machinery take-up detailed results

Figure 4.13 to Figure 4.17 illustrate the percentage penetration of the main machinery types for the core decarbonisation scenarios, separated by fuel and stroke type. As with the fuel mix evolutions presented earlier in Section 4.4, there is a clear distinction between the scenarios on the rapidity of the introduction of ammonia engines from the early 2030s, in line with the steepness of the GHG emission reductions required for each scenario during that decade.

Throughout the period, and in all decarbonisation scenarios, the dominant energy-conversion machinery remains the internal combustion engine. There are limited examples of fuel cell take-up or of battery electric propulsion take-up in international shipping fleets, but for the majority of machinery installations (which are ship type, size and operational parameter specific) these technologies are not identified to be a competitive way to achieve the CO_2 reductions target.

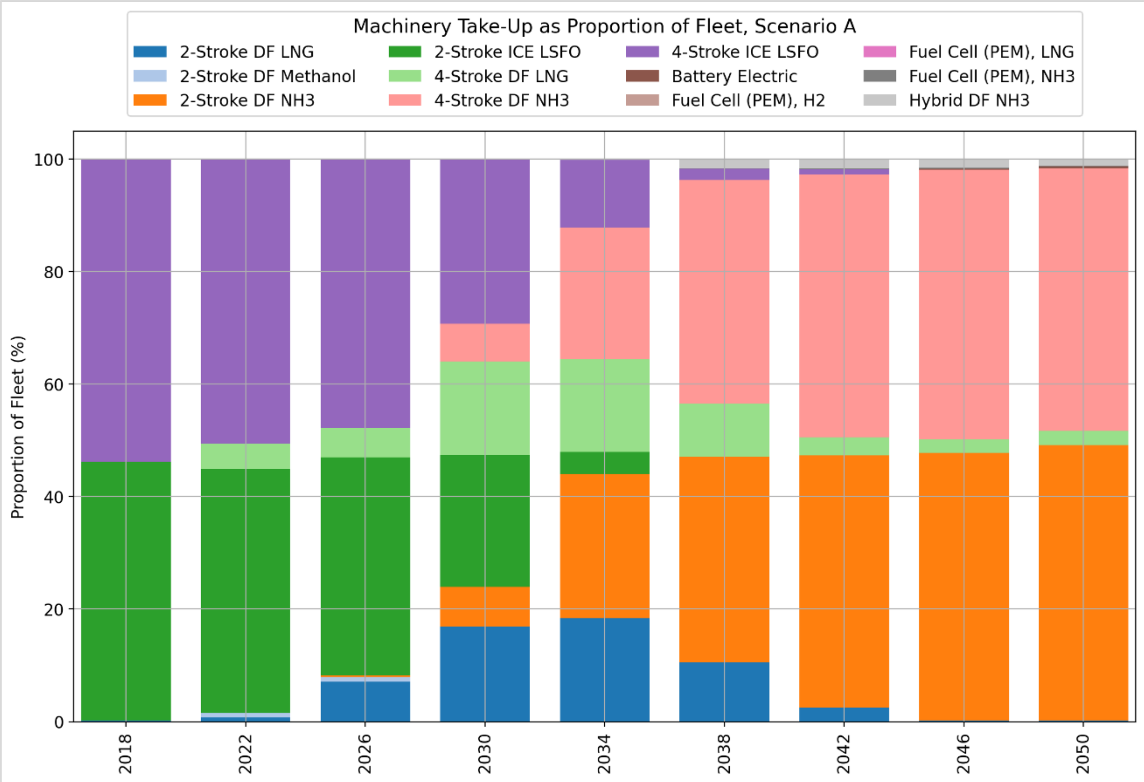


Figure 4.13 – Machinery take-up, Scenario A

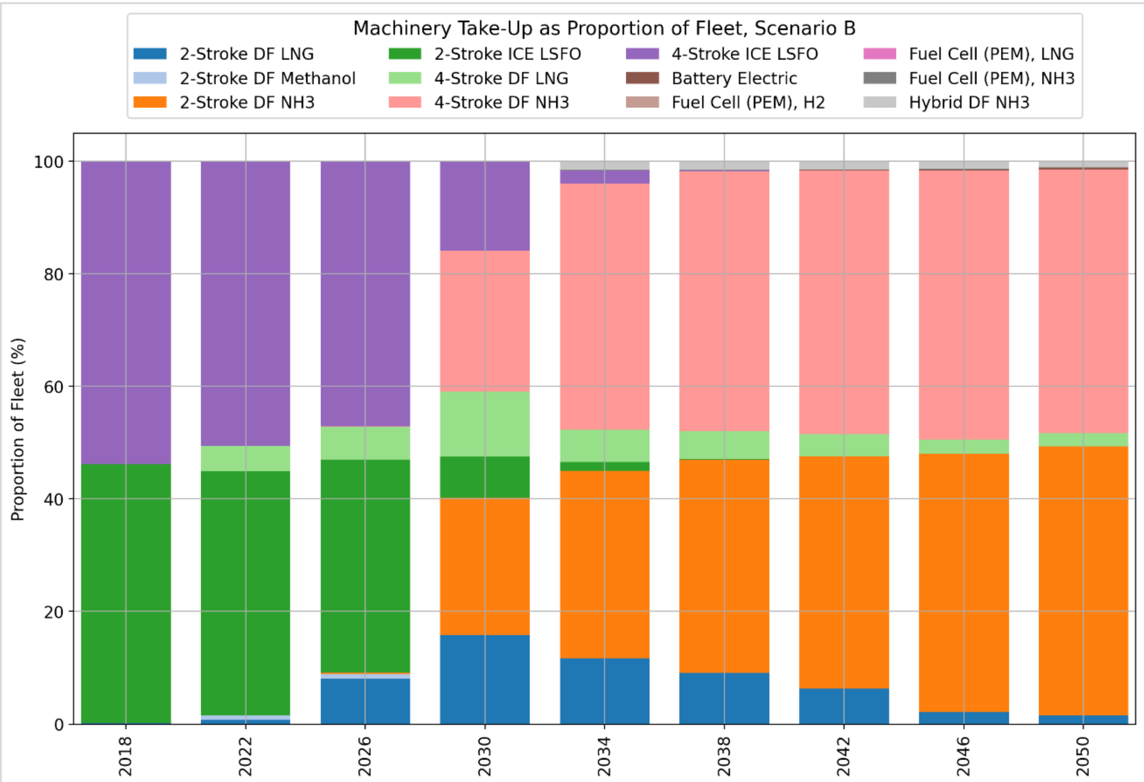


Figure 4.14 – Machinery take-up, Scenario B

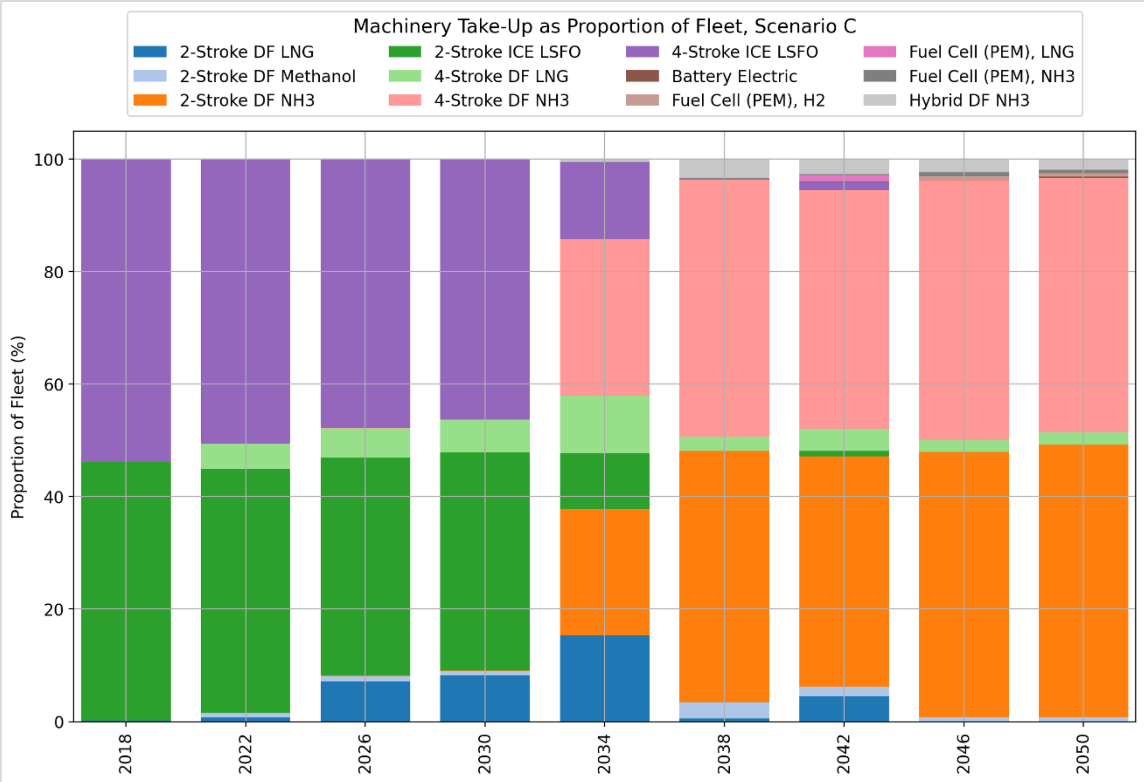


Figure 4.15 – Machinery take-up, Scenario C

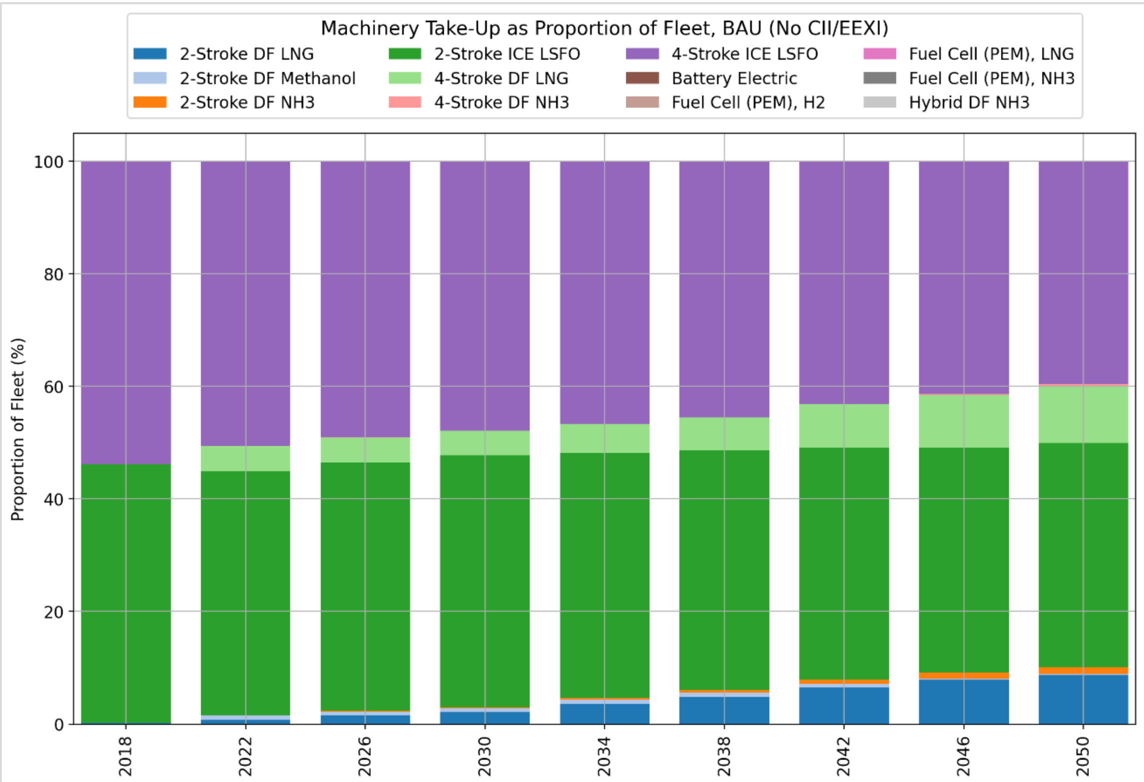


Figure 4.16 – Machinery take-up, BAU (No CII/EEXI)

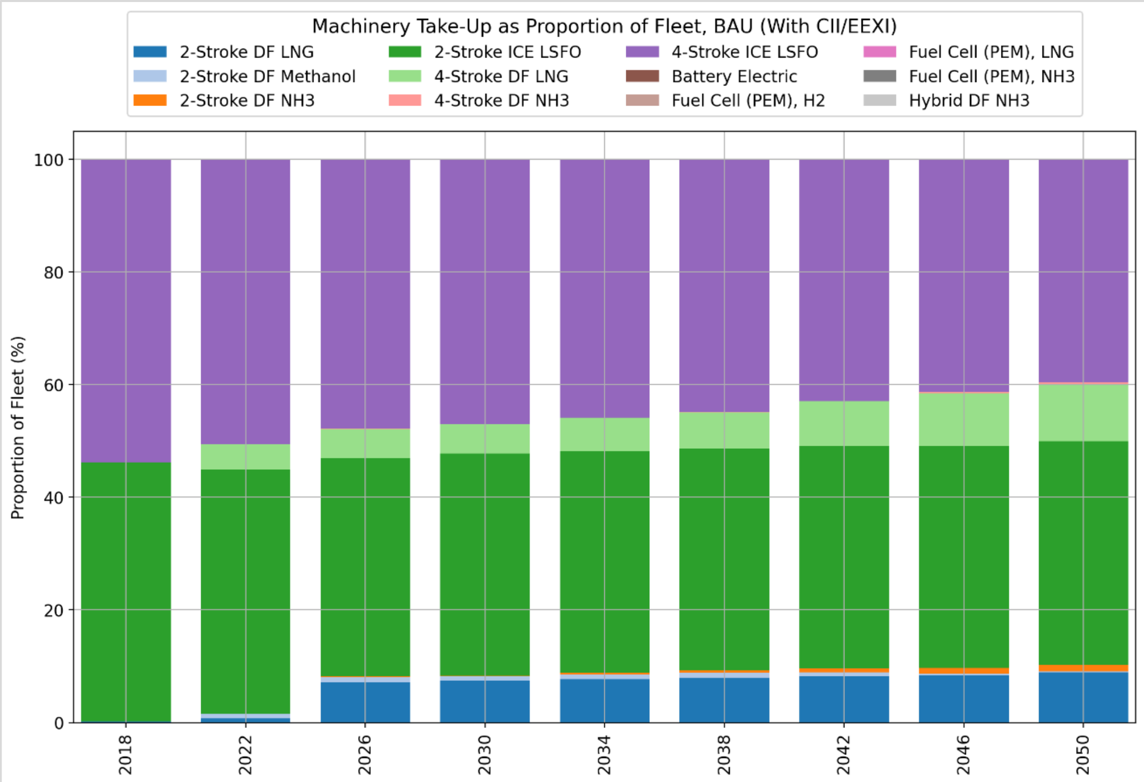


Figure 4.17 – Machinery take-up, BAU (With CII/EEXI)

Figure 4.18 to Figure 4.22 below break down the components of the amortised CAPEX (e.g. the CAPEX cost spread over a period of annual payments) incurred for each of the core scenarios, into new-build and retrofit machinery and EET respectively. There is a notable contrast between the two BAU scenarios, where the inclusion of CII/EEXI forces retrofit take-up through until 2040, well past the point at which the annual reduction factor stipulated in those policies would have been frozen (2027). In contrast, there is almost no retrofit activity in the BAU scenario without CII, suggesting that without the imposition of a carbon price or the CII scheme there is no market-forces argument for retrofitting to occur.

For the decarbonisation scenarios, the key differences can be seen in the cumulative machinery retrofit costs by 2050, where Scenario C exceeds the other two scenarios by USD35-128 billion. Conversely, while Scenario B has the highest cumulative retrofit costs by 2030, it finishes 2050 with the lowest overall retrofit costs of the three scenarios, and the lowest CAPEX overall. This highlights the fact that with an initially more rapid but overall slower decarbonisation trajectory, as in Scenario B, there is more opportunity for the necessary emission reductions to be achieved through new-builds which, overall, would be less disruptive to the operation of the international fleet.

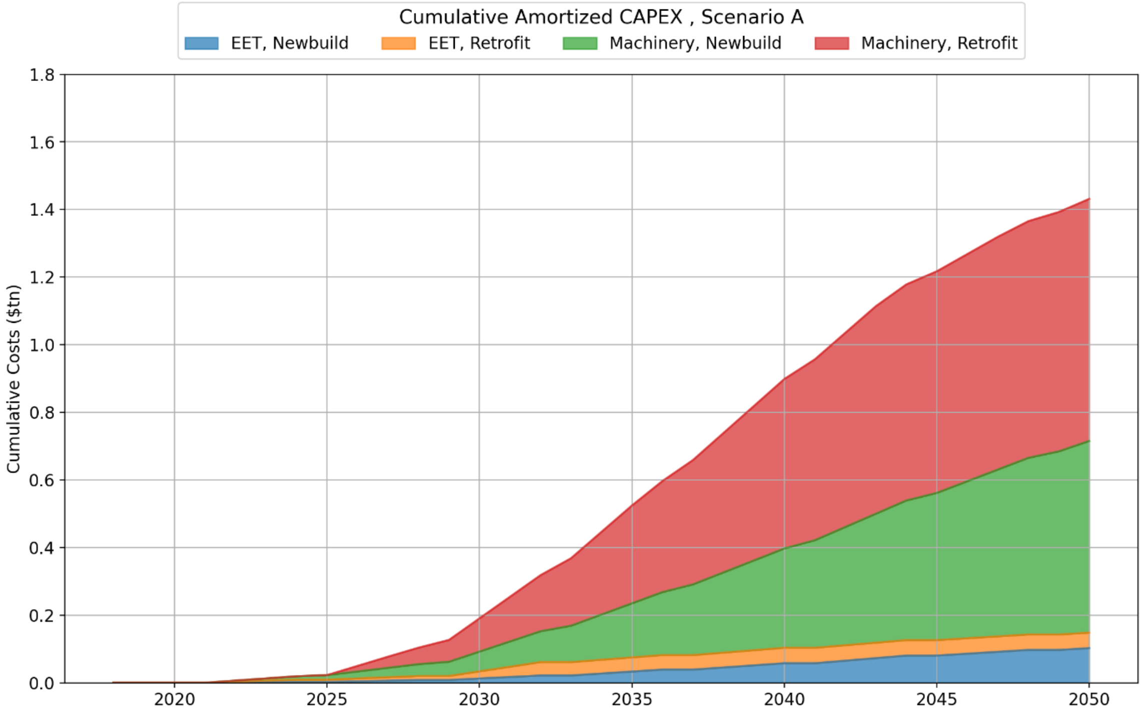


Figure 4.18 – Cumulative amortised CAPEX breakdown by source, Scenario A

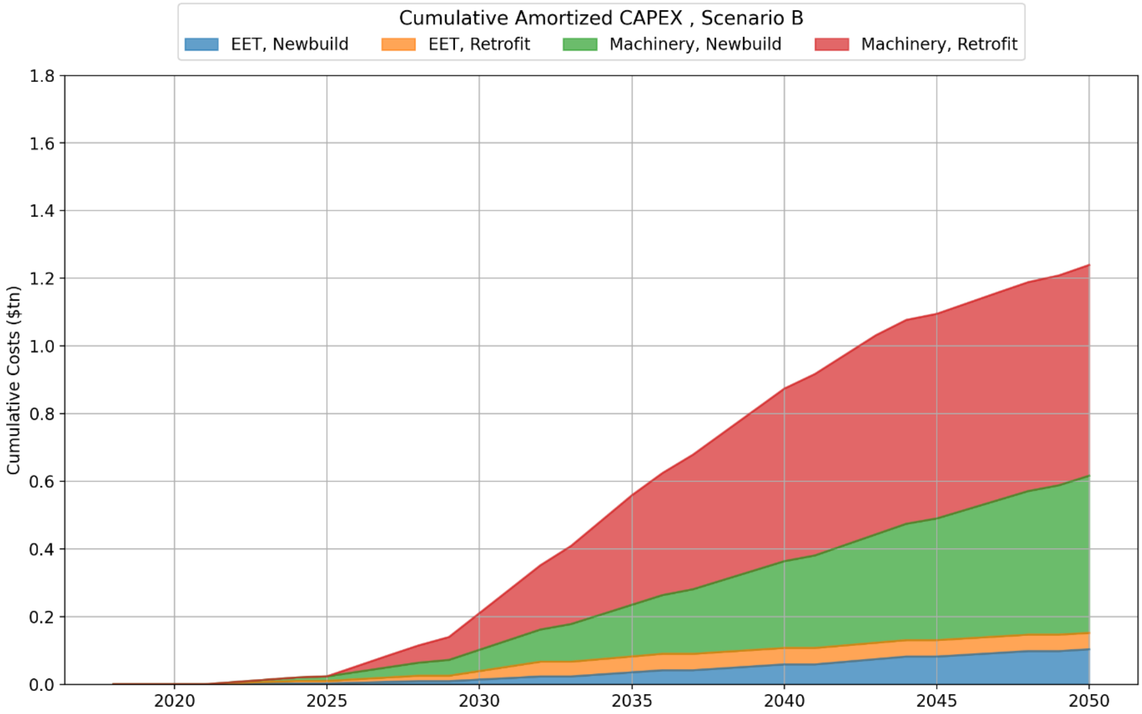


Figure 4.19 – Cumulative amortised CAPEX breakdown by source, Scenario B

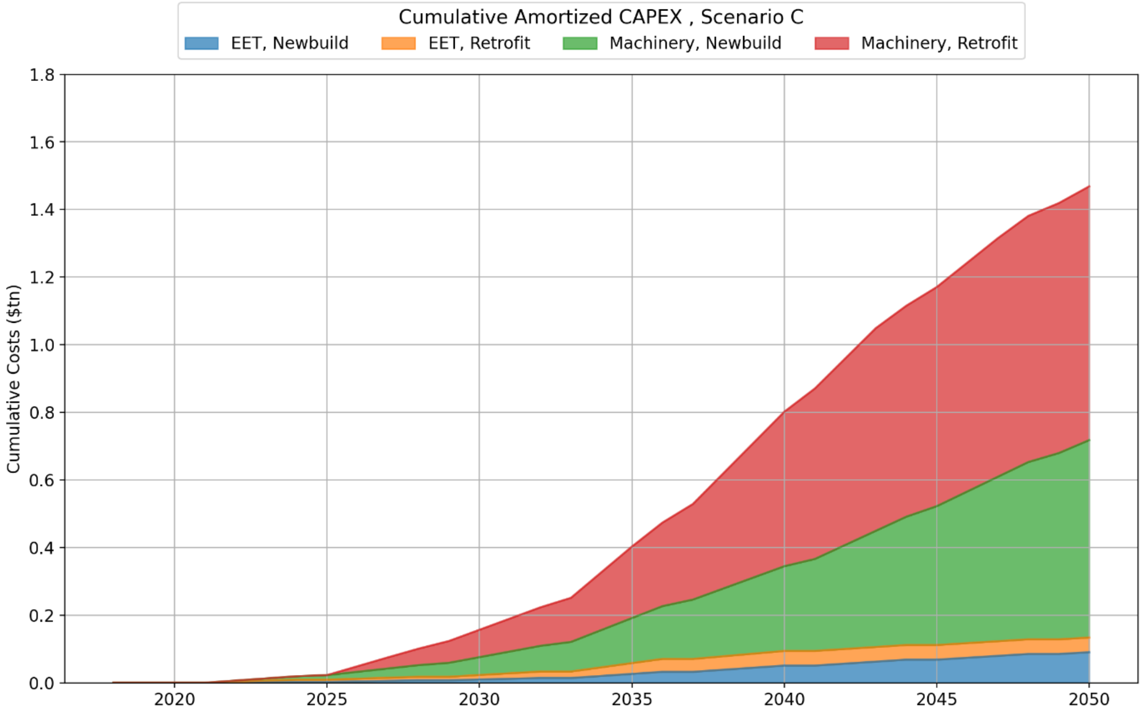


Figure 4.20 – Cumulative amortised CAPEX breakdown by source, Scenario C

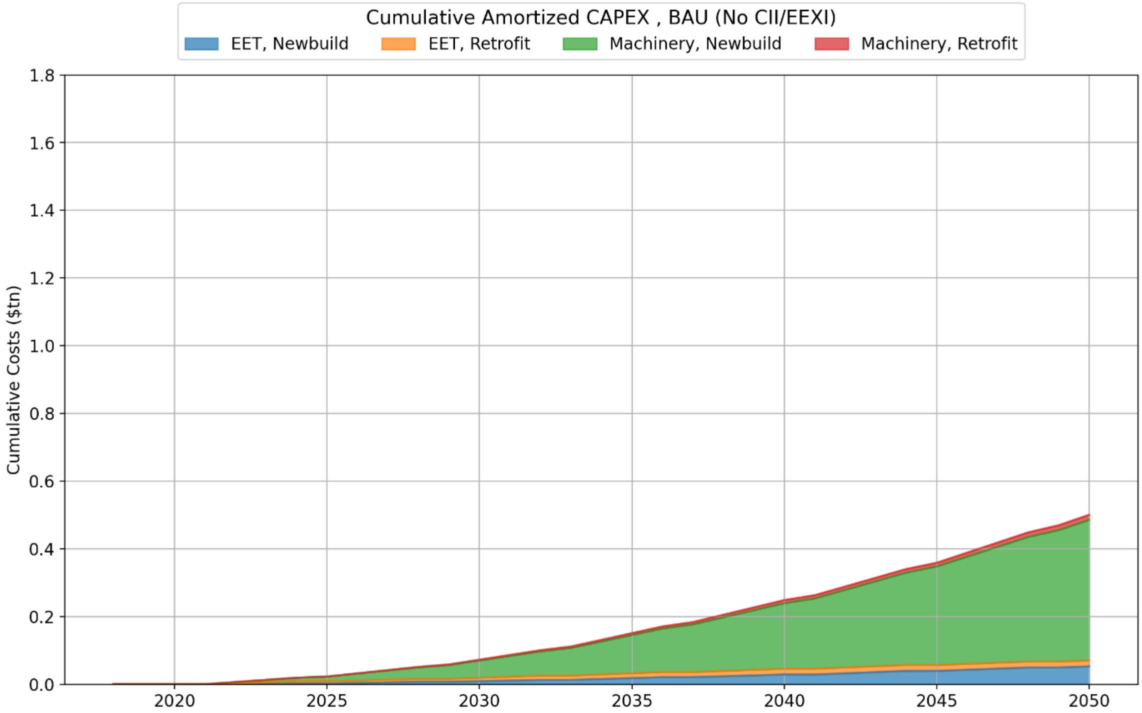


Figure 4.21 – Cumulative amortised CAPEX breakdown by source, Scenario BAU (without CII/EEXI)

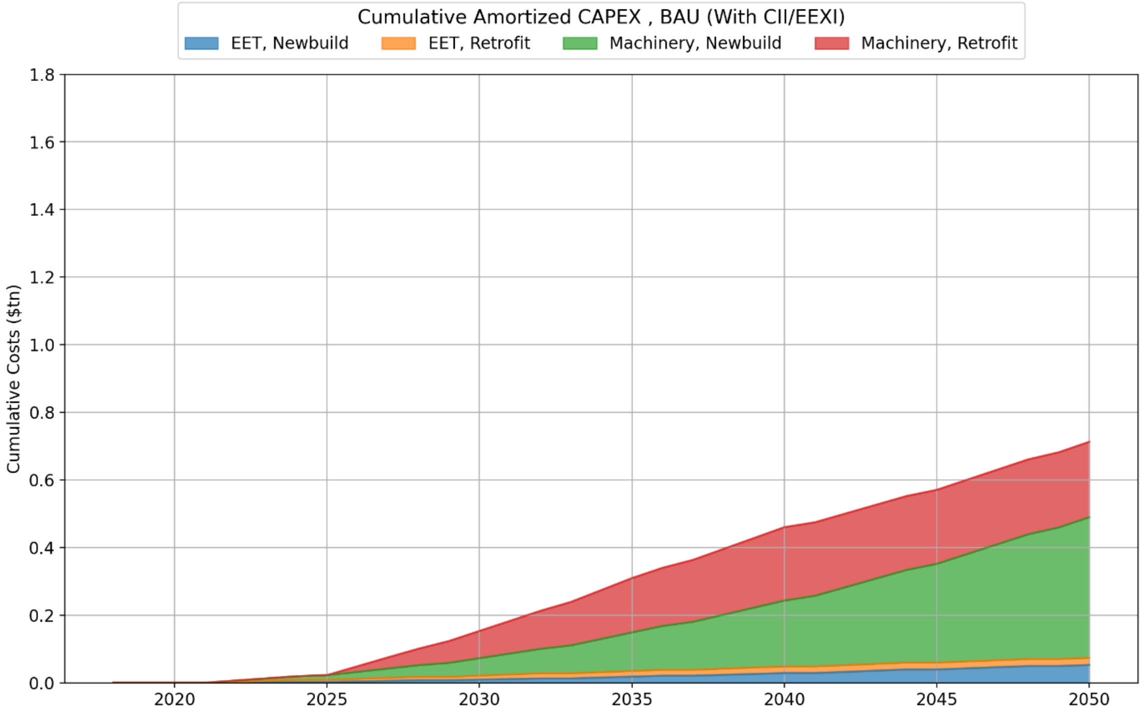


Figure 4.22 – Cumulative amortised CAPEX breakdown by source, Scenario BAU (with CII/EEXI)

5 Comparison between estimated demand for new fuels and likely availability and supply of new fuels

5.1 Supply ramp-up constraints

This section analyses the feasibility and implications of the GloTraM fuel demands by considering any constraints on the supply chain of the fuels required in the transition and discusses what this means for available fuel supply to the maritime sector over time. The analysis is compiled by determining the key constraints that apply to each fuel and technology pathway used – these are typically either feedstock-related or related to the build-out rate of production plants. For fuels with non-negligible demand in the GloTraM scenarios, the various feedstock and conversion routes available for each fuel are examined, assessing these key constraints and the potential supply ramp-up of each fuel for comparison against the GloTraM demands.

5.1.1 Methodology

As noted in the Technical Annex, biofuel take-up in the GloTraM model is assumed to occur through blending with conventional fossil fuels. Biofuels are therefore grouped within the model according to which marine fossil fuel they are to be blended with, as follows:

- Biogenic low sulphur heavy fuel oil (bioLSFO), as the sum of:
  - Straight vegetable oil (SVO)
  - Hydrothermal liquefaction and upgraded pyrolysis oils (HTL-UPO)
- Biogenic marine diesel oil (bioMDO), as the sum of:
  - Hydrotreated vegetable oil (HVO)
  - Fatty acid methyl ester (FAME)
  - Gasification + Fisher-Tropsch synthesis (FT-diesel)
- Biogenic liquid natural gas (bioLNG), as the sum of:
  - Anaerobic digestion + biomethane upgrading + liquefaction (AD LNG)
  - Gasification + methane synthesis + liquefaction (bioSNG)
- Biomethanol, made via gasification + methanol synthesis

Synthetic fuels are similarly grouped, with GloTraM using a blend of blue and green pathways for each of these three synthetic fuel options:

- Liquid hydrogen, as the sum of:
  - Renewable electricity + polymer electrolyte membrane (PEM) electrolysis + liquefaction (green hydrogen)
  - Fossil gas steam methane reforming with carbon capture and storage (CCS) + liquefaction (blue hydrogen)
- Ammonia, as the sum of:
  - Renewable electricity + PEM electrolysis + ammonia synthesis (green ammonia)
  - Fossil gas steam methane reforming with CCS + ammonia synthesis (blue ammonia)
- Synthetic methanol, as the sum of:
  - Renewable electricity + PEM electrolysis + direct air capture (DAC) + methanol synthesis (green methanol)

- Fossil gas steam methane reforming with CCS + DAC + methanol synthesis (blue methanol)

Each of these individual pathways has different constraints on their possible rates of growth or maximum possible fuel production; this may depend upon feedstock, conversion technologies, or wider industry characteristics. For this reason, the pathways have been grouped in the following sections according to their primary feedstocks and/or main constraints, as follows:

- **Advanced biofuels** (FT-diesel, biomethanol, HTL-UPO, bioSNG): these pathways are constrained by the rate at which the nascent lignocellulosic biofuel industry can grow, based on current developer activity and technology maturity. Lignocellulosic feedstocks refer to feedstocks where the biomass is composed of cellulose, hemicellulose and lignin, which forms a lignocellulosic structure that is difficult to break down. As a result, biomass with this composition does not have a competing use as a food source. Examples include virgin biomass (e.g. grasses or trees), waste biomass (e.g. agricultural/forestry residues or the organic component of MSW), or energy crops such as switchgrass.
- **Lipid-based fuels** (SVO, FAME, HVO): these pathways rely on lipid-based (triglycerides, a type of fat) feedstocks, such as used cooking oil, which have limited availability.
- **BioLNG** (AD LNG): biogas is already produced in significant volumes, and is increasingly also being upgraded to biomethane for gas grid injection or transport applications. Shipping demands will be constrained by availability of this biomethane.
- **Hydrogen**: grouped according to end-product, given GloTraM merges green and blue routes. Supply constraints are considered from the standpoint of an individual fuel pathway to liquid hydrogen, and also as a gaseous feedstock (without liquefaction) for ammonia and methanol production.
- **Ammonia**: grouped according to end-product, given GloTraM merges green and blue routes. Availability is most likely to be constrained by global ammonia production capacity. For green ammonia, the availability of renewable energy is unlikely to be an issue at current industry growth rates, while electrolyser manufacturing capacity can scale rapidly. In the case of blue ammonia, CCS storage is plentiful and highly unlikely to be a factor at the scales required for 2050.
- **Methanol:** grouped according to end-product, given GloTraM merges green and blue routes. Availability is most likely to be constrained by global DAC capacity: as ammonia, there are few constraints on input energy supplies, hydrogen availability, or CCS storage, while the methanol industry currently operates with significant overcapacity.

Where data are available, additional quantitative evidence is used to support the commentary below. Fully quantitative and consistent data sources such as Integrated Assessment Models are not used, due to the lack of technology granularity in those models. The implications of the GloTraM demand scenarios are discussed below, including what they mean for the feasibility of the modelled scenarios and what must happen for them to be realised.

Fuel supply is a global and cross-sectoral system. Conversion technology choices for the maritime sector will be affected by, and may also affect, conversion technology choices made in other sectors, given several conversion technologies produce a range of product and co-product fuels that can be used across multiple sectors. For some pathways, therefore, it is only possible to analyse the potential maximum global ramp-up in supply of fuels from each conversion technology to 2050, rather than determining the supply of fuels specifically to the maritime sector.

5.1.2 Biofuel demand and biomass availability

The 0.92EJ a year of biofuels assumed to be available for use in maritime by 2050 in the Central biofuel availability scenario used by GloTraM is relatively conservative, being derived from the Energy Transitions Commission (ETC)[50] study for sustainable biomass resources. Figure 5.1 shows how biofuel use differs between each of the core GloTraM demand scenarios, under this common Central biofuel availability scenario.

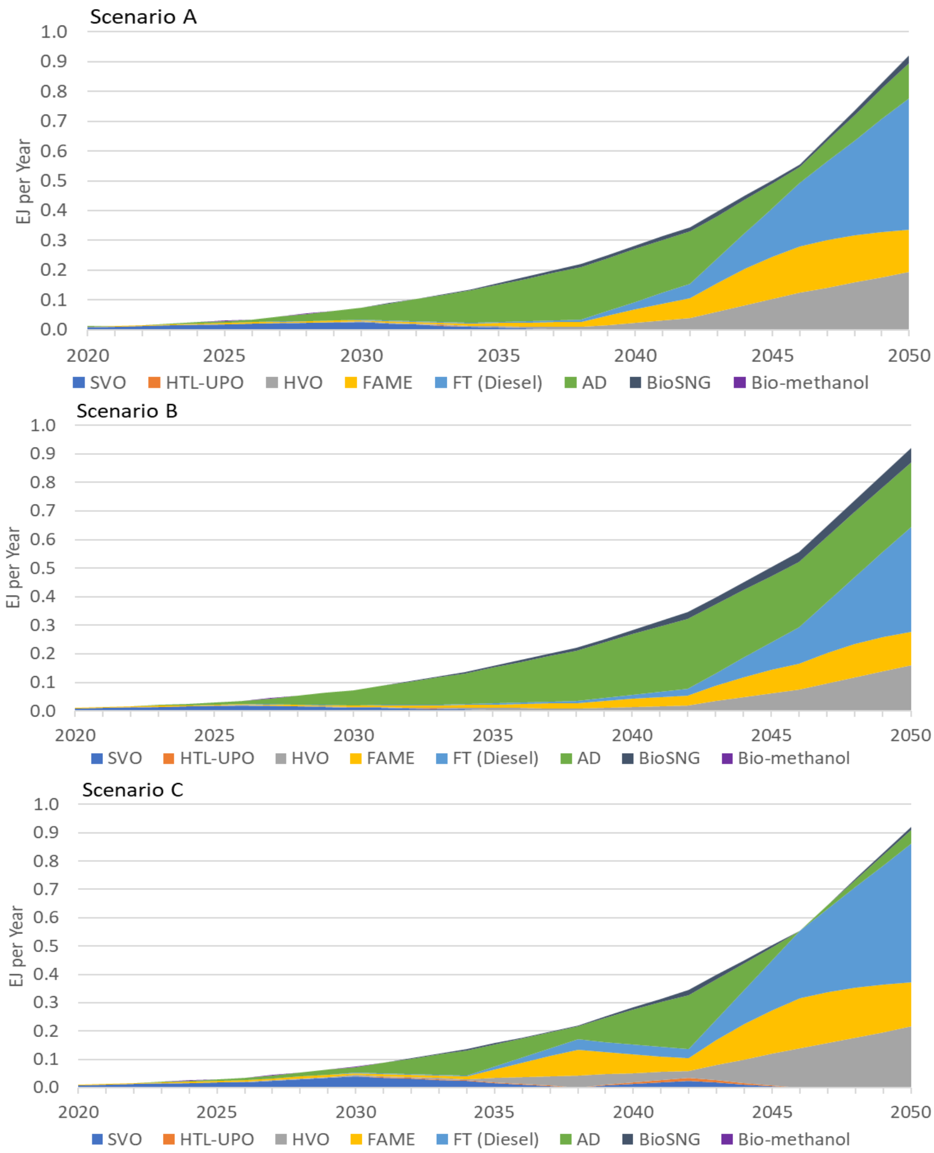


Figure 5.1 – Total biofuel use in international shipping in each of the three core GloTraM scenarios: Scenario A (top), Scenario B (middle) and Scenario C (bottom)

[50] ETC (2021). *Bioresources within a Net-Zero Emissions Economy*. Available at https://www.energy-transitions.org/wp-content/uploads/2021/07/ETC-bio-Report-v2.5-lo-res.pdf.

This total biofuel use is modest compared with literature projections of biofuel demand in other competing sectors. For example, in the International Energy Agency (IEA) Net Zero scenario (which is the High biofuel availability scenario used by GloTraM), global transport biofuel demands reach 12.9EJ a year by 2050, including 6.3EJ a year within the aviation sector and 2.1EJ a year in maritime[51]. In contrast, the GloTraM Low biofuel availability scenario assumes no maritime biofuels are used to 2050. Further details regarding the derivation of the Low, Central and High biofuel availability scenarios are given in the Technical Annex.

The finding in Section 4.2, that the emissions do not quite reach zero by 2050 because of a small residual demand for fossil fuels, is important in this context. The modelling produces this result because the use of ammonia is expected to require pilot fuel. Where the limit given to the modelling on biofuel availability cannot meet all the pilot fuel demand, a small residual emission remains. However, in practice given the assumptions on biofuel supply have been selected for their conservatism, a small additional supply beyond the Central scenario limits assumed is feasible, which could then ensure shipping's emissions did reach zero by 2050. In combination, this analysis of both demand for energy (Section 4) and supply of energy (Section 5) suggests the need for policy that can manage supply of biofuel as well as different sector's demand for biofuel, in order to maximise efficient use of this constrained resource.

After accounting for biofuel conversion efficiencies and biorefinery product slates, the GloTraM maritime biofuel availability scenarios only equate to use of up to 2–4EJ a year of biomass feedstocks. This is about 2–4% of the global sustainable biomass potential in 2050 according to IPCC estimates[52], or 3–6% if using the prudent biomass estimates from the ETC[53]. The overall supply of total sustainable biomass is therefore not the constraining factor for the maritime sector; rather it is the expected competing demands for use of the same biomass feedstocks in power, heat, industry and other transport sectors. Specific biomass feedstocks (e.g. lipids in Section 5.1.4) will be explored further below.

5.1.3 Advanced biofuels

GloTraM results for HTL-UPO and biomethanol indicate that demand for these fuels in the three main scenarios is negligible, and they are therefore not affected by any constraints. However, demand for FT-diesel is much greater in each of the three core scenarios, particularly by the mid-2040s, mainly due to displacement of MDO as a pilot fuel. Bio-SNG also has a modest demand during the 2040s, displacing residual fossil LNG.

For each fuel pathway, two supply ramp-up scenarios (high and low), were estimated using ERM's Advanced Fuel Ramp-Up Model. This employs a bottom-up methodology, considering announced projects, the number of active developers today, and assumptions on project development timelines, utilisation rates and future build rates. The detailed assumptions behind the ramp-up model are explained in the Technical Annex.

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[51] International Energy Agency (2021). *Net Zero by 2050*, IEA, Paris.
[52] IPCC (2018). *Special Report on 1.5 degrees*, Chapter 4. Available at https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter4_Low_Res.pdf.
[53] ETC (2021). *Bioresources within a Net-Zero Emissions Economy*. Available at https://www.energy-transitions.org/wp-content/uploads/2021/07/ETC-bio-Report-v2.5-lo-res.pdf.

The supply ramp-up scenarios for each pathway represent the total annual fuel output of known and projected production plants. These plants typically produce a mix of fuel products: as a result, actual fuel availability for the maritime industry in these scenarios is likely to be lower, given co-production of other fuels such as jet, naphtha etc. The exact mix of products and co-products (known as the product slate) is inherently uncertain, and projects often have flexibility to vary their product slates in design or operation of the plants, hence it is not appropriate to assume a fixed output of fuels suitable for the maritime sector.

These total fuel supply ramp-up scenarios are represented by the green (low) and yellow (high) shaded regions in Figure 5.2, Figure 5.3 and Figure 5.4. The international shipping fuel demand results from GloTraM are then compared against these supply ramp-up projections.

5.1.3.1 Gasification to FT-diesel

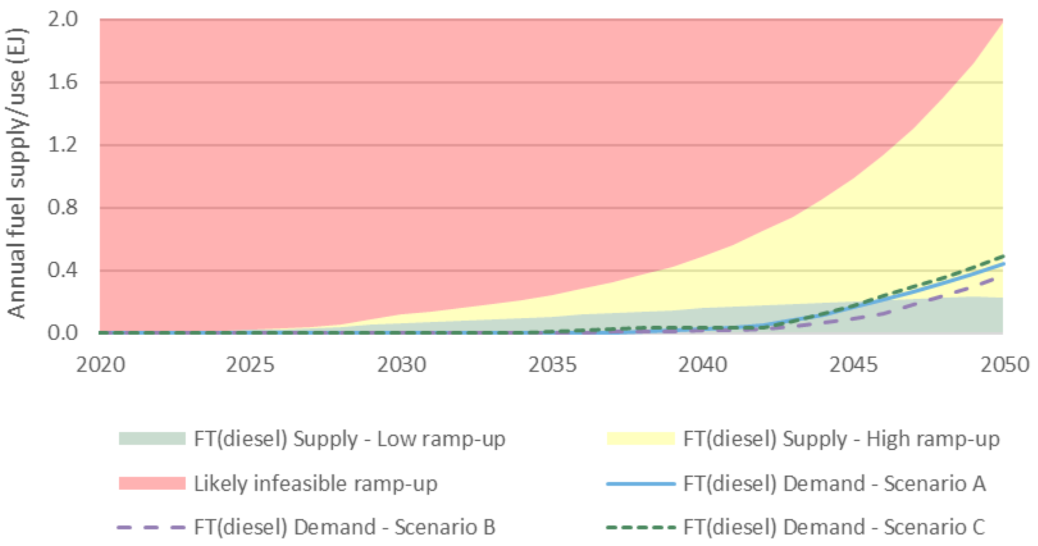

Figure 5.2 – Comparison of GloTraM international shipping FT-diesel demands (lines) and Ramp-Up Model production projections (shaded regions) for FT fuels

The comparison of supply versus demand in Figure 5.2 indicates that in low ramp-up scenarios, where FT technology develops slowly, projected maritime demand for this FT-diesel would outstrip total global biogenic FT fuel production capacity by 2050. In the high ramp-up scenario, where biomass gasification to FT technology develops more rapidly, maritime demand still amounts to approximately 20% of global supply in 2050. For context, 0.4EJ/year equates to the full output of approximately 110 commercial-scale biomass gasification to FT plants, if each produced 80 kt/year of FT-diesel. The rate of demand growth in all three GloTraM demand scenarios is roughly equivalent to 19 full-scale biomass gasification to FT-diesel production facilities coming online globally each year between 2044 and 2050. For comparison, under the High Ramp-up fuel supply scenario (yellow region), the 2050 growth rate corresponds to 47 plants being built per year, with ~10 being built per year under the Low Ramp-up scenario.

Biomass gasification to FT is also a pathway of interest to other industries, most notably aviation, and so there is likely to be significant competition for FT biofuel supplies. However, FT plants focused on jet production will likely produce some heavier co-products (diesel and LSFOs) that would be suitable for maritime use, so development of FT biofuel plants could serve both the aviation and maritime sectors. The GloTraM results indicate that the maritime sector is therefore likely to be an important market in the long-term for FT-diesel plants, but it may not drive significant demand during the 2030s.

5.1.3.2 Biomethanol and HTL-UPO

Advanced marine biodiesel could also be generated as a co-product of oligomerisation of biomethanol to jet, and from further hydro-processing of heavier HTL-UPO oils. (Neither upgrading option was modelled within GloTraM, due to pathway simplifications, but upgrading efficiencies would typically be high.) The ERM Advanced Fuel Ramp-Up Model predicts significant production capacity available for both biomethanol and HTL-UPO production pathways under the high scenario by the 2040s, as illustrated in Figure 5.3. Maritime fuels arising from these alternative pathways could be used as an alternative to FT-diesel, spreading the burden of supply across multiple pathways.

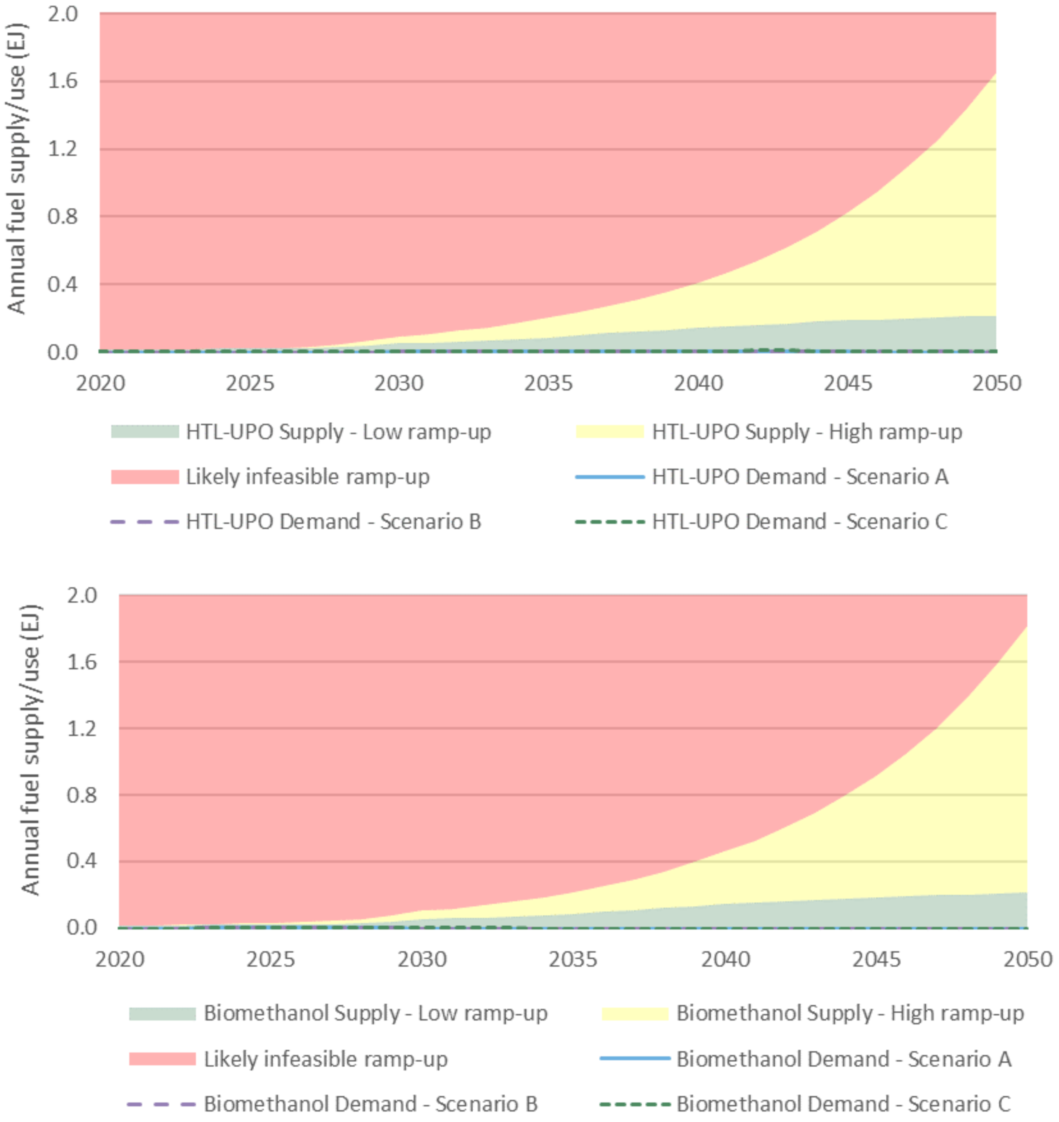

Figure 5.3 - Comparison of GloTraM international shipping demands (effectively nil throughout) and Ramp-Up Model production projections (shaded regions) for HTL & UPO combined (top) or biomethanol (bottom)

HVO and FAME (both modelled in GloTraM) are other potential options for replacing FT-diesel but, as discussed in Section 5.1.4, these are likely to be constrained by feedstock availability, and it is much more likely that FT-diesel and similar advanced routes will have to support shortfalls in HVO and FAME lipid feedstock supplies, rather than the other way round.

Fischer-Tropsch diesel could also be synthesised from another pathway not modelled in GloTraM (due to high costs): power to liquids (PTL) using renewable hydrogen combined with DAC CO_2. There are few constraints on electrolyser capacity growth (as discussed in Section 5.1.6) or renewable electricity supply globally, meaning that PTL-FT capacity could be significant by 2050. However, near- to mid-term DAC potential is likely to be constrained (as discussed in Section 5.1.8), and the fuel costs are likely to be significantly higher than other synthetic fuels such as renewable hydrogen or ammonia. While PTL-FT plants designed specifically for maritime diesel output might be unlikely, PTL-FT is currently being developed for aviation with projects starting after 2025, and commercial-scale plants may produce some heavier co-products suitable for maritime.

In summary, while maritime sector demands for low-carbon diesel might not be significant by 2030, the availability of conversion technologies could be a heavy constraint on the sector by the 2040s. This would be the case if key pathways such as gasification to FT-diesel do not attract sufficient investment at commercial scale during the 2020s, and a range of alternative conversion and upgrading pathways are not sufficiently developed during the 2030s. Coordination with fuel developers in other sectors, particularly in aviation, will also be required to optimise plant designs for maritime co-products.

5.1.3.3 Comparison of combined demand and supply

As noted in Section 5.1.1, biofuels within the GloTraM model are grouped according to which fossil fuels they are intended to be blended into. In practice, many biofuel intermediates can be upgraded to various degrees in order to produce different drop-in fuels (e.g. gasoline, diesel) as required, and are not fixed to a particular end-fuel. Figure 5.4 compares the combined UPO-HTL, FT-diesel and biomethanol demand against the combined ramp-up supply in the low and high scenarios for each pathway. However, biomethanol values are adjusted to account for the required conversion to diesel (via a methanol-to-diesel route, or MTD), at a 75% yield[54]. Total demand in all three core scenarios remains within low ramp-up estimates, and is roughly equivalent to total estimated global HVO production capacity as of 2022 (~0.5EJ). The combined capacity for the fuels HTL, UPO, biomethanol and FT-diesel is approximately 0.5EJ a year in the low ramp-up scenario by 2050, and 5EJ a year in the high ramp-up scenario (i.e. significantly more than FT-diesel alone).

[54] IRENA (2021) 'Innovation Outlook: Renewable Methanol.' International Renewable Energy Agency. Available at: https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol

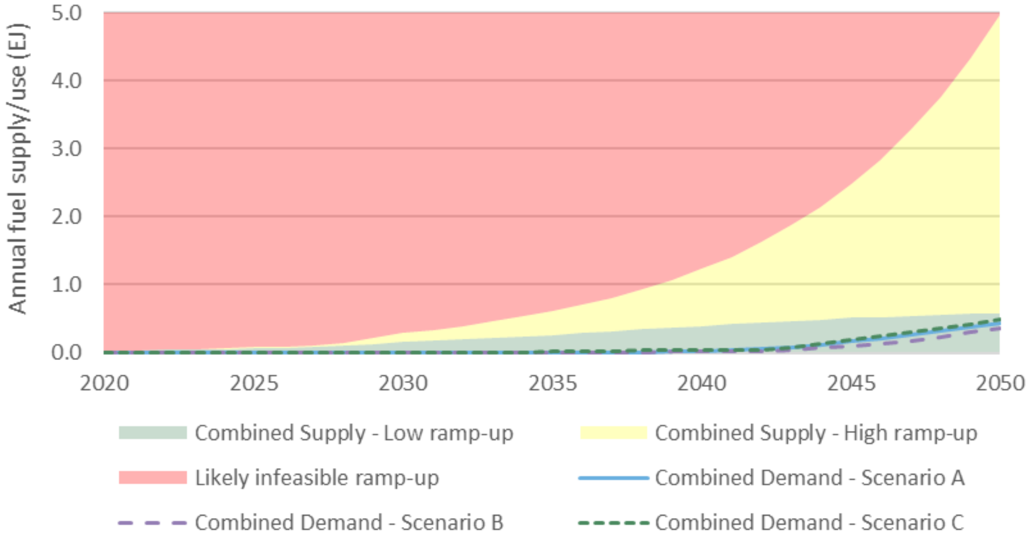

Figure 5.4 – Comparison of combined HTL-UPO, FT and MTD international shipping demands from GloTraM (lines) against Ramp-Up Model production projections (shaded regions)

In addition, there are several other fuel production pathways, such as HVO, FAME and PTL-FT, which are not constrained by plant capacity and build rates, but by other factors. In the case of HVO and FAME, feedstock is the main constraint on production capacity growth (Section 5.1.4), while for PTL-FT the main constraint will be the extent to which the technology developers and engineering, procurement and construction (EPC) contractors will be capable of expanding their services, similar to the situation for ammonia (Section 5.1.7) and methanol (Section 5.1.8). When accounting for all of these different pathways and the potential combined capacity from them, the modelling shows that supply would be sufficient to meet the total advanced biofuel demand within the core scenarios, even with competition from other industries.

5.1.4 Lipid-based biofuels

In this context 'lipids' is an umbrella term for a range of hydrocarbon-containing fats and oils, including vegetable oils and animal fat feedstocks. Vegetable oils, either virgin oils or used/recycled oils, can be used in combustion engines as a fuel with modest modifications, known as straight vegetable oil (SVO). Oils and fats can also be converted to biofuels. This can be achieved through chemical processing with methanol to produce FAME biodiesel, or through more intensive thermal catalytic processing with hydrogen to produce HVO, a drop-in diesel fuel.

Figure 5.5 shows maritime demands for SVO, HVO and FAME fuels in 2040 and 2050, as modelled using GloTraM across the three core scenarios. Demands for these fuels before 2035 are limited, and the demand for SVO is also negligible across the model time frame in all three core scenarios, given the phasing out of fossil LSFO into which SVO would be blended. The lipid feedstock demands underlying these HVO and FAME scenarios are also compared against the availability of the main feedstock groups for each of these fuels: used cooking oil, waste animal fats (tallow), and in a high scenario, sustainable virgin vegetable oils grown as cover crops or on marginal land.

As shown in Figure 5.5, feedstock availability estimates vary greatly, due to the underlying assumptions made on sustainability and collection rates, which are explained further in the Technical Annex. These estimates do not have a specified timeframe, so are only to be interpreted as comparative reference points rather than definite in-year projections. Importantly, these feedstock availabilities are the total lipids available for all sectors, including production of road, aviation and maritime biofuels, heat, power and oleochemical uses. The high scenario represents the absolute maximum available waste oils and fats potential: the available feedstock after considering collection rates, inefficient supply chains and geographical factors will be lower. The study did not consider the current or future potential of virgin vegetable oils grown as primary crops on agricultural land, due to food competition concerns, in line with the ETC's estimates of global sustainable biomass potential (see Section 5.1.2).

The main limiting factor on supply of FAME and HVO biofuels to shipping will be the availability of sustainable lipid feedstocks. FAME and HVO are already produced at commercial scales, with multiple active technology and plant developers, and numerous operational and planned plants due to demand from road transport and aviation. Therefore, the rate at which FAME and HVO capacity can grow, or the rate at which HVO co-processing can be introduced at refineries, is highly unlikely to be a limiting factor over the modelled time frames. For context, an estimated 0.45EJ a year of HVO production capacity will be online in 2022, indicating that a significant proportion of current HVO production capacity is using crop-based feedstocks to satisfy global demands for HVO.

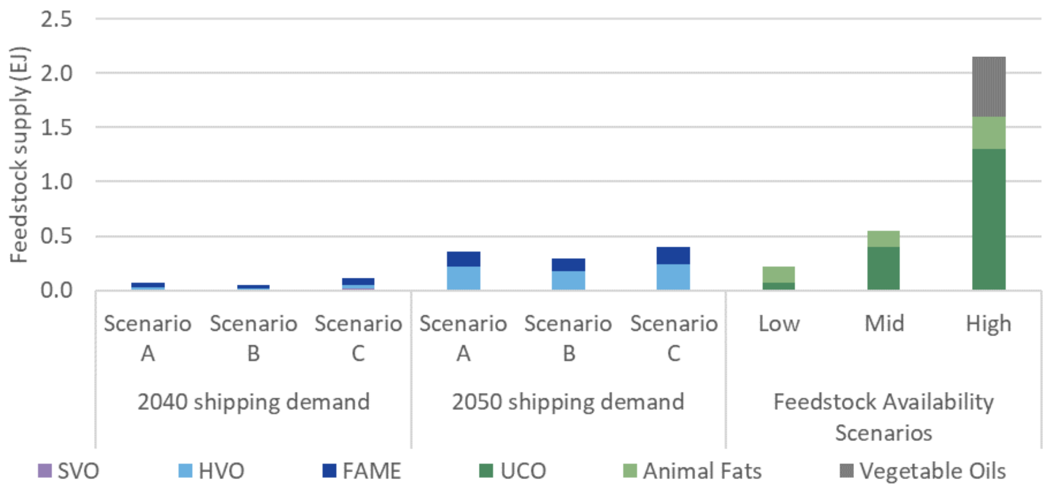

Figure 5.5 – Comparison of international shipping lipid feedstock demands for SVO, HVO and FAME (left, blue/navy) in the core GloTraM scenarios against feedstock availability (right, green/grey)

In all three core scenarios HVO and FAME demand is limited before 2035, given limited displacement of fossil MDO. In the 2040s the projected maritime demand for waste oils/fats rises above the most pessimistic availability scenarios cited in literature, and represents a significant portion (54–72%) of the feedstock available in the 'Mid' scenario derived from the literature (see Figure 5.4, green bars). However, this is before considering that the maritime sector will face strong competition for these same waste feedstocks from aviation (where hydrotreated lipids are currently the only fully mature biojet pathway and so likely to dominate near-term biojet take-up) and from use of FAME and HVO in heavy goods vehicles and other industrial applications.

It would therefore be highly unrealistic to assume that the maritime sector will be able to access and utilise the majority of waste oils and fats available globally by the 2040s, because competing transport sectors would have to completely transition to other advanced biofuels, PTL, hydrogen or full electrification by the 2040s, and other demands from oleochemicals, heat and power also disappear. It therefore appears likely that increased low-carbon diesel production from pathways that do not rely on lipid feedstocks (e.g. FT-biodiesel, PTL-FT, further upgraded HTL-UPO) will be required to ensure there is sufficient supply to meet maritime biodiesel demands.

5.1.5 Liquid biomethane

Liquid biomethane (bioLNG) can be sourced from a range of biomass feedstocks, and is chemically identical to fossil methane (the principal component of LNG), thereby acting as a direct low-carbon substitute for fossil LNG. Figure 5.6 shows the projected maritime demand for bioLNG (AD LNG and bioSNG pathways combined) in the three core GloTraM scenarios.

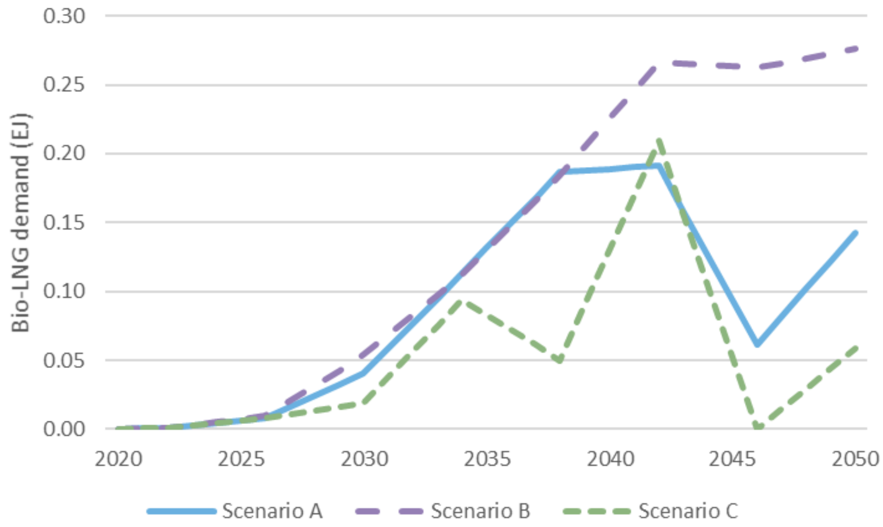

Figure 5.6 – Comparison of bioLNG international shipping demands in each GloTraM core scenario

The IEA Net Zero scenario gives projected global supplies of biomethane in 2020, 2030 and 2050 (Table 5.1). Biomethane supply is expected to increase significantly by 2030, with over 8EJ biomethane available a year by 2050. The large majority of this biomethane will come from AD biogas, given its commercial status, as shown in Table 5.1.

Table 5.1 – Biomethane and biogas supply projections and potential

Energy supply (EJ)	Biomethane	Total biogas
2020 production[1]	0.3	2.1
2030 production[1]	2.3	5.4
2050 production[1]	8.3	13.7
Technical sustainable potential[2]	31	24

[1] IEA (2021). *Net Zero by 2050*, IEA, Paris https://www.iea.org/reports/net-zero-by-2050.
[2] IEA (2020). *Outlook for biogas and biomethane: Prospects for organic growth*, IEA, Paris https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth.

By 2030 maritime demand for biomethane in GloTraM is still under 0.1EJ a year, or less than 5% of the expected global biomethane supply as projected by IEA. The largest bioLNG demand arises in Scenario B, where demand peaks at roughly 0.25EJ a year in the late 2040s, but this peak is also less than 3% of the IEA's projected 2050 biomethane supply. The maritime sector is therefore not expected to place major pressures on global biomethane supplies, particularly in light of the larger technical potentials highlighted by IEA.

5.1.5.1 Biomass gasification to methane

BioSNG is another advanced biofuel route within GloTraM. This route uses lignocellulosic biomass feedstocks and the conversion technology is yet to be commercialised. In each of the three GloTraM core scenarios the demand for bioSNG remains well within the fuel supply ramp-ups obtained in both of ERM's Advanced Fuel Ramp-Up scenarios, as shown in Figure 5.7. The greatest proportion of demand against supply is found in 2046 in all three core scenarios, where shipping bioSNG demand in Scenario B is equivalent to approximately 45% of the available supply in the low ramp-up scenario, and around 20% of the available supply in the high ramp-up scenario.

BioSNG plants typically focus only on biomethane output, with limited co-products, so there is unlikely to be significant demand from the aviation sector, with the main competing demand likely to be heavy goods vehicles prior to their electrification (batteries, catenaries or fuel cells). The results show bioSNG demands as being smaller and lying well within the green low ramp-up scenario zone, indicating that while this pathway likely still needs to be developed, it faces less pressure than FT-diesel. Demand growth rates correspond to a maximum of two gasification plants being built globally per year, starting in 2040. As discussed in Section 5.1.5 above, biomethane from AD (a commercialised pathway) also has the potential to fill any shortfall in bioSNG production.

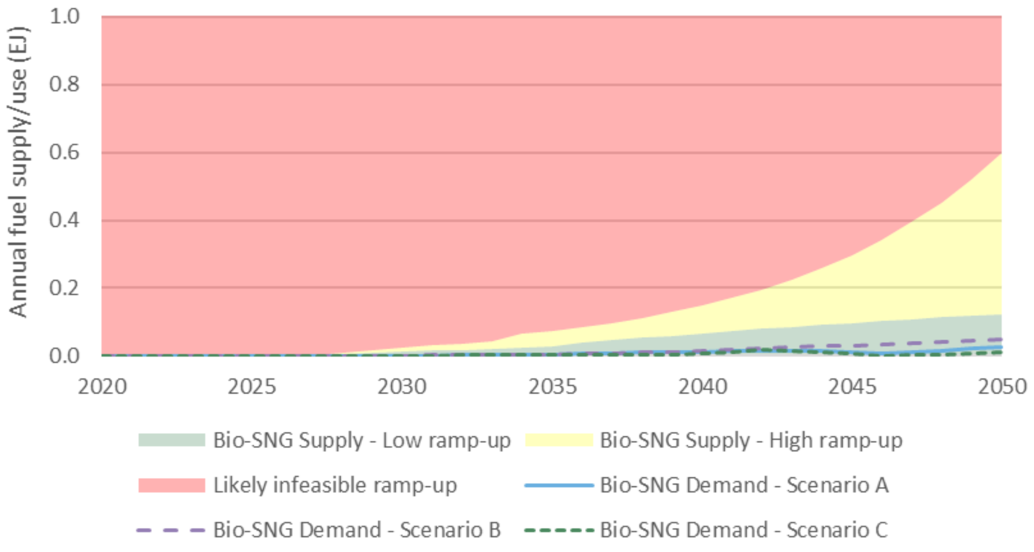

Figure 5.7 – Comparison of GloTraM international shipping demands (lines) and Ramp-Up Model production projections (shaded regions) for bioSNG

5.1.5.2 Biomethane liquefaction

Liquid biomethane will likely be supplied through the broader LNG supply chain – which is already extensive – because biomethane can be transported or traded via the gas grid, or trucked to more remote locations. Fossil LNG is already traded globally in large volumes, facilitated by a significant expansion in liquefaction capacity over the last two decades: LNG export liquefaction capacity has increased threefold since 2002, from 180 billion cubic metres (bcm) (~7EJ) to 646bcm (~25EJ) in 2022, with global LNG demand forecast to be around 455bcm (~17EJ) in 2022[55]: although recent market and geopolitical developments may affect future forecasts. The IEA models that global LNG trade will have to peak in the mid-2020s at 500bcm (~19EJ) per year to stay on track for net zero emissions by 2050[56], with global LNG trade falling to 160bcm (~6EJ) by 2050. This would mean liquefaction capacity will likely remain accessible to the maritime industry at levels far above the GloTraM demand model results for liquid biomethane. It would require further regional/spatial analysis to examine whether biomethane supply potentials are in the correct locations to be able to connect to liquefaction plants.

A comparison of fossil LNG demands to fossil LNG supply infrastructure was not within the scope of the study, but it is of note that the core GloTraM results have around 5EJ a year of fossil LNG consumed during the early 2030s, which would be a significant fraction of IEA's projected global LNG trade, particularly given IEA's projected decline after the peak in the late 2020s. Recent market developments, most notably the sanctions imposed on Russia as a result of the Ukraine crisis, have led to drastic changes in LNG demand in the short term. LNG demand from Europe is expected to increase by 20% in 2022, while demand from Asia is expected to slow from 8% in 2021 to 2% in 2022[57]. The effect this will have on long-term demand outlooks is unclear.

[55] IEA (2019). *LNG Market Trends and Their Implications*. IEA, Paris. See Figures 2 and 3, available at https://www.iea.org/reports/lng-market-trends-and-their-implications.
[56] IEA (2021). *Net Zero by 2050*, IEA, Paris. Available at https://www.iea.org/reports/net-zero-by-2050.
[57] https://www.reuters.com/business/energy/global-lng-demand-growth-shifts-asia-europe-russia-sanctions-2022-03-09/ Accessed 13th April 2022.

5.1.6 Synthetic hydrogen

The scenarios modelled using GloTraM show demand for liquid hydrogen in shipping will be negligible through to 2050 (Figure 5.8). Beyond 2030, availability of green hydrogen will be governed by the availability of renewable electricity and electrolyser manufacturing capacity; while for blue hydrogen, availability will be governed by the rate at which CCS can be installed at existing plants or new-build facilities that include CCS. Peak hydrogen demand is observed in Scenario C, at approximately 0.05EJ a year by 2046, which is equivalent to 5GWe of renewable electricity generation and electrolyser input capacity[58].

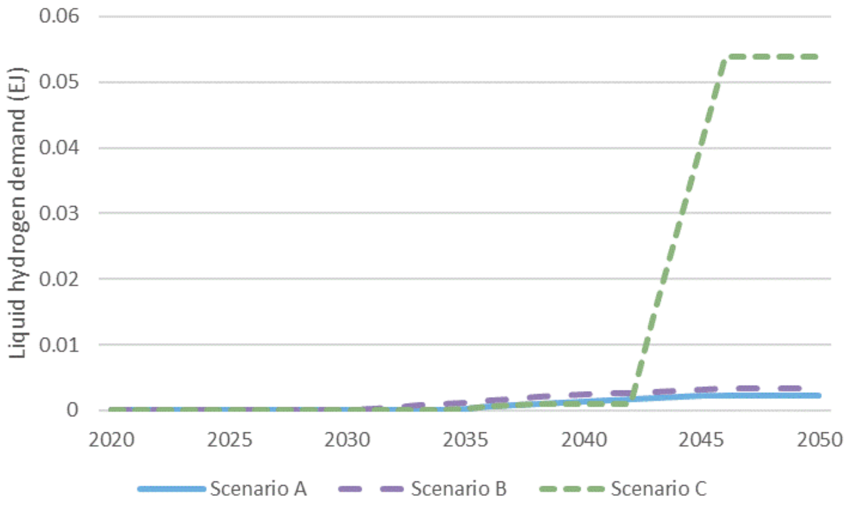

Figure 5.8 – Comparison of liquid hydrogen international shipping demands in each core scenario

For green hydrogen, renewable electricity availability is unlikely to be a constraint on supply in either the short or long term, because the renewable electricity industry is already large and projected to grow significantly over the next few decades. In 2020 alone, a combined 200GW of additional solar and wind capacity was installed globally, bringing total global renewable energy capacity up to 2,700GWe[59]. By 2050, combined solar and wind capacity additions could reach around 1,000GWe a year, according to the IEA Net Zero scenario, with over 200EJ a year of renewable electricity supply available from installed wind and solar[60]. In this case, liquid hydrogen demand in shipping in all three core scenarios would account for less than 0.2% of the available renewable energy supply. In addition, there appear to be few constraints on the electrolyser industry in terms of growing its manufacturing capabilities. Electrolyser manufacturing is considered to generally be demand driven, rather than supply constrained. Manufacturing processes are easily scalable, requiring relatively low investment in terms of critical components.

The infrastructure and technologies for fossil hydrogen production are already in place, and the main constraint on blue hydrogen industry growth is the rate at which the CCS industry can expand its operations. The IEA Net Zero scenario projects that ~450MtCO_2 will be captured from hydrogen production by 2030, equivalent to ~62MtH_2 production[61] (7.5EJ a

[58] Assuming an electrolyser efficiency of 50kWh/kg hydrogen and a capacity factor of 0.45 (4,000 load hours per year).
[59] IRENA (2021). *Renewable Energy Capacity Statistics*.
[60] IEA (2021), Net Zero by 2050, IEA, Paris https://www.iea.org/reports/net-zero-by-2050.
[61] 9kg CO_2 per kg hydrogen produced, and assuming an 80% capture rate. Sun, Pingping and Amgad Elgowainy. (2019). *Updates of hydrogen production from SMR process in GREET® 2019*. Argonne National Laboratory.

year). By 2050, this increases to 1,353MtCO_2 captured, or 22.5EJ a year of hydrogen. Therefore, it appears there are few constraints on supplying shipping with blue hydrogen.

Hydrogen liquefaction capacity is currently constrained as it is estimated at only around 450t/day of global capacity (0.018EJ a year)[62]. The technology has been in commercial operation at small scales for decades (90t/day global capacity in 1980), so has grown by around 4% year-on-year since that date, although industry growth has been much more rapid since 2019. There are now a number of green and blue hydrogen projects looking at using liquefaction to enable trade of hydrogen by truck or ship during the 2020s, at significantly larger scales than current rocket fuel or semiconductor industries, with efficient plant designs capable of up to 790t/day[63]. The peak maritime liquid hydrogen demand in Scenario C would only require around seven of these large plants to be operational by the mid-2040s. So although the requirement is for an order of magnitude scale-up in the current industry, demands are still modest, and the GloTraM results suggest that hydrogen liquefaction will not be a significant bottleneck to achieving the maritime demands from 2030 onwards.

As hydrogen is a key feedstock in both the production of ammonia and methanol, the combined total gaseous hydrogen demand in shipping for ammonia, methanol and liquid hydrogen must also be considered. Figure 5.9 shows the GloTraM results for combined hydrogen demand in all three core scenarios, for liquid hydrogen, hydrogen for ammonia production, and hydrogen for methanol production. Hydrogen demand increases substantially beginning in 2025–2030, mainly due to demand for ammonia (Section 5.1.7). All three scenarios peak at a hydrogen demand of around 15.5EJ per year by 2050, equivalent to 1,600GWe of renewable power generation if all generated as green hydrogen[64], or approximately 7% of the IEA expected global wind and solar photovoltaic power output in 2050. Maritime demands will therefore become increasingly important to the green (and blue) hydrogen industries, particularly during the 2030s, but it will still be feasible to meet these demands as well as competing demands for renewable power and fossil fuels. The peak rate of demand growth, observed in Scenario C between 2034 and 2038, corresponds to an increase of ~8EJ hydrogen demand (~66 Mtonnes): this rate of growth would require a minimum 200 GW of electrolyser production capacity being added each year if satisfied solely by green hydrogen, before taking into account competition from other industries.

[62] Linde (2019). *Latest global trend in Liquid Hydrogen Production*. Available at https://www.sintef.no/globalassets/project/hyper/presentations-day-1/day1_1430_decker_latest-global-trend-in-liquid-hydrogen-production_linde.pdf.

[63] IEA (2020). *The Future of Hydrogen: Assumptions* (annex). Available at https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf.

[64] Assuming an electrolyser efficiency of 0.417kWh/MJ hydrogen and a capacity factor of 0.45 (4,000 load hours per year).

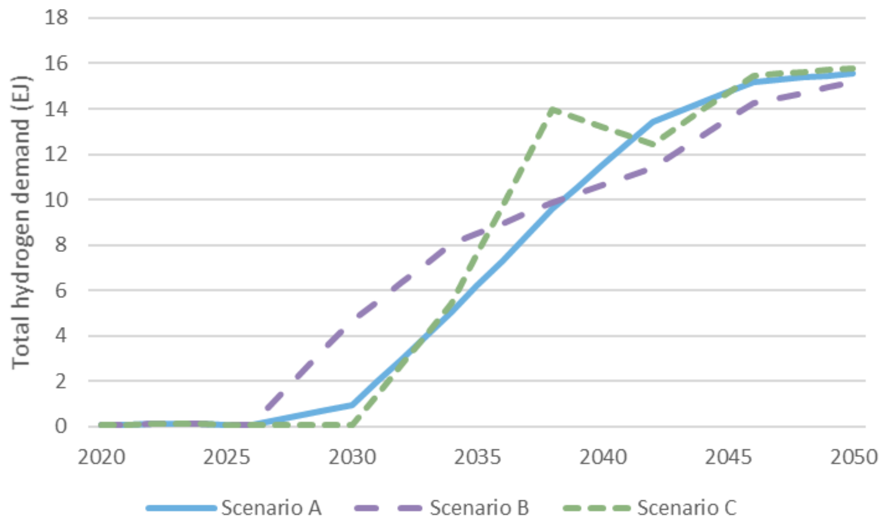

Figure 5.9 – Total international shipping demand for hydrogen as a fuel, and as a feedstock for other fuels, in GloTraM core scenarios

GloTraM shipping fuel demand for hydrogen by 2030 is very high in Scenario B compared to announced hydrogen projects globally. The IEA Hydrogen Projects Database[65] indicates that there are 8.0Mt (0.96EJ) of dedicated electrolytic green hydrogen production projects either currently operational, under construction, or at the final investment decision stage (FID), that are expected to be online by 2030. However, there are several large hydrogen projects at a "concept" or pre-investment stage of development with an expected start date of 2030 or before. If all of these concept projects were to come online, there would be 23.6Mt (2.8EJ) of dedicated hydrogen production available by 2030. There are also 52.8Mt of green ammonia projects currently planned before 2030, corresponding to a further ~10Mt H_2 production (1.2EJ), and an additional 0.5 Mt (0.06EJ) of green methanol projects. This indicates that a total of 2.2EJ - 4.1EJ of green hydrogen capacity is expected to be online by 2030: a figure that will only increase before 2030. Estimates of announced green hydrogen production capacity are summarised in Table 5.2.

Table 5.2 – Total currently announced green hydrogen production to 2025 and 2030

Planned production (EJ)	2025	2030
Hydrogen (Excluding concepts)	0.39 (0.31)	2.84 (0.96)
Ammonia	0.23	1.20
Methanol	0.06	0.06
Total **(Excluding concepts)**	**0.68** **(0.60)**	**4.10** **(2.22)**

[65] Accessed April 2022. Available at: https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

5.1.7 Ammonia

As noted in Section 5.1.6, ammonia demand in the GloTraM core scenarios is the most significant source of hydrogen demand. As of 2020 ammonia industry capacity is equivalent to approximately 4EJ/year, mostly from demand for nitrogen fertilisers[66]. However, by 2050, maritime demand for ammonia in all three core scenarios is between 12.5-13EJ a year, as illustrated in Figure 5.10.

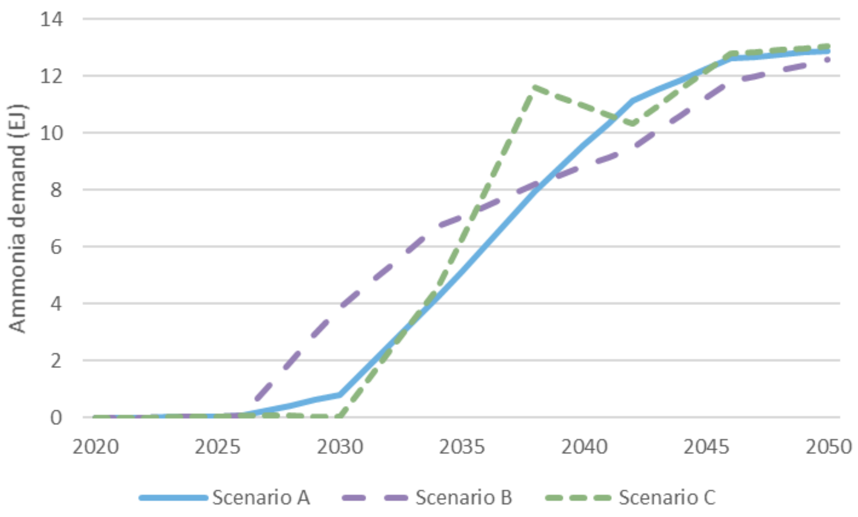

Figure 5.10 – International shipping ammonia demand in core GloTraM scenarios

Ammonia demand from existing industries, such as for fertiliser production, is projected to grow by approximately 50% by 2050 from 2020 levels[67]. Figure 5.11 compares the projected demand growth from these existing industries (black dotted line) plus the GloTraM core scenario demands (red lines) against the current global production capacity (grey columns, given current use of unabated natural gas), and planned green and blue ammonia production capacity to 2030 (green/blue columns).

[66] FAO, 2019. World fertilizer trends and outlook to 2022. Available at: https://www.fao.org/3/ca6746en/ca6746en.pdf

[67] FAO, Food. "The future of food and agriculture: alternative pathways to 2050." Food and Agriculture Organization of the United Nations Rome (2018). https://www.fao.org/publications/card/en/c/I8429EN/#:~:text=The%20report%20%27The%20future%20of,in%20agriculture%2C%20and%20climate%20change.

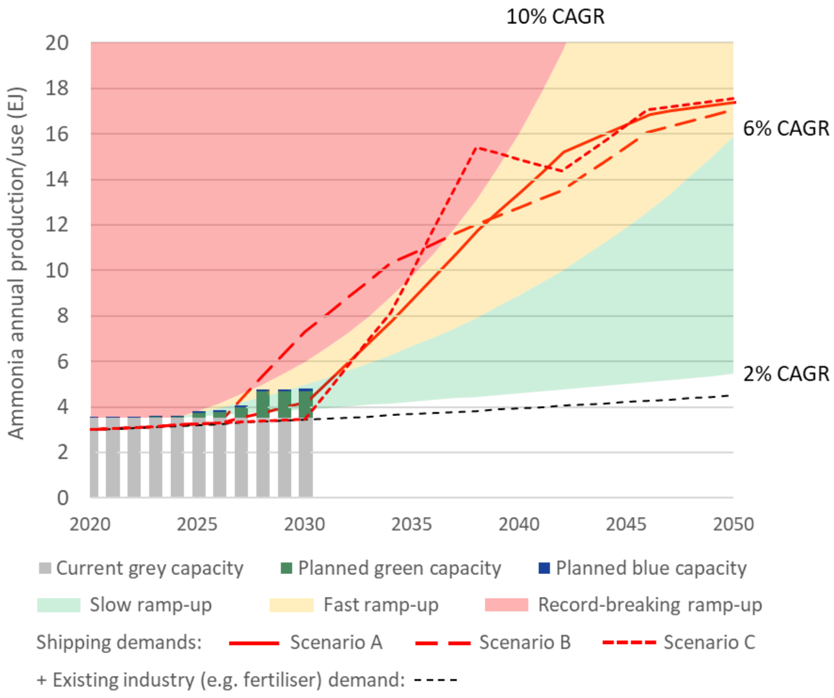

Figure 5.11 – Comparison between current and planned global ammonia capacity (columns), projected industrial and international maritime demands (lines) and required growth rates from 2025 (shaded regions)

The green and yellow shaded regions in Figure 5.11 represent historical ammonia industry growth rates, used as a proxy for indicating the capacity for technology providers and EPC contractors to expand their services. The compound annual growth rate (CAGR) represents year-on-year industry growth starting in 2025. Since 2010 the industry has grown at a 2% CAGR: continuing at this rate of growth would be far below what is necessary to meet the GloTraM core demand scenarios. The green–yellow boundary represents the average growth rate of the ammonia industry since 1945 (approx. 6% CAGR), while the yellow-red boundary reflects the rate of growth between 1945 and 1980, when the industry experienced accelerated growth (approx. 10% CAGR)[68].

If starting from 2025, only the demands from Scenario A stay within this record CAGR, requiring sustained industry growth of around 9% per year between 2025 and 2040. In contrast, Scenarios B and C would (at different times) require the ammonia industry to grow faster than its past highest sustained growth rate. If ammonia growth is delayed to 2030, as in Scenario C, a CAGR of 18% is then required over the 8-year period between 2030–2038 to meet maritime demands. This is far beyond what has been observed in the past and, despite ammonia being a well-established technology with multiple EPCs, there is a risk this may be beyond industry capabilities, because this is close to an upper bound of what other synthetic fuel projections in this study credibly assume. It would require a huge pipeline of

[68] Vroomen, 2012. The History of Ammonia to 2012 (Presentation). The Fertiliser Institute, November 19th 2013. http://www.firt.org/sites/default/files/2vroomen.pdf Accessed December 2021.

projects to be simultaneously developed in the late 2020s, with high levels of international and national coordination regarding associated infrastructure.

In addition to examining whether industry growth rates are sustainable over the next 15 years, the study also examined how the nearer-term capacity pipeline to 2030 compares with emerging maritime demands. ERM's data on ammonia projects indicates that green ammonia project development typically takes between 3 and 5 years from concept to first operation, depending on scale[69]. Within this timeline, the delivery lead-time for electrolyser manufacturers can be significant ranging from 6 months to 2 years[70], with additional time then required for balance-of-plant.

The retrofitting of renewable electrolysis to existing ammonia facilities is likely to be slightly quicker[71], but there are limits as to the scales possible, because green hydrogen is typically constrained to a maximum of 10–20% of the existing plant capacity[72]. Blue ammonia may also be developed via CCS being retrofitted to existing ammonia facilities[73]. However, in the case of both green and blue hydrogen retrofits, if these retrofits lead to diversion of the resulting ammonia into energy applications, then the wider ammonia industry will likely still have to expand to meet conventional ammonia demands unless there is available Haber-Bosch capacity headroom to utilise at the plant (unlikely in many cases, given global production was above 80% of global capacity in 2020[74]). New maritime demands for low-carbon ammonia are likely to have to be met by new green and/or blue ammonia facilities being constructed.

The new-build timeline of 3–5 years indicates that meeting near-term maritime ammonia demand growth for Scenario B in 2025–2030, as shown in Figure 5.10, will be extremely challenging. A review of globally announced green and blue ammonia projects indicates that 1.2EJ/year of green ammonia projects and 0.1EJ/year of blue ammonia projects are currently expected to be operational by 2030. Much of this planned new low-carbon ammonia capacity is not scheduled to come online until the late 2020s, and is unlikely to be dedicated to use in the maritime sector. (Several larger ammonia projects are focusing on global hydrogen trade, i.e. using the green ammonia produced as a hydrogen carrier, and not consuming it onboard a ship.) Under Scenario B an immediate increase (i.e. within the next 12–18 months) in the global ammonia project pipeline to more than double its current level would likely be required to meet the supply gap in 2027–2030, with a focus on projects serving the maritime sector. A more modest but still significant increase in the project pipeline within the next 2–3 years would be required to meet Scenario A demands from 2029–2030.

[69] As an example of an extremely large project, in early 2020 Saudi Arabia announced the greenfield NEOM project, which is currently expected to start producing 1.2Mt (0.022EJ) ammonia per year in 2025.
[70] Available at https://arena.gov.au/assets/2021/08/bp-ghd-renewable-hydrogen-and-ammonia-feasibility-study.pdf.
[71] For example, in December 2020, Yara announced plans to install a 24MW electrolyser at the existing Porsgrunn ammonia plant: the project is scheduled to produce 20,500t (0.00038EJ) green ammonia per year from mid-2023.
[72] https://www.globalmaritimeforum.org/content/2021/06/The-Nordic-Green-Ammonia-Powered-Ship-_Project-Report.pdf
[73] The Tomakomai blue ammonia demonstration project in Japan had a development timeline of four years, being announced in 2012 and beginning CCS demonstration activities in 2016.
[74] Statistical Division of the Food and Agriculture Organization of the United Nations (FAO). http://faostat.fao.org/.

There are a few important emerging uses for ammonia that will further increase competition and market demands above the values given in Figure 5.11; however, these are modest relative to the maritime demands in the three core scenarios:

- Under the IEA Net Zero scenario[75], an additional demand of 100Mt (1.9EJ) per year will likely arise from the use of ammonia for power generation by 2050
- Ammonia is a candidate for use as a hydrogen carrier due to its energy density and storage properties. IRENA estimates that 30% of all hydrogen may be traded across borders by 2050[76], while the IEA indicates that 528Mt of low-carbon hydrogen will be required by 2050[77]. For comparison, if ammonia were to be used as an energy carrier for 10% of this trade, this would further increase ammonia demand by 80Mt (1.5EJ) per year: equivalent to 43% of current global ammonia production capacity.

5.1.8 Synthetic methanol

The projected demand for blue and green methanol modelled with GloTraM is negligible through to 2050. In addition, methanol can be sourced through other pathways, including biomass gasification to methanol or biomethane reforming to methanol. As such, the minimal projected demands in each of the GloTraM core scenarios from shipping are very likely to be able to be met.

As of 2020, the fossil methanol industry had 150Mt (3EJ) per year of production capacity[78], although annual production was 30% below this capacity level (i.e. some available headroom). In the near-term, there are only a few green methanol projects planned globally, with 0.052EJ estimated capacity by 2030 from currently announced projects, using point source CO_2. Blue methanol production is currently minimal, and no commercial-scale projects have been announced (given the requirement to combine blue hydrogen with CO_2 that is sourced separately from the blue hydrogen production). None of the announced projects are currently focusing on DAC CO_2 sources.

A further consideration is that the methanol and ammonia supply split in the GloTraM model scenarios is the result of the selected input assumptions: should costs of production change, for instance due to an unforeseen technological advancement, maritime demand for methanol could be significantly larger. Under a hypothetical scenario where ammonia demand switches entirely to methanol production (i.e. approx.12EJ a year of methanol demand), this would equate to four times the current total capacity (3EJ) of the methanol industry, and require significant investment. A very similar growth discussion to that for ammonia would apply in this hypothetical scenario for the methanol industry, in terms of the industry starting position and required CAGR for the core scenarios, with Scenario C requiring what could be an unrealistically fast expansion.

In this hypothetical scenario, roughly 0.93GtCO_2 a year would be required as feedstock for methanol synthesis by 2050[79]. The IEA Net Zero scenario indicates that only 0.98GtCO_2 of

[75] IEA (2021a) 'Net Zero by 2050 A Roadmap for the Global Energy Sector.' Global Status Report [Preprint].
[76] IRENA (2020) 'Green Hydrogen Cost Reduction.' Available at: https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction (Accessed: February 22, 2022).
[77] IEA (2019b) 'The future of hydrogen.' IEA, Paris https://www.iea.org/reports/the-future-of-hydrogen
[78] IRENA (2021b) 'Innovation Outlook: Renewable Methanol.' International Renewable Energy Agency. Available at: https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol
[79] Assuming 0.0745 kg CO_2/MJ MeOH. JEC (2020). 'JEC Well-to-Tank report v5', Publications Office of the European Union, Luxembourg.

DAC would be installed per year by 2050, with an additional 6.6GtCO_2 captured from other sources, such as industrial combustion and processes, and biofuels and hydrogen production. As GloTraM assumes that methanol combustion onboard a ship goes uncaptured, the feedstock CO_2 used would need to not be sourced (diverted from) CCS applications because this would increase global emissions and temperatures). Instead, the feedstock CO_2 would likely need to be captured from additional DAC plants. Maritime demands for methanol in this hypothetical scenario therefore would effectively require a doubling of the global DAC market by 2050.

In the GloTraM core scenarios, demand for ammonia by 2030 varies significantly: between 0.3EJ (Scenario C) and 3.4EJ (Scenario B). If fully substituted by methanol, this would require a CO_2 supply for methanol production ranging from 18.5Mt to 210Mt per year, respectively[80]. While the IEA estimates under its Net Zero scenario that a total of 1.66GtCO_2 a year will be captured by 2030, only 90Mt of this will be from DAC. For Scenarios A and B in particular, supply of methanol for shipping under these hypothetical scenarios would be heavily reliant upon CO_2 capture from sources other than DAC.

One alternative might be onboard capture of CO_2 from methanol use, which is at an early stage of development (with likely significant but uncertain vessel design and cost impacts). This concept might allow a closed carbon loop to be established whereby the same methanol-related carbon atoms are being repeatedly reused as a carrier for green/blue hydrogen atoms, thereby substantially reducing the need for DAC or other CO_2 feedstock sources.

5.1.9 Key conclusions

The following are the main conclusions from the supply ramp-up constraint analysis:

- Total GloTraM biofuel shipping demand in 2050 (0.92EJ) is far exceeded by the availability of biomass feedstocks, and the expected availability of biofuels across various routes.
- Significant quantities of advanced biofuels are not required before 2040.
- Low supply ramp-up scenarios estimate a combined 0.5EJ of advanced biofuel production capacity in 2050: similar to shipping demand in the three core GloTraM scenarios. This may be insufficient to meet demand once competing industries are considered. High supply ramp-up scenarios do not share this concern.
- The maritime sector will face significant competition for lipid-based feedstocks for HVO and FAME production, and fuels made via other low-carbon pathways such as pyrolysis or Fischer-Tropsch may be required to compensate.
- Demand for synthetic methanol and fuel hydrogen is minimal across all three core GloTraM scenarios.
- Ammonia demand is significant in all three GloTraM scenarios: equivalent to three times the total capacity of the ammonia industry in 2020.
- Meeting the growth in ammonia demand from shipping in GloTraM scenarios B and C would require the ammonia industry to grow at growth rates comparable to or exceeding the maximum historic growth rates experienced by the industry.

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[80] 3.4EJ methanol at an LHV of 22.7 MJ/kg corresponds to roughly 150 Mt of MeOH.1.4 kg CO_2 per kg MeOH is assumed, corresponding to reported Carbon Recycling International figures (Methanol Institute, Renewable Methanol Report 2018. Available at: https://www.methanol.org/wp-content/uploads/2019/01/MethanolReport.pdf)

- The current pipeline of green and blue ammonia projects is not sufficient to meet demand from shipping in Scenarios B and C, before considering demand from competing emerging industries. A substantial increase in project announcements within the next few years would be required.

6 Comparison of necessary new-build and retrofit rates to global shipbuilding capacity

This chapter aims to explain and highlight any shipbuilding capacity constraints that could limit progression against the core decarbonisation trajectories modelled within this study. This has been conducted at two levels; firstly, as an input to the shipbuilding process, the SZEF machinery and efficiency technologies available within GloTraM are evaluated for any fundamental input material or manufacturing constraints: that is, can the shipyards obtain the major components needed to build or upgrade sufficient vessels? Secondly, the global shipbuilding and ship upgrade capacity is considered: is there enough shipyard capacity to build and upgrade the fleet as predicted by GloTraM?

The first level of analysis shows that the SZEF machinery and efficiency technology options within GloTraM do not require any supply-constrained materials or special manufacturing processes. Therefore, the supply chain of key components is unlikely to represent a constraint in the rate of vessel new-builds or mid-life retrofits. The details of this analysis can be found in the Technical Annex.

The second level of analysis is discussed below: Section 6.1 analyses the global shipbuilding capacity and its feasible growth rates, and compares that to the total deadweight tonnage (dwt) of the new-build vessels predicted by GloTraM; and Section 6.2 qualitatively discusses the number and type of mid-life retrofit upgrades selected by GloTraM to indicate the retrofit challenge.

6.1 Historical new-build vessels delivery trend vs modelled new-build vessel requirement

This section uses the historical new-build vessel delivery trend to estimate the maximum historical new-build growth rate that the ship building industry can deliver. This growth rate is then used to project the maximum dwt of new-build vessels that can be built out to 2050[81]. This is then compared with GloTraM's modelled new vessel build requirements based on this study's three underlining scenarios (Scenario A, Scenario B and Scenario C) along with the BAU (with CII/EEXI) scenario. The comparison uses dwt as the evaluation metric, because this effectively combines vessel size and vessel numbers in a single value, providing a better analysis than using vessel numbers alone. Figure 6.1 shows the result of this analysis.

[81] Rehmatulla and Kapur (2022), Will shipyards have the capacity to deliver new build vessels at the rate needed to reach Paris climate goals? - Decarbonising UK Freight Transport (decarbonisingfreight.co.uk).

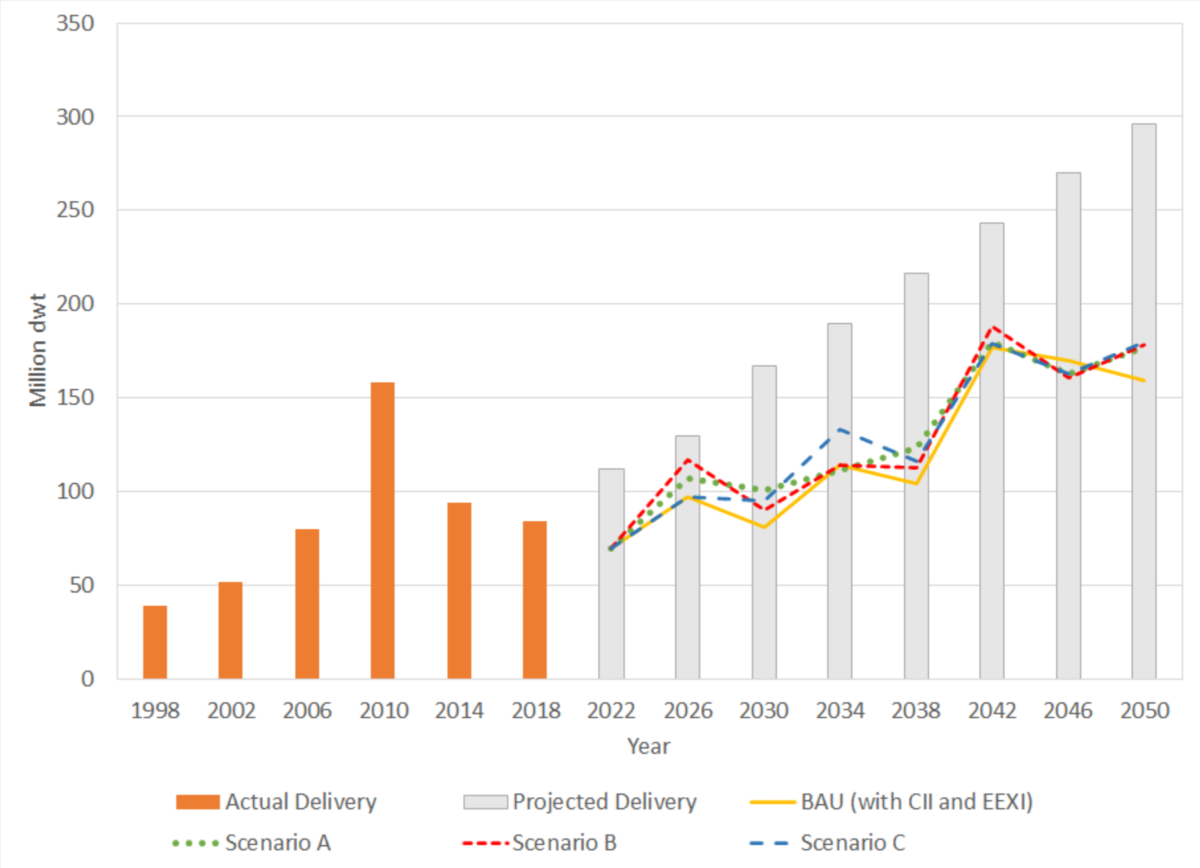

Figure 6.1 – Historical new-build vessel delivery trend vs modelled new-build vessel requirement. Bars represent actual values for the denoted year (i.e., no averaging has been applied)

The orange bars in this graph, Actual Delivery, illustrate the four-yearly vessel delivery trend, in dwt, from 1998 to 2018, showing a positive growth trend from 1998 to 2010, with 2010 logging record global deliveries. This 2010 delivery record is primarily attributed to the orders placed during buoyant market conditions immediately preceding the 2007–2008 Global Financial Crisis[82]. Nevertheless, the 1998–2010 growth rate shows that the global shipbuilding industry can grow at that rate, given the appropriate market or policy signals.

As 2018 is considered the base year for the GloTraM analysis, the grey bars, Projected Delivery (considering 2018's data as a base), represent the predicted growth rate for vessel deliveries from 2022 to 2050. This growth rate has been derived from the growth rate observed from 1998 to 2010. Finally, the plotted lines are the new vessel demand results taken from GloTraM for the underlining three core scenarios, along with BAU (with CII/EEXI).

Figure 6.1 shows only slight differences in the shipbuilding demand across the various scenarios. This is because, in the first instance, the GloTraM model is building ships to meet a global transport demand that steadily increases from now until 2050 (see Figure 2.4). The transport demand is a GloTraM input and is the same across the scenarios – resulting in similar shipbuilding demands. What differs across the decarbonisation scenarios is *what* gets built; that is, what fuel is used and what level of energy efficiency technology is selected.

[82] (OECD 2017) Imbalances in the Shipbuilding Industry and Assessment of Policy Responses. Available here: https://www.oecd.org/industry/ind/Imbalances_Shipbuilding_Industry.pdf

This analysis shows that, with sufficient notice and the correct market or policy signals, the global shipbuilding industry can scale to meet the future need for ships on a dwt basis. This is true for all the modelled scenarios.

6.2 Mid-life upgrade via retrofit

As well as modelling for new-build lower carbon vessels, GloTraM can model for the situation where vessels are upgraded at mid-life by applying lower carbon machinery or efficiency technology retrofits. The number and level of the upgrades varies from scenario to scenario.

It is challenging to analyse retrofits in the same way as new-builds (above), for three reasons:

- Information on the number and scale of historical retrofitting is not readily available, which makes testing the modelling outputs against a projection of retrofitting capacity difficult
- Some retrofittable technologies can be fitted outside of the traditional shipyard environment (i.e. not all need drydock capacity)
- The cost, complexity and time required for a retrofit is a function of whether it has been planned for at the point of new-build. Many ships already exist with an 'LNG-ready' notation, and ships are now starting to be built that are 'ammonia-ready'[83]. These notations indicate that some preparation has already been made, but with few actual examples of retrofitting to operate on a new fuel, there is no evidence base to estimate timescales.

Figure 6.2 shows that the number of ships retrofitted peaks at around 15,000 to 16,000 ships per annum across the core scenarios. In the periods that these magnitudes occur, they represent of the order of 15% of the total fleet. For reference, Figure 6.2 also includes the number of new-builds undertaken in the BAU (with CII/EEXI) scenario, highlighting that the number of retrofits actions exceed the number of new-builds.

However, at least some equipment, if not all, for the required retrofits may be fitted during a scheduled drydock period (i.e. when the vessel undergoes scheduled maintenance in a dry dock allowing full access to the hull and propeller etc). Generally, the drydock interval for the majority of the international fleet is around 5 years, which is similar to one period in the modelling. The results therefore do not indicate that drydocking outside of normally scheduled periods is necessary. Hence, it can be argued that for any component of retrofitting absorbed during the normally scheduled period of maintenance, there is no added demand for drydock time and shipbuilding capacity. A key sensitivity to this finding is whether retrofit to a new fuel (e.g. retrofit to use of ammonia) can be achieved within a conventional mid-life drydock period. There is little experience to date on the timescales for retrofitting to a new fuel, but one example (a first of a kind) of an LNG retrofit took months[84]. There are two reasons that justify why the retrofit to ammonia could be shorter than this one example. Firstly, because this was a first of a kind it is not representative of the production efficiency and learning that would be obtained when thousands of ships undergo a similar

[83] See https://www.ship-technology.com/news/avin-international-ammonia-ready-ship/.
[84] See https://www.transportandlogisticsme.com/smart-sea-freight/hapag-lloyd-to-retrofit-15000-teu-vessel-in-world-first

procedure. Secondly, if ships are anticipated to be retrofitted at the point they are first built and experience from retrofitting fed back into the design process, the time needed for their retrofit could be minimised. If however additional time is needed, then drydock periods can be extended, which then could have an impact on capacity. The period of time a ship occupies a drydock when it is being built is over a period of years. A scheduled maintenance drydock is typically weeks. Therefore, even if the time spent in drydock is doubled or tripled for a fraction of the retrofits (say 15% as an estimate), the implications relative to the number of drydock berths and shipbuilding capacity is significantly less than a 15% increase. Therefore, placing that additional retrofit-based demand for drydock capacity in the context of the estimated excess shipbuilding capacity in Figure 6.1 (i.e., the difference between the line plots and the grey bars), shows that there are no expected drydock constraints versus the retrofits required by the modelled scenarios.

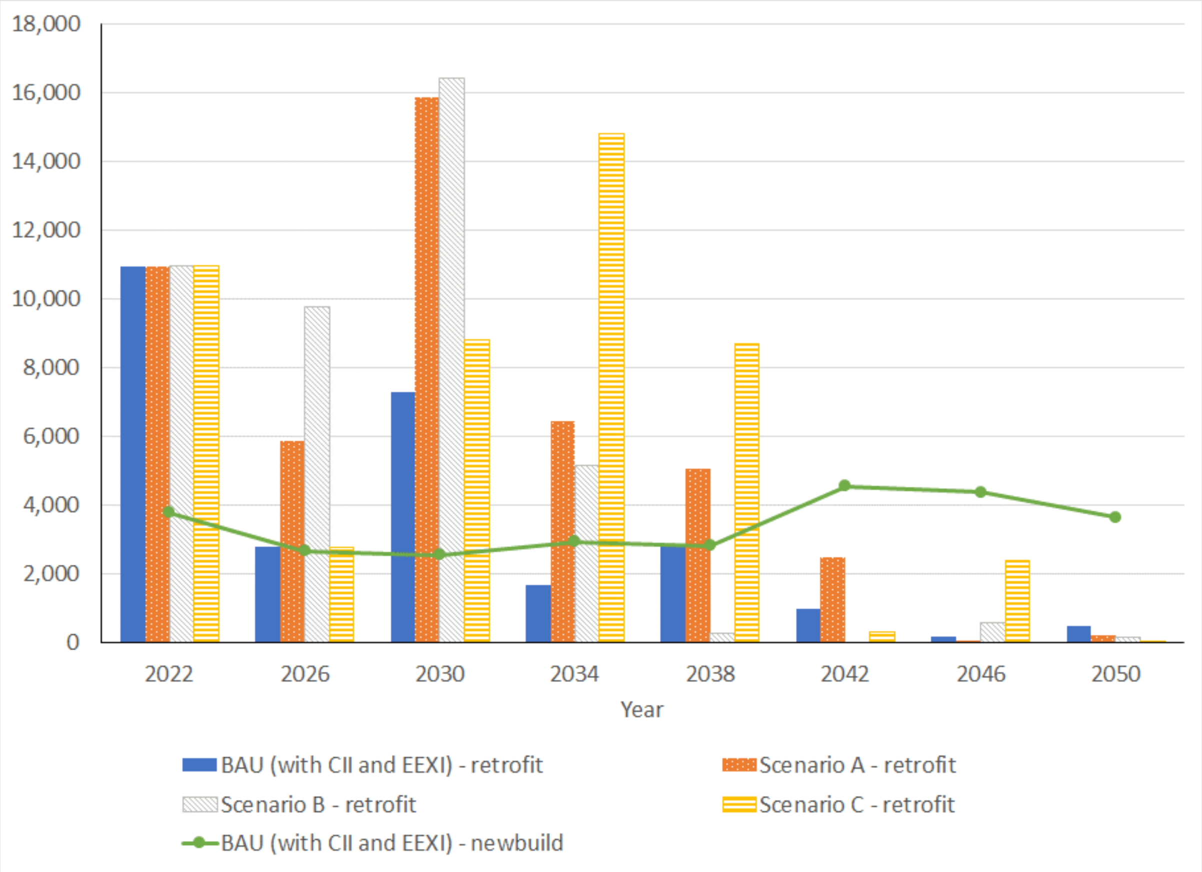

Figure 6.2 - Number of retrofits versus number of new-build vessels per year

Glossary

- AER – Annual Efficiency Ratio, a measure of the carbon intensity per unit of transport work, defined as AER = gCO_2/(deadweight x annual distance).
- AIS – Automatic Identification System, a global network of satellite and terrestrial receivers that maps the identity, location and speed of all vessels required to have an AIS tracker as per IMO regulation[85].
- Alternative fuels – Are fuels that can displace the incumbent crude oil-derived fuels (such as LSFO).
- BAU – Business-As-Usual, the set of scenarios where no carbon budget or pricing mechanism is applied.
- Carbon costs – Costs seen by operators in shipping when paying a carbon price/tax, so not a resource cost but an economic transfer.
- CAPEX – CAPital EXpenditure – the capital cost of machinery and energy efficiency technology, presented as either absolute costs at point of purchase or amortised over a given payback period.
- CCS – Carbon Capture and Storage, the process of feeding process exhaust through a chemical sieve to extract a high proportion of the CO_2 before ejection to the atmosphere. The CO_2 can then be used downstream as an ingredient in other processes, or liquefied/compressed and stored.
- CII – Carbon Intensity Indicator, a new regulatory mechanism due to be enforced from 2023 that requires vessels to adhere to a yearly-decreasing AER trajectory that is unique to a specific vessel's type and size. Vessels receive ratings from A to E based on their deviation from the required CII, and must submit plans to improve their performance if three consecutive Ds or an E rating are conferred.
- Cohort – In the context of this work a cohort is a group of vessels that belong to a particular vessel type, size class and generation (here generation refers to the time step that the vessel was introduced into the fleet).
- DAC – Direct Air Capture, whereby CO_2 is extracted from the atmosphere through mechanised or chemical means, with methods varying in heat and power requirements.
- EEDI – Energy Efficiency Design Index, a regulatory mechanism that stipulates a minimum energy efficiency requirement for new-build vessels, based on its technical characteristics, that increases in severity with time.
- EEOI – Energy Efficiency Operational Indicator, a more accurate measure of a vessel's true carbon intensity, but harder to estimate in practice. Defined as EEOI = gCO_2/transport work, where the transport work is defined using the actual cargo carried by the vessel in a given year rather than using deadweight as a proxy.

[85] Further information on IMO regulations for carriage of AIS is available here: AIS transponders (imo.org)

- EET – Energy Efficiency Technology, any onboard equipment installed with the purpose of increasing the operational energy efficiency of the vessel without modifying the type of scale of fuel and main machinery.
- EEXI – Energy Efficiency eXisting ship Index, similar to the EEDI, but applied to vessels built before the introduction of the EEDI, and designed to be no more stringent than the equivalent EEDI requirement for that vessel in a given year.
- Energy-related costs – The combination of energy/fuel costs, and capital and other operating costs associated with the equipment needed for the storage and conversion of energy/fuel onboard ships, and the costs associated with energy efficiency improvements.
- Energy-machinery costs – Capital and operating costs for any machinery onboard associated with either the conversion of energy (e.g. internal combustion machinery, generator etc.) or the increase in energy efficiency (e.g. air lubrication, wind assistance technologies etc.)
- FUSE – Fuel Use Statistics and Emissions, a modelling suite developed by UMAS Int. that estimates the hourly fuel consumption and emissions of all the global fleet.
- GHG – Greenhouse Gas emissions, defined in this study as CO_2, CH_4 and N_2O, collectively expressed as CO_2-equivalent (CO_2e) according to a 100-year global warming potential.
- LHV – Lower Heating Value, also referred to as the net calorific value, of a fuel is defined as the amount of heat released by combusting a specified quantity of material (initially at 25°C) and returning the temperature of the combustion products to 150°C, without accounting for the latent hear of vaporisation of any water involved in the products.
- LNG – Liquefied Natural Gas, liquid methane held at cryogenic temperatures to facilitate a higher gravimetric density suitable for maritime transport and consumption.
- LSFO – Low sulphur heavy fuel oil, the use of which became compulsory following the 2020 IMO sulphur cap.
- Machinery – Refers to the main engine machinery, auxiliary engine machinery, motors and fuel system.
- MDO – Marine Diesel Oil, including Marine Gas Oil (MGO) and other distillates.
- Normalised energy-related costs – The cost premium/differential for the energy and energy-machinery costs of the total fleet in a given scenario. Normalisation is applied using the transport demand parameter, which enables the normalised cost premium/differential to be comparable both over time (because transport demand increases over time in all scenarios and is a driver of total cost itself), and between scenarios (e.g. when comparing between two scenarios that have different underlying transport demand).
- OPEX – OPerational EXpenditure, the annual cost of energy-related operational and maintenance activities on board the vessel.

- Scenario A – Decarbonise fully by 2050, with the bulk of emissions reductions made between 2025 and 2050. I.e., a slow and steady transition with costs spread out over time.
- Scenario B – Decarbonise fully by 2050, with the bulk of emissions reductions made between 2025 and 2035. I.e., an early, steep decarbonisation trajectory.
- Scenario C – Decarbonise fully by 2050, but the bulk of emissions reductions are left until the 2030's. I.e., a longer BAU period with a later, steep decarbonisation trajectory.
- SZEF – Scalable Zero Emission Fuel, defined here as any hydrogen-derived fuel that can achieve zero WTW CO_2 emissions (e.g. hydrogen, ammonia, methanol derived from DAC CO_2).
- TTW – Tank-to-wake – defines the scope of emissions as those occurring solely due to the operational (or 'downstream') actions of a vessel.
- WTT – Well-to-tank – defines the scope of emissions as those occurring during the fuel extraction and processing or fuel production including and up to placement in a vessel's fuel tank. Also known as 'upstream'.
- WTW – Well-to-wake – defines the scope of emissions as those occurring from the upstream point of extraction of the fuel on land through to its combustion and processing on board the vessel. WTW is the sum of TTW and WTT emissions.

Appendix – Modelled Scenarios

The modelled scenarios are fully described in the Technical Annex, but are listed below for reference.

Table A.1 – Scenario descriptions: core scenarios (white background), sensitivity scenarios (grey)

Scenario ID	Scenario description	Carbon price	Transport demand	Learning rates	Scrappage	Fuel prices	Bioenergy
BAU	**BAU (No CII/EEXI)**	None	SSP2 RCP2.6 L	EET Only	30 Year Lifetime	Core Assumptions	None
BAU2	**BAU (CII/EEXI)**	None	SSP2 RCP2.6 L	EET Only	30 Year Lifetime	Core Assumptions	None
A	**Scenario A**	Scenario A, Gradual Decrease	SSP2 RCP2.6 L	Scenario A Curves	30 Year Lifetime	Core Assumptions	0.9 EJ by 2050
B	**Scenario B**	Scenario B, Early Action	SSP2 RCP2.6 L	Scenario B Curves	30 Year Lifetime	Core Assumptions	As Scenario A
C	**Scenario C**	Scenario C, Delayed Response	SSP2 RCP2.6 L	Scenario C Curves	30 Year Lifetime	Core Assumptions	As Scenario A
SS1A	**Scenario A, Low Transport Demand**	As Scenario A, Gradual	OECD RCP2.6 G	Scenario A Curves	30 Year Lifetime	Core Assumptions	As Scenario A
SS3AL	**Scenario A, Low SZEF Prices**	As Scenario A, Gradual	SSP2 RCP2.6 L	Scenario A Curves	30 Year Lifetime	Low SZEF, High Fossil Fuel Prices	As Scenario A
SS3AH	**Scenario A, High SZEF Prices**	As Scenario A, Gradual	SSP2 RCP2.6 L	Scenario A Curves	30 Year Lifetime	High SZEF, Low Fossil Fuel Prices	As Scenario A
SS3BL	**Scenario B, Low SZEF Prices**	As Scenario B, Early	SSP2 RCP2.6 L	Scenario B Curves	30 Year Lifetime	Low SZEF, High Fossil Fuel Prices	As Scenario A
SS3BH	**Scenario B, High SZEF Prices**	As Scenario B, Early	SSP2 RCP2.6 L	Scenario B Curves	30 Year Lifetime	High SZEF, Low Fossil Fuel Prices	As Scenario A
SS3CL	**Scenario C, Low SZEF Prices**	As Scenario C, Delayed	SSP2 RCP2.6 L	Scenario C Curves	30 Year Lifetime	Low SZEF, High Fossil Fuel Prices	As Scenario A
SS3CH	**Scenario C, High SZEF Prices**	As Scenario C, Delayed	SSP2 RCP2.6 L	Scenario C Curves	30 Year Lifetime	High SZEF, Low Fossil Fuel Prices	As Scenario A
SS2AL	**Scenario A, No Biofuel**	As Scenario A, Gradual	SSP2 RCP2.6 L	Scenario A Curves	30 Year Lifetime	Core Assumptions	None
SS2AH	**Scenario A, High Biofuel**	As Scenario A, Gradual	SSP2 RCP2.6 L	Scenario A Curves	30 Year Lifetime	Core Assumptions	2.1 EJ by 2050
SS2BL	**Scenario B, No Biofuel**	As Scenario B, Early	SSP2 RCP2.6 L	Scenario B Curves	30 Year Lifetime	Core Assumptions	None
SS2BH	**Scenario B, High Biofuel**	As Scenario B, Early	SSP2 RCP2.6 L	Scenario B Curves	30 Year Lifetime	Core Assumptions	2.1 EJ by 2050
SS2CL	**Scenario C, No Biofuel**	As Scenario C, Delayed	SSP2 RCP2.6 L	Scenario C Curves	30 Year Lifetime	Core Assumptions	None
SS2CH	**Scenario C, High Biofuel**	As Scenario C, Delayed	SSP2 RCP2.6 L	Scenario C Curves	30 Year Lifetime	Core Assumptions	2.1 EJ by 2050
SS4A	**Scenario A, High Vessel CAPEX**	As Scenario A, Gradual	SSP2 RCP2.6 L	Scenario SS4A Curves	30 Year Lifetime	Core Assumptions	As Scenario A
C_scrap	**Scenario C, Advanced Scrappage**	As Scenario C, Delayed	SSP2 RCP2.6 L	Scenario C Curves	30 Year Lifetime, scrapped if retrofit needed after 20 Years	Core Assumptions	As Scenario A