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Technological, Operational and Energy Pathways for Maritime Transport to Reduce Emissions Towards 2050

Final report

Report for OGCI/Concawe

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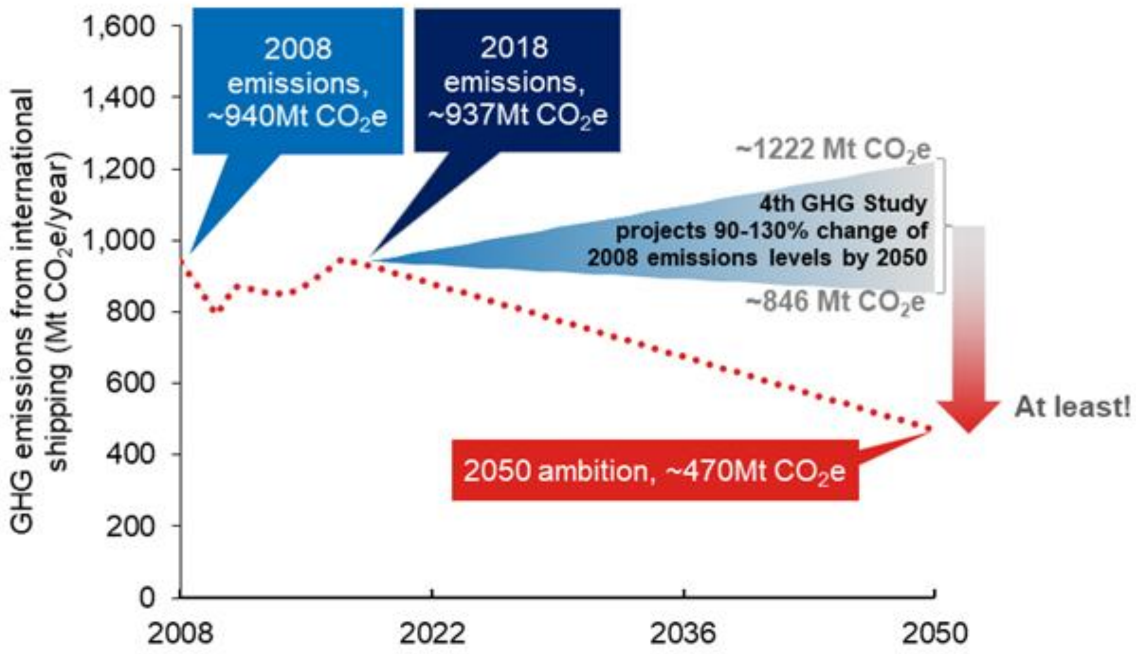
Executive summary

Introduction

This is the final report from a study for OGCI and Concawe on the "Technological, Operational and Energy Pathways for Maritime Transport to Reduce Emissions Towards 2050". The context for this study is the International Maritime Organization's level of ambition to reduce the total carbon emissions from international shipping by 50% in 2050 compared to 2008 levels, as well as reducing the carbon intensity of international shipping by at least 40% by 2030 and 70% by 2050 (again compared to a 2008 base year)[1]. Given the commitments at a country level for the reduction of GHG emissions under the Paris Agreement, and that global GHG emissions from shipping if ranked among countries would be the sixth largest in the world, it is important that work is done to reduce GHG emissions from international shipping that will otherwise not be addressed at a country level.

The IMO's fourth greenhouse gas study, published in 2020, gave their forecasts for the future development of emissions from international maritime transport, under wider global economic scenarios consistent with limiting global temperature rise to less than 2°C.



These projections emphasised the considerable challenges that the industry faces to meet the 2050 ambition.

Context – historic and future trends

Historically, seaborne trade has been closely correlated with world GDP, at least since 1990. World seaborne trade grows approximately in line with world GDP and has more than doubled over the last 20 to 25 years. Therefore with anticipated growth in global GDP, there is a need to decouple international shipping emissions from economic growth.

Population, economic growth and energy access are the key drivers of demand for transport in all modes. Higher economic activity, triggered by an increase in consumption, production, intensification of trade, or a combination of several factors, usually implies an increase in demand for transport. With

[1] It should be noted that the IMO has started to discuss potential tightening of the ambition level, including a possible revision of the ambition in 2023.

continued economic growth, it is expected that there will continue to be strong growth in the demand for the international transport of freight, although different levels of growth in different global regions are likely to lead to changes in the distribution of demand. Overall, the OECD expects global freight demand (measured in tonne-miles) to triple by 2050, relative to 2015 (OECD, 2019). If this is realised, seaborne trade will exceed 120,000 billion tonne-miles by 2050 (double that of today).

There will be changes to the nature of the goods to be transported. Continued global efforts to decarbonise all sectors is expected to lead to a significant reduction in the demand to transport wet and dry bulk fossil fuels (oil and coal); this may be accompanied by an increase in demand for the transport of other goods, including raw materials and finished goods. Economic growth and regionalisation add uncertainty to the projections as they act as opposite forces. Geopolitics is shaping the trade routes; the development of trade is highly dependent on international agreements.

In 2020, the growth in trade has been halted, and even reversed, by the effects of the COVID-19 pandemic. This adds considerable uncertainty to the future, particularly in the short to medium term. In the long term, it is likely that the world will return to a more stable growth pattern, but whether it will recover the previous economic (and hence transport demand) trajectory is far from certain.

Other changes in society will also affect demand: the continued digitalisation of our economies, as well as novel technologies such as 3-D printing, could disrupt the “Asia-production for US and EU consumers” model that emerged over the last decades and promote a shift to regionalisation and/or an overall reduction in demand. The increasing emphasis (particularly in Europe) to try to shift to a more circular economy – where virgin resource use is decreased, and waste streams are re-purposed as products for other industries – could lead to structural changes in the maritime industry, as well as potentially demand for new routes.

The rapid growth in demand over the past 20 years has led to significant changes in the structure of the fleet, with increases in the size of new ships to leverage economies of scale. This has been largely driven by the requirements to reduce fuel costs, as such costs are one of the strongest incentives for operators. This has been particularly evident in the container sector, which has also been supported by a trend of increased containerisation of goods for transport, a trend that is expected to continue. Continued pressure to increase efficiency could lead to changes in transport practices with, for example, better use being made of empty containers returning from western economies to Asia, thus displacing capacity of other vessels such as dry bulk.

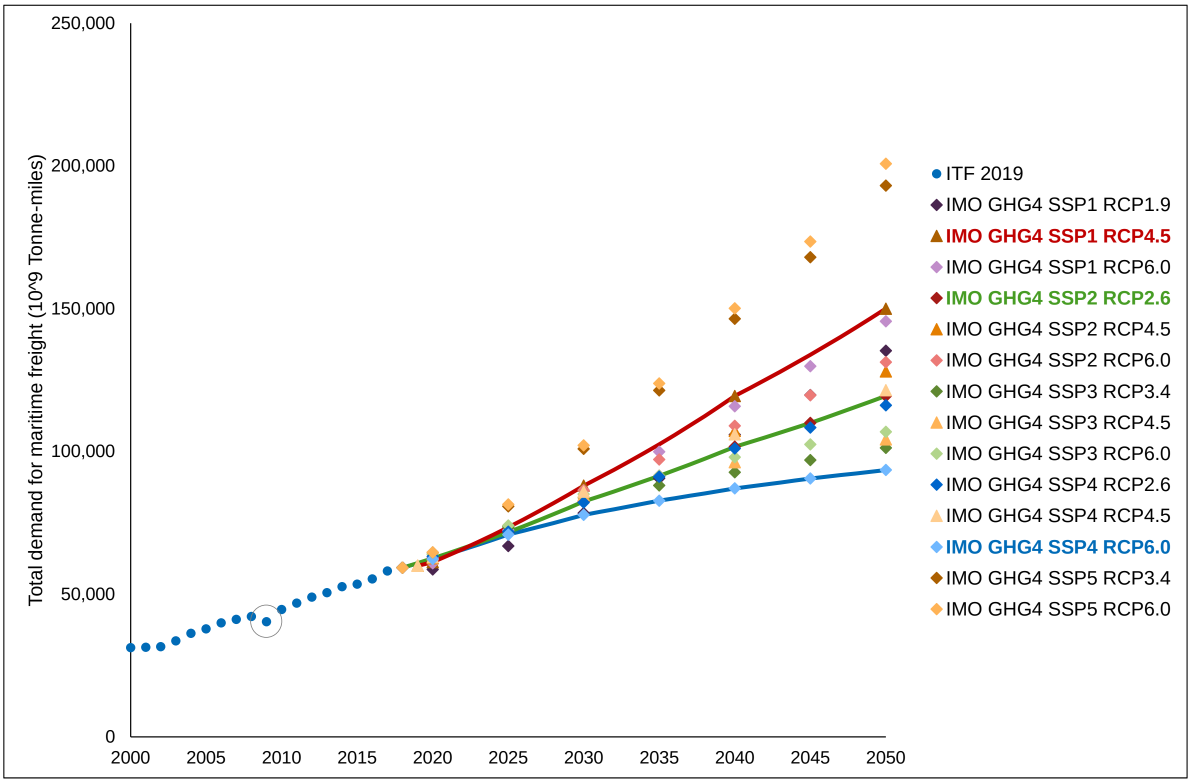
To address the challenges of climate change, all sectors of the economy, including all modes of transport, are under pressure to decarbonise. In aviation (the most comparable mode to maritime shipping in terms of the distances covered per vessel), there are strong commercial incentives for aircraft manufacturers and airlines to continuously improve the fuel efficiency of their aircraft. The International Civil Aviation Organisation has also introduced a CO_2 standard that new aircraft types need to meet from 2020 (and all newly built aircraft will need to meet from 2028). Aircraft have long operating lifetimes (similar to the maritime sector), but the strong economic pressures lead, in many cases, to airlines replacing their fleet more frequently, leading to a more rapid penetration of the latest technology into the operating fleet than is, perhaps, evident in the maritime sector.

The light-duty road transport sector is easier to decarbonise as demands for vehicle range are lower, and vehicles have much shorter lifetimes leading to a more rapid fleet turnover. Heavy duty vehicles, particularly goods vehicles, also have challenges in decarbonising due to the high energy requirements of transporting payloads for the long distances travelled.

There is also pressure on the rail sector to decarbonise. In this case, a significant part of the sector is already electrified, using electricity supplied through the rail infrastructure (e.g. overhead line or third rail), rather than rechargeable batteries. This provides an option that can be extended more widely, although at considerable infrastructure cost, to achieve a greater decarbonisation (depending on the source of the electricity used). Other technologies, such as hydrogen, are also considered by the rail sector to lower its GHG emissions.

Because of the structure of the shipping sector, it is more susceptible to a specific potential barrier to the introduction of new technologies, known as the "split incentive" problem, than other transport sectors. This is because responsibilities such as fuel charges, operational measures, technological investments and cargo loading can be allocated to either ship owners or ship charterers. Whether there is an incentive for a Ship Owner to implement energy efficiency measures is often highly dependent on the charter rate that the charterer pays to the ship owner. If the benefit of the energy efficiency measure is not accrued by the party paying for its implementation, this can act as a barrier to the adoption of the measure when ordering a new ship.

Analyses of different sources of data have shown that global CO_2 emissions from international shipping were about 860 million tonnes in 2019, with a growth rate of over 2% per annum from 2013 to 2018. The three main ship categories for CO_2 emissions were bulk carriers, container ships and tankers. Projections of future demand growth from different sources show considerable variations, ranging from 34% to 185% growth by 2050 (relative to 2018). The different future growth scenarios analysed for this study, are shown in the figure below[2].



If the average carbon intensity of the fleet remains constant over time, these scenarios would lead to emissions in 2050 being between 1.3 and 2.8 times those in 2018 (between 1.2 and 2.5 billion tonnes CO_2 in 2050).

Data published from the EU monitoring, reporting and verification (MRV) programme for 2019 show that the carbon intensity[3] of newly built ships has been reducing by approximately 4.2% per year on average since 1990. This is a higher rate of improvement than is generally considered appropriate for other

[2] The three scenarios were selected as being representative of the lower and upper bounds of those identified (and approximately in the middle), having eliminated those that assume high continued growth in the demand for transporting fossils fuels, as not being consistent with the global focus on climate change.

[3] Carbon intensity defined as CO_2 emissions per unit of work, measured in g/tonne-mile

transport modes (usually closer to 1% to 1.5%) and may reflect a growth in the average size of newly delivered ships over time as well as the introduction of the International Maritime Organization's Energy Efficiency Design Index (EEDI) Phase 1 (2015) and Phase 2 (2020) regulations. However, the literature reviewed and stakeholders interviewed during the course of this study have indicated that the EEDI may not be as effective as previously, with many ships already meeting the Phase 2 regulations; the agreement reached in 2019 to bring Phase 3 of the regulations forward from 2025 to 2022 will further increase the fleet energy efficiency, recognising that improvements to date have been achieved quicker than anticipated. Concerns have been expressed, however, that the unequal targeting of the regulation by different sectors (vessel types) will still limit its effectiveness.

Nonetheless, the improvements in ship efficiency that have been achieved are significant and, if maintained, should enable the IMO's ambition on carbon intensity to be achieved in 2050. However, given the potential for future growth in demand, that would still be insufficient to achieve the IMO's ambition on total CO_2 emissions for 2050.

Stakeholders interviewed for this study have indicated that regulatory intervention or guidance, particularly regarding the adoption of alternative fuels, may be needed to achieve decarbonisation in line with the IMO ambition, unless price parity with conventional fuels can be achieved.

Fuel costs are a key component of vessel operating costs, despite the tendency for the maritime industry to use the lowest cost (fossil) fuel. The COVID-19 pandemic initially led to further price reductions (average prices in May 2020 were nearly 50% lower than the average over the last five years). As a result, the price differential to alternative fuels is further increasing the challenge of achieving competitiveness for alternative fuels. Fuel prices have since rebounded to 2019 levels.

Many operators have implemented reduced vessel speeds to reduce fuel consumption, emissions and costs. Speed reductions are especially effective in reducing fuel consumption when waiting times at ports are converted to a slower cruising speed (just in time arrival) and the cargo carrying capacity of vessels is maximised. Speed reductions of up to 30% have been used, though not for time-sensitive cargos. The use of reduced vessel speeds also requires more ships to be at sea to achieve the same delivery rates, reducing the overall effectiveness of the measure. Nonetheless, it is seen as having overall benefits, which will increase further as new ships are delivered with lower design speeds.

Analyses of ship demolition ages show that for most categories the average retirement age is about 25 years, while for Roll-on-Roll-off (Ro-Ro) ships it is about 35 years. These long lifetimes limit the rate of penetration of new technologies into the operating fleet, so developments such as lower design speeds will take several years to have an effect on the overall fleet efficiency. Some technologies, such as waste heat recovery (WHR) have the potential to be retrofitted to the in-service fleet, thus accelerating the penetration of such technologies. However, these technologies tend to have a smaller impact on the overall fuel efficiency than other technologies that need to be incorporated at the design stage.

Meeting the IMO's 2050 decarbonisation ambition will need significant change in the shipping industry

The IMO's fourth greenhouse gas study, published in 2020, indicated that significant progress has been made, with global emissions in 2018 being almost the same as those in 2008. However, their future projections[4] of emissions from the sector in 2050, of between 90% and 130% of 2008 levels, miss the 2050 ambition by a considerable margin. To achieve the IMO ambition will require the introduction and large scale deployment of new technologies and/or alternative low-carbon fuels across international shipping.

Traditionally, demand for maritime transport is well correlated to global gross domestic product. Although projections for the future development show changes in the nature of goods transported – largely due to decarbonisation efforts in other sectors leading to a reduction in demand for transporting

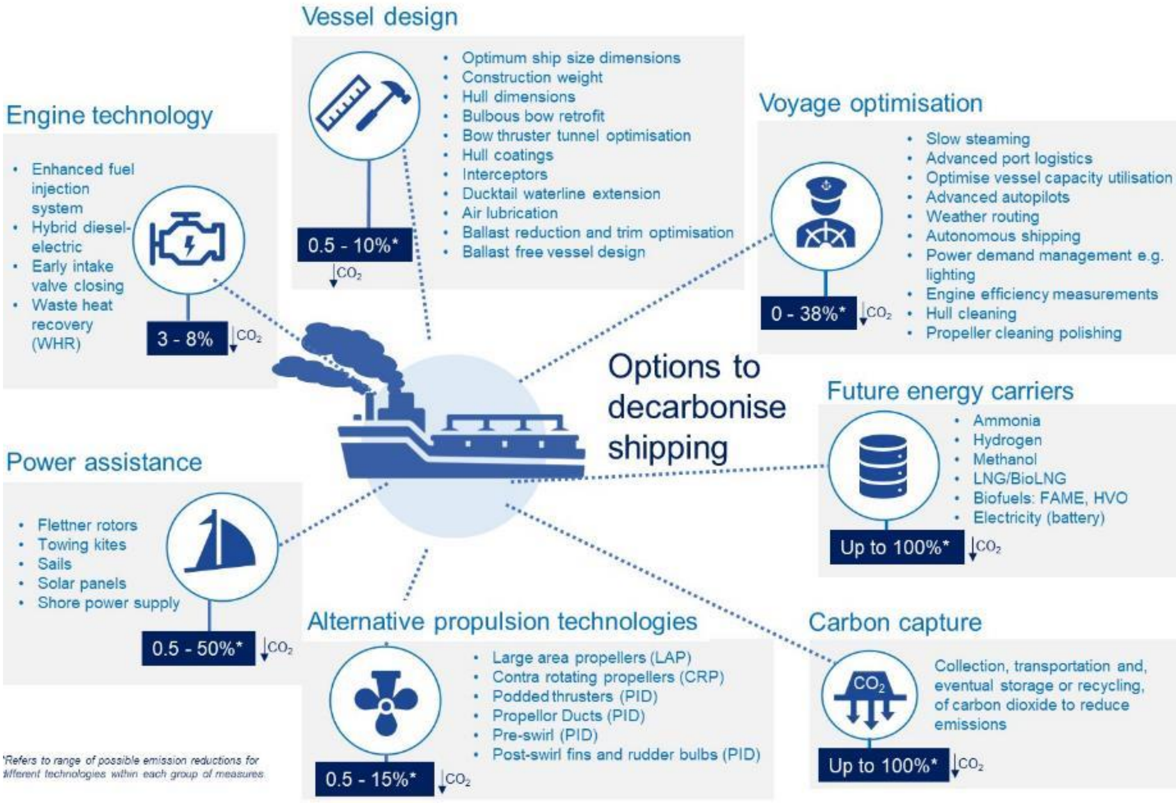
[4] Projections without additional GHG abatement technologies or fuels other than already agreed policies and measures. The projections are principally driven by demand scenarios consistent with achieving a global temperature increase of less than 2°C

oil and coal, but a commensurate increase in demand for transporting raw materials and products – the majority continue to show strong growth in demand. The demand projections in the IMO's fourth greenhouse gas study show demand growth of 58% to 153% by 2050, relative to 2018, depending on the scenario.

Historically, emissions of greenhouse gases from the maritime sector have been dominated by carbon dioxide (CO_2), with three vessel categories (bulk carriers, container ships and tankers) contributing the majority. In recent years, emissions of methane have increased strongly as more vessels using liquefied natural gas (LNG) as fuel have entered service. These methane emissions are largely associated with fugitive emissions from the engines (known as methane slip) and the strong growth has caused concern in the maritime industry. Recent technological developments, such as the use of low-speed and high-pressure diesel-cycle engines now provide significant reductions in methane slip.

Fuels, technologies and operational measures for decarbonising shipping have been selected into three 'packages' depicting possible pathways to reaching the IMO ambition

The study reviewed available literature, and interviewed multiple stakeholders, to identify the technologies and alternative fuels that are available to decarbonise international shipping. The different technologies and fuels are shown in the following figure.



Each of these technologies has been assessed for its applicability (ship categories), availability (entry-into-service dates), carbon reduction potential and cost (capital and operating).

The different alternative fuels and technology options were combined into three “fuels and technology” packages for subsequent analyses of their impacts. The packages were not defined as the “most likely pathways”, but more to exemplify possible pathways, with significant variations to illustrate the range of routes available towards decarbonisation. These packages were characterised as:

- Package 1 ‘early pursuit of zero carbon fuels’
    - Ammonia and hydrogen for some new build vessels from 2025, ramping up to all new-build ships by 2035. Transitioning from “grey” to “blue” to “green” pathways for alternative fuels.
    - Medium take up of energy efficiency technologies and operational measures. 10% speed reduction assumed for slow steaming.
- Package 2 ‘moderate uptake of interim and drop-in fuels’
    - From 2025, HFO, MDO and LNG use increasingly substituted with drop-in biofuels (FAME, HVO and bio-methane (BioLNG)).
    - Medium take up of energy efficiency technologies and operational measures. 20% speed reduction is assumed for slow steaming.
- Package 3 ‘initial maximisation of vessel decarbonisation measures’
    - Focuses on maximising technology use with subsequent transition to alternative fuels.
    - High take up of energy efficiency technologies and operational measures. 30% speed reduction assumed for slow steaming. Onboard carbon capture included in some new vessels (using carbon-containing fuels) post-2030.
    - Ammonia and methanol fuel gradually introduced on new-build vessels by 2035, with LNG being used by the remainder of new vessels. Transitioning from grey to blue to green pathways (and LNG to BioLNG) for alternative fuels.

Grey: Fossil fuel based

Blue: Fossil fuel based with carbon capture

Orange: Combining fossil & Green; fossil & blue; or Bio and fossil

Green: Fully renewable

Further information on the fuels and technologies assigned to the three packages are shown below.

	Package 1	Package 2	Package 3
	Early pursuit of zero-carbon fuels (hydrogen and ammonia), with some limited adoption of new technologies	Moderate uptake of interim and drop-in fuels (LNG, BioLNG, FAME and HVO)	Initial maximisation of vessel decarbonisation measures, with later transition to lower carbon fuels (LNG, BioLNG, methanol, ammonia)
Future energy carriers	• Ammonia • Hydrogen • Electricity (battery)	• LNG/BioLNG • Biofuels: FAME, HVO	• Ammonia • Methanol • LNG/BioLNG
Vessel design	• Form optimisation • Bulbous bow retrofit • Bow thruster tunnel optimisation • Hull coatings • Ballast reduction & trim optimisation	• Form optimisation • Bulbous bow retrofit • Bow thruster tunnel optimisation • Hull coatings • Ballast reduction and trim optimisation	• Form optimisation • Bulbous bow retrofit • Bow thruster tunnel optimisation • Hull coatings • Ballast reduction and trim optimisation • Interceptors • Construction weight • Air lubrication
Power assistance	• Flettner rotors • Sails	• Flettner rotors • Sails	• Flettner rotors • Sails • Towing kites • Solar power
Propulsion technologies	• Large area propellers • Pre-swirl	• Large area propellers • Contra-rotating propellers • Pre-swirl • Podded thrusters • Ducts	• Large area propellers • Contra-rotating propellers • Pre-swirl • Post-swirl • Podded thrusters • Ducts
Engine	• Waste heat recovery		• Carbon capture
Operational	• Speed reduction • Voyage planning & weather routing • Power demand mgmt • Efficiency measurements • Hull cleaning • Propeller cleaning	• Speed reduction • Voyage planning / weather routing • Power demand mgmt • Efficiency measurements • Hull cleaning • Propeller cleaning • Advanced port logistics • Capacity optimisation • Advanced autopilots	• Speed reduction • Voyage planning / weather routing • Power demand mgmt • Efficiency measurements • Hull cleaning • Propeller cleaning • Advanced port logistics • Capacity optimisation • Advanced autopilots [5]

In addition to the packages shown above, a sensitivity analysis was performed in which the alternative fuels assumptions of packages 1 and 2 were combined with the advanced technology assumptions of package 3, forming packages 1A and 2A.

[5] Under package 2, FAME (Fatty Acid Methyl Esters) and HVO (Hydrotreated Vegetable Oils) were selected as examples of drop-in biofuels. Other examples of drop-in fuels are under development, such as alternative conversion pathways based on similar biological feedstocks (such as hydrogenated palm oil (HPO) or hydrothermal liquefaction of biomass) or synthetic fuels (e-fuels). These may provide alternative options for drop-in fuels for the maritime sector in the future. For this report, FAME and HVO were selected as biofuel examples based on their higher level of maturity.

A new model was developed to estimate the impacts that these packages would have on the future fleet, operations, CO_2e emissions and costs

An entirely new bottom-up modelling methodology was developed to assess the impacts that these fuel and technology packages would have on the future fleet, operations, emissions and costs. The modelling methodology started from a definition of the present day fleet and used as input three baseline scenarios (low, central, high) of future demand out to 2050 selected from the IMO's fourth GHG study. The model calculates:

- The future development of the fleet (number of vessels by build year) under each of the baseline scenarios, using a fleet retirement and growth/replacement approach;
- The future development of fuel consumption and emissions under the baseline scenarios, using derived fuel consumption and emissions per unit work (tonne-mile);
- The impacts of the fuel and technology package assumptions on the future fleet efficiency and fuel used (for the different fuel types);
- The impacts of the different types of fuels used on the emissions;
- The impact of the changes in the fleet definition (including the new technologies) on the vessel prices and hence the capital costs;
- The impact of the changes in the fuel consumption on the operating costs.

The overall analysis presented in this report is based on a scenario model, investigating the potential emissions to 2050 under the three scenarios, together with the potential reductions in those emissions arising from the implementation of the sets of technologies and alternative fuels identified. It is important to recognise that these scenarios do not indicate the "most likely" future, nor definitive indications of the costs to achieve particular levels of emissions savings, but indicate what may be achieved under certain assumptions.

The impacts on the capital and operating costs of the fuel production infrastructure were also calculated. Although they are not included in the overall cost calculations, as they would be expected to be amortised through the increased fuel prices, these impacts are of importance to the oil and gas industry, who would be critical in ensuring the availability of the alternative fuels to meet the future demand.

The IMO ambition is estimated to be met by all three packages when emissions are calculated on a well-to-wake basis; however only packages 1 and 3 would meet the ambition on a tank-to-wake basis

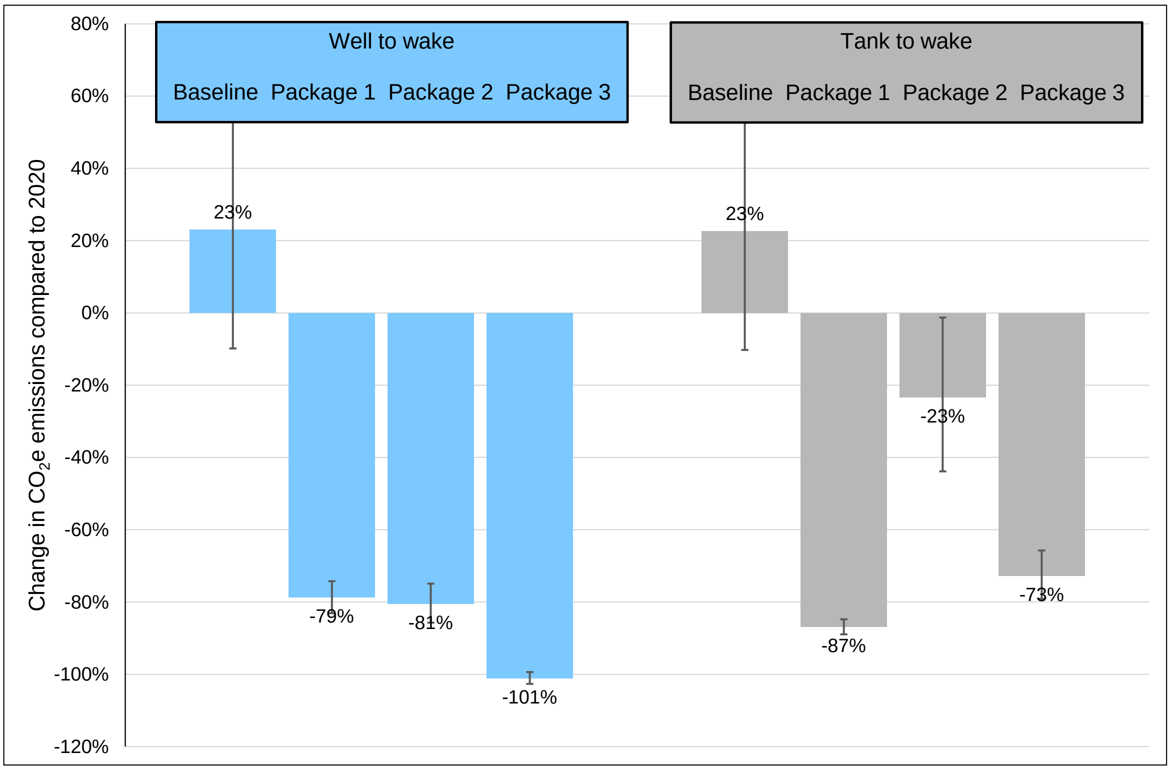
The results of the modelling showed that, by 2050, the emissions under the baseline scenario would be between 4% and 82% higher than in 2008, depending on the demand scenario assumed, compared to the IMO ambition of a 50% reduction (also relative to 2008). These increases in emissions were calculated on a "well-to-wake" (WTW) basis, as this represents the full impact on the global climate and is important when considering the impact of alternative fuels.

Under the three fuel and technology packages, these increases in emissions are replaced by significant decreases in most cases by 2050:

- Under package 1, emissions are reduced by over 70% relative to 2008 under all three demand scenarios, comfortably exceeding the IMO ambition.
- Under package 2, the reductions in emissions are very similar to those under package 1.
- Under package 3, the reductions in emissions relative to 2008 reach approximately 100% under all three demand scenarios. The package includes a transition to "green", but carbon-containing, fuels and the use of on-board carbon capture technology. The combination leads to a net capture of CO_2 over the complete fuel production and combustion process, leading to a net negative emission and a reduction of slightly over 100%. Carbon capture is therefore assumed to be

available in time for this scale of deployment; under the assumptions used in the modelling, for the central scenario, by 2050, approximately 35% of the global fleet is equipped with carbon capture technology. Carbon capture then contributes approximately 16% of the total well-to-wake emissions reductions under this package.

These changes in CO_2e emissions are shown in more detail for 2050 (relative to 2020) in the figure below. Results are shown for both well-to-wake and tank-to-wake emissions, with the results for the central demand scenario shown as coloured bars and the range between the low and high demand scenarios represented by the error bars.



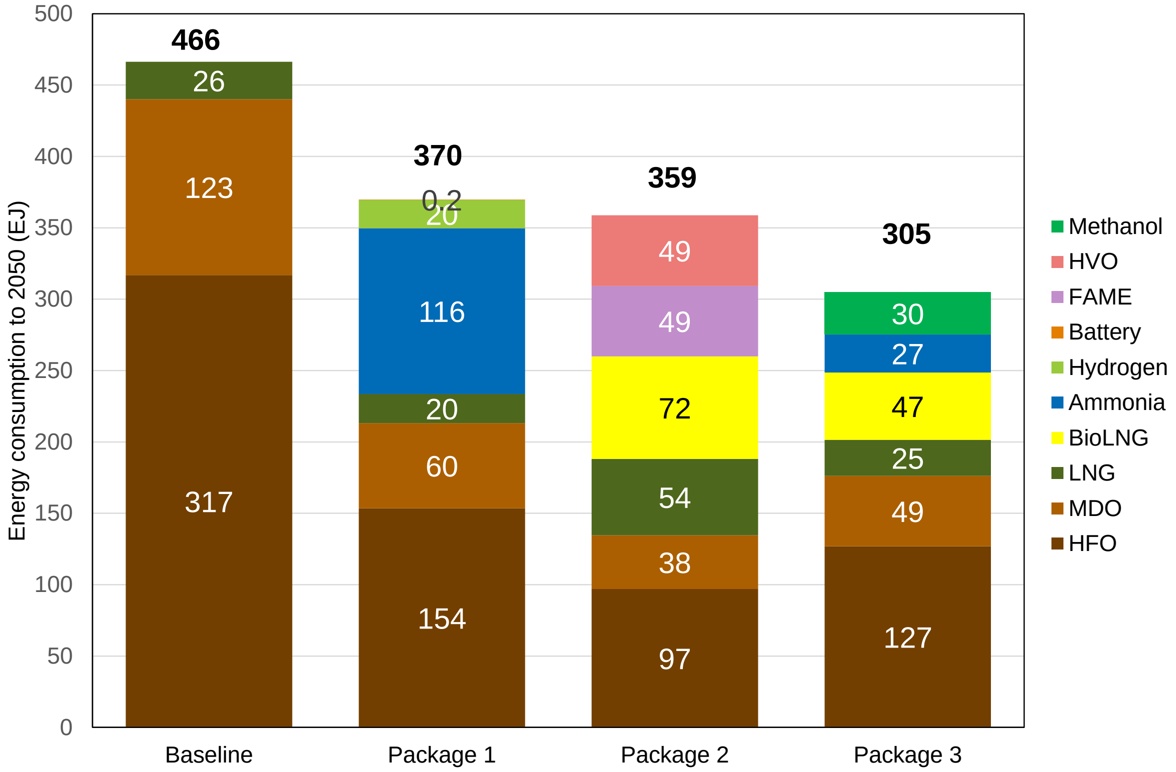
All three packages are estimated to exceed the IMO ambition on maritime decarbonisation by 2050, but this is only assured if the emissions are considered on a well-to-wake basis. The continued use of carbon containing alternative fuels under package 2 still produces significant levels of emissions at the ship exhaust, even though they are offset by zero or negative emissions in the production ("well-to-tank") process. Consideration may need to be given to reformulating the IMO ambition on a well-to-wake basis and incorporating well-to-wake emissions in policy measures to capture the decarbonisation benefits of such alternative fuels and to enable their deployment.

Under package 3, about 16% of the total reduction in emissions to 2050 (relative to the baseline) is due to the use of on-board carbon capture. The relative contributions of vessel technologies, alternative fuels and carbon capture to the emissions reductions achieved under the three packages are shown below.

	Package 1	Package 2	Package 3
Technology	31%	34%	44%
Fuel	69%	66%	40%
Carbon Capture	-	-	16%

The reductions in CO_2e emissions shown above are accompanied by improvements in carbon intensity (CO_2e emissions per unit work, expressed as g/tonne-mile) of between 50% (Package 1) and 65% (Packages 2 and 3) in 2030, relative to 2008, and between 91% (Packages 1 and 2) and 101% (Package 3) in 2050. These changes in carbon intensity are similar across the three demand scenarios.

The cumulative quantities of the different fuels required to 2050 under the three packages to achieve the emissions reductions described are shown below.



The additional costs of implementing the packages are likely to be significant but vary between the packages

The overall costs of implementing the packages described above have been estimated. The total capital investment costs and operating costs to 2050 (both discounted to 2020 at a 10% discount rate) are presented in the next two tables respectively, with the costs separated by the part of the industry affected.

Change in discounted capital costs from baseline ($ billions)	Vessel capital costs	*Alternative fuels production investment*	*Port investment for alternative fuel handling*
Package 1	+$39	*+$386*	*+$8.4*
Package 2	+$34	*+$29*	*$0.0*
Package 3	+$413	*+$79*	*+$0.2*

Change in discounted operating costs from baseline ($ billions)	Vessel fuel costs	Vessel operating costs (exc. fuel)	*Fuel production operating costs*	*Ports fuel infrastructure operating costs*
Package 1	+$113	+$83	*+$51*	*+$79*
Package 2	+$364	+$91	*+$37*	*+$0.5*
Package 3	-$186	-$46	*+$26*	*+$0.7*

In practice, it would be expected that the increased costs for the fuel supply industry (both capital investment and operating costs) would be recovered through the increased fuel prices. Therefore, it is inappropriate to sum the different cost elements in the cost tables above, as that would double-count those costs. As shown in the results in the next sections, the total costs can be summarised as the vessel capital costs, plus the fuel costs and the other vessel operating costs, i.e. excluding those *italicised* above.

The investment costs in vessel fleets and in fuel production infrastructure are of similar magnitudes (though both vary significantly between packages), while those in the ports infrastructure are significantly lower. Under packages 1 and 3, the additional investment in fuel production infrastructure (compared to the baseline) significantly exceeds the increase in vessel fuel costs (and hence the increase in income for the fuel producers). This reflects the need for new production infrastructure for all alternative fuel production, while much of the conventional fuel required in the baseline will be produced by existing infrastructure, so the saving in investment in conventional fuel production infrastructure (under the packages) is comparatively smaller.

There are greater variations in the operating costs, with large positive changes for vessel operating costs under packages 1 and 2, but negative ones under package 3. The increases in fuel production operating costs are of a similar magnitude for all three packages, while the ports infrastructure operating costs are significant for package 1, but much lower for packages 2 and 3.

The results of the emissions analyses indicate that the IMO ambition can be met (and, indeed, surpassed) with a high confidence under the assumptions described – that is to say that if the fuels are switched to as described, there is high confidence on the resulting emissions from using these fuels; there is however naturally a lower level of confidence in the calculated costs. In addition to the uncertainty inherent in the fuel price projections, the actual costs will be sensitive to decisions made in the future (for example, a high uptake of one alternative fuel type could lead to prices for different fuel types significantly different from those assumed for this study, which were based on projections assuming a more balanced marketplace)

The net present value of the accumulated additional total costs on the ships from 2020 to 2050 of packages 1 and 3 are estimated to be less than half those of package 2

The cost analyses show that the achievement of the emissions reductions will increase costs by 4% (package 1), 9% (package 2) and 3% (package 3) over the central baseline scenario, based on total costs to 2050 (using a 10% discount rate). The total additional costs incurred are a combination of vessel capital costs, fuel costs and other vessel operating costs[6]. The fuel price projections used in this

[6] The additional vessel capital costs include the addition of specific technologies but do not change with fuel type. The fuel costs are based on specific pathways for the production – these were selected from a range of options identified as providing high levels of well-to-wake emissions reductions, but they are not necessarily the pathways that would be adopted most widely

study were provided by IHS Markit. The modelling also includes estimates for the additional fuel bunkering costs. Some insight into the additional fuel production infrastructure costs is provided in Section 8 of the report; however, as the additional fuel production costs are expected to be amortised through higher fuel prices, they are not separately included in the results discussed here. These costs are calculated for each of the fuel and technology packages and the baseline; the impacts of the packages are then seen as the difference from the baseline.

These costs are calculated as incurred over the full period from 2020 to 2050; net present values (NPV) are then calculated using a range of discount rates. The results for the central demand scenario using a discount rate of 10% are shown below.

Discounted costs in $ billions	Vessel capital costs	Fuel costs	Other operating costs[7]	Total NPV
Baseline	$52	$1,638	$3,848	$5,539
Package 1	$91	$1,751	$3,932	$5,774
Package 2	$86	$2,002	$3,939	$6,027
Package 3	$465	$1,452	$3,803	$5,720

The total NPV increases under each of the packages relative to the baseline: package 3 is the least expensive and package 2 the most expensive. Packages 1 and 3 produce delta NPV values (from the baseline) of similar magnitudes (and the differences may be within the uncertainty of the calculations). Further insight can be gained by examining the changes in NPV from the baseline for the three packages, again for a discount rate of 10%, shown in the following table.

Change in discounted costs from baseline ($ billions)	Vessel capital costs	Fuel costs	Other operating costs	Total delta NPV
Package 1	+$39	+$113	+$83	+$235
Package 2	+$34	+$364	+$91	+$489
Package 3	+$413	-$186	-$46	+$181

For packages 1 and 2, the additional total costs over the baseline are dominated by the increased fuel costs, while for package 3 vessel capital costs dominate (as expected as it has the highest level of additional vessel technologies applied of the three packages). The high fuel costs under package 2 are primarily related to the use of drop-in fuels, principally BioLNG, FAME and HVO[8]. The investigations under this study identified higher projected fuel prices to 2050 for these fuels than other types.

Combining the calculated emissions reductions and additional costs, with a discount rate of 10% applied to both emission savings and costs, gives cost-effectiveness values in $/tonne$CO_2$e:

[7] Other operating costs include crew costs, stores costs, lubricant costs, maintenance costs, insurance costs and administration costs.

[8] There is a higher level of uncertainty in the price projections for BioLNG as IHS Markit did not provide projections for it consistent with those for the other fuels; therefore, additional information was used when deriving the projection for BioLNG for this study. Further information on the fuel price assumptions, and their contribution to the overall cost calculations, is given in Sections 6.2.1 and 7.3 of the report.

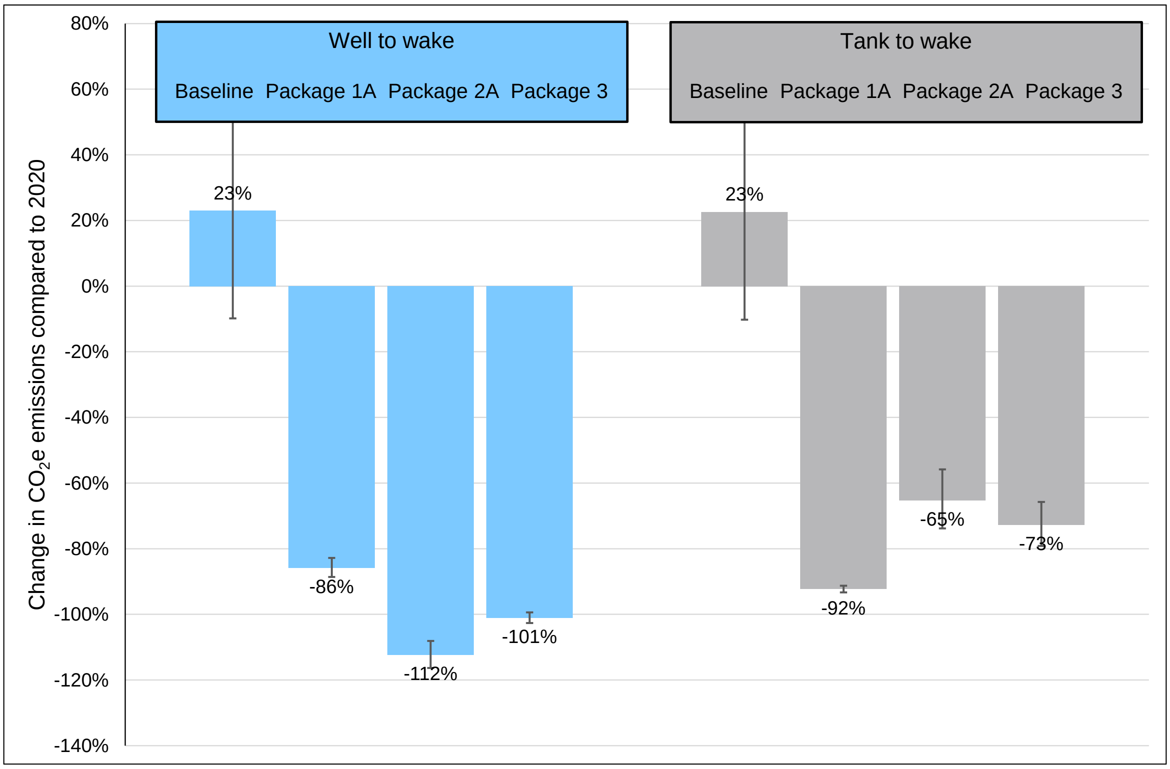
Discounted cost-effectiveness ($/tonne$CO_2$e)	Vessel capital costs	Fuel costs	Other operating costs	Total NPV
Package 1	$12	$35	$26	$73
Package 2	$8	$84	$21	$113
Package 3	$88	-$40	-$10	$39

Package 3 has a slightly lower cost increase over the baseline than Package 1 and has significantly greater emissions savings, leading to a lower cost per tonne CO_2. Both packages have lower (better) cost-effectiveness values than Package 2; as for the cost results presented above, the higher cost per tonne CO_2 for Package 2 is primarily due to the higher fuel costs (noting the uncertainty in the relative and absolute price evolution of alternative fuels).

In general, as in the table above, when presenting cost-effectiveness results, it is conventional to discount the emissions savings at the same rate as the additional costs, to recognise the greater benefits of emissions savings in the short-term. However, there can be interest in viewing the results with the full aggregated emissions savings (i.e. undiscounted). Using such an approach, with the costs discounted (at 10%), but the emissions savings are not discounted, the total NPV values reduce to $13 per tonne CO_2e (package 1), $22 per tonne CO_2e (package 2) and $8 per tonne CO_2e (package 3).

The calculated emissions reductions and costs vary significantly under a sensitivity analysis combining the advanced technology assumptions of package 3 with packages 1 and 2A sensitivity analysis considered cases in which the alternative fuels assumptions of packages 1 and 2 were combined with the technology assumptions of Package 3 (referred to as packages 1A and 2A, respectively).

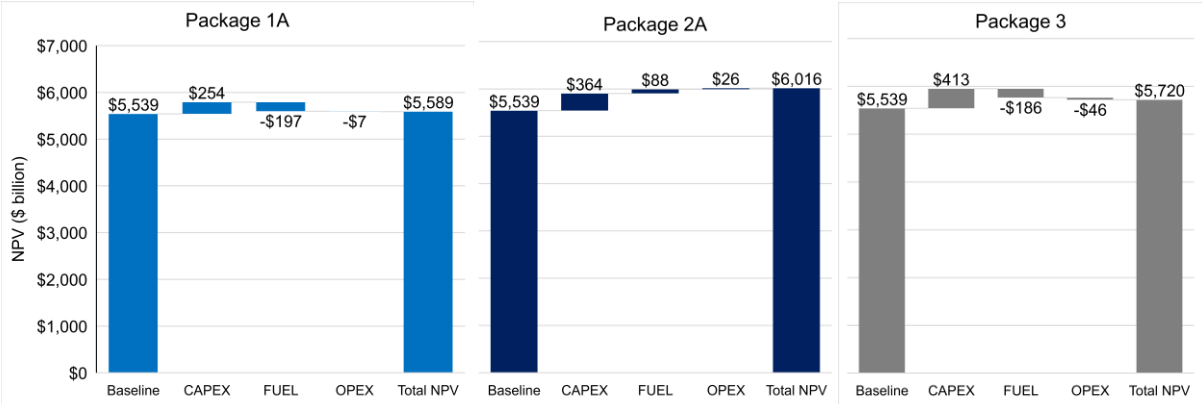
The increased deployment of vessel technologies under packages 1A and 2A (relative to packages 1 and 2) give increased emissions reductions, so that packages 1A, 2A and 3 all meet the IMO ambition on both a tank-to-wake and a well-to-wake basis. These reductions in 2050, relative to 2020, are shown in the figure below.



A significant additional technology that is included in packages 1A and 2A (that is not included in packages 1 and 2) is the use of on-board carbon capture. This has only limited impact on package 1A, as almost all fuel used by new vessels is zero-carbon by 2035 (the technology is assumed not to be incorporated in vessels that use zero-carbon fuels), but it has a significant impact on package 2A. As a result, package 2A has the greatest reduction in emissions of all three on a well-to-wake basis.

The inclusion of the additional vessel technologies in packages 1A and 2A (compared to packages 1 and 2) reduces the energy demand and hence the fuel costs. Under package 1A, this reduction in fuel costs is greater than the increase in vessel costs associated with the additional technologies, leading to overall costs that are significantly lower than under package 1. Under package 2A, however, the increased vessel costs are almost equal to the reduction in fuel costs, leading to a small reduction in total costs compared to package 2. These results assume a 10% discount rate.

The cost stack-ups (shown as net present values of the aggregated costs from 2020 to 2050, using a 10% discount rate, in the figure below) show that package 2A has the greatest increase in costs over the baseline, with the majority being due to vessel capital costs (CAPEX). Package 1A has the smallest increase in total costs, with fuel costs showing a significant reduction relative to the baseline. Package 3 also has a lower fuel cost than the baseline (slightly less than under package 1A), but a greater increase in CAPEX than package 1A, due largely to the greater deployment of on-board carbon capture systems.



The table below shows the overall cost-effectiveness (as $ per tonne CO_2 abated) of the main analysis packages and the sensitivity analysis packages.

	10% discount rate	5% discount rate
Package 1	$73	$120
Package 1A	$11	$47
Package 2	$113	$149
Package 2A	$83	$120
Package 3	$39	$83

The sensitivity analysis packages (packages 1A and 2A) show significantly lower cost per tonne CO_2 abated than packages 1 and 2 in the main analysis with, in particular, very low values for package 1A. This is largely due to a significant negative contribution to the cost per tonne from the fuel costs, arising due to the significant reduction in fuel demand (due to the use of the additional vessel energy efficiency technologies) combined with a moderate increase in fuel price relative to the baseline (primarily due to ammonia fuel). Package 2A also shows a reduction in fuel consumption relative to package 2; however, the costs do not show such a large reduction due to the prices of the alternative fuels used in this package.

Barriers identified to the successful deployment of the fuels and technologies include:

- For all three packages, the production and supply of alternative fuels will need to be substantially increased
- By 2050, between 9 EJ and 12 EJ of alternative fuels will be required per annum, compared to a total fuel demand in 2020 of approximately 14 EJ; the fuel production infrastructure investment needed to achieve this is estimated to be between $66 billion and $436 billion (between 2020

and 2050 under the central demand scenario, combining capital and operating expenditure, using a 10% discount rate)[9]

- The adoption of alternative maritime fuels depends on the availability of the associated infrastructure for their supply to vessels. With the exception of 'drop-in' fuels, associated bunkering infrastructure and port refuelling facilities will need to be scaled up significantly and rapidly. Given the increased number of fuel types included in the future projections, it might be challenging for all ports to offer all fuel types, in particular during transition. Therefore, vessel operators will need to pay attention to the availability of the fuels they require at the locations they need.
- Although engine technology to accommodate alternative fuels (such as ammonia) is already under development by engine manufacturers, this will need to be scaled up once demonstrated. Similarly, the development of fuel cells needs to scale up to the MW capacities needed, if fuel cells rather than engines will power the vessels (e.g. from hydrogen).
- Significant investments will need to be made in the developments of technologies (particularly those associated with the use of alternative fuels). There is currently a lack of certainty regarding the specific fuels (and, perhaps to a lesser extent, technologies) that will be required. The industry needs greater clarity on these issues before committing to such investments.
- The price differential between traditional marine fuels and alternative fuels remains a large barrier to successful deployment of all three packages. While there is a clear desire on the part of stakeholders for the maritime sector to achieve the decarbonisation targets set by the IMO, the increased costs of the alternative fuels are a significant commercial barrier to a widespread uptake. Some regulatory intervention may be required to reduce the price differential and, hence, the commercial disadvantages of changing to the alternative fuels.
- Marine fuels considered in this study that can be produced from fossil fuels or renewable energy (ammonia, hydrogen, methanol), will need to have reliable certification schemes to provide assurance that the chemically-identical fuel is from green sources. Class Rules are yet to be developed by ship classification societies for most alternative fuels.
- Other transport modes, and other sectors, are also attempting to decarbonise in the same timeframe as maritime shipping. Competition for alternative fuels, or feedstocks, may provide additional challenges to the industry in its efforts
- Slow steaming has shown benefits to date in reducing emissions from shipping. However, there is little further benefit to be gained as it is already widely practised and the benefits for an individual vessel on a single voyage are offset by the reduction in productivity and, hence, the increased number of voyages (and, possibly vessels) necessary to meet the demand.

Recommended actions for the supply of alternative fuels:

Taking a lead on refining the choices of alternative fuels. The analysis has shown that a transition away from conventional fuels to alternative fuels will be needed if the maritime sector is to meet the IMO ambition by 2050. However, maritime industry stakeholders have indicated that there is a lack of clarity regarding the "right" or "best" options for such fuels, leading to difficulties in planning for future fleets and investments. The oil and gas industry, in cooperation with the IMO and/or states, should help in developing a roadmap for the future supply of alternative fuels to reach IMO ambitions for the maritime sector. This needs to account for the well-to-wake emissions benefits, and account for the impacts of other greenhouse gases in addition to CO_2, such as N_2O and methane.

[9] The fuel production infrastructure investment required is not included in the cost results presented above; however, as noted, it would be expected that the investment costs would be recovered through the increased fuel prices.

Supporting proof of concept demonstrations. Although all the alternative fuels described in this report are widely considered to be suitable for maritime transport, there has been only limited demonstration of their practicality for long-distance transport with the key vessel categories of bulk carriers, container ships and tankers. The oil and gas industry could support the design of infrastructure for alternative fuel proof of concept demonstrations, to provide confidence that the supply of these fuels can be scaled up to meet the potential future demand. This would also provide assurance to vessel owners regarding future acquisitions of vessels using these fuels. Taking this a step further, oil and gas industry players could work (and have been working) at the vessel level with designers and builders to prove the concepts of working with alternative fuels on board.

Accommodating the increased demand for alternative fuels. This report has shown the scale of future demand for alternative fuels under different scenarios and fuel and technology packages. These have shown that significant scaling up of production and supply of these fuels, including a transition to decarbonised pathways. To ensure the availability of these alternative fuels in the future, investment in new production facilities, and ensuring the availability of the relevant feedstocks, will need to be planned.

Providing "green" certification and fuel sustainability information. The different pathways for the alternative fuels produce chemically-identical products. To provide assurance that an operator is purchasing sustainable fuels will need the introduction systems to certify products and inform the operator. The oil and gas industry could help in developing and implementing such systems as the market for, and supply of, alternative maritime fuels develops.

Supporting a reformulation of the IMO ambition. Benefits of low carbon fuels occur in the production process, giving low or zero well-to-tank emissions. The industry could, through activities in the IMO, support a reformulation of the IMO ambition for 2050 and policy measures to be focused on reductions in well-to-wake emissions, rather than tank-to-wake as at present, to be able to recognise the true carbon intensity of these alternative fuels.

Recommendations for the maritime industry are:

Vessel designers and builders to ensure that the vessels that they design and produce incorporate the best available technology for energy efficiency.

Vessel owners and operators should plan their future investments in new vessels to include the additional costs associated with decarbonisation technologies and low, or zero, carbon fuels. They could consider obtaining "green" finance from banks to support these investments.

Vessel operators could lobby for regulatory changes to support the uptake of alternative fuels. These fuels currently have a significant cost over conventional fuels. Regulatory support for alternative fuels may be needed to reduce the cost differential and ensure that they are commercially competitive against conventional fuels. Support from the industry for such regulatory changes may enable their uptake to be accelerated.

As their fleets transition to alternative fuels, **vessel operators will need to ensure that the relevant fuels are available at the ports at which they need to refuel**. Early discussions with port operators are required to ensure that the necessary fuels infrastructure will be in place as they begin to use the new fuels.

A potentially key technology for maritime decarbonisation (if continuing to use conventional fuels as in package 3) is the use of on-board **carbon capture technology in conjunction with carbon-containing fuels**. The industry should monitor and support the development of this technology to ensure that it can be incorporated in new vessels if the demand arises. The need for carbon capture technology is avoided if a rapid switch to zero carbon fuels is made.

Table of contents

1 Introduction

The Oil and Gas Climate Initiative (OGCI) and Concawe contracted Ricardo to perform a study on the decarbonisation of the global maritime sector. The study comprised two phases:

- Phase 1 – Identify and assess the vessel level technologies and opportunities to reduce maritime greenhouse gas (GHG) emissions by 2050, including the corresponding challenges, through a literature review, analysis of historical data and expert interviews.
- Phase 2 – Assess potential GHG emissions reduction scenarios for the sector using a range of "fuel and technology packages" in different vessel types and applications.

This report presents the final outcomes from the study. The main body of the report presents an introduction and the results and conclusions from Phase 2.

The detailed descriptions of the technologies and alternative fuels considered in the study, as presented to OGCI and Concawe in the Phase 1 report, are given in the appendices.

1.1 Context: the IMO Decarbonisation Ambition

At its 72nd session of the Marine Environment Protection Committee (MEPC), the International Maritime Organization (IMO) adopted its initial strategy on the reduction of GHG emissions from ships as Resolution MEPC.304(72). This set out the IMO's vision of reducing GHG emissions from international shipping, with the aim of phasing them out as soon as possible.

The initial strategy included three levels of ambition:

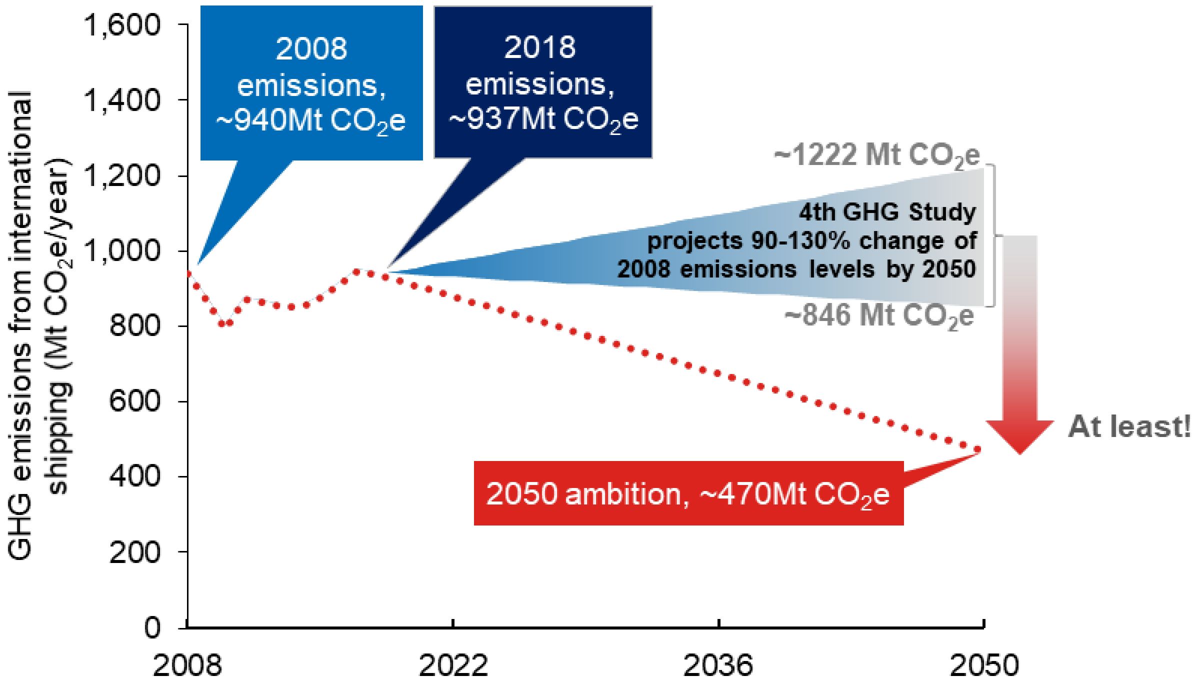
1) Carbon intensity of the ship to decline through implementation of further phases of the energy efficiency design index (EEDI) for new ships;
2) Carbon intensity of international shipping to decline;
3) GHG emissions from international shipping to peak and decline.

Ambition (1) noted that the further phases of the EEDI for new ships would involve percentage reductions in the limit values for each phase to be determined by ship type. Ambition (2) specified that (fleet average) CO_2 emissions per transport work (i.e. per tonne-mile or equivalent) should be reduced by at least 40% (relative to 2008) by 2030, with the pursuit of reductions of 70% by 2050. Ambition (3) included the aim to peak (total) GHG emissions from international shipping as soon as possible and to reduce the total emissions by 50% (relative to 2008) by 2050, while continuing to pursue efforts to phase them out.

Importantly, while the strategy targets reductions in GHG emissions from international shipping, it remains largely fuel and technology-neutral as to how they should be achieved. This study is rooted in the context of how the IMO's decarbonisation ambition might be achieved in terms of technologies, operation measures and energy pathways, and what the implications may be for the sector.

The IMO resolution identified potential emissions growth (in the absence of further action) to 2050, based on the results presented in the third IMO GHG study (2014). Since then, the IMO has published its fourth GHG study (International Maritime Organization, 2020), which provides an update on historic emissions and forecasts of future emissions growth. These are summarised in Figure 1-1.

Figure 1-1: CO_2e emissions from international shipping from 2008 to 2018 and projections to 2050 under scenarios consistent with a 2°C global temperature rise



Source: Ricardo analysis of results presented in the IMO 4th GHG study for vessel-based allocation of emissions of CO_2, CH_4 and N_2O.

These latest estimates are projecting emissions in 2050 to be between 90% and 130% of the emissions in 2008. This result was obtained using projections for economic activity and (non-shipping sector) decarbonisation efforts consistent with a 2°C global temperature rise over pre-industrial levels. The report also includes results for other scenarios that are consistent with different impacts on temperature rise, ranging from 1.5°C to 2.8°C (referred to as reference concentration pathways (RCP) 1.9 and 6.0; Figure 1-1 uses data for RCP2.6). For the analyses presented later in this report, the scenarios selected were based on the full range presented in the IMO report, not just those represented in Figure 1-1.

1.2 Report structure

This report is structured as follows:

- Section 2 provides an overview of the development of the demand for maritime transport and the drivers of that demand.
- Section 3 describes key metrics associated with maritime transport, including the environmental footprint (carbon dioxide and other pollutants), carbon intensity and costs. It also provides an overview of the current regulatory situation.
- Section 4 presents the different alternative fuels, vessel technologies and operational measures identified to decarbonise maritime transport.
- Section 5 presents the collation of the alternative fuel options and technologies into three “fuel and technologies” packages for assessment of their costs and benefits.
- Section 6 describes the methodology developed to assess the impacts of the fuel and technology packages on future emissions and costs.
- Section 7 presents the results of the emissions and cost modelling, including the overall cost-effectiveness of the three packages.
- Section 8 discusses the risks associated with achieving the targeted decarbonisation and the investments that will be required by both the oil and gas industry and the maritime industry.
- Sections 9 and 10 discuss the implications of the results of the analyses for the oil and gas industry and the maritime industry.
- Section 11 presents an analysis of the regional aspects of the outcomes of the study.
- Section 12 then completes the study with conclusions and recommendations.

Additional details of the analyses are provided in the appendices.

2 Maritime transport market overview

Key points:

- Ships carry 80-90% of international goods by weight or distance, and 60-70% by value.
- Demand for maritime transport is closely tied to economic development, and is expected – despite a short term shock due to the COVID-19 pandemic – to continue with significant growth to 2050 at annual average growth rates of 3 to 3.5% (both freight and passenger)
- Economic growth is not expected to be uniform geographically nor across shipping subsectors. Trends in energy resource demand, shifts in economically growing regions to service based economies, containerisation and geopolitical factors will all influence maritime transport demand.
- Technological trends are also affecting maritime transport demand by improving end-to-end efficiency. Ship fuel efficiency gains reduce fuel costs; economies of scale reduce costs; and digitalisation optimises operations as well as enabling new business models.
- Regulation is seen as the main way to advance the decarbonisation of shipping in the short and medium term, until new solutions become economically attractive.
- Split incentives, where ship owners responsible for ship energy efficiency do not pay for fuel when the ship is chartered, are a barrier to reducing GHG emissions in many maritime segments.
- Other transport sectors are also under pressure to decarbonise and are taking steps to do so. Competition for fuels between modes could affect the decarbonisation of the maritime sector.

2.1 Evolution of transport demand

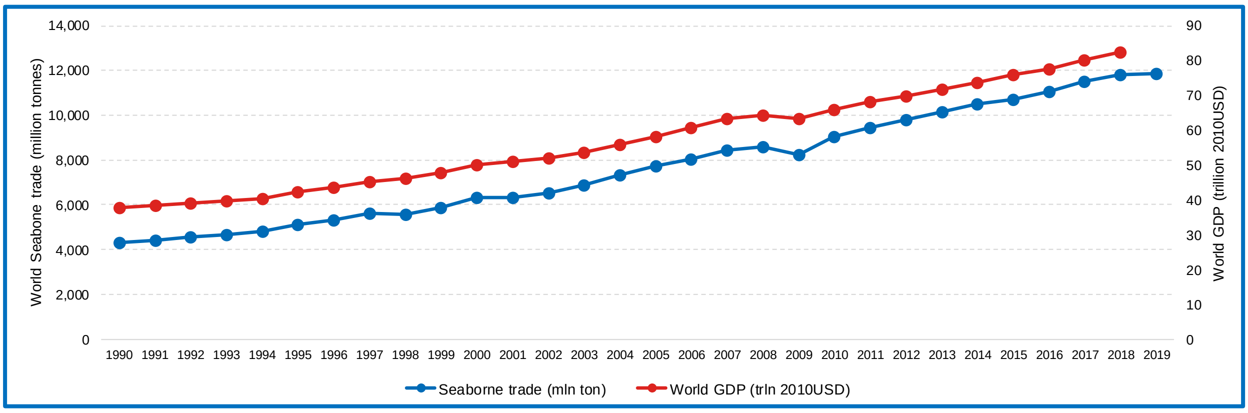
Shipping carries the vast majority of international trade, with its share ranging between 80% and 90% of total trade[10] in terms of both tonne-miles transported (OECD, 2019) and weight of transported goods (United Nations Conference on Trade and Development, 2018). In terms of trade value, the shipping share is considerably lower with various estimates being around 60% to 70% of trade, as higher value cargo is often transported by air. The predominance of sea transport is particularly pronounced in developing countries, where trade structures and volumes of intraregional trade give a smaller role to land transport.

Regardless of the mode considered, higher economic activity, triggered by an increase in consumption, production, intensification of trade, or a combination of several factors, usually implies an increase in demand for transportation (OECD, 2019). Population growth, economic growth and their geographical distribution are key determinants of the structure and distribution of demand by mode and geography.

Figure 2-1 shows the historic data on seaborne trade and world gross domestic product (GDP) being highly correlated. Historically, world GDP doubles approximately every 25 years, while seaborne trade has been increasing at a faster rate – around 2.5 times every 25 years.

[10] Contribution of maritime transport to international trade compared to other modes is discussed in more detail in Section 2.3.

Figure 2-1: Correlation between world GDP and seaborne trade



Source: World Bank (World GDP), Clarksons Research (seaborne trade)

OECD projects both passenger and freight demand to triple in the period between 2015 and 2050 as well as change its regional distribution. With this growth rate, seaborne trade would increase from approximately 11,800 million tonnes in 2019 to almost 30,000 million tonnes in 2050. Asia is expected to increase its demand significantly, and to increase its capacity to be able to accommodate this increasing demand. Sea transport is projected to remain the main mode for freight (Table 2-1).

Projecting transport demand requires a deep understanding of economic growth and international activity patterns; increased protectionism or a global economic downturn would have an important impact on demand for transport. This is especially true for maritime transport, being highly dependent on the international trade intensity, more than other transport modes. The OECD (2019) notes that the future of the maritime freight sector depends in particular on international trade agreements, the development of transcontinental inland routes, changes in global energy use and e-commerce growth.

Table 2-1: OECD projected growth rates of transport demand (global compound annual growth rate of tonne-miles in %)

Transport demand	Share in 2015	2015-30	2015-50
Sea	**70%**	**3.0**	**3.6**
Road	18%	3.5	3.2
Rail	9%	2.7	2.5
Inland waterways	2%	3.4	3.8
Aviation	1%	5.5	4.5
Passenger transport (pas-miles)	-	4.3	3.4
Freight transport (tonne-miles)	-	3.1	3.4

Source: OECD, ITF Transport Outlook 2019

The long-term impacts of the response to the COVID-19 pandemic on maritime transport remain highly uncertain. While it is clear that the demand for transport decreased significantly in 2020 relative to 2019, over 4% according to UNCTAD[11], it is still not fully clear what shape the recovery will take. As the experience of the financial crisis a decade ago shows (see the figure above), seaborne trade returned to its pre-crisis path one year after the negative shock in 2009, while the economic growth has been recovering at a slower speed. UNCTAD also anticipates that the global maritime trade may recover in 2021 and show growth of 4.8%.

[11] https://unctad.org/news/covid-19-cuts-global-maritime-trade-transforms-industry

2.2 Maritime transport market drivers

Economic growth is the basis for demand for trade, regardless of the type of goods transported. As economies grow, existing routes accommodate higher volumes of transport and new sea routes may emerge, reflecting changes in trade patterns for deep sea, short sea and coastal shipping.

There are, however, multiple levels of the relationship between economic activity and trade. In addition to the economic growth and total transport demand relationship on a macro level, the structure of economic growth shapes the structure of transport demand in terms of cargo type.

2.2.1 Markets, policies and geopolitics

Energy trends

Although almost all modes of transport currently rely heavily on oil and gas products as fuels, maritime transport is also strongly related to the oil and gas industry, through the transport of resources. More than 30% of wet bulk cargo transported currently is crude oil, oil products or natural gas[12]. Further, a significant part of the dry bulk cargo transported consists of coal.

As the result of new policies in energy and environment implemented across the globe, the share of fossil fuels in the overall primary energy mix is expected to decline in coming years. IEA's World Energy Outlook projects oil demand decreasing by a third and coal demand by two thirds by 2030 in their Sustainable Development Scenario[13], which will lead to a reduction in demand for coal bulk carriers and oil tankers in the medium to long term. Oil price reductions, however, might contribute to an initial increase or softer decrease in oil trade before entering long-term decline.

The demand for liquefied natural gas (LNG) as a fuel on land, and hence its transport by sea, has been increasing recently and is expected to continue to increase in the medium term, although there is much uncertainty associated with the level of activity and significant differences across regions. On the supply side, natural gas trade has emerged in new locations due to the recent evolution of costs and shale gas production, and it is expected that gas flows will change significantly in the future. Overall, ship operators expect that LNG business will show continuing growth over the next 20 years.

For all energy products, significant variations in shipping demand may arise due to geographical redistribution of routes in medium to long term.

Economic growth trends

Global minor bulk trade (e.g. steel products, sugars, cement) will continue to reflect basic production activity, including production of metals, steel, wood and other materials. Demand for bulk carriers for agricultural products will likely continue following growth patterns of population and output per capita of well established and emerging grain-importing regions.

Global non-coal bulk volume has been dominated by growth in China, where the trend in recent years indicates a slower industrial production growth and a gradual shift towards a more service-oriented and consumption-driven economy. These trends would translate to lower demand growth for non-coal bulk carriers. Ship operators have noted that demand to carry iron ore/coal to Asia is decreasing, but this may be offset by growing demand from developing countries.

In the container segment, the relationship between seaborne trade and GDP has been gradually weakening in recent years (DNV GL, 2017). Ship operators recognise that demand would be impacted by moves toward local production, especially for roll-on-roll-off (RoRo) ships.

Containerisation of trade continues to develop into new areas. As well as increasing container trade, it may also reduce other cargo trades. For example, food importers in Asia are switching from dry bulk

[12] UNCTAD (2019), Clarksons Research data

[13] Oil and coal demand by region and scenario, 2018-2040 https://www.iea.org/reports/world-energy-outlook-2019/oil#abstract

carriers to container vessels, filling empty containers after unloading consumer goods in Western countries. With all these developments, container trade is expected to continue to grow in the near term. Lloyds projects container trade to increase at 4.6% per annum for the next 5 years (Lloyd's List, 2019).

Geopolitical factors

UNCTAD projects that maritime freight volumes will be conditioned by the development of international trade agreements. The Economic Partnership Agreement between the European Union and Japan as well as the Comprehensive Economic and Trade Agreement between the EU and Canada will likely lead to further increases in trade volumes. Changing global value chains in rapidly developing economies such as China and India will also determine how freight flows evolve.

Significant trade volumes between big actors – such as China and India on one side, and Russia and Central Asia countries on the other – may flow via other modes, such as rail and pipelines, as an alternative to seaborne transportation. Large infrastructure-development projects, such as China's One Belt and One Road initiative and the Japan-Asian Development Bank partnership, will stimulate growth and demand for seaborne transport (United Nations Conference on Trade and Development, 2016).

For the energy segment, geopolitics is key for trade patterns: North America is already, and is expected to remain, a major global LNG exporter, while developments in Australia are likely to play a key role in providing LNG to the Asian countries. In addition, new projects such as Yamal in Russia, Malaysia and Cameroon will also influence the future global trade of LNG.

The geopolitical situation in the Middle East will determine the development for oil tanker owners. The evolving strategy of the Organization of Petroleum Exporting Countries on production will determine crude oil shipping in the short to medium term. Stability in Iran, Iraq, Saudi Arabia, and neighbouring countries is also considered important for the oil sector.

2.2.2 Technological factors

Many studies assume a significant improvement in transportation fuel efficiency worldwide over the next few years, partially due to technological improvements and partially due to reductions in navigation speed. Ship operators note that since 2008, the significant reduction in ships' navigation speed has led to a general reduction in engine power output (for a given vessel size) in newer vessels. Innovative ship concepts may also emerge to create a leap forward in performance. Examples include ballast-free ships, and low- and zero-emission hybrid ships, incorporating various advances such as innovative light materials, alternative powering, and energy-storage modules. These are the subject of later sections of this report.

On the other hand, ship size is increasing, driven by economics of shipping, especially for container vessels, now available for 20,000+ twenty-foot equivalent units (TEU) and ore carriers (e.g. Valemax). The impacts of increasing vessel size, the expansion of the Panama Canal, and the emergence of mega alliances could also lead to improved fleet capacity utilisation.

Digitalisation can reduce the cost of shipping, while improving safety. It is set to enable reduced downtime, predictive maintenance, performance forecasting, real-time risk management, and energy efficiency. Operators will generate cost savings through advanced data analytics, process digitalisation, robotic process automation, and connecting and sensing technology (DNV GL, 2014b). Improvements in logistics and operations, as well as optimal weather routing, also contribute to reductions in fuel costs.

Indirectly, digitalisation can enable new business models and better ship operation, with a positive impact on energy use. Autonomous ships could sail at very low speeds without incurring high crew costs, allowing greater use of batteries and other fuel types (DNV GL, 2014b).

2.2.3 Regulatory factors

The industry players and port authorities consulted during this study agree that regulation is the main force that is likely to advance the decarbonisation agenda for shipping in the short and medium term.

The role of investment in research and development (R&D) is key in this process to inform regulatory effort or accelerate technological maturity and cost reductions.

Regulation is seen as the main driver of decarbonisation now, and is expected to stay in this role in the near future, as operators react to economic incentives. R&D expenditures are viewed as enablers for development and implementation of novel technologies and are helpful to inform policy decisions.

Other potential regulatory mechanisms, such as market-based measures or voluntary agreements are also considered to be important to encourage fuel efficiency and potentially the uptake of cleaner fuels. The effectiveness of these instruments, however, will need to be carefully assessed against social and economic costs as well as benefits.

2.3 Split incentives

The structure of the shipping sector makes it more susceptible than other transport sectors to introducing new technology, known as the ‘split incentive’ problem.

Currently, some seemingly cost-effective carbon reduction measures (including the use of technologies and alternative fuels) are not implemented to the scale expected. The difference between the higher implementation level appearing to be cost-effective from the consumers or firms’ point of view and techno-economic analysis, and the actual/observed lower implementation levels of cost-effective measures, is known as the ‘energy efficiency gap’ (Jaffe et al, 1994). One such barrier causing this gap has been recognised as the ‘principal agent’ or ‘split-incentive’ problem. Split incentives refer to any situation where the benefits of a transaction do not accrue to the actor who pays for the transaction. For example, in the context of energy efficiency, this can occur when the party paying for the investment in the efficiency measure, is not the direct beneficiary of the financial gains of that implemented measure, i.e. fuel cost savings (European Commission, 2013).

Table 2-2: Cost allocations in the shipping sector

Cost element	Voyage Charter ($/tonne)	Time Charter ($/day)
Cargo handling	Charterer	Charterer
Voyage Expenses	Ship Owner	Charterer
Operating Expenses	Ship Owner	Ship Owner
Capital Costs	Ship Owner	Ship Owner

Adapted from (Rehmatulla et al, 2015)

For the shipping sector the specific structure of the market means it is particularly susceptible to this challenge (Rehmatulla et al, 2015). The reason why the shipping sector is more susceptible to this problem than other transport sectors is because of cost allocations, see Table 2-2. In the shipping sector, responsibilities such as fuel charges, operational measures, technological investments and cargo loading can be allocated to Ship Owners or Ship Charterers. Chartered ships can constitute a significant portion of the global vessels in operation. For example, over 60% of ships operated by “leading container ship operators” are chartered (Statista, 2020). In this way there is an asymmetry between the Ship Owner and Ship Charterer financial gains.

These split incentive barriers have been investigated in the building & manufacturing industry. Third-party financing models from the built environment could be adapted for the shipping industry to enable significant capital costs to the Ship Owner or Ship Charterer to be overcome. The key to these financing mechanisms is that they incorporate measurement and verification technology into the financial package (Stulgis et al, 2014).

Further analysis on the split incentive problem in the context of the shipping sector can be found in Appendix A.1.

2.4 Comparison with other transport sectors

As noted in section 2.1, maritime transport meets the majority of global demand for freight transport. Based on data from OECD and the International Civil Aviation Organisation (ICAO), maritime transport meets approximately 81% of global demand for freight transport (in tonne-miles), with road and rail providing approximately 12% and 7% respectively and aviation an almost negligible 0.16% of demand ((OECD, 2019) and (International Civil Aviation Organisation, 2019)). These fractions have not changed in the recent years despite the overall increase in global freight demand.

Although there is a dominant position for maritime transport in meeting the demand for moving freight, there are other aspects to consider. Much of maritime freight transport is over very long distances, while road and rail transport tend to be over much shorter distances. The delivery of the freight carried by maritime shipping also frequently depends on road or rail (or inland waterway shipping) to reach its final destination. Although the quantity of freight transported by air is a very small part of the total demand, the products that are transported tend to be of higher value than those transported by other modes, so the percentage of the total value of goods transported by air is much higher.

While the dominance of long-distance transport by sea (when measured by volume of goods transported) provides the potential for significant global savings in emissions as the industry decarbonises, it is already relatively efficient and the associated low costs of transport provide additional challenges in achieving decarbonisation without significantly increasing transport costs.

Other transport sectors are also under pressure to decarbonise and are taking steps to do so. As well as continuing strong efforts to improve the efficiency of aircraft (largely driven by economics, but also with additional impetus from a new regulation on the fuel efficiency of new aircraft[14]), ICAO has implemented the Carbon Offsetting and Reduction Scheme for International Aviation[15] (CORSIA), which is intended to keep net emissions from international aviation at or below 2019 levels. Aviation may prove more challenging to decarbonise, given the need for high energy densities by both mass and volume (related to aircraft mass and aerodynamic drag) and the requirement for certification of fuels from a safety perspective. If countries or regions implement mandates on minimum blends of sustainable aviation fuels (SAF), as has been suggested, this could lead to a prioritisation of particular fuels and pathways for aviation use.

The light duty vehicle road transport sector is much easier to decarbonise. At least for individual passenger transport (i.e. cars) the vehicles have much shorter lifetimes leading to a more rapid fleet turnover. Further, most road transport is owned and operated primarily within an individual country, increasing the role that national regulation can play. Heavy duty vehicles, particularly goods vehicles, also have challenges in decarbonising due to the increased energy requirements of transporting payloads for the long distances travelled; most of the current (short-term) focus is on the use of bio-diesel for such vehicles, although there has also been significant progress in using LNG as a fuel for long distance heavy goods vehicles, with, for example, about 11,000 LNG-fuelled trucks and over 300 public LNG refuelling stations already in use in Europe[16]. There is also considerable interest in hydrogen as a zero-emissions future fuel.

Similarly to the other transport modes, there is also pressure on the rail sector to decarbonise. In this case, a significant part of the sector is already electrified, using electricity supplied through the rail infrastructure (e.g. overhead line or third rail), rather than recharging batteries. This provides an option that can be extended more widely, although at considerable infrastructure cost, to achieve a greater decarbonisation (depending on the source of the electricity used).Other technologies, such as hydrogen, are also considered by the rail sector to lower its GHG emissions.

[14] https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2016/ENVReport2016_pg112-114.pdf

[15] https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx

[16] https://www.ngva.eu/medias/the-necessary-rise-of-lng/

In summary, the demand to decarbonise other transport sectors will also affect the decarbonisation of the maritime sector, in particular for cases where alternative fuel demands overlap, such as demand for LNG from the road transport sector and demand for feedstocks for drop-in fuels for aviation, which could lead to challenges in meeting the demand for alternative fuels from the maritime transport sector. Cross-sectoral benefits could accrue however through the development of technology in one sector leading to cost reductions for another (e.g. battery development driven by the road vehicle sector increasing opportunities for small battery powered vessels).

3 Historic maritime metrics

This section presents the historic development of maritime metrics such as environmental footprint and carbon intensity of the fleet.

Key points:

- The fourth IMO greenhouse gas study identifies that total emissions in 2050 are expected to lie between 90% and 130% of 2008 levels
- Over 75% of global emissions are produced by three vessel categories: bulk carriers, container ships and tankers
- Illustrative examples of total annual vessel costs, including capital, operating and voyage costs, have been estimated for these three key vessel types. Voyage costs were found to make up 60%-70% of total costs. Because fuel costs form the largest component of voyage costs, total costs are sensitive to (volatile) fuel prices.
- Existing IMO level regulatory measures to decrease GHG emissions include the Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SEEMP), mandatory Fuel Oil Data Collection System (DCS) and the Energy Efficiency Operational Indicator (EEOI).
- Upcoming measures include Energy Efficiency Existing Ship Index (EEXI), and the establishment of a Carbon Intensity Indicator (CII), both of which will likely enter into force in 2023 following adoption at MEPC 76 in June 2021.
- Port area regulations and voluntary incentive schemes can also be useful drivers in decarbonising the shipping sector

This section presents the historic development of maritime metrics such as environmental footprint and carbon intensity of the fleet.

3.1 Environmental footprint

Carbon dioxide

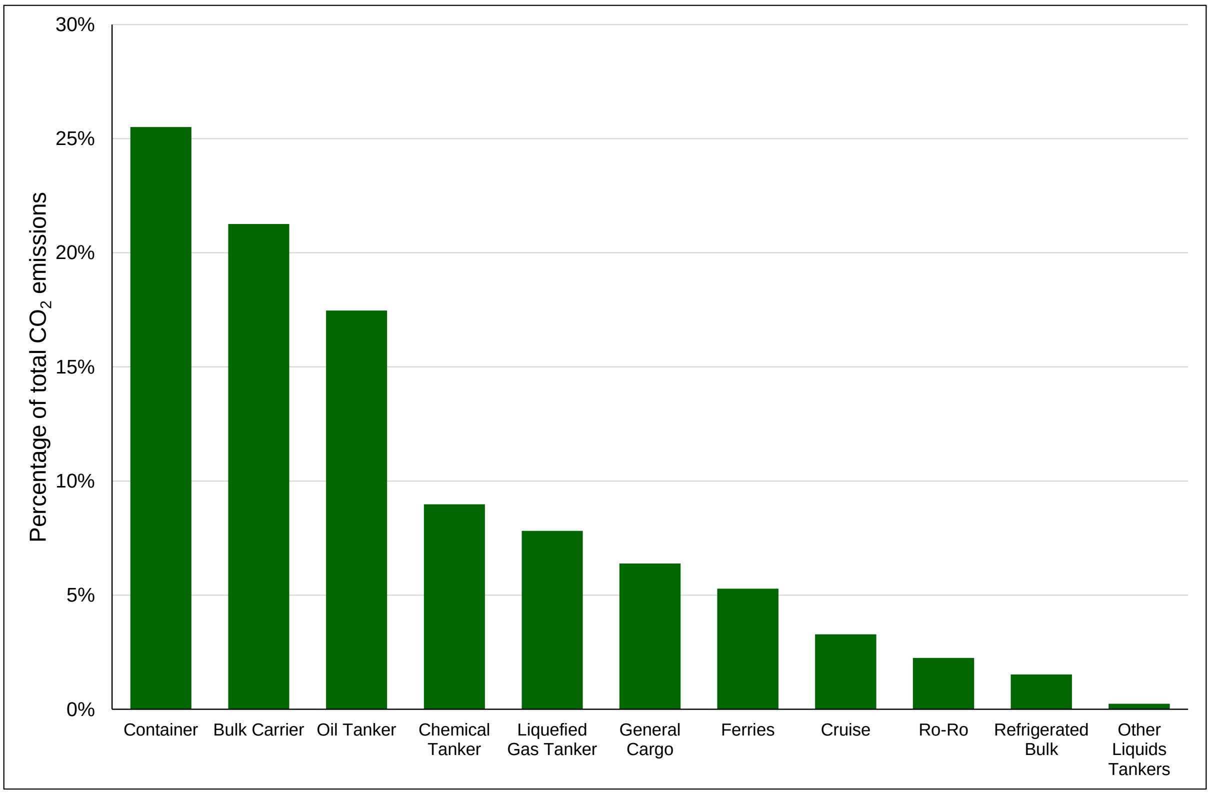
CO_2 remains the most important greenhouse gas to account for from maritime transport. The fourth IMO GHG study (International Maritime Organization, 2020) includes two methodologies for estimating emissions from shipping[17]. Its voyage-based allocation method estimates that international shipping produced 740 million tonnes of CO_2 (or 755 million tonnes CO_2e) in 2018, which is about 2% of global total emissions. Its vessel-based allocation method estimates that international shipping produced almost 920 million tonnes of CO_2 (or almost 940 million tonnes CO_2e) in 2018, representing about 2.5% of total man-made emissions in that year.

The report also estimated that by 2050, emissions are projected to be between 90% and 130% of the levels in 2008 under different scenarios that are consistent with a 2°C global temperature rise. This growth, set against the vessel-based allocation estimates, was shown in Figure 1-1 for context against the IMO decarbonisation ambition.

[17] The third IMO GHG study used a calculation of CO_2 emissions from shipping based on the vessel type and size, with assumed allocations of vessel categories (combinations of types and sizes) to either domestic or international operations. The calculation of emissions then assumed that all vessels within a category operated similarly. The fourth GHG study introduced a new approach, using automatic identification system (AIS) data to identify port calls and, hence, identify individual voyages as either domestic or international. The two approaches have been termed "vessel-based" and "voyage-based", respectively.

Further insight into the distribution of the emissions between the different elements of the maritime transport sector can be obtained from the fourth IMO GHG study. Figure 3-1 shows the percentage of the total emissions emitted by different ship categories in 2018.

Figure 3-1: Percentage of total CO_2 emitted by different ship categories in 2018



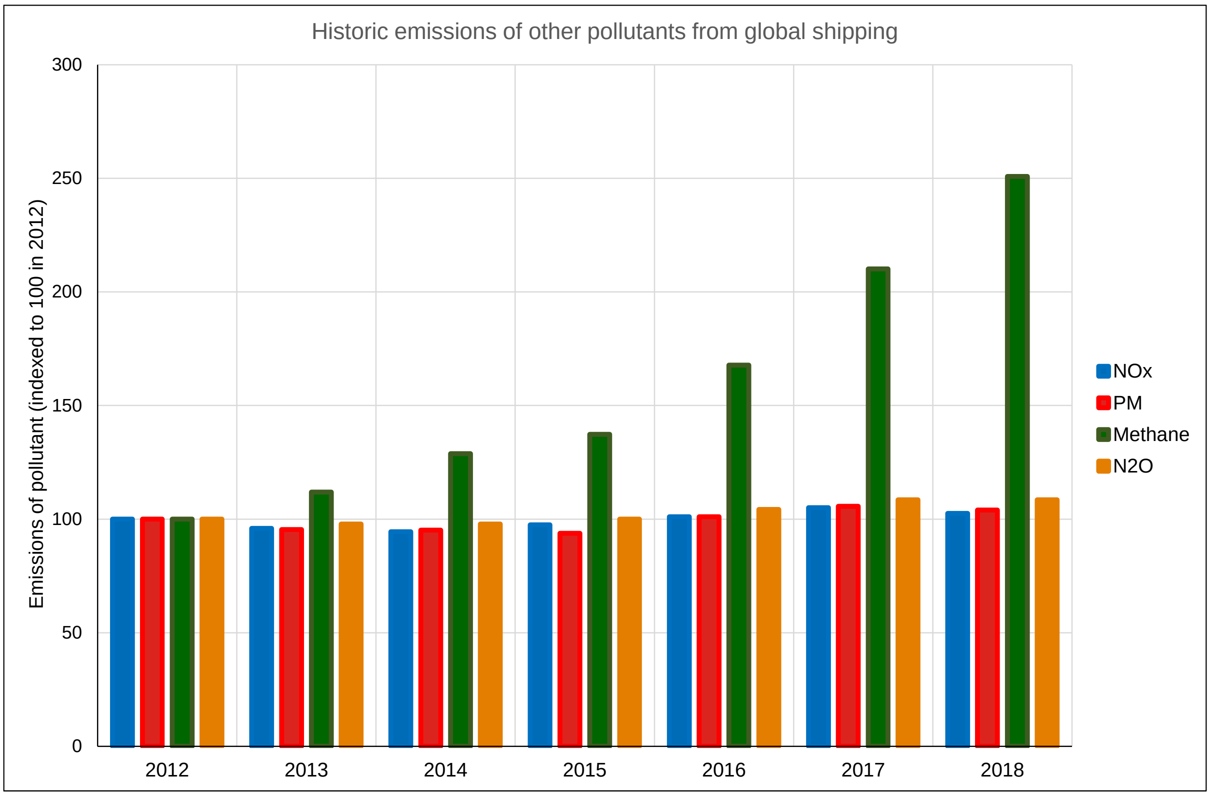
Source: Fourth IMO GHG study

The three highest emitting types of ship are container ships, bulk carriers and oil tankers (with significant emissions also by other tankers, such as chemical and liquefied gas). Between them, these three categories of ship produced 75% of the total GHG emissions from international maritime shipping.

Other key pollutants, including recent trends in methane emissions from LNG fuelled vessels

The fourth IMO GHG study also presented historic evolutions of other pollutants, including oxides of nitrogen (NOx), particulate matter (PM), methane (CH_4) and nitrous oxide (N_2O). The first two of these are primarily of concern in relation to local air quality (e.g. around ports), although they are also implicated in climate change (indirectly, through the production of ozone, in the case of NOx), while the latter two are primarily of concern as greenhouse gases. Figure 3-2 shows the evolution of the global emissions of these four pollutants since 2012. The changes are shown relative to a 100% baseline in 2012.

Figure 3-2: Evolution of emissions of other pollutants from global shipping, 2012 to 2018 (indexed to a value of 100 in 2012)

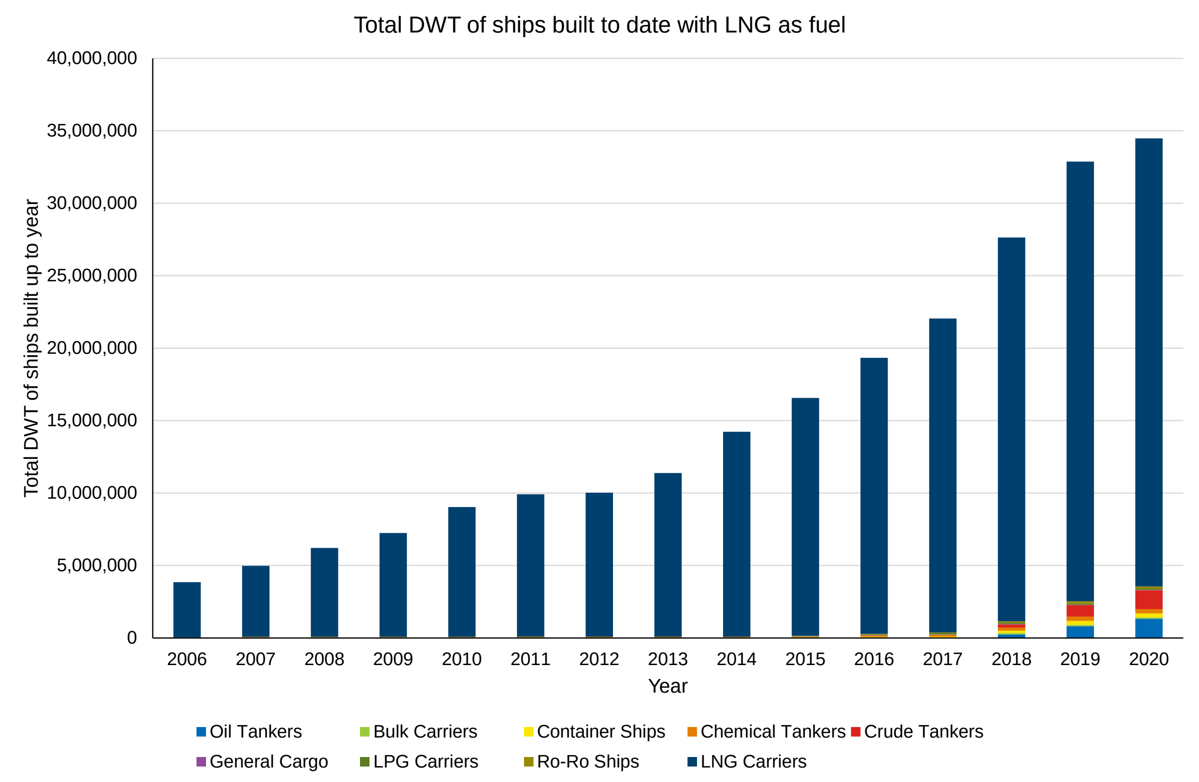


Source: Fourth IMO GHG study

The results in Figure 3-2 show almost constant levels of NOx, PM and N_2O emissions (average annual increases of 0.4%, 0.7% and 1.4%, respectively), but quite rapid increase in methane emissions (17% average annual increase). This reflects the recent trend to using more LNG-powered vessels and their associated 'methane slip'. The fourth IMO GHG study also notes that the nature of the propulsion systems of vessels using LNG has changed since 2012, with a greater proportion using low-pressure Otto-cycle engines and a reduced number using steam turbines (which have comparatively low methane emissions) The actual emissions of methane from shipping are still small in comparison to other sources such as agriculture (global methane emissions have been estimated at about 9.4 billion tonnes CO_2e[18], or about 290 million tonnes methane, so international shipping represents about 0.05%), but such a rapid growth could lead to a significantly higher percentage in the future if left unchecked. This also shows the increasing importance of considering non-CO_2 greenhouse gases for future fuel scenarios. As context, Figure 3-3 shows the growth in total DWT of ships delivered that can use LNG as a main fuel since 2006, showing the continued growth in the LNG-powered fleet, predominately in the LNG carrier category.

[18] https://www.globalmethane.org/documents/gmi-mitigation-factsheet.pdf

Figure 3-3: Cumulative DWT of ships capable of using LNG as fuel by year



The size of the LNG-powered fleet (in terms of total DWT) is now over three times the size that it was in 2012. The IMO 4th GHG study takes account of emissions of unburnt methane from LNG-fuelled engines, with different emission factors depending on the engine type (slow-speed or medium speed Otto-cycle (spark ignition), lean-burn spark ignition or diesel cycle) . Most recent LNG-fuelled vessels either use high-pressure diesel-cycle engines (which have lower methane slip) or use other technologies to reduce methane slip from Otto-cycle engines. Recent commentary from Lindstad (2019) also concurs that LNG fired in 2-stroke high pressure dual fuel engines provides overall a reduction in GHG intensity compared to HFO (in comparison to LNG fired in e.g. low pressure engines which does not offer GHG savings or worse, increases, compared to HFO).

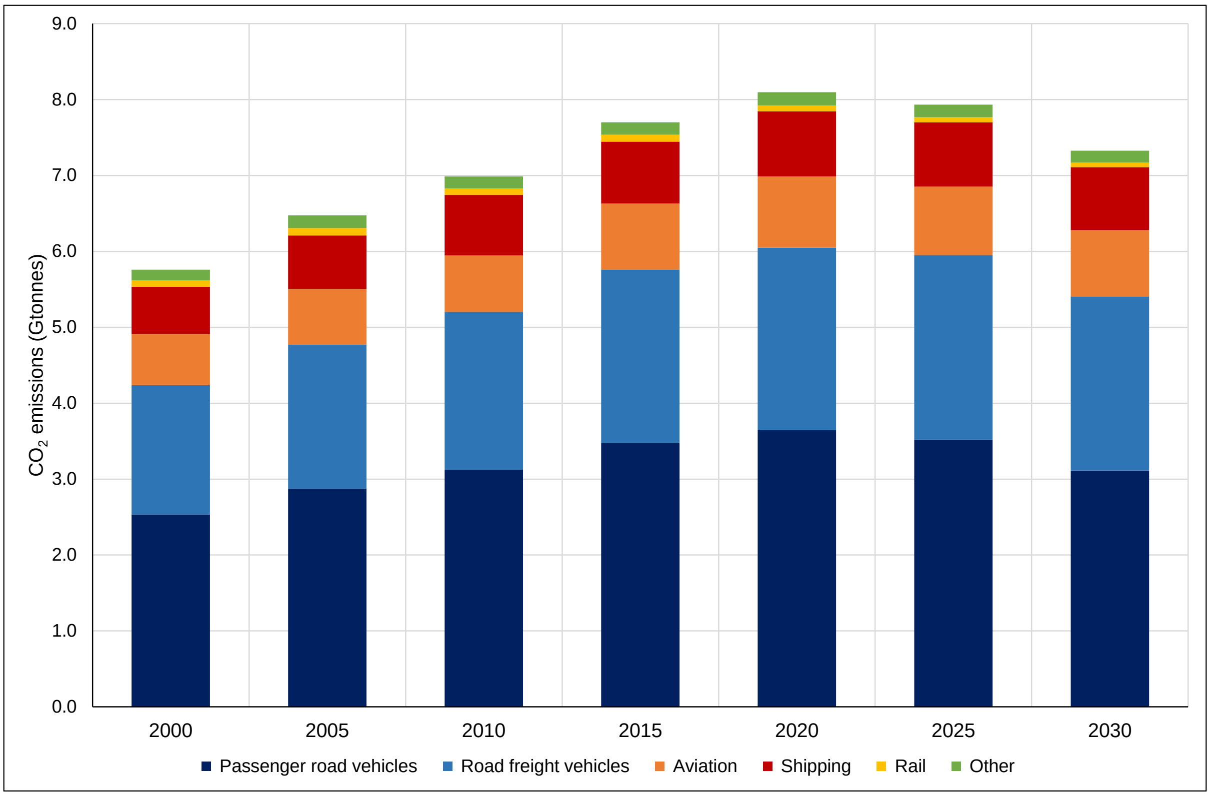
Comparison with other modes

In 2018 all modes of transport were responsible for ~8 Gtonnes[19] of CO_2 emitted into the atmosphere, an increase of ~15% since 2010 and ~40% since 2000 (International Energy Agency, 2019) (Figure 3-4). Road transport, both passenger and freight, makes up the majority of these emissions, and has been responsible for the majority of the increase in emissions in the 2000-2020 period (around 75% of total emissions). In comparison, shipping is responsible for around 11% of total emissions, only about one-third that of road freight, while representing five times more tonne-miles moved (International Transport Forum, 2019).

The IEA projections to 2030, based on the Sustainable Development Scenario, suggest that total CO_2 emissions from transport will decline to 7.3 Gtonnes, with road transport responsible for over 80% of the reduction in emissions. This reduction is expected to happen because of the diminishing reliance on petroleum-based fuels (partially replaced by electricity from renewable sources in the road sector, for example). The proportion of total transport emissions attributable to shipping is not expected to change by 2030.

[19] A gigatonne (Gtonne) is 1,000 million tonnes.

Figure 3-4: Transport sector CO_2 emissions by mode, historically and projected, 2000-2030[20].



Source: (International Energy Agency, 2019).

3.2 Carbon intensity

In July 2020, the EU published information on the CO_2 emissions by ships that had performed maritime transport activities related to the European Economic Area (EEA) in 2019[21], through the THETIS-MRV portal[22]. This follows the introduction of the requirement from 2018 for large ships that load or unload cargo or passengers at ports in the EEA to monitor and report their related CO_2 emissions in conformity with Regulation 2015/757. Although the data are only a subset of the global fleet, they do cover almost 11,200 ships of a full range of categories and sizes, representing 38% of the world merchant fleet (above 5,000 gross tonnage).

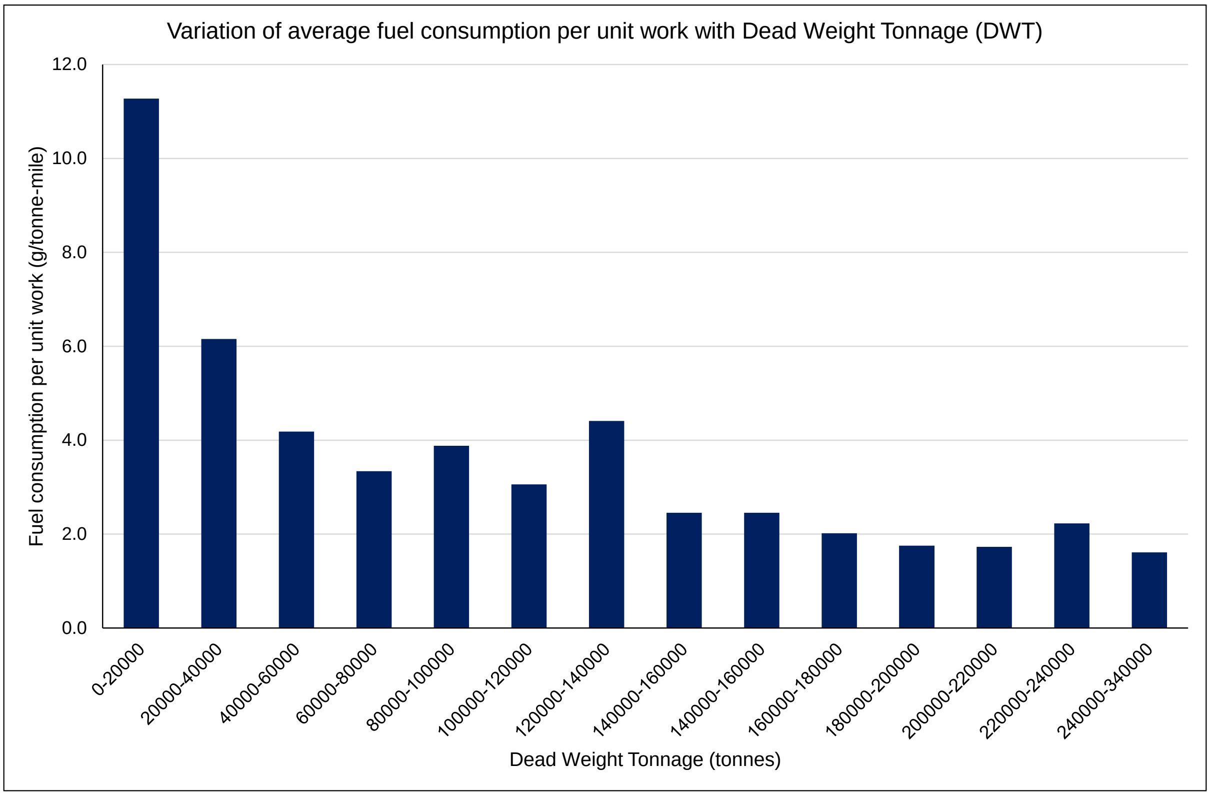
Using the ship data from the World Fleet Register, published by Clarksons Research (Clarksons Research, n.d.), where feasible, the entries in the THETIS-MRV data have been mapped to the relevant ship information, such as the deadweight tonnage (DWT) and gross tonnage (GT). This allows the carbon intensity (mass of CO_2 emission per unit of transport work, such as per tonne-mile) and fuel consumption per unit work to be analysed against the size of the ship (as represented by DWT) for different ship types. Figure 3-5 shows the average fuel consumption per unit work, split into different bands of ship DWT.

[20] Please note that while this IEA forecast predicts a decrease of 6% in aviation CO_2 emissions between 2018 and 2030, the International Civil Aviation Organisation (ICAO) forecasts that emissions of the aviation sector will increase around 45% in the same period (ICAO, 2019).

[21] https://ec.europa.eu/clima/news/commission-publishes-information-co2-emissions-maritime-transport_en

[22] https://mrv.emsa.europa.eu/#public/eumrv

Figure 3-5: Average fuel consumption per unit work for DWT ranges



Source: Ricardo analysis using EU ship emissions MRV data and Clarksons World Fleet Register data

Figure 3-5 shows that, on an overall average, the fuel consumption per unit work decreases from about 11 g/tonne-mile for the smaller ships to less than 2 g/tonne-mile for the largest. As well as the overall vessel size, these results are influenced by the characteristics of individual vessel categories and the manner in which they are operated (for example, gas carriers and Ro-Ro ships have consistently higher fuel consumption per tonne-mile than container ships or tankers).

For input to the fleet and emissions modelling (Section 6.1), the same THETIS-MRV data have been analysed in greater detail, considering the variations with vessel category, size (DWT) and build year (i.e. age in 2019).

Additional details of these analyses are given in Appendix A.2.

3.3 Costs

Costs of owning and operating a vessel vary significantly in terms of routes, vessels types, sizes and ages. Although the data is available for all vessel types and sizes[23], to illustrate the most representative elements of the maritime sector, this section outlines the illustrative cost structure of three vessel types: dry bulker, oil tanker and container ship. These three vessel types were chosen as they make up the largest proportion of the sector's CO_2 emissions (section 3.1) and are the most representative ones in terms of fleet size, according to fleet statistics published by UNCTAD (2019).

3.3.1 Vessel costs methodology

For all types of vessels, the main components of the costs are:

[23] This data will be used in the analysis performed in the second phase of the Project.

- **Capital costs**, that is the costs associated to ownership of the vessel, permanent or temporary. The costs presented below were built under the assumption of an ownership model[24]. In this case, the capital costs were composed of the following components:
    - Capital (or equivalent of capital amortisation when the vessels are purchased with a loan). These costs also reflect the average depreciation schedule of the vessels over their useful life. The useful life of the vessels for the depreciation schedule is assumed to vary by vessel type: for example, 25 years for bulk carriers and tankers and 20 years for container ships, corresponding to average demolition ages by vessel type (Clarksons Research fleet data).
    - Costs of capital or interest payments, that is additional capital costs associated with the weighted average cost of capital in the sector. The rate is assumed to be 6.75%, reflecting the assumption of 60% debt financing and corresponding interest rates of debt (6.3%) and equity (7.4%)[25].
    - Other costs, such as pre-delivery expenses, initial registration fees and taxes. This component of the costs is small and varies across countries. For simplicity, the costs outlined below exclude these costs.
- **Operating costs**, that is, the costs associated with operation of the vessel but not to the voyages the vessel makes. The operating costs were obtained from benchmarks published by Moore Stephens (Dec 2017) and BCG Shipping Benchmarking Initiative. The main components of shipping operating costs are:
    - Crew costs, including crew wages, travel and training.
    - Stores (including materials, supplies, equipment) and lubricants.
    - Maintenance, including repairs, dry dock and spares.
    - Insurance costs.
    - Administration costs, including inspection and overheads.

  Operating costs vary significantly across vessels, fleets and companies. Stakeholders admit that operating cost optimisation is one of the most used strategies of cost management for larger fleets.
- **Voyage costs** are the variable costs associated with the voyages or trips that a given vessel makes in a year. These costs will be zero for a vessel not used in a particular year. The main components of voyage costs are:
    - Fuel costs, calculated as the product of vessel fuel consumption (UNCTAD, 2019) and fuel price (The Association of European Vehicle Logistics, 2020) according to average fuel consumption composition (REPSOL, 2019). For this assessment of cost breakdown we used average values for the last 5 years for the results presented in the next sub-section and explore sensitivities after discussing main results.

      Fuel costs are highly dependent on fuel prices, so that oil and fuel price fluctuations are the most important determinants of shipping costs and vary between 30% to 50% under pre-COVID-19 fuel prices (e.g. average fuel price of 540 USD/tonne under Brent prices of 60 to 65 USD/barrel) as of Q4-2019) and varied between 25% to 35% under the low fuel prices at the beginning of 2016 during the oil price crisis (e.g. average fuel price of 280 USD/tonne under Brent prices of 30 to 35 USD/ barrel as of Q1-2016).

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[24] For rented or chartered vessels, it is assumed that, on average, the capital-related charter rate would be equivalent to the sum of capital and interest payments plus a premium to reach a reasonable level of profitability.

[25] Hamburg Financial Research Center (2015), "Maritime Investment Appraisal and Budgeting"

- Port charges paid to the port authorities and cargo handling costs paid to port operators. These were calculated as averages by vessel type taken from benchmarks by Hong Kong's and South Africa's maritime authorities[26].
- Canal dues and tolls paid to the canal operators for using the facilities (e.g. Panama Canal company, Suez Canal company).

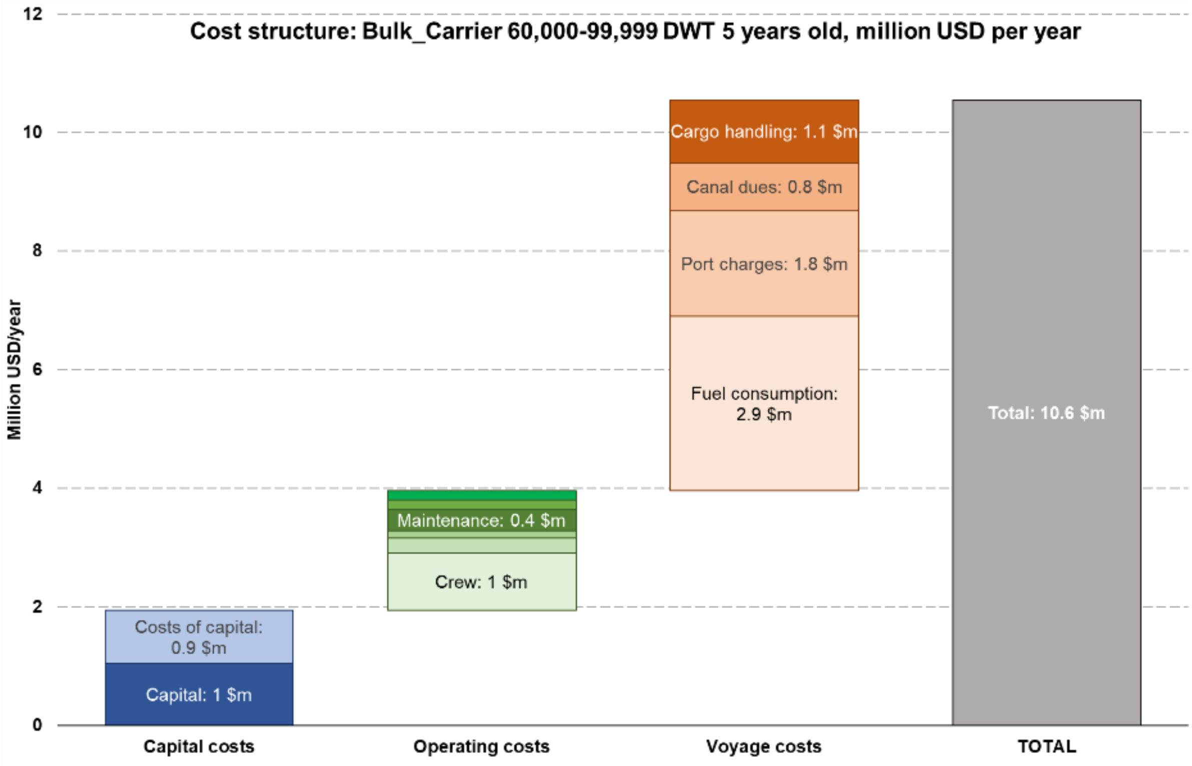
For each vessel type, a typical route portfolio was assumed, according to the most representative routes for each vessel type and size (Baltic dry index routes, EEX tanker index routes and World Shipping Council trade routes as a proxy for container routes).

3.3.2 Illustrative average annual costs for three vessel types

The costs for three vessel types are presented in Figure 3-6 (dry bulker), Figure 3-7 (tanker) and Figure 3-8 (container). All costs are expressed in millions of USD per year, the most common metrics used at the global scale, and assume an average fuel price of 481 USD/tonne under average Brent prices of 50 to 55 USD/ barrel in 2015-2019.

For relatively new vessels, on average, capital costs represent around 15%-25% of total costs of the vessels, while operating costs account for 10%-25% of the costs. Voyage costs are by far the most significant costs component for all vessel types and sizes due to the fuel consumption, and account for 60% to 70% of total costs per year.

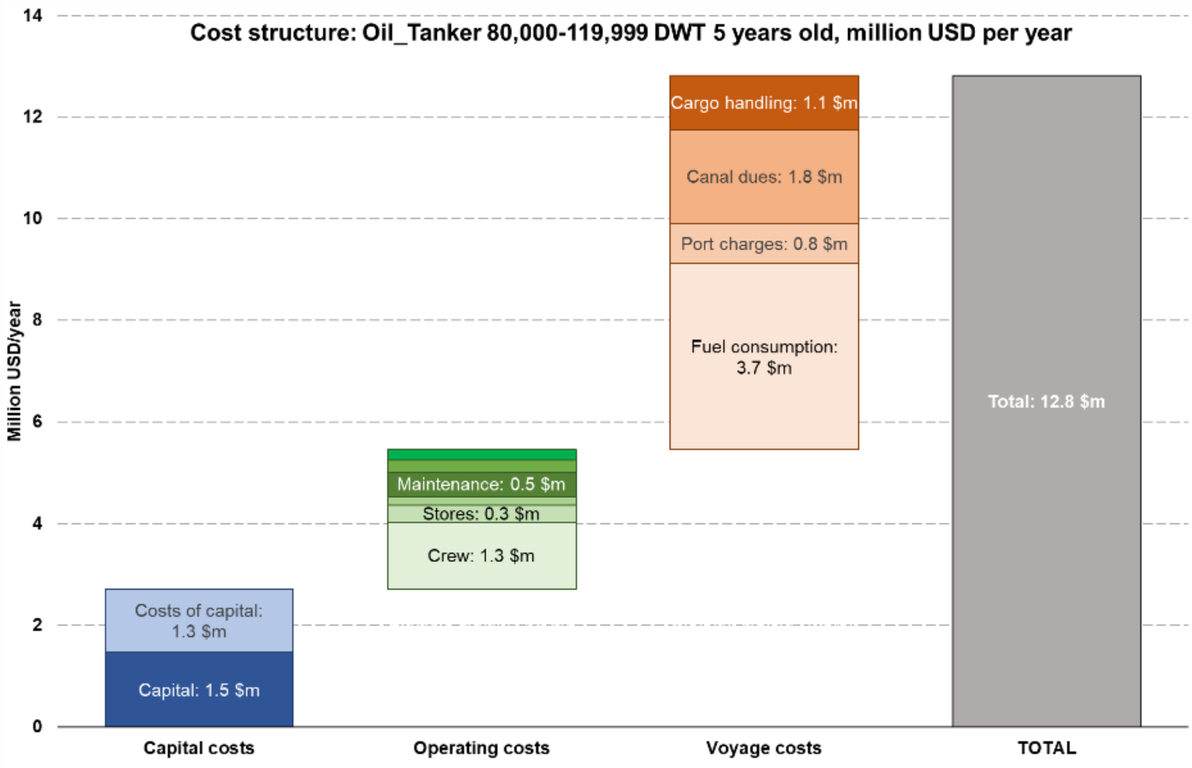
Figure 3-6: Illustrative annual costs for a 75,000 dwt Panamax dry bulk carrier, 5 years old, USD per year



Source: Ricardo literature review and calculations

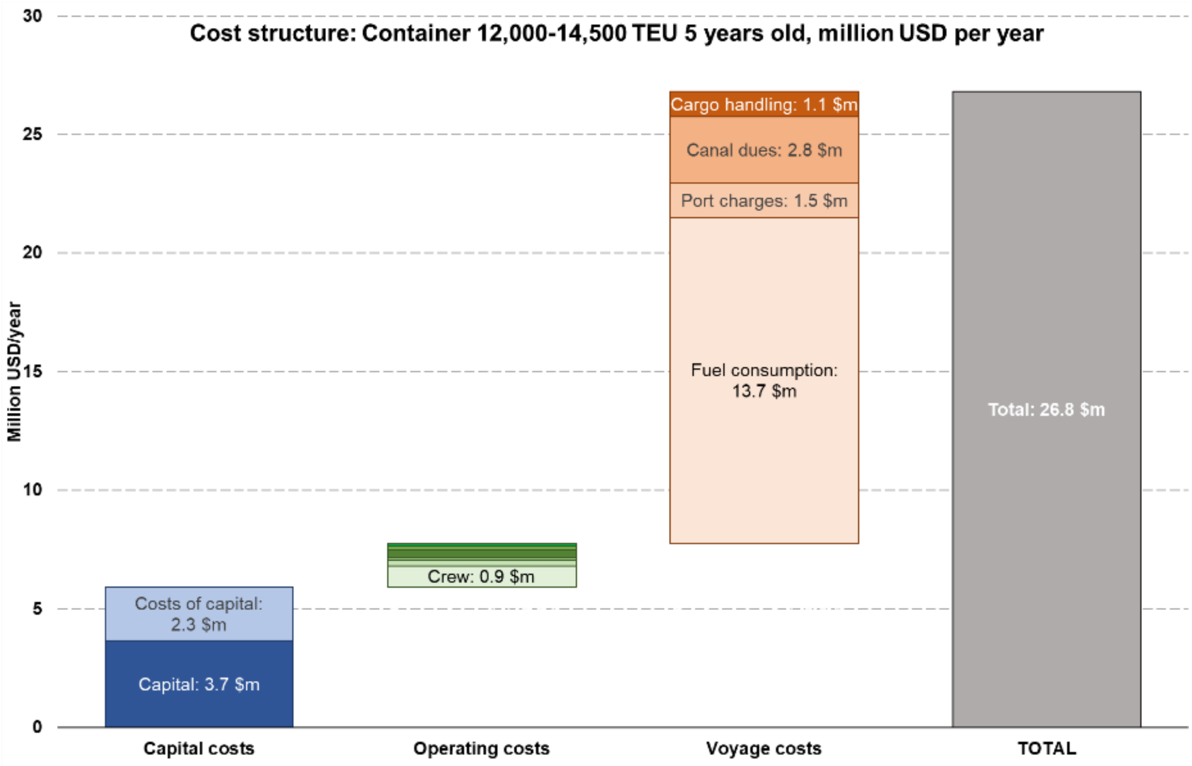
[26] Note: These charges do not factor in the nature of future fuels and their associated implications (e.g. storage).

Figure 3-7: Illustrative annual costs for a 100,000 dwt Aframax oil tanker, 5 years old, USD per year



Source: Ricardo literature review and calculations

Figure 3-8 Illustrative annual costs for a 13,000 TEU container liner, 5 years old, USD per year



Source: Ricardo literature review and calculations

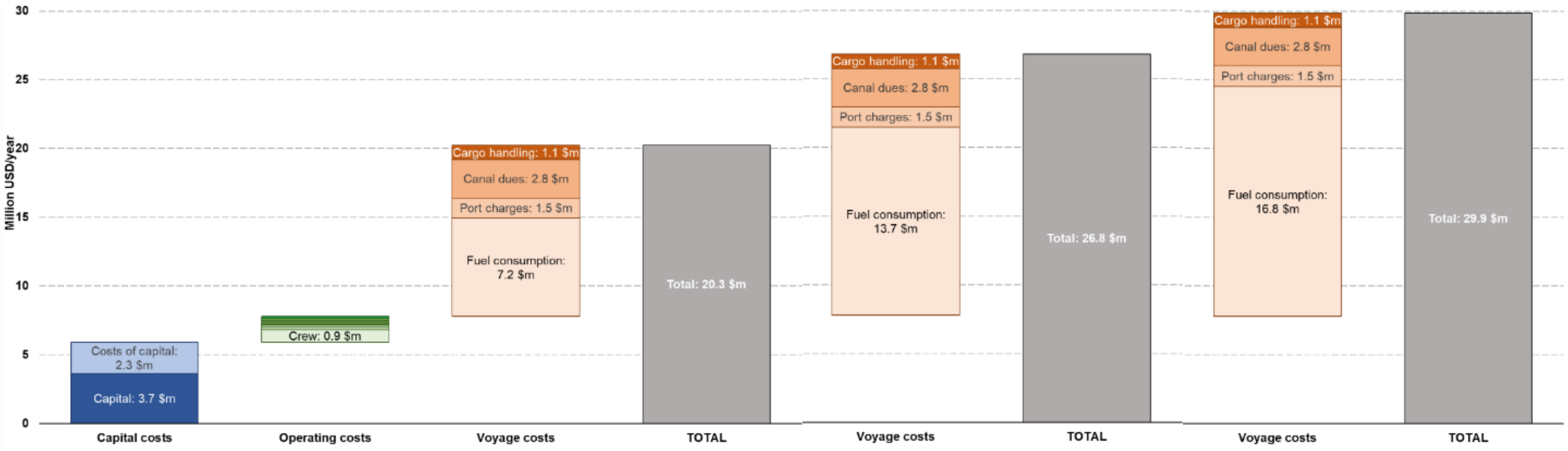
3.3.3 Key determinants and sensitivities

Fuel price is by far the most important and most volatile determinant of the average vessel costs, being especially pronounced for older and less efficient vessels. Figure 3-9 highlights this[27]. A calculation performed in May 2020 showed average fuel prices of $251/tonne, 47% lower than the average price in the preceding 5 years (i.e. average fuel price of $481/tonne under average Brent prices of $50 to $55 per barrel in 2015-2019) and 57% lower than average prices in 2018, the highest in this 5 year period (e.g. average fuel price of $588/tonne under Brent prices of $65 to $70 per barrel in 2018). This high dependence of vessel operating costs on fuel price provides a strong driver to reduce the cost of fuels used, and has been a key determinant in the almost universal adoption (historically) of HFO (in general the lowest priced liquid fossil fuel) for maritime transport.

For a 13,000 TEU 5-year-old container ship, the fuel costs change from $7.2 million per year under current prices to $13.7 million per year under average historic prices or to $16.7 million per year under high prices as in 2018. This means very important increments of 32% and 47% in total annual costs respectively (Figure 3-9).

[27] These are for illustration of the variability. Different fuel price assumptions are used in the modelling described in later sections of the report.

Figure 3-9 Fuel price sensitivities for 13,000 TEU container liner, 5 years old, USD per year

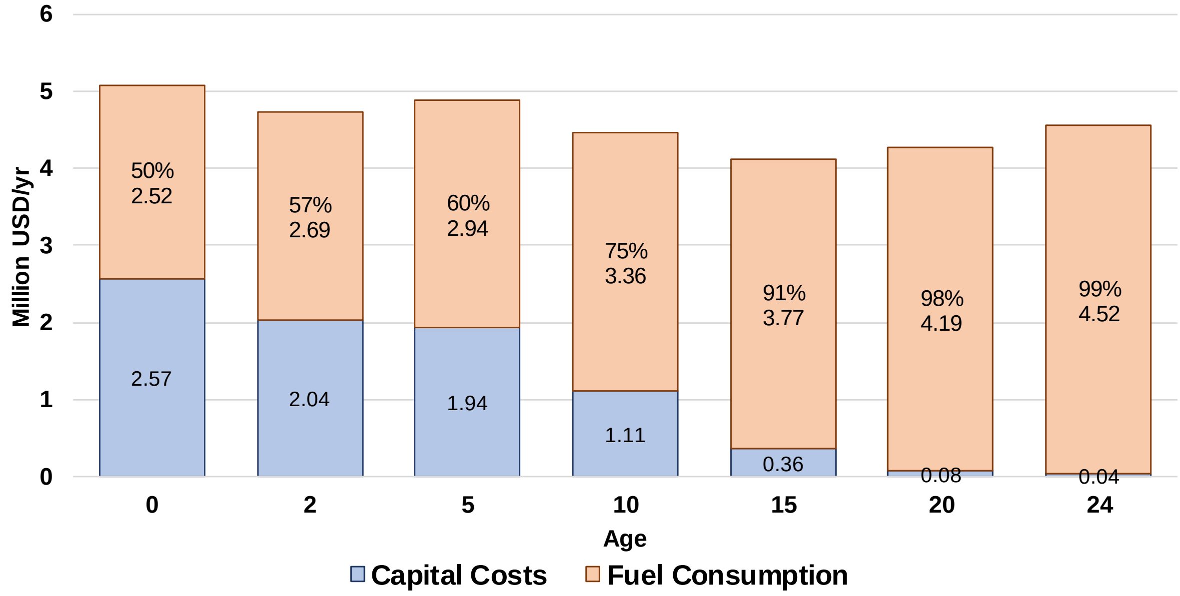


251 USD/tonne 481 USD/tonne 588 USD/tonne

Source: Ricardo literature review and calculations

The age of the vessel is a key determinant of both capital and fuel costs (Figure 3-10), because in general, the vessels depreciate faster at the beginning of their useful life and newer vessels are more efficient.

Figure 3-10 Age sensitivities for a 75,000 dwt bulk carrier on capital and fuel costs (fuel costs of 481 UDS/tonne), USD per year



Fuel consumption data derived from analyses of EU MRV data (European Commission (DG CLIMA), 2019)*; capital cost data derived from analyses of Clarksons Global Fleet Register* (Clarksons Research, n.d.)

For new bulk carriers, for example, capital costs are of the same magnitude as fuel costs, 2.5 million USD per year approximately. For older vessels, however, the capital costs are lower and the fuel costs are higher, with the latter more pronounced for higher fuel prices scenarios.

3.4 Regulations and incentives

3.4.1 IMO and MARPOL

The international maritime sector is subject to a range of regulations, both international and national. At a global level, maritime regulations are defined by the International Maritime Organization (IMO). The IMO is the specialised agency of the United Nations with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships. The IMO provides the forum for the agreement, adoption and implementation of international regulations.

The primary international regulations for maritime environmental protection fall under The International Convention for the Prevention of Pollution from Ships[28] (MARPOL). Regional implementation of such regulations can be stricter than MARPOL. The sixth Annex of MARPOL limits emissions of oxides of sulphur (SOx) by limiting the sulphur content of fuel[29]; limits oxides of nitrogen (NOx) through engine NOx controls; and aims to address greenhouse gases (GHG) through technical and operational energy efficiency measures.

[28] http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx

[29] SOx emissions occur when sulphur in fuel is oxidised during combustion. Therefore, limiting the fuel sulphur content also limits the SOx emissions from the ship. The latest rules came into force from 2020 limiting marine fuel sulphur content to 0.5% globally and 0.1% in emission control areas.

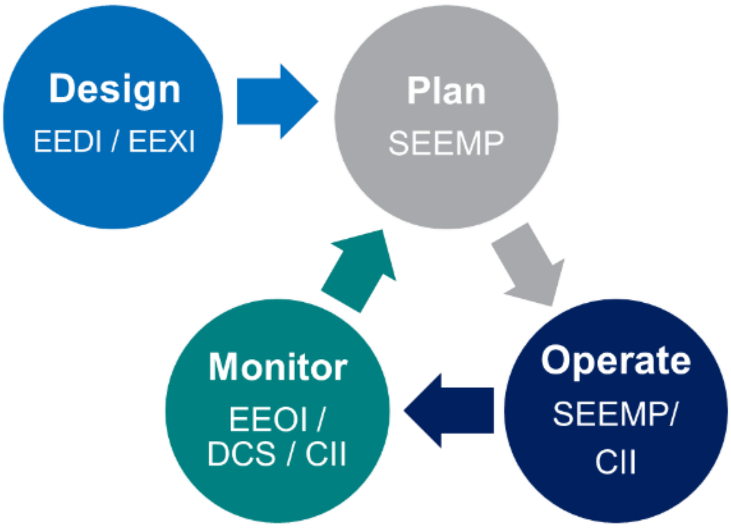
3.4.2 IMO measures to address GHG emissions

The IMO has been working on possible solutions to reduce GHG emissions from shipping for several years. The measures that have been put in place for addressing maritime GHG emissions are the Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SEEMP), mandatory Fuel Oil Data Collection System (DCS) and the Energy Efficiency Operational Indicator (EEOI).

During MEPC 75 in November 2020, draft new mandatory regulations were approved by the IMO, including the introduction of a measure or existing vessels, known as the Energy Efficiency Existing Ship Index (EEXI) (IMO, 2020). Following their adoption at MEPC 76 in June 2021 (IMO, 2020), these requirements will enter into force in 2023. These amendments also include the establishment of a Carbon Intensity Indicator (CII), which will further address ship performance. The IMO will likely review the effectiveness of the implementation of the EEXI and CII by January 2026 (IISD, 2020). Issues around the development of lifecycle GHG/carbon intensity guidelines for all relevant types of fuels have also been discussed. The position of the EU is that the guidelines should include a methodology that allows ship operators to compare the well-to-wake emissions of different alternative fuels (European Parliament, 2020).

Under the new amendments, ships will be required to meet a specific EEXI. The CII indicates the average CO_2 emissions per transport work applied to individual ships. A reference line and a reduction factor will be determined to target continuous improvement of the ship's operational carbon intensity (IISD, 2020). The contributions of SEEMP, CII, EEDI, EEXI, EEOI and DCS to different ship efficiency strategy components are visualised in Figure 3-11.

Figure 3-11: Contributions of SEEMP, CII, EEDI, EEXI and EEOI to different ship efficiency strategy components



- **EEDI** is an index that estimates gCO_2 per transport work (gCO_2 per tonne-mile) and is calculated based on the technical design parameters for a new ship. It is a function of installed power, speed of vessel and cargo carried. The EEDI aims to increase the uptake of more energy efficient equipment and engines within the sector, requiring new ships to adhere to a minimum energy efficiency level. The regulation will be strengthened every five years, with the level adjusted according to ship type and size.
- **EEXI** is an efficiency design index for *existing* ships, approved in November 2020 (IMO, 2020). The EEXI is very similar to the newbuilding related EEDI, with adjustments to extend to existing vessels
- **SEEMP** provides a mechanism for shipping companies to manage the efficiency and performance of their fleets, allowing for an assessment of technological or operational changes (e.g. through the

EEOI)). SEEMP urges the ship owner and operator at each stage of the plan to consider new technologies and practices when seeking to optimise the performance of a ship.

- **CII** is an indicator that determines the annual reduction factor needed to ensure continuous improvement of the ship's operational carbon intensity within a specific rating level. The actual annual operational CII achieved will be verified against the required annual operational CII. This would enable the operational carbon intensity rating to be determined. The rating will be given on a scale that shows the performance level (rating A, B, C, D or E). The performance level will then be recorded in the ship's SEEMP (IMO, 2020).
- **EEOI** is the total carbon emissions in a given time period per unit of revenue tonne-miles. This was developed by the IMO in order to allow ships to monitor the carbon emissions of their shipping activities. The EEOI enables operators to measure the fuel efficiency of a ship in operation and to gauge the effect of any changes in operation.
- **MRV** refers to the monitoring, reporting and verification (MRV) of CO_2 emissions for vessels during their voyages from 2018, and globally amendments to MARPOL Annex VI on Data collection system (DCS) for fuel oil consumption of ships entered into force on 1 March 2018 (IMO, 2018). The EU's MRV regulation has additional elements compared to the IMO's Data Collection System: data are published, the data are verified, and the data include cargo tonnages carried which enables a view on the operational efficiency of the ships.

3.4.3 IMO regulation effectiveness

In April 2016 a review of EEDI target values indicated over two-thirds of new built container ships, half of cargo ships and over a quarter of tankers launched in 2015 already meet or exceed EEDI standards set for 2020 without using innovative novel technologies. This raised concerns that the EEDI is not stringent enough to significantly reduce GHG emissions and that there is still a large amount of scope to improve its effectiveness (The Royal Institution of Naval Architects, 2017).

The literature also indicates it is now widely accepted that ship design efficiency requirements alone will fall short of what is required in order to achieve the targeted decarbonisation of the shipping sector by 2050. The European Commission has stated it will propose further measures to tackle GHG emissions from ships, in the absence of adequate progress in the framework of IMO, thereby effectively highlighting that the adoption of EEDI is not sufficient (Psaraftis H. , 2012). Further analysis regarding EEDI effectiveness is found in Appendix 3 – EEDI effectiveness

As for the more recent set of amendments, (covering EEXI and CII), opinions on the effectiveness of these measures are divided. Whilst welcomed by industry, NGOs such as Transport & Environment (T&E) see the amendments as simply 'business as usual draft text', and state they will not reduce emissions this decade (T&E, 2020). According to T&E, this is due to three reasons. Firstly due to the reduced stringency of the EEXI for many vessels, secondly because non-compliant ships will be able to continue underperforming for three consecutive years before they have to file a plan to make improvements, and thirdly because there is a lack of enforcement as all clauses that would create consequences for non-compliance (e.g. increased EEXI stringency) have been removed (T&E, 2020).

3.4.4 Port area regulations and incentive programmes

Port area regulations can also be useful drivers in decarbonising the shipping sector. Specific port area regulations and policies include those at IMO level (e.g. Port development under the IMO Initial Strategy 2018), EU level (Directive 2009/16/EC on Port State Control[30]) and local level (e.g. California Air Resources Board Regulation (CARB) on airborne toxic control of auxiliary diesel engines operated on

[30] Under review at present (2021): https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12641-Port-State-control-Further-improving-safety-security-and-sustainability-of-maritime-transport

vessels at-berth) (International Chamber of Shipping, 2018). Generally, Port Authorities do not monitor and enforce regulations. It is under the remit of Port State control (PSC) authorities to inspect foreign ships in national ports to verify ship condition, equipment and certificates of compliance with international regulations. Any Party to the MARPOL Convention can exercise enforcement jurisdiction against any ships visiting its ports to ensure compliance with the Convention (International Maritime Organization, 2018).

The IMO has encouraged the establishment of regional PSC co-operation on enforcement[31]. To this end, nine Memoranda of Understanding on PSC have been concluded covering much of the world's oceans. In the possible enforcement of future carbon-based policies these MoU may become useful means through which Port States check compliance on behalf of larger regions.

Another lever that ports can use to incentivise decarbonisation measures is through differentiated port fees. As noted in section 3.3, whilst port fees are not a dominant proportion of total ship operator costs, they are sufficiently large to provide the possibility to provide an incentive. In this way, ports utilise the pre-existing fees paid by ships by applying either a fixed or proportionate reduction for low emission ships (and may need, in order to remain revenue neutral, to as a compensation increase the fees for high emission ships). Early adoption of this measure began in Sweden with the introduction of their *Differentiation of Fairway Dues* in 2018 which incentivises low SOx and NOx emissions (Vierth, 2020).. Similar measures have been used in many ports since. Many ports' incentive schemes are based on the Environmental Ship Index[32] (ESI). The ESI rates ships in four separate elements, three of which rate the environmental performance of the ship against the international standard for a particular pollutant (NOx, SOx, CO_2 with bonus points available for the latter for energy efficiency), while the fourth reflects the ability to use shore-side power while at berth. Appendix A.4 includes the structure of the calculation of the ESI and lists the ports using the ESI in different regions.

Environmental Ship Index (ESI)

- Falls within the scope of the **World Ports Sustainability program (WPSP),** a commitment from the world's key ports to reduce greenhouse gas emissions
- Is a voluntary numerical **index that can be used to promote clean ships** and to reward the most efficient ships
- The **ESI is used by over 50 ports and has over 8,000 ships** registered.

Discounted port dues and other incentives (for example use of clean ship scores as promotional instruments) are examples of how voluntary measures can encourage early adoption of emission reduction measures in advance of regulations. Voluntary incentive programmes may be an important driver for the introduction of new technologies within fleets. However, there is some uncertainty about the effectiveness and appropriateness of voluntary measures (Clyde&Co, 2017). Nevertheless, several voluntary instruments have contributed to the uptake of gas engines, selective catalytic reductions (SCR) catalysts, sulphur oxides (SOx) scrubbers and other technologies, resulting in an increase of experience with these technologies in the industry (Anderson, et al., 2015). Globally, in total around ten extra-legal incentive schemes are in place to improve air quality, with the Environmental Ship Index (ESI) being the most widely implemented (Tester, MacKenzie, Kouboura, & Hanly, 2017). However, compared to the overall number of cargo ships in operation worldwide, the share of ships joining voluntary schemes is estimated to be around 5%.

The use of alternative fuels as a basis for port-incentive schemes is again growing in popularity. Initial fuel incentives supported the reduction of SOx and NOx outputs but since the adoption of the 0.1% fuel oil sulphur limit, attention could be directed to decarbonisation fuels. There are several LNG schemes

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[31] Resolution A.682(17) on Regional co-operation in the control of ships and discharges

[32] https://www.environmentalshipindex.org/Public/Home

established in major ports and they are an important driver for uptake of this fuel. A more recently developed incentive scheme surrounds berth times and berth priority based on the environmental impact of the ship. Ports' berth allocation policies have evolved from traditional first-come-first-serve to a system which minimises waiting times, and there is room to incorporate the environmental impact of the ship, as evidenced by Panama's implementation of the Environmental Premium Ranking in 2017, which contributes to ships' allocation in the booking system for the canal.

Despite relatively low overall participation rates in terms of global fleet, incentive programs have been known to develop into compulsory programs, therefore they can remain a key driver in not only shaping future shipping fleets but are often a prerequisite for future regulation. For example, following on from initial voluntary programs, management of ships' ballast water and sediments became a mandatory requirement adopted by consensus at IMO Headquarters in London on 13 February 2004, complete with fines, penalties and potential civil liability exposure as well (International Maritime Organization, 2017).

3.4.5 Carbon offsetting

Another potential market-based measure that can be considered to mitigate GHG emissions is the use of "carbon offsetting". According to the IPCC, "a carbon offset is a reduction in emissions of carbon dioxide or other greenhouse gases made in order to compensate for ("offset") an emission made elsewhere" (IPCC, 2018). Planting trees (removing CO_2 from the atmosphere as they grow) or investing in energy efficiency and renewable projects (avoiding future CO_2 emissions) are examples of carbon offsetting initiatives (UN Environment, 2019). Carbon offsetting has been criticised as being "a free pass for inaction", allowing sources of GHG emissions to buy carbon offsetting credits without acting to reduce their emissions (UN Environment, 2019). For the Paris Agreement climate goals to be achieved carbon offset projects will not be enough to reduce emissions to the level required (UN Environment, 2019).

In the transport industry, the most prominent example of carbon offsetting is the 'Carbon Offsetting and Reduction Scheme for International Aviation' (CORSIA). Under this programme, airlines will have to offset all their emissions resulting from international flights above a certain threshold, based on the 2019 emissions of the sector (Flight Global, 2020). In the maritime industry, there are currently no plans to use carbon offsetting as part of the strategy to achieve the IMO's decarbonisation targets. In 2009, Cyprus, Denmark, the Marshall Islands, Nigeria and the International Parcel Tankers Association (IPTA) submitted a proposal[33] to the IMO for the creation of an international fund for GHG from ships. This proposal would establish a target for decarbonisation[34], and any emissions above the target would be offset by the use of carbon offsetting. This offsetting would be financed by a contribution paid by ships on every tonne of bunker fuel purchased (IMO, 2020). While some organisations have put forwards proposals for the use of carbon offsetting in the maritime sector[35], at the IMO level the topic does not currently appear to be under consideration.

[33] An International Fund for Greenhouse Gas emissions from ships, MEPC 60/4/8 (IMO - MEPC, 2009).

[34] A target was eventually adopted in 2018 (see section 1.1).

[35] See, for example, Kachi et al. (2019) and Cabbia Hubatova (2020).

4 Fuels and technologies to decarbonise shipping

Key points:

- A long list of measures to decarbonise the shipping sector was developed. Key decarbonisation measures identified include:
  - **Future energy carriers** with lower well-to-wake GHG emissions compared to traditional marine fuels, such as LPG, LNG, BioLNG, biofuels (FAME, HVO), ammonia, hydrogen, methanol and batteries.
  - **Vessel design measures** that reduce vessel resistance and fuel consumption (such as hull coatings and optimum ship size dimensions)
  - **Power assistance measures** that reduce main engine power demand (e.g. solar panels, flettner rotors, sails)
  - **Alternative propulsion technologies** including different propellers (large area propellers, contra-rotating propellers and podded thrusters) as well as propulsion improving devices such as post-swirl fins and rudder bulbs.
  - **Engine technologies** that improve engine/vessel efficiency, including enhanced fuel injection systems, early intake valve closing and waste heat recovery.
  - **On-board carbon capture** reducing exhaust emissions of CO_2 (the captured CO_2 may then be stored or re-used).
  - **Voyage optimisation** measures that reduce fuel consumption (e.g. advanced port logistics, speed reduction, weather routing).
- The detailed analysis of the decarbonisation potential and practical considerations related to each of these measures can be found in this section.

The main fuel used for shipping was and remains residual fuel, or heavy fuel oil (HFO[36]). Specifically, the global demand for marine fuel is predominately met by HFO (66%), followed by marine diesel oil (MDO) (30%) (IMO, 2020). However the shipping fuel landscape is evolving.

The falling costs of net zero carbon energy technologies has reduced the cost differential of **sustainable alternative fuels** to conventional fuels, although it remains significant. Whilst the use of alternative fuels (such as LNG) have long been explored previously, in recent years the search for alternative fuels has expanded. Now, some fuels that until very recently were not considered as marine fuel alternatives are included in research and development activities. For example, key recent outlook reports such as ABS's Setting the Course to Low Carbon Shipping (2019) and DNV GL's Maritime Forecast to 2050 (2018) feature newly considered fuel solutions such as ammonia, hydrogen and methanol.

As well as fuels, different **technologies** for decarbonising the shipping sector have also been explored. Categorisation of technologies tend to be broadly agreed upon, such as vessel design, power and propulsion, operational measures (e.g. slow-steaming) and alternative energy sources.

[36] Following the introduction of the IMO regulation on the sulphur content in fuel from 2020, the fuel used should be very low sulphur fuel oil (VLSFO) or ultra-low sulphur fuel oil (ULSFO), unless the vessel is equipped with an approved exhaust gas cleaning system (scrubber). For simplicity, this report refers to all residual fuels as HFO.

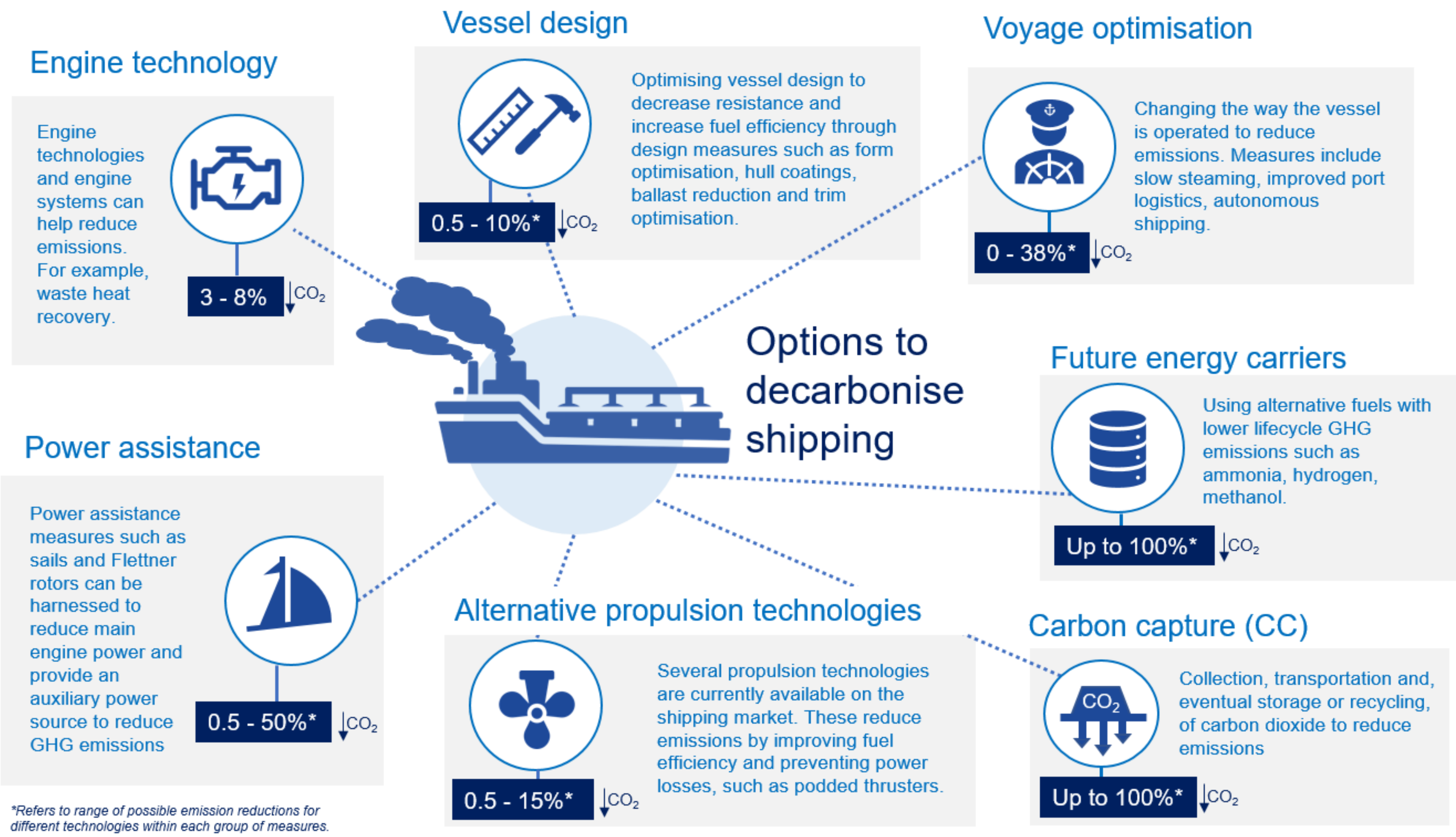
The cumulative emission reductions these technologies entail and their contribution to decarbonisation by 2050 vary across studies. For example, a literature review by Bouman et al[37] indicates that emission reductions between 33-77% could be achieved in 2050 based on current technologies, encouraged through a combination of policy measures (Bouman et al, 2017). Another aspect to be considered is the relative role of current technologies versus alternative fuels in decarbonisation by 2050. Other studies, such as the OECD report on zero-carbon shipping by 2035, have highlighted a greater role of alternative fuels, such as hydrogen and ammonia penetrating the sector and supplemented by technical and operational measures (European Commission, 2018) (OECD, 2018).

This section considers the alternative fuel options as well as vessel and engine technologies, together with operational measures, to decarbonise the shipping sector. Looking forward to 2050, this section identifies and quantifies the emission reduction potential of measures and establishes their current implementation. Figure 4-1 provides a broad overview of the options to decarbonise shipping by 2050[38].

[37] Bouman et.al.(2017), State-of-the-art technologies, measures, and potential for reducing greenhouse gas emissions from shipping – a review, Transportation Research Part D 52, 408-421

[38] Note: this diagram serves as an overview and is not an exhaustive list of technologies and fuels.

Figure 4-1 Broad overview of options to decarbonise shipping by 2050



To assess GHG reduction potential it is also important to understand the Technology Readiness Levels (TRL) of different measures and fuels. TRL show the steps required from research through to vessel deployment and indicate the market maturity of technologies. These are summarised in Figure 4-2. Some decarbonisation measures may already be at deployment whilst others are at earlier stages of development or demonstration. TRLs have been identified for each technology and fuel to enable comparison.

Figure 4-2: Technology Readiness Levels (TRL)

	TRL	Explanation	
Basic research	1	**Basic principles** of scientific research observed and reported	Significant R&D effort required for marine
	2	**Invention and research** of practical applications	
	3	**Proof of concept** with analytical and experimental studies to validate the critical principles of individual elements of the technology	
Development	4	Development and validation of component in a **laboratory**	Limited R&D requirement
	5	**Pilot scale** testing of component in a simulated environment to demonstrate specific aspects of the design	
	6	**Prototype system** built and tested in a **simulated environment**	
Demonstration	7	**Prototype system** built and validated in a **marine operational environment**	
Deployment	8	**Active commissioning** where the actual system is proven to work in its final form under expected marine operating conditions	
	9	**Operational application** of system on a commercial vessel	

Source: Based on US DoD TRL

A full detailed analysis of the different GHG emissions and production pathways of the fuels assessed can be found in Appendix 5 (A.5). A more detailed breakdown of the applicability to different vessels, current implementation, and future ownership of each of the technologies is presented in Appendix 6 (A.6).

The remainder of this section summarises alternative fuel options, power assistance measures, alternative propulsion measures, engine and aftertreatment technologies, carbon capture (CC), voyage optimisation and fuel quality improvements, and their potential contributions to decarbonising the sector.

4.1 Future energy carriers

This section assesses in detail the GHG reduction potential of different alternative fuels, their costs and the GHG emissions associated with their different production routes. The practical limitations of these fuels in terms of storage, market feasibility and infrastructure as well as their capital costs and other environmental impacts are discussed. Table 4-1 shows an overview of the candidate fuels considered. The TRL for each fuel considers both the readiness of the fleet (i.e. the existence of in-service vessels using the fuel) and the production and bunkering infrastructure (e.g. blue and green alternative fuels may not be at the same technology readiness as their grey counterparts).

Table 4-1: Summary of future potential energy carriers.

Fuel *Pathway*	GHG reduction potential(%)*	TRL for trans-oceanic	Compatibility
HFO *(low sulphur)*	-	**9**	-
MDO	-	**9**	-
LNG *Global average*	**10**	**9**	Requires gas/dual fuel engine and associated cryogenic storage.
BioLNG *Liquid manure***	**72**	**9**	Same requirements as for LNG.
LPG *Natural gas (propane)*	**20**	**9**	Requires LPG/dual fuel engine.
Methanol (Grey) *Natural gas*	**(emissions > HFO)**	**9**	Not drop-in. Compatible with internal combustion engines.
Methanol (Green) *Synthetic (renewable)*	**95**	**7**	
Ammonia (Grey) *Natural gas*	**(emissions > HFO)**	**7**	Not drop-in. Compatible with engines under development (spark ignition with a hydrogen blend, or dual-fuel with pilot diesel). Safety and toxicity concerns.
Ammonia (Blue) *Natural gas + CCS*	**85**	**4/5/6**	
Ammonia (Green) *Renewable electrolysis*	**75**	**3/4/5**	
Hydrogen (Grey) *Natural gas*	**(emissions > HFO)**	**7**	Not drop-in. Compatible with internal combustion engines (spark ignition & dual-fuel) but requires development and a supporting fuel.
Hydrogen (Blue) *Natural gas + CCS*	**84**	**4/5/6**	
Hydrogen (Green) *Renewable electrolysis*	**75**	**3/4/5**	
FAME *e.g. Waste cooking oil*	**73**	**9**	Drop-in (blended only < 20% FAME)
HVO *e.g. Waste cooking oil*	**77**	**9**	Drop-in (blended and neat)
Batteries	**66%**	**4/5/6**	Not compatible with ICE. Require their own storage systems and equipment. Weight and size challenges.

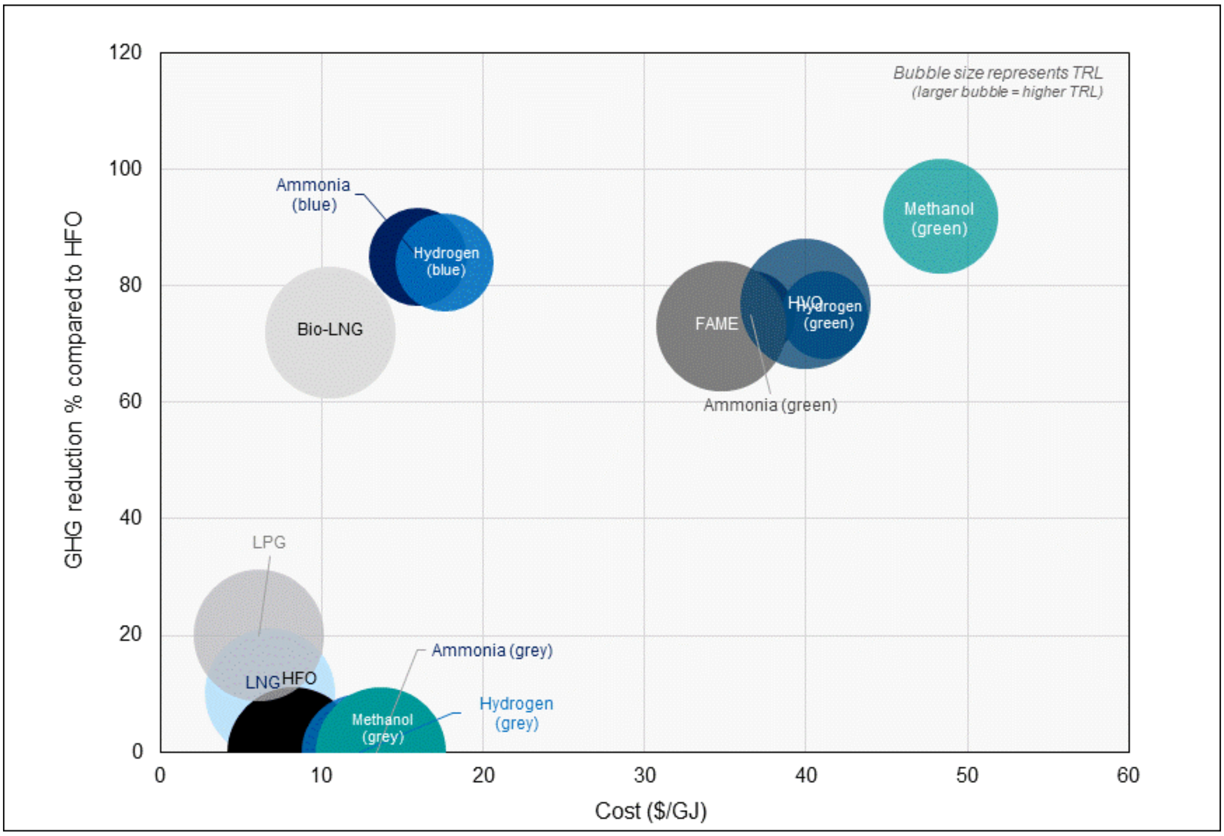
Attractive	**Moderate**	**Unfavourable**

*TRL =Technology readiness level. CCS = Carbon capture and storage. Cost = production cost of alternative fuel pathway (USD 2020). Costs presented are based on estimates available from the literature. Costs are those associated with production costs excluding transportation costs. For blue ammonia and hydrogen theoretical costs were calculated based on detailed research rather than data from actual projects. *Refers to % reduction in Well-to-Wake emissions compared to HFO emission baseline. Maximum potentials are shown with the exception of green ammonia, green hydrogen, green methanol and battery electric. In theory, 100% reduction (or higher) may be achievable with 100% renewable electricity for these fuels and with off grid renewable energy; however the timeframe and costs for these production pathways are not clear at present. **The processing of manure for the production of BioLNG can capture methane that would otherwise be emitted to the atmosphere. Accounting for this can increase the emissions reduction potential to over 170%.*

In Table 4-1, the GHG reduction potential values given for "green" hydrogen and ammonia are based on life cycle analyses performed by Ricardo and include the emissions embedded in the renewable electricity generation plant. As the production of these fuels involves large quantities of electricity, these embedded emissions have a significant effect on the potential GHG reductions, to the extent that the green hydrogen and ammonia appear to have lower reduction potential in 2020 than their blue counterparts. These embedded emissions are forecast to reduce significantly over time as technology improves, so by 2050, the GHG reduction potentials for green hydrogen and ammonia improve to 90%.

Included in Table 4-1 are examples of drop-in alternative fuels (i.e. those compatible with existing diesel-cycle engines) that have a high level of maturity. There are other examples of drop-in fuels that are under development, such as alternative conversion pathways based on similar biological feedstocks (such as hydrogenated palm oil (HPO) or hydrothermal liquefaction of biomass) or synthetic fuels (e-fuels). These may provide alternative options for drop-in fuels for the maritime sector in the future. For this report, FAME and HVO are used a examples of drop-in fuels, based on their higher level of maturity. Figure 4-3 also provides a graphic overview of the key characteristics of candidate fuels assessed in this study to facilitate comparison. For this figure, the cost per GJ values are those used for year 2030 in the cost modelling for this study; further details on their derivation are given in Section 6.2.1.

Figure 4-3 Candidate marine fuel comparison of cost, GHG reduction potential and Technology Readiness Level (TRL) – fuel cost values for year 2030



TRL =Technology readiness level. Cost = production cost of alternative fuel pathway (USD 2020). Costs presented are based on estimates available from the literature. For blue ammonia and hydrogen theoretical costs were calculated based on detailed research rather than data from actual projects. GHG reduction refers to % reduction in Well-to-Wake emissions compared to HFO emission baseline. Maximum potentials are shown with the exception of green ammonia, green hydrogen, green methanol and battery electric. In theory, 100% reduction (or higher) may be achievable with 100% renewable electricity for these fuels; however the timeframe and costs for these production pathways are not clear at present. The processing of manure for the production of BioLNG can capture methane that would otherwise be emitted to the atmosphere. Accounting for this can increase the emissions reduction potential to over 170%.

A key barrier to the widespread uptake of low-carbon alternative fuels (with the possible exception of LNG) is their considerably higher production costs, and hence price to the end-user, compared to conventional maritime fuel. This cost differential will need to be addressed if alternative fuels are to be commercially competitive with conventional fuels.

For many of the candidate fuels, (e.g. green/blue ammonia and hydrogen, green methanol and BioLNG), their GHG emissions hinge on the share of renewables of the electricity used in their production. The exact evolution of renewable electricity in the sources available to fuel producers (whether from the national grid or from their own generation) is not clear at present. To deliver the full potential reductions in GHG emissions, it is important that the electricity used in their production is 100% renewable; fuel produced with other electricity sources may not be truly "green".

In 2017 the global estimated renewable share of total final energy consumption was 10.6% (REN21, 2020). Looking forwards global renewable energy share projections for 2050 vary. The exact share will be highly dependent on geopolitics, national level policies and supply.

For example, in IRENA's 2020 Global Renewables Outlook report, the ambitious deeper decarbonisation perspective projects that the global share of renewable electricity in generation has to rise to 57% by 2030 and 86% by 2050 (IRENA, GLOBAL RENEWABLES OUTLOOK, 2020). In contrast, the Stated Policies Scenario (STEPS) developed by IEA and based on existing and announced policies predicts the global share of modern renewables will reach 15.4% of total final energy consumption in 2030.

Despite this variation, what is clear is that projections indicate increases in renewable energy share and the generation of renewable electricity is growing fast.

The renewable electricity supply (grid mix) and cost will also vary by region and this will impact specific fuel pathways. The international nature of shipping means fuels may be produced all around the world. In this way, the region in which a fuel is produced, impacts its carbon reduction potential. For example, currently the EU has a renewable energy share higher than the global average. In 2019, renewable energy represented 19.7% of energy consumed in the EU and is expected to meet 2020 target of 20% (Eurostat, 2020). The EU's current targets stand at a 32% share by 2030, working towards 1.8%-3.4% annual increases over the period 2030-2050 (from a range of eight scenarios published in the Commission's 2050 long term strategy).The long term objective being 100% renewable energy sources of electricity by 2050 (EEA, 2019).

Further, at least for the initial pilot plants for green fuels, the locations in which the plants are built may be selected because of the local availability of feedstocks and renewable electricity. If this continues as production increases to match future demand, a result could be an increased need to transport maritime fuels from the production facilities to the ports. The additional energy consumption and costs associated with this transport may be reduced by locating production facilities closer to key shipping routes (and to the major maritime ports), provided that this does not result in significant increases in transport costs for the feedstock to the production facility.

As well as cost and renewable electricity availability, fuel characteristics are also important in determining a fuel's suitability and hence uptake. For example, fuels with lower energy densities require a larger volume of storage for a given amount of energy. Key fuel characteristics are summarised in Table 4-2.

Table 4-2: Comparison of fuel properties

Fuel type	Lower heating value (MJ/kg)	Liquid Density at 15°C at 1 bar (kg/l)	Gaseous Density at 0°C at 1 bar (kg/m^3)	Energy density (GJ/m^3)*	Flash point	Auto-ignition temperature
HFO	40.2	0.98	-	39.40	65~80°C	400°C
MGO	42.8	0.855	-	36.59	>60°C	232°C
LNG	48.6	-	0.742	0.04	-175°C	537°C
LPG	45.5	-	1.986	0.09	-104°C	470°C
Methanol	19.9	0.791	-	15.74	11-12°C	464°C
Ammonia	18.6	-	0.72	0.01	132 °C	651°C
Hydrogen	120.0	-	0.09	0.01	-	560°C

Fuel type	Lower heating value (MJ/kg)	Liquid Density at 15°C at 1 bar (kg/l)	Gaseous Density at 0°C at 1 bar (kg/m^3)	Energy density (GJ/m^3)*	Flash point	Auto-ignition temperature
Methane (BioLNG)	48.6	-	0.742	0.04	-175 °C	537°C
FAME	37.2	0.88	-	32.74	173°C	261°C
HVO	34.0	0.78	-	40.48	55 °C	204°C

**for liquids presented at 15°C at 1 bar and for gases presented at 0°C at 1 bar*

4.1.1 Liquefied natural gas (LNG)

LNG
GHG performance and production route emissions
• **Well-to-tank:** Emissions estimated at 18.5 g CO_2eq/MJ (Thinkstep, 2019). • **Tank-to-wake:** Variation between studies. Some indicate GHG reduction levels up to 26% compared to traditional marine fuels (DNV GL, 2019) (American Bureau of Shipping, 2019), whilst others indicate no climate benefit of LNG compared to HFO (ICCT, 2020) once emissions of unburnt methane (methane slip) are taken into account (Lutsey et al, 2013). Most recent high-pressure engines are considered to reduce methane slip to very low levels. • **Expected Well-to-wake GHG reduction potential:** 10.4% for a *global average* production pathway (Thinkstep, 2019). Emissions reduction for BioLNG depends on the production pathway; 69% for biomethane production using liquid manure and closed digestate storage (Verbeek, 2015)[39] .
Production pathway availability
• Commercially mature.
Compatibility and technology
• The technology needed to use LNG as a maritime fuel is commercially available and mature (TRL=9). • By the end of 2019 the LNG fleet encompassed 601 vessels (Statista, 2021). • Methane slip could be reduced through new technologies, for example through Intelligent Control by Exhaust Recycling (iCER). This recirculates methane to reduce the amount that is left in the exhaust system (Vessel Performance Optimisation, 2021). Also, the latest high-pressure diesel-cycle engines produce low levels of methane emissions.
Infrastructure
• Global infrastructure is growing but remains a limitation. Over 40 European coastal ports have LNG bunkering in operation; 10 more in the Australasia/Middle East region. In the EU by 2025 more than 100 bunkering facilities should be available; at least 15 projects are under development in the Australasia/Middle East regions; projects under development across the USA as well (Gulf of Mexico, Southeast region and Pacific Northwest). Delivery by rail or truck is also possible. • Rules on LNG bunkering have been developed locally at each port, however harmonisation is lacking. consistent port-level bunkering regulation has not been established, which may cause information barriers
Storage & handling
• **Low energy density**: LNG requires more storage-tank volume than HFO for the same range. • **Cryogenic storage handling:** LNG fuel supply and containment systems require three or four more times on board deck space, as the spatial arrangement of cryogenic tanks involves specific segregation distances between cryogenic tanks. • **Flammability;** gas under pressure: More crew training is needed to ensure safety requirements are reached. It is also critical that safeguards prevent a flammable mixture from occurring and that ignition sources are far way (American Bureau of Shipping, 2019).
Supply
• Global LNG demand for all sources in 2019 ~360 Mt, and expected to double by 2040 (Shell, 2020) Available worldwide (at large-scale import and export terminals). Further investments underway to improve availability (DNV GL, 2019). • Total global shipping LNG consumption in 2018 ~11.4 Mt (HFO equivalent Mt) (IMO, 2020) the most widely consumed fuel in the maritime sector other than HFO and MDO.
Cost
• LNG prices are similar to conventional fuels (on a per unit of energy basis.) • Capital costs and operational costs remain significantly higher for LNG compared to conventional fuels.

[39] The differences are due to feedstock. Biomethane using liquid manure can be seen as producing negative emissions if viewed as avoiding methane emissions.

Other environmental impacts
• Near zero SOx emissions and lower particulate matter compared to HFO. • Significantly lower NOx emissions, allowing spark ignition (Otto cycle) engines to meet IMO Tier III regulation without exhaust aftertreatments. Diesel-cycle gas-fuelled engines require aftertreatment to meet Tier III. • During LNG storage and transportation heat enters the cryogenic tank which results in a part of the LNG in the tank continuously evaporating, referred to as Boil-Off Gas (BOG). Tank pressure and temperature are maintained by means of oxidizing BOG in a gas combustion unit (e.g. the vessel engine) or via re-liquefication. BOG is not normally vented to atmosphere. (Tagliaferri et al, 2017) • Depending on the design of the engine (combustion pressure and fuel injection design), combustion of LNG may result in some gas escaping to atmosphere without being combusted, known as methane slip. High pressure engine design can be effective at reducing methane slip to very low levels.
Remaining challenges
• Fugitive methane emissions, being addressed by IMO.

4.1.1.1 LNG drop-in fuels

LNG powered ships could also use LNG-compatible drop-in fuels in the future. Liquefied bio-methane (“BioLNG”) and liquefied synthetic methane (LSM) have recently been shown to be compatible with LNG fuelled ships without requiring major modifications (CE Delft, 2020). BioLNG can be used in existing LNG engines with little, or no, modification and transported, stored and bunkered in ports utilising existing LNG infrastructure (EBA, SEA-LNG, GIE and NGVA, 2020).

Some key examples of commercial applications where BioLNG is already being supplied include; CM-CGM’s container ship Jacques Saadé (13% BioLNG), ESL Shipping’s dry bulk carrier m/s Viiki, Preem’s two tankers (10% BioLNG blend), and Destination Gotland’s two high-speed ropax ferries that are both using a BioLNG blend (EBA, SEA-LNG, GIE and NGVA, 2020).

BioLNG demand volume for maritime shipping by 2030 is expected to increase, although opinions diverge on feedstock availability and allocation between sectors. Whilst future demand varies according to different projects, in the CE Delft study, under a scenario where national policies proceed in line with Paris agreement commitments, 30% of LNG is replaced by BioLNG by 2030.

BioLNG can be produced through anaerobic digestion or gasification. The majority of anaerobic digestion technologies (e.g. manure digestion) are commercially mature. The digestate pathways are available now. BioLNG from municipal waste production is already regionally present in/near some ports, such as Rotterdam and Bristol (CE Delft, 2018) (GENECO, 2020). In contrast, gasification technologies are not as commercially mature and demonstration units are only available at a semi-commercial scale.

The CE Delft analysis of the global sustainable biomass resource showed that biomethane from energy crops, agricultural residues, forestry products and residues could already exceed the global total energy demand of the maritime sector. However, this does not include potential competition from other transport modes.

Another feedstock that can be used to produce BioLNG is liquid manure. This BioLNG production pathway has been identified in the literature as having very high GHG reduction potential. In 2018, global biogas production from animal manure feedstocks reached 11Mtoe (IEA, 2020).

BioLNG production emissions are estimated as follows:

- Well-to-tank: Emissions estimated at 26.5 g CO_2eq/MJ (JRC, EUCAR and Concawe, 2020)
- Tank-to-wake: Variation between on GHG savings and depend on methane accounting and production technology
- Expected Well-to-wake GHG reduction potential: 70% for liquid manure (closed digestate storage) production pathway (calculated using WTW emissions above)..

4.1.2 Liquefied petroleum gas (LPG)

Liquefied petroleum gas (LPG) is a by-product of oil and gas production / oil refining processes. It is a mixture of mainly butane and propane. LPG is already available globally (HellenicShipping, 2020).

LPG
GHG performance and production route emissions
• Well-to-tank: Emissions are highly dependent on the source (natural gas, petroleum), ranging from about 8g CO_2eq/MJ to 13g CO_2eq/MJ). • Tank-to-wake: Emissions estimated at 65.4g CO2eq/MJ (JRC, EUCAR and Concawe, 2020) • *Expected Well-to-wake GHG reduction potential: 16% for natural gas derived LPG production pathway (calculated using* (JRC, EUCAR and Concawe, 2020)*)*
Production pathway availability
• Both conventional natural gas and petroleum derived LPG production pathways are available now.
Compatibility and technology
• Engine technologies as well as retrofitting options have been developed for LPG, for example MAN ME-LGI dual fuel engine and Wärtsilä's retrofit LPG Fuel Supply Systems (LFSS) . • Engine developments for LPG have led to new potential for ammonia. Materials used for LPG tanks and systems will in most cases be suitable for ammonia (MAN Energy Solutions, 2019)
Infrastructure
• Terminals still need to be developed into a dedicated network to enable LPG supply where demanded. • Developing LPG bunkering infrastructure, operating systems and equipment, would be less costly than those required for LNG, predominately due to easier handling and storage properties (American Bureau of Shipping, 2019). • Many ports already have LPG import/export terminals, and safety procedures already exist to deal with the substance. • Simple modifications would be needed to adapt existing LPG installations to also become bunkering facilities.
Storage & handling
• **Low energy density**: LPG storage requires three times the volume of HFO for the same energy content. Tanks can be up to 5,000 m^3. However, LPG does not require cryogenic storage. • **Safety and flammability**: LPG is heavier than air, therefore leaks can accumulate in the lower sections of a space. LPG vaporises rapidly and is flammable when the percentage in air is between 1.5-11%.
Supply
• Currently natural gas and petroleum reduction leads to surpluses and an LPG supply ranging from 15 to 27 million tonnes per year. This has driven low prices along with the shale gas revolution (WLPGA, 2017). However, LPG supply remains a barrier. This is because LPG is a by-product and with decreasing future demand for fossil fuels, LPG production will also decrease. Future LPG availability will likely be limited as renewables increase.
Cost
• Between May 2020 and February 2021 the price of propane has ranged from \$0.33 to \$0.92 per gallon (Trading Economics, 2020), equivalent to approximately \$160 to \$440 per tonne[40].
Other environmental impacts
• Emits 90% to 97% less sulphur (SOx), 20% less nitrogen oxide (NOx), 90% less particulate matter (PM)..
Remaining challenges
• LPG was not considered by stakeholders as a viable alternative fuel given the need to transition to lower-carbon fuels. It has a likely limited future supply.

[40] Note: the market price of LPG varies and depends on pressure and temperature

4.1.3 Ammonia

Ammonia
GHG performance and production route emissions
• **Well-to-tank:** Varies depending on production pathway. Traditionally, (grey) ammonia production involves steam reforming, which produces no GHG saving. The production of green ammonia uses renewable electricity powered electrolysis to separate hydrogen from oxygen using electrolysers. • **Tank-to-wake:** No emissions. • **Expected Well-to-wake GHG reduction potential**: 0% for grey *natural gas* ammonia production pathway, 85% for blue *natural gas & CCS* ammonia production pathway and 75% for green *renewable electrolysis* ammonia production pathway (if the electricity is 100% renewable the WTW emissions are zero) (DECHEMA, 2017)
Production pathway availability
• **Electrolysis:** Ammonia production through electrolysis can be achieved with commercially proven equipment (Ash, 2019). These production pathways have not yet become widely available due to renewable electricity costs. However, green ammonia plants are being developed such as the Enaex project in Chile, Incitec Pivot in Australia and the JGC Corporation project in Japan (Ammonia Industry, 2019) (Ammonia Energy Association, 2019). A pilot project by Yara and Nel to reduce electrolyser costs should be in operation in Norway by 2022 (Yara, 2019). Given these developments, there may be wider availability as early as 2025 of the ammonia production pathways using electrolysis. • **High temperature electrolysis:**. This production pathway may not be available until 2030 or beyond. • **Conventional production:** Steam methane reforming using natural gas technology available now but do not offer GHG savings. This production route can be coupled with CCS to make blue ammonia.
Compatibility and technology

• Ammonia can be used in modified internal combustion engines that use spark- or compression-ignition systems. Marine engine supplier MAN Energy Solutions recently embarked in October 2020 on a project to design, develop and demonstrate at full-scale a large marine two-stroke engine running on ammonia as well as an associated fuel supply system. Development of the engine is scheduled for 2024 (MAN Energy Solutions, 2020).
• Various collaborations are researching and developing ammonia-engined vessels, including:
    o Malaysia-based shipowner MISC, Samsung Heavy Industries (SHI), Lloyd's Register and MAN Energy Solutions are developing an ammonia-fuelled tanker (announced early 2020)
    o Japanese shipping company NYK Line, shipbuilder Japan Marine United Corporation (JMU), and ClassNK are aiming to commercialise an ammonia-fuelled ammonia gas carrier and an ammonia floating storage and regasification barge (announced August 2020).
    o **The Nordic Green Ammonia Powered Ships (NoGAPS)** project aims to prove the concept of an ammonia powered vessel and potentially a first demonstration green ammonia powered ship in operation by 2025 (announced May 2020) (Nordic Innovation, 2020).
    o The American Bureau of Shipping (ABS), MAN Energy Solutions and the Shanghai Merchant Ship Design & Research Institute (SDARI) announced a collaboration to produce an ammonia fuelled 2,700 TEU feeder vessel (December 2019) (ABS, 2019)
• Ammonia may not be opted for as a fuel for passenger-carrying vessels due to odour concerns.
• In the longer term, ammonia could potentially be used in fuel cells for propulsion so that even emissions of NOx are eliminated. The ShipFC consortium project was awarded €10m funding in 2020 to deliver the first high-power fuel cell to be powered by green ammonia. The result will be an offshore vessel, named Viking Energy, that can sail solely on the clean fuel for up to 3,000 hours annually by using an ammonia-powered fuel-cell (Equinor, 2020).

Infrastructure
• Currently no bunkering infrastructure for ammonia as a fuel in place. • Dedicated ammonia infrastructure would need to be rolled out. American classification society ABS, Nanyang Technological University (NTU), Singapore, and the Ammonia Safety and Training Institute (ASTI) are investigating supply and safety challenges around bunkering ammonia in Singapore (announced January 2021) (Offshore-Energy, 2021). • While not used as a maritime fuel, ports are already experienced in dealing with ammonia, with facilities available for loading/unloading and safety procedures developed to deal with the substance. • No known efforts to install ammonia as a fuel supplied in ports.

Ammonia (continued)

Storage & handling

- **Corrosion:** Ammonia is corrosive to skin and some substances such as copper, brass and zinc-containing alloys as well as natural rubber and some plastics. Material compatibility requirements are well understood, and it is straightforward to select suitable materials to avoid damage to onboard equipment, piping, valves and other fittings
- **Highly toxic and combustible:** Although also combustible and toxic, safety standards are already understood because it has an existing market as a fertiliser. Stakeholders indicated that no barriers were foreseen that could not be overcome through engineering or safety-based protocols.
- **Low volumetric density**

Supply

- 'Grey' ammonia is already produced in large quantities (~180 Mt/year) for e.g. use in fertiliser; ~11% of this is imported/exported. Ammonia plants are located where natural gas is abundantly available.
- 'Green' ammonia is not currently produced, apart from in demonstration plants. Recent announcements of planned green ammonia plant include a pilot plant producing 0.005 Mt/year in Denmark from 2022 (Skovgaard Invest, Vestas, Haldor Topsoe) and a production plant for 1.2 Mt/year in Saudi Arabia from 2025 (Air Products, ACWA Power, NEOM)
- By comparison, 30% of maritime fuel consumption would be equivalent to ~220 Mt/year of ammonia (based on the calculated total maritime energy consumption in 2020).

Cost

- The cost of building a green ammonia plant varies depending on capacity. Upcoming Air Products hydrogen-based ammonia plant is expected to cost $5 billion (Bloomberg Green, 2020).

Other environmental impacts

- Zero SOx emissions.
- NOx emissions are expected to be similar to conventional fuels (requiring selective catalytic reduction (SCR) to meet Tier III standards) and so are higher than some of the other zero-emitting fuels. Further tests may be required to understand the levels of NOx emissions produced.
- As a nitrogen-containing fuel, there is a potential for increased emissions of nitrous oxide (N_2O). There is currently limited information on the likely scale of such emissions, but there is some indication that they may be lower than conventional diesel engines (Ash, 2019). It is possible that the use of an ammonia slip catalyst could affect N_2O out. Further research is needed to understand this issue better.
- In case of a marine spill, is toxic to aquatic life. Ammonia has a distinct and unpleasant odour.

Remaining challenges

- Establishing first green ammonia production facilities at scale. Potential for regional infrastructure requirements to resolve chicken/egg problem, e.g. in the EU through the Alternative Fuels Infrastructure Directive
- Marine engines are yet to be developed and low pressure injection type engines may produce N_2O.
- Certification of ammonia fuel systems for use on-board vessel, including related safety regulations and guidance (IGF Code needs to be amended to accommodate ammonia as a fuel).
- Certification of blue and green ammonia to differentiate from chemically identical grey ammonia.
- Developing bunkering infrastructure for ammonia at maritime ports.

4.1.4 Hydrogen

Hydrogen

GHG performance and production route emissions

- **Well-to-tank**: Reduction potential of hydrogen hinges on its production emissions as well as other supply chain emissions. Steam methane reforming using natural gas (grey hydrogen) leads to GHG emissions (87.9 g CO2eq/MJ) very similar to the well-to-wake emissions of conventional fuels. However, the production pathway of electrolysis powered by 100% renewable electricity leads to zero GHG emissions.
- **Tank-to-wake:** At the point of combustion (or if used in a fuel cell) – zero GHG emissions
- **Expected Well-to-wake GHG reduction potential:** 0% for grey *natural gas* hydrogen production pathway[41], 84% for blue *natural gas & CCS* hydrogen production pathway and 75% for green *renewable electrolysis* hydrogen production pathway (up to 100% if 100% renewable electricity share) (Ricardo, 2019)

Production pathway availability

- **Natural Gas and Steam Methane Reforming (SMR):** Multiple technologies exist that enable the production of hydrogen from natural gas, but steam methane reforming (SMR) is currently the most widely use and is available today.
- **Renewable Electrolysis:** Electrolysis is a mature technology, but has not been scaled up. The production pathway using the current electricity mix is available today. To be zero-carbon, the electricity should be generated by renewable sources.
- **Gasification (coal and biomass) :** Coal gasification is commercially mature. This broad gasification process can be applied to biomass feedstocks. However, the formation of tar during gasification can be an issue and the technology is less developed (TRL less than 5). Biomass gasification has not yet reached a commercial stage (IEA, 2020).

Compatibility and technology

- Hydrogen can be used in (suitably designed) internal combustion engines and in fuel cells. For example four-stroke engine concepts: Spark-ignited (SI) engines with low-pressure hydrogen admission, and dual-fuel (DF) engines with low-pressure hydrogen and pilot fuel ignition have been developed by MAN Energy Solutions (MAN ES, 2021).
- Fuel production pathway commercially mature, but on-vessel application at scale is not yet widely commissioned or operated (TRL = 3/4/5). Smaller demonstration vessels using hydrogen fuel cells have started (GreenPort, 2020). Demonstrations are underway to improve its use in shipping propulsion and for use as a fuel for longer crossings. The Norwegian Maritime Authority is currently working on the HYBRIDShips innovation project in Trondheim which is developing the world's first hydrogen powered ferry (Norweigan Maritime Authority, 2017).

Infrastructure

- Currently no bunkering infrastructure for hydrogen as a fuel in place. Dedicated infrastructure would need to be rolled out

Storage & handling

- **Cryogenic storage and low density:** For hydrogen the additional required storage is 7.6 times the size of storage required compared to MGO (Ash, 2019). In liquid form, storage tanks for hydrogen can be smaller, but the trade-off this entails is the need for cryogenic storage (-235°C). Because of limited deck space, this is a particular challenge for its application to nonstop, long-distance voyages.
- **Flammable and gas under pressure**
- **Lack of regulation**: The IMO is not currently developing hydrogen-focused requirements, therefore an additional practical constraint may be establishing safe handling of hydrogen. Additional safety measures and optimal design to emphasise ventilation and space configuration are required.

Supply

- Green hydrogen is not currently produced at scale. The recently announced ammonia production plant in Saudi Arabia (Air Products, ACWA Power, NEOM) may also produce green hydrogen.
- The supply of hydrogen hinges on whether current power generation systems can support hydrogen production from renewables. Different levels of national transition to renewables may slow its adoption.

Cost

- Projections suggest production plant capital cost reductions over time, which will lead to lower fuel costs.
- Green hydrogen production capital expenditure has been predicted to decrease to 840 USD$/kW between 2020-2030 with the potential decrease to 200 USD$/kW between 2040-2050 (IRENA, 2019).

[41] As with any of the emissions values presented, there is a level of uncertainty around these emissions savings. As a result, the use of grey hydrogen could produce slightly greater overall emissions than conventional fuels.

Other environmental impacts

- When used in fuel cells, hydrogen leads to zero CO_2, PM, SOx and NOx.
- When hydrogen is combusted in an ICE, NOx is generated.
- Hydrogen is not toxic to aquatic life.

Remaining challenges

- Hydrogen density is a limiting factor on vessel range, but new developments indicate with minor changes such as one additional port call, major shipping route voyages could be completed with hydrogen as a fuel (ICCT, 2020).
- Developing bunkering infrastructure for hydrogen at maritime ports.

4.1.5 Methanol

Methanol

GHG performance and production route emissions

- **Well-to-tank**: Varies depending on production pathway (whether grey or green) Currently, methanol is mainly produced from natural gas but can be produced from a number of different feedstock resources, these can be renewable such as black liquor from pulp and paper mills, agricultural waste or forest thinning, or even directly from CO_2 that is captured from power plants (DNV GL, 2019). If electricity is provided by the grid is 100% renewable the CO_2 emissions of this production pathway are zero.
- **Tank-to-wake:** Emissions estimated 22.2g CO2eq/MJ (Winebrake, 2018) (Nyári, 2018)
- **Expected Well-to-wake GHG reduction potential:** 0% for grey *natural gas* methanol production pathway, and 92% for green *synthetic (renewable)* methanol production pathway (Winebrake, 2018) (Nyári, 2018)

Production pathway availability

- **Conventional production:** Natural gas and coal-based pathways are available now.
- **Biomass gasification:** Methanol derived from biomass expected to be available from 2030 (IEA, 2020).
- **Flared and landfill gas production:** Methanol flared gas and landfill gas will most likely not be available until 2030. Small scale pilot projects such as the Primus Green Energy Methanol demonstration plant are underway. This process being is suitable for deployment with landfill and flared gas (Mazanec, 2016)). (Primus Green Energy, 2020)
- **Synthetic production:** Commercially available now at limited scale – a renewable methanol plant (Carbon Recycling International) in Iceland delivering industrial scale synthetic methanol since 2012, demonstrates feasibility. Significant expansion would be required to meet maritime fuel demand.

Compatibility and technology.

- Green (synthetic) methanol production and methanol vessel technology has been achieved.
- Commercial deployment has been achieved but mostly for vessels carrying methanol and using methanol produced by conventional methanol production (from fossil fuels).
- Dual methanol-HFO engines are already commercially available. Methanol can be used either in a two-stroke diesel-cycle engine or a four-stroke, lean-burn Otto-cycle engine.
- There are various example of newbuild vessels running on methanol: in 2020 Waterfront Shipping confirmed the addition of eight newbuild methanol-fuelled tankers to its fleet. Retrofitting is also a possibility with RoPax, Stena Germanica, vessel being the first vessel to be retrofitted to burn methanol (American Bureau of Shipping, 2019).

Infrastructure

- Methanol has extensive established chemical industry infrastructure (Methanex, 2020). This is an advantage, as this existing infrastructure could be leveraged and extended for distribution to marine terminals and port (DNV GL, 2019).
- In 2017 the first methanol infrastructure for shipping supply chain was successfully established in Germany.
- While not used as a maritime fuel, ports are already experienced in dealing with methanol, with facilities available for loading/unloading and safety procedures developed to deal with the substance.
- Limited/no bunkering infrastructure for methanol as a fuel in place. Simple modifications to current bunkering infrastructure would be needed.

Storage & handling

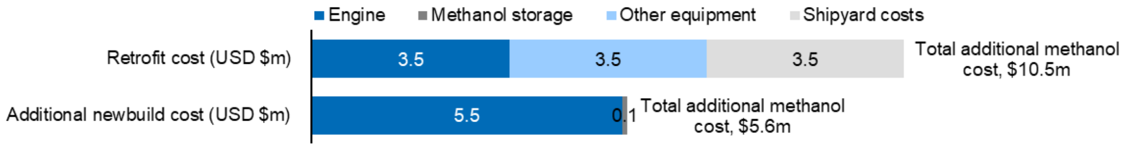
- **Low energy density:** Methanol still requires 2.3 times more storage volume than conventional fuels for the same energy content (Ash, 2019).
- **Safety regulations are required**: Methanol has a low flashpoint, is flammable, has acute toxicity and causes specific target organ toxicity. Methanol is not covered by current IGF Code, although in September 2018, the IMO sub-committee on carriage of cargos and containers indicated its intention to draft interim guidelines for ships using methanol or ethanol fuels[42]. Understanding the characteristics and properties of low flashpoint methanol gas is key to minimise safety hazards associated with its alternative use as a marine fuel.
- **Methanol vapour leaks**: For the fuel supply system, consideration is also needed in terms of methanol leakage. Methanol vapour is heavier than air and leaks can accumulate in the bilges or low sections of a space. Double-walled piping should be installed and the use of nitrogen as inert gas in the fuel storage tank itself could also be an additional safety measure (Offshore Energy, 2018)

Supply and demand

- As methanol is already produced for other industries, globally it has a high annual production, with over 80m t/y of production in 2018.
- Maritime sector used ~0.16 Mt methanol (HFO-equivalent Mt) as fuel in 2018 (International Maritime Organization, 2020)

Cost

- Between 2017-2020 global methanol prices varied from $220 to $500 USD per tonne. The $220 minimum value was during the COVID-19 pandemic (MMSA , 2020).
- The investment cost for a methanol plant varies from 200-1200 € /kW fuel.
- Approximate additional costs for a newbuild and a retrofit methanol RoRo vessel with 24 MW main engine power and tank capacity for 3 days of sailing (IMO, 2016):



Other environmental impacts

- Methanol is readily dissolvable in water, which from an environmental perspective means it could lessen potential impacts from spills (American Bureau of Shipping, 2019).
- NOx emissions upon combustion require SCR or EGR systems to be used (DNV GL, 2019)
- Although methanol is not as toxic as ammonia, it still presents health hazards to humans.

Remaining challenges

- Scaling up of methanol production, in particular securing supply of *green* / *blue* methanol.
- Ensuring adequate port bunkering infrastructure of methanol.

4.1.6 Biofuels (FAME and HVO)

Currently, biofuels are not widely used in shipping. In Europe, almost all biofuels are consumed in the road transport sector (ECOFYS, 2019). Whilst their use in shipping and aviation is currently negligible, several of the world's largest container shipping companies are exploring or using biofuels, and this use is growing. Examples include; Maersk's 2019 pilot of a vessel sailing solely on a second–generation biofuel blend that has yielded positive results (Maersk, 2019), MSC Group's successful trials that were completed with a minimum 10% blend fuel that paved the way for the company to now use much higher (30%) blends (MSC, 2019), and Hapag Lloyd's successful trial using "B20" fuel, which consists of 80 percent low-sulphur fuel oil and 20 percent biodiesel based on cooking oils and fats (Hapag-LLoyd, 2020)

[42] https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/CCC-5-5th-session.aspx

Two major biofuels used in biofuel blends include Fatty Acid Methyl Esters (FAME) and Hydrotreated vegetable oils (HVO). Other examples of drop-in fuels are under development, such as alternative conversion pathways based on similar biological feedstocks (such as hydrogenated palm oil (HPO) or hydrothermal liquefaction of biomass) or synthetic fuels (e-fuels). These may provide alternative options for drop-in fuels for the maritime sector in the future. For this report, FAME and HVO were selected as biofuel examples based on their higher level of maturity.

FAME consists of esters of fatty acids. FAME is produced from vegetable oils, animal fats or waste cooking oils by transesterification, and has properties similar to conventional diesel (Swedish Knowledge Centre for Renewable Transportation Fuels (F3), 2017). FAME is often referred to as renewable biodiesel and depending on feedstock, could have GHG reduction potential when used as a marine fuel compared to HFO.

HVO is also known as hydrotreated esters and fatty acids (HEFA). HVO is a high-quality fuel in which the oxygen has been removed using hydrogen, which results in long-term stability. HVO is free of sulphur and aromatics and usually consists of vegetable oils or animal fats that have undergone hydroprocessing and refining, in the presence of a catalyst. HVO is considered as a fuel that can substitute HFO and reduce GHG emissions and SOx (IEA Bioenergy, 2017).

FAME	HVO
GHG performance and production route emissions	
• **Well-to-tank:** Depend on feedstock and allocations (indirect and direct land use change) (as high as to 111gCO_2eq/MJ for rapeseed feedstock) (European Commission, 2013) • **Well-to-wake:** Estimated at 13.8g CO_2eq/MJ (Verbeek, 2015). Includes zero TTW emissions as they are offset by the absorption from the atmosphere by the feedstock crop. • **Expected Well-to-wake GHG reduction potential:** 84% for *waste cooking oil FAME* production pathway (Verbeek, 2015) as pure (unblended) FAME.	• **Well-to-tank:** Depend on feedstock and allocations (indirect and direct land use change) (as high as 112 gCO_2eq/MJ for rapeseed feedstock) (European Commission, 2013) • **Well-to-wake:** Estimated at 8.1g CO_2eq/MJ (Verbeek, 2015). Includes zero TTW emissions as they are offset by the absorption from the atmosphere by the feedstock crop. • **Expected Well-to-wake GHG reduction potential:** 91% for *waste cooking oil HVO* production pathway (Verbeek, 2015) as pure (unblended) HVO.
Production pathway availability	
• **Transesterification**: FAME production is already at a commercial scale. All FAME feedstock production pathways are available now.	• **Hydroprocessing/Hydrotreatment**: Production is already at commercial scale. HVO can also be produced in oil refineries, as they are already equipped with hydrotreating facilities. • **Transesterification**: All HVO purification and transesterification production pathways are available now.
Compatibility and technology	
• FAME in blends with conventional marine fuels such as HFO has been proven as compatible in blends containing up to 20% FAME. • Higher FAME blends have not yet been widely deployed and their uptake towards 2050 is not foreseen • Higher blends require engine modernisation, maintenance adaptations and fuel system modifications (Moirangthem et al, 2016).	• Drop-in fuel and no upper limit for blend-in of HVO according to the ISO 8217:2017 fuel standard, i.e. up to 100%. • Despite engine compatibility, currently there is limited commercial application of HVO in the shipping sector and low bunkering availability. • Algal oils could be hydrotreated and would also function as a non-sulphur ‘drop-in’ fuels. However, algae biofuel companies are still in the technology development phase.
Infrastructure	
• Not an issue as drop-in fuel	• Not an issue as drop-in fuel
Storage & handling	
• Few requirements: Low FAME blends should be able to be stored and handled in the same storage and machinery as that used for conventional marine distillate fuels	• Due to the hydrogenation process all of the oxygen from the feedstock is removed therefore HVO can be stored for longer and there is less of a chance of fuel oxidation (IEA Bioenergy, 2017).

FAME	HVO
• Short degradation time: can be negative for long-term storage, due to producing corrosive hydrogen sulphide than can corrode metal storage tanks. Fast degradation in water can reduce the environmental impacts of oil spills (American Bureau of Shipping, 2019). • Potential oxidation - loss of lubrication which may cause wear and require anti-static additives.	• HVO has a higher fuel efficiency which is attributed to its almost zero oxygen content (Dimitriadis, 2018).
Supply	
• The current FAME production could satisfy just under 60% of the energy needs of the maritime sector (DNV GL, 2019). However, real FAME supply is likely to be lower when factoring in direct and indirect land use change as well as competition from other sectors • The potential supply of sustainable renewable diesel (including both FAME and HVO) is estimated to be 10-20 Mt per annum (IEA Bioenergy, 2017).	• Production of HVO is currently concentrated in the US, Singapore, the Netherlands and Finland with ~4.5 million tonnes (5.5 billion litres) of HVO produced in 2017 (SEA LNG Ltd, 2019). • Currently, HVO fuel volumes required to support short and long-distance maritime energy demand are not sufficient (SEA LNG Ltd, 2019). • The potential supply of sustainable renewable diesel (including both FAME and HVO) is estimated to be 10-20 Mt per annum (IEA Bioenergy, 2017).
Cost	
• The 2020 price of FAME per metric tonne has been estimated at ~ 1180 /tonne according to Neste data and stakeholder inputs.	• The 2020 price of HVO is ~ $1600/ tonne according to stakeholder inputs and average from S&P Global Platts. Production process of HVO is typically more costly than for FAME.
Other environmental impacts	
• FAME is not toxic. • The sulphur content of FAME is very low • Exhaust gas treatment systems needed to control NOx and PM. • Indirect land use change impacts	• HVO is not toxic. • Near zero sulphur content and hence emissions. • Exhaust gas treatment systems needed to control NOx and PM. • Indirect land use change impacts
Remaining challenges	
• Availability of supply • Biofuel competition with sectors such as aviation • Difficulty in ensuring sustainability of feedstock	• Availability of supply • Biofuel competition with sectors such as aviation • Difficulty in ensuring sustainability of feedstock

For both FAME and HVO, a significant issue is ensuring the sustainability of feedstocks. After factoring direct land use change (LUC) and indirect land use change (ILUC), the supply of sustainably produced FAME and HVO are likely to be lower than estimates in the literature. This is because a major challenge is securing a sustainable feedstock supply, which is particularly pronounced given the global nature of the shipping sector. Global shipping fuel consumption has been estimated at ~339 Mt/year according to the Fourth IMO Greenhouse Gas Study (International Maritime Organization, 2014). However, the potential supply of sustainable renewable diesel is estimated to be 10-20 Mt per annum, and these current renewable diesel type fuels are mainly produced from plant-based oils or products thereof, such as used cooking oil (UCO) (IEA Bioenergy, 2017). Other biofuel technology such as algae-based third generation fuels are not at a technological level that enables long term projections of their supply potential. Further information on the sustainability of biomass supply for biofuel production is given in the box below.

Sustainable biomass supply

Global primary energy supply from biomass is currently around 53 exajoules (EJ) per year, reduced to around 25 EJ if traditional uses of biomass are excluded (Sustainable Ship Initiative, 2019), (International Energy Agency, 2017). Biofuels used in road transport only account for around 3.6 EJ of this total, and for shipping this value is far lower. The fuel production pathways of many of the fuels covered in this report (including FAME, HVO, DME, Ammonia), have different levels of scalability towards 2050 depending on biomass availability.

How much sustainable biomass supply may become available by 2050?

A range of studies have estimated future biomass supply and many of these values depend on key assumptions made. The table below highlights this variation and summarises total biomass availability of different feedstock under different scenarios (Sustainable Ship Initiative, 2019). Nevertheless, despite this variation, there is a level of agreement in the literature that about 50-100 EJ per year of bioenergy could be produced sustainably.

Source	Total availability (EJ /yr)	Energy crops	Municipal solid wastes	Agricultural Residues	Forestry (including residues)
UK CCC (2050)	14-84	4-57	-	3-12	7-15
IEA (2060)	131-240	60-100	10-15	46-95	15-30
Energy Transition Commission (2050)	70	Excluded	10	45	15

Source: (Sustainable Ship Initiative, 2019)

Projected availability also varies by feedstock type (IEA Bioenergy, 2020):

- **Municipal wastes (MSW):** global supplies are more limited than some other feedstock types.
- **Forestry (including residues)**: much larger supplies of wastes and residues from forestry and agriculture are expected in the coming years than currently available.
- **Agricultural residues:** Much larger supplies of wastes and residues agriculture are expected than currently available.
- **Energy crops:** There is considerable scope for raw material supply from crops that can be co-produced with food crops or using contaminated or abandoned land[43]. However, ensuring sustainability is a challenge and the crops must be produced on land in ways which do not threaten food crop availability/security.

How would this meet the demands of the shipping sector?

Global shipping fuel consumption has been estimated at ~339 Mt/year according to the Fourth IMO Greenhouse Gas Study (International Maritime Organization, 2014). One tonne of HFO contains ~42 GJ of energy, hence the energy needs of the total shipping sector from recent years is ~14 EJ/year, which could increase to ~19 EJ/year by 2050 according to the upper trajectory in the IMO 4th GHG study.

If 50 to 100 EJ of sustainable bio-feedstock becomes available, it is difficult to anticipate what proportions this will be demanded by different sectors. However, it is clear that the cumulative energy demands from other sectors aviation, road transport and construction will far exceed ~50-100 EJ. Although, in reality, this energy demand may be lower if the road transport sector electrifies. Even if shipping's demand remains below the reasonable supply range of 50-100EJ/year by 2050, meeting all sectors' demands with the projected available biomass will be extremely challenging (Sustainable Ship Initiative, 2019). The European Commission Joint Research Centre also publishes estimates of European biomass availability through its ENSPRESO database (European Commission, Joint Research Centre, 2019), with an estimated 12.3EJ of biomass available across Europe in 2050.

Given the differing fuel quality requirements for different transport modes (at least based on current engine technologies), with aviation requiring the highest fuel quality and maritime the lowest, with their associated cost implications, there may be scope for differentiating the demand for feedstock and processing for the different transport modes by quality and processing costs.

The SSI (2019) inquiry into the Sustainability and Availability of Biofuels for Shipping asked stakeholders their views. The majority agreed that 10-30% of shipping's energy needs could be met by biofuels in 2030 to 2050 (those stakeholders with responses of over 50% represented outliers). The stakeholders also anticipated that biofuel use would be higher in 2030 than 2050, implying this is a short rather than long-term solution. This is consistent with the findings of this study, although the achievement of high levels of biofuel availability by 2030 will be highly dependent on the availability of feedstock and the development of commercial production facilities.

[43] This list can be expanded to include unused, degraded, marginal and fallow land.

4.1.7 Batteries

Batteries

GHG performance and production route emissions

- The energy efficiency of electric propulsion systems can exceed 90%, compared to about 40% for conventional propulsion with diesel engines (American Bureau of Shipping, 2019).
- Zero tailpipe emissions (of e.g. CO_2, NOx and SOx) of pure battery-electric vessels; reduced tailpipe emissions of hybrid (battery and diesel) configurations.
- Life cycle emissions of batteries accounts for energy intensive battery manufacture. CO_2e emissions of battery RoRo passenger vessel are estimated to be two thirds lower than an equivalent diesel vessel (Perčić, 2020).

Compatibility and technology

- Battery powered vessels use electric motors, and may be used in diesel-electric propulsion, hybrid propulsion or all-electric battery drive systems. Examples of battery hybrid vessels: RoRo Stena Jutlandica.
- Fully electric operation of vessels is currently only technically feasible for short-sea shipping / smaller vessel types that have lower power demands. This limitation is likely to remain in the future: Stena announced in February 2021 a launch of battery electric Ro-Pax vessels by 2030 (60,000–70,000 kWh, 50nm range). With current and anticipated battery technology the size and weight of batteries needed to supply the power demands of a trans-oceanic voyage would sink the vessel. For deep-sea shipping, increased uptake of hybrid systems or use of battery-electric for auxiliary power only appears more likely.
- TRL 9 with examples of fully electric (small) vessels: 70m Ro-Ro ferry 'Ellen' in Denmark (2019; 4300 kWh; 22 nm range); 80m car ferry 'Ampere' in Norway (2015; 1,000kWh); 70m 120 TEU container vessel 'Yara Birkeland' (2020; 9,000 kWh; 30nm range).

Infrastructure

- Shore power required to recharge ship batteries when in port. This is an additional demand beyond that considered when designing the current shore power systems which are typically sized to replace the auxiliary engine supply.
- Onshore power is now available at many ports. In 2020, around 58% of European ports offered onshore power supplies, up from 53% in 2019, with 46% of those (i.e. 27% of all ports) offering high-voltage supplies (suitable for larger vessels) (ESPO, 2020). Given public pressure for cleaner air around ports, it is expected that the number of ports making onshore power available will continue to grow, regardless of the adoption of electric-powered ships. Limited electrical capacity and space at port to allow ships to fully charge could be an issue.

Storage & handling

- **Thermal runaway** remains the largest risk related to the use of lithium ion batteries, which can lead to fires and explosions (Ship Technology Global, 2018). In 2019, a fire on the car ferry MF Ytteroyningen highlighted the need for improved battery fire safety in the industry (GCaptain, 2019). Whilst classification and standardisation societies help ensure the quality control of systems, this remains a key safety issue.
- **Inadequate space** for retrofitting existing ships with batteries and associated machinery for an electric propulsion system. The additional weight and spatial arrangement of the battery system means ship stability will most likely need to be recalculated and adjusted, and the hull structure reconfigured.

Supply

- Maritime demand for batteries currently represents <1% of global lithium-ion battery production.
- However, one pure battery electric transoceanic ship would require battery capacity of about 15 GWh. For comparison, this is approximately one third of the Tesla Gigafactory annual output; therefore the supply of battery capacity for significant maritime industry take-up would impact significantly on global production.

Cost

- Battery cost has previously been a large barrier to electric powered ships. For a trans-oceanic pure-battery ship, the cost of the battery alone with present day technology could exceed the cost of the rest of ship.
- With battery technology development, and with scale, battery prices are however decreasing rapidly due to demand from the automotive and consumer electronics sectors (American Bureau of Shipping, 2019): lithium ion batteries have halved in price since 2016.
- But, as well as the battery itself, large scale installations in ships also require battery control hardware and software, system integration, thermal management and power electronics. These costs are often significant with the system integration cost of the battery system sometimes equivalent to the cost of the battery system itself (American Bureau of Shipping, 2019).

Batteries (continued)

Other environmental impacts

- Require large quantities of mined material, which can have both environmental and human rights considerations.
- Depleted lithium-ion cells can also cause environmental degradation if not correctly recycled.
- Electrifying cargo ships could significantly accelerate this problem if the recycling industry is not ready to handle a rapid increase in depleted lithium-ion cells, which entail several storage and handling challenges
- Current problems with end-of-life stage vessels being inappropriately dumped on Indian and Pakistani beaches (as highlighted by the NGO Shipbreaking Platform) could be exacerbated by a switch from fossil-fuel engine based vessels to lithium-ion battery powered vessels leading to potential exposure to toxic chemicals (NGO Shipbreaking Platform, 2020)

Remaining challenges

- Reductions in battery size, weight, and cost.
- Shore power systems to provide enough capacity to recharge as well as displace auxiliary engine hotel load.

4.1.8 Fuel cells

Fuel cells

GHG performance and production route emissions

- Fuel cells offer the potential for zero tailpipe emission operation. This is because, if the fuel used is hydrogen, the only products of fuel cell reactions are water, electricity and excess heat. However the emissions depend on the fuel used to power the fuel cell. Using LNG or methanol will produce CO_2 emissions unless a carbon capture system is installed.

Compatibility and technology

The fuel used to power fuel cells is usually hydrogen, but other fuels can be used (e.g. LNG, methanol and ammonia) (UMAS, 2016). To date, different fuel cell types with distinct characteristics have been developed, including:

- **Low and high temperature polymer electrolyte membrane fuel cell (LT/HT-PEMFC),** also known as proton exchange membrane.
- **Solid oxide fuel cell (SOFC)**
- **Phosphoric acid fuel cell (PAFC)**
- **Molten carbonate fuel cell (MCFC)**

Fuel cells would likely need significant battery electric capability to operate successfully in a ship system, allowing for load variation. Fuel cells also require their own storage systems and equipment. Corvus Energy and Toyota are set to start development and production of sustainable, large scale maritime-certified hydrogen fuel cell systems which will be located in Norway. The development is expected to showcase its first marine fuel cell system onboard a vessel in 2023 with the product marine certified and ready for commercial delivery from 2024 (Corvus Energy, 2021).

Storage & handling

Main fuel cell considerations:

- **Complex support and control systems** and unfamiliarity with handling procedures means adequate training and safety precautions are needed when transitioning to using fuel cells.
- **Size and weight:** The combined size and weight of fuel cells and their associated support systems and fuel storage (of e.g. hydrogen, ammonia) is higher than that of an internal combustion engine.
- **Longevity of fuel cells**: shorter lifetimes than diesel engines, particular in harsher marine environments. The exchange of individual fuel cells within a fuel cell stack could help to alleviate this technological concern, but cost may still be an issue.

Supply

- The supply electrofuels requires transportation to site for fuel cell use as well as production and distribution. Current bunkering stations and distributional networks are at different levels of maturity for some of these fuels. See respective sections 4.1.1 (LNG), 4.1.4 (hydrogen), 4.1.3 (ammonia), and 4.1.5 (methanol). Scaling up of the fuel cells to the capacities required for large vessels is a challenge.
- Solid oxide fuel cells (necessary for using ammonia) are not yet commercially available (Ash, 2019).
- Lack of access to bunkering facilities may also prove a challenge if journeys are in areas without adequate production and distribution networks for the fuels powering the fuel cells.

Fuel cells
Cost
• Cost remains a key barrier to fuel cell use, and to date, fuel cell systems remain significantly more expensive than ICEs (American Bureau of Shipping, 2019).
Other environmental impacts
• Hydrogen fuel cells have zero emissions. • Ammonia used in low temperature fuel cells can also offer zero NOx emissions (Ash, 2019). However, if ammonia is used in a SOFC which operates at higher temperatures, thermal NOx emissions may occur. • As with batteries, future disposal of fuel cells may cause environmental impacts in relation to ship recycling
Remaining challenges
• Cost, robustness in a harsh marine environment and scaling up

4.2 Vessel design measures

The efficiency of new vessels has improved substantially since the 1980s, primarily driven by the cost of fuel and freight rates (CE Delft, 2016). Nevertheless, there remain vessel design measures offering further GHG reduction potential, through reducing vessel resistance and fuel consumption. The measures are not only for optimisation at the design and build stage of new vessels, but some are also applicable as retrofits to improve existing design.

The GHG reduction potential of each of these measures, as well as the associated costs of the measure per vessel and their TRLs, are summarised in Table 4-3. These measures are mostly technologically mature (TRL 9) and have already been widely implemented with high market penetration (confirmed by stakeholders). Stakeholder feedback highlighted that how much these additional measures will reduce emissions will depend on existing vessel design (Naval architect).

In Table 4-3 (and the subsequent similar measures), the cost estimates are based on information related to the application of the technology in 2020.

Table 4-3: Summary of vessel design measures

Vessel Design Measure	Brief description	GHG reduction potential (%)	Cost of measure (USD $) per vessel	TRL
Optimum ship size dimensions	Large ships tend to be more fuel efficient as they have lower total hull resistance.	**~9%**	Included in total new-build cost	9
Construction weight	Lighter ships are more fuel efficient.	**~9%**		9
Hull dimensions (form optimisation)	The shape and dimension of hulls impact ship resistance. Computational fluid dynamics modelling is used.	**4 - 8%**	$150,000 to $500,000	9
Bulbous bow retrofit	Initial ship design is sometimes optimised for an operating profile different to the operating profile of the vessel at sea. Retrofitting a new bulbous bow may enable fuel savings to be achieved with bespoke bow designs.	**3% - 5%**	$100,000 with additional material cost of $250,000 to $700,000 depending on size	9
Bow thruster tunnel optimisation	Bow thrusters are propulsion devices in the bow or stern of a ship to make manoeuvring easier without using the main propulsion mechanism. Improving their design can reduce drag.	**0.5% - 1%**	~ $10,000	9
Hull coatings	Coatings prevent/reduce the build-up of waste deposits and counteract organic growth, reducing surface friction.	**0.5 - 5%**	$30,000 to $500,000	9
Interceptors	Trim tabs used to optimise trim are horizontally installed at the end of the vessel. The interceptor reduces resistance and controls the trim by changing the interceptor height.	**1 - 5%**	-	9/8
Ducktail waterline extension	Lengthening the stern of a ship reduces the resistance of the ship.	**3 - 7%**	-	9
Air lubrication	The pumping of compressed air into a recess in the bottom of the ship's hull. The entrained air reduces frictional resistance between the hull and the water, reducing propulsion power demand.	**7%**	$130,000 to $3,380,000	7/8/9
Ballast reduction and trim optimisation	By effectively loading cargo, vessel trim and/or draft can be optimised to reduce hull resistance. In order to effectively optimise the trim and draft, additional equipment is necessary such as a better loading computer or a dedicated trim optimiser.	**0.5 - 3%**	$15,000 to $75,000	9
Ballast free vessel design	An extension to ballast reduction is the ballast free ship concept. Ballast free designs are based on multi-hull concepts and make use of low-weight materials such as composite thermoplastics and aluminium. Through the reduced weight this leads to emissions savings.	**~9%**	Included in total new-build cost	5/6/7

Sources : (Ciuffo, Giovine, Marra, & Miola, 2010) (International Maritime Organization, 2009) (GloMEEP IMO, 2015)

4.3 Power assistance measures

Alternative power sources reduce GHG emissions by reducing main engine power demand. Table 4-4 summarises such power assistance technologies. Most alternative propulsion and power assistance technologies are not yet widely implemented (confirmed with stakeholders).

The wind power assistance measures require integration with weather / fleet / logistics and voyage optimisation software, to maximise overall voyage fuel consumption reduction. Fuel savings that can be achieved from wind-assistance technologies depend on ship design, operating speed, and the wind speeds and directions experienced (Rehmatulla et al, 2017). In general, wind assistance measures can be applied with slow steaming (International Transport Forum, 2018) because wind propulsion is most effective at slow speed.

Table 4-4: Summary of power assistance measures

Power assistance technology	Brief description	GHG reduction potential (%)	Cost of measure (USD $) for one vessel	TRL
Flettner rotors	Cylindrical rotors placed on the deck are spun using an electric motor to capitalise of the Magnus effect.	10-30%	$1,000,000 - $3,000,000 (for typical delivery with multiple rotor sails, a single rotor is $400,000 to $950,000)	9
Towing kites	Dynamic kites installed on a ship's bow to make use of higher-altitude winds.	1-5%	$280,000 -$2,590,000* (installation cost)	7/8/9
Sails	Fixed installations in the form of a flexible sail, rigid sail or turbosail.	6%	$300,000-$1,000,000 (installation and mast)	9
Solar panels	Use of conventional solar panels on top deck roofs to replace some of the power generated by auxiliary engines.	1.25% (of auxiliary engine fuel consumption**)	~$1,400,000	9
Shore power supply	Shoreside electrical power is provided to a ship whilst it is at berth, so allowing the ship to turn its auxiliary engines off.	50-100%*	$50,000 - $750,000***	8/9

*this reduction is in port only and refers to the reduction of the electrical motors on board
**although overall GHG reduction in practice may be less (~0.1%).
***this cost excludes the costs for ports of fitting the connection and power provision
Sources: (Ciuffo, Giovine, Marra, & Miola, 2010) (International Maritime Organization, 2009) (GloMEEP IMO, 2015)

4.4 Alternative propulsion measures

Several propulsion technologies are currently available on the shipping market. Fixed pitch propellers are currently the most common type and occupy the greatest proportion of the shipping fleet (Royal Academy of Engineering, 2013) (Westshore Marine & Leisure, 2020). However, harnessing alternative propulsion technologies such as Large Area propellers (LAPs), contra-rotating propellers (CRP) and podded thrusters could lead to energy efficiency improvements and GHG emissions reductions. Propulsion improving devices (PIDs) are devices that can help improve vessel hydrodynamics. Much of their effectiveness hinges on original ship design, hull geometry and the operational profile of the vessel. If the existing vessel design has been optimised, the additional savings from these measures are most likely lower than the values reported. Further, applying multiple technologies together (where feasible) may not deliver the total improvement obtained by adding those for the different technologies. The GHG reduction potential, costs and the TRL of these measures are summarised in Table 4-5. Propeller design measures are widely applicable to different vessel types and are already widely implemented (confirmed with stakeholders).

Table 4-5 Summary of alternative propulsion technologies and adaptions measures

<table>
<tr><th>Propulsion technology / adaptations</th><th>Brief Description</th><th>GHG reduction potential (%)</th><th>Cost of measure (USD $) for one vessel</th><th>TRL</th></tr>
<tr><td>Large area propellers (LAP)</td><td>Concept involves moving the propeller towards the stern behind the hull to allow larger propeller diameters to be used.</td><td rowspan="2">2-5%</td><td rowspan="2">$630,000-$2,690,000</td><td rowspan="2">9</td></tr>
<tr><td>Contra rotating propellers (CRP)</td><td>CRP technology improves fuel efficiency because the aft propeller recovers energy loss from the rotational flow behind the fore propeller.</td></tr>
<tr><td>Podded thrusters (PID)</td><td>This propulsion device is external to the ship’s hull and houses a propeller powering capability.</td><td>Up to 15%</td><td>$2,000,000 - $3,000,000</td><td>9</td></tr>
<tr><td>Propellor Ducts (PID)</td><td>Propellor ducts (also known as Kort nozzles) consist of an annular duct that surrounds the propeller (which operates inside the duct). By fitting the propeller with a non-rotating nozzle, the efficiency of the propeller is improved.</td><td>0.5-5%</td><td>$525,000 – $575,000</td><td>9</td></tr>
<tr><td>Pre-swirl (PID)</td><td>There are often substantial rotational energy losses in the propeller slip stream. Pre-swirl PIDS are mounted on the stern boss in front of the propeller. Pre-swirl PIDS optimise flow into the propeller and prevent power losses.</td><td>Up to 10%</td><td>$250,000 – $300,000</td><td>9</td></tr>
<tr><td>Post-swirl fins and rudder bulbs (PID)</td><td>Post-swirl fins and rudder bulbs can recover some of the associated flow energy losses through customised design of the propulsion and steering system.</td><td>0.5-2%</td><td>$100,000 – $150,000 (Boss cap fin)
$250,000 – $300,000 (Costa bulb)</td><td>9</td></tr>
</table>

Sources (GloMEEP IMO, 2015) (Wärtsilä , 2017) (Ciuffo, Giovine, Marra, & Miola, 2010) (ThordonBearings, 2016)

4.5 Engine and aftertreatment technologies

The vast majority of the global maritime fleet is currently powered by diesel cycle engines, either two-stroke or four-stoke cycles, running on heavy fuel oil (HFO) (from 2020 usually a very-low sulphur variant to comply with the IMO 2020 regulation) or a distillate fuel such as marine diesel oil (MDO). The literature survey performed for this study identified a number of "new" technologies with the potential to improve the efficiency of the engines, or the overall energy use of the vessel (Table 4-6). However, discussions with industry stakeholders indicated that the technologies were all already implemented in engines when appropriate (with some contributing to reductions in other pollutants, such as NOx, more than CO_2). Marine engine manufacturers indicated that most future reductions in emissions from engines are likely to be achieved through the use of alternative fuels. The engine manufacturers are now putting significant efforts into developing engines compatible with alternative fuels such as hydrogen and ammonia (the engines for these fuels are not included in Table 4-6 as the emissions reductions are achieved through the characteristics of the fuel rather than improved efficiency). Other developments are also underway to address the issue of methane slip from LNG-fuelled engines, including exhaust gas recycling systems and exhaust aftertreatments.

Table 4-6: Summary of engine technologies

Propulsion design / technology	Brief description	GHG reduction potential (%)	Cost of measure (USD $) for one vessel	TRL
Enhanced fuel injection system	Changes to fuel injector design and control parameters (e.g. pressure, timing) to improve mixing of fuel with air; assists in controlling pollutant emissions	-	-	9
Hybrid diesel-electric	Engine configuration in which the diesel engine drives a generator to produce electricity. Vessel propulsion is then achieved by electric motors driving multiple propellers. Can assist in improving flexibility for particular categories of ships (e.g. ferries), but generally less efficient than direct-drive systems on key vessel categories (tankers, bulk carriers, container ships) due to multiple energy conversion processes.	-	-	9
Early intake valve closing	Also known as Miller cycle engines. Early closure of the cylinder intake valve reduces the pumping work required to compress the air in the cylinder, but the normal opening of the exhaust valve allows the full power stroke to be retained. High-pressure turbocharging is used to recover the full engine power output.	-	-	9
Waste heat recovery (WHR)	Extraction of energy (as heat, or electricity through steam turbine or turbo-generator systems) to reduce the use of on-board auxiliary power systems during voyages (and hence their additional emissions). Some waste heat is already used for onboard heading to heat the fuel and the amount of waste heat available reduces significantly at the lower power settings used for slow steaming.	3% - 8%	$5,000,000 to $9,500,000	9

4.6 Carbon capture (CC)

Carbon capture (CC), defined as the collection, transportation and eventual storage or recycling, of carbon dioxide emissions, has been seen as a way to reduce emissions from existing CO_2-creating processes. While most discussions revolve around land-based and stationary CC solutions (a field where there are already many commercial applications and many more under study), more recently there has been a discussion on the potential of onboard CC as a way to reduce emissions in shipping. Onboard CC has potential to help the maritime industry meets its CO_2 reduction targets, but the concept is not well developed enough at this point to be of practical use in the short term. Although several theoretical technological concepts and estimated costs have been put forward, as far as we are aware, only one effort is planning to move to the prototype stage (the HyMethShip project[44]). Another project (from PMW Technology and Houlder (Willson, et al., 2019)) will test the possibility of applying cryogenic CC in the maritime sector. Furthermore, onboard CC has many challenges associated with it. These include the capital and operational costs, space and energy requirements (increases in fuel consumption of up to 20% can be expected) and the effectiveness in capturing CO_2 (can potentially reach 100% but this is untested; 80% is a more realistic expectation).

Table 4-7: Summary of carbon capture emissions reduction and cost

Technology	Brief description	GHG reduction potential (%)	Cost of measure (USD $) for one vessel	TRL
Carbon capture (CC)	Onboard collection of CO_2 emissions resulting from the combustion of carbon-containing fuels	80% carbon capture potential. May be accompanied by up to 20% increase in fuel consumption.	Up to $27,000,000 for an average ship size	5-6

In addition to the feasibility of implementing carbon capture systems on board vessels, the adoption of this technology will also depend on the availability of handling facilities in ports and subsequent storage or use options. Projects are now underway to establish facilities for receiving, and transporting to long-term storage, captured CO_2. These include the Northern Lights[45] project, in which the first phase aims to build a facility with a capacity of 1.5 million tonnes CO_2 per year by mid-2024. In the Netherlands, the project Porthos, based at the port of Rotterdam, also plans to build a facility with a capacity of 2 to 2.5 million tonnes CO_2 per year. Although these projects are not specifically targeted at CO_2 captured on-board vessels, they are indicative of progress being made towards a capability for receiving captured CO_2 at ports and for the subsequent long-term storage of that CO_2.

Expert opinion from Ricardo is that some additional time will be required to build up the complete infrastructure to allow vessels equipped with on-board CC to routinely off-load their captured CO_2; regulations similar to the EU Alternative Fuels Infrastructure Directive[46] (AFID) may be required to ensure a sufficient network of facilities. Even if the on-board technology is technically feasible in advance, initial implementations of the complete system are unlikely before 2030.

There is currently very little information on the potential costs, capital and operational, of facilities for receiving and transporting captured CO_2. A study[47] for the UK Department for Business, Energy and Industrial Strategy (BEIS), identified amortised costs of £10 ($14) per tonne CO_2 if transported by ship and £21 ($29) per tonne CO_2 if transported by pipeline. Averaging these two values gives a cost of $21.62 per tonne CO_2.

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[44] Project website availabe at https://www.hymethship.com/

[45] https://northernlightsccs.com/

[46] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0094&from=EN

[47] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/761762/BEIS_Shipping_CO2.pdf

4.7 Voyage optimisation

New voyage optimisation and operational measures as well as existing measures such as slow-steaming offer GHG reduction potential. The GHG reduction potential, costs and the TRL of these measures are summarised in Table 4-8.

Table 4-8: Summary of vessel operational measures

Propulsion design / technology	Brief description	GHG reduction potential (%)	Cost of measure ($) for one vessel	TRL
Speed reduction (10%)	Speed reduction or 'slow steaming' is an operational practice that reduces fuel consumption (and hence costs and emissions).[48]	10-15%	No investment costs, but may impact the total revenue due to longer sailing time.	9
Speed reduction (20%)		18-28%		9
Speed reduction (30%)		24-38%		9
Advanced port logistics	Through flexible planning, improved collaboration, real-time data exchange and digitalised cargo flows, a smoother ship-port interface can result in a significant reduction in the time ships spend waiting.	Up to 1%	-	8/9
Optimisation of vessel capacity utilisation	This measure is based on the ability to counterbalance supply and demand. Optimising capacity utilisation reduces the cost per transported unit and save emissions per tonne-mile.	0-30%	-	8/9
Advanced autopilots	Minimises movements from the rudder, which otherwise creates additional drag to the hull and consequently increases ship resistance.	0.25-1.5%	No cost of implementation assuming that autopilot is already installed.	9
Weather routing	Weather routing and voyage planning minimise exposure to unsheltered water.	0-5%	$25,000	9
Autonomous shipping	Rapidly advancing technology is making crewless operations increasingly possible.	Up to 6%	Due to low TRL, reliable data on capital costs per vessel are lacking.	5/6/7

[48] The "baseline" speed against which the improvement from slow steaming is measured varies with vessel design (and when it was built) Recent vessels are designed for a lower design speed, so increase the benefit further. As a general rule (and for the derivation of the GHG reduction potential), the measure is interpreted as being relative to vessel speeds for vessels built prior to about 2010.

Propulsion design / technology	Brief description	GHG reduction potential (%)	Cost of measure ($) for one vessel	TRL
Power demand management e.g. lighting	Each piece of equipment and machinery on board consumes energy and can individually be assessed to optimise the energy efficiency and possibly be replaced with higher efficiency models.	0.25-5%	$100,000* compared to traditional lighting installations	9
Engine efficiency measurements	Main engine efficiency measurement enables improved power management of the engine(s).	Up to 5%	$20,000 to $75,000	9
Hull cleaning	Thorough cleaning of the vessel's hull on a regular basis can improve the surface finish, reducing resistance and improving fuel efficiency.	1-5%	$5,000 to $50,000	9
Propeller cleaning polishing	Cleaning and polishing the propeller regularly can improve the surface finish and, hence, the propeller efficiency.	3-4%	$4,000 to $8,000	9

** Refers to the additional cost of $100,000 (USD) compared to traditional lighting installations on normal ships and $200,000 to $1,000,000 (USD) on passenger and cruise ships. Sources:* (Ciuffo, Giovine, Marra, & Miola, 2010) (International Maritime Organization, 2009) (GloMEEP IMO, 2015) (Seatrade-Maritime, 2018) (MDPI, 2018) (Smith, et al., 2019).

4.8 Fuel quality

The global shift of the maritime sector to using higher quality low-sulphur fuels, reduces SOx, PM and black carbon emissions. However, the CO_2 reduction potential from the switch in fuel quality is limited, when considering life cycle emissions. This may even cause a marginal increase in overall CO_2 emissions.

The global shift of the maritime sector to using higher quality low-sulphur fuels, will have marginal or positive impacts on lube oil and consequently engine efficiency, with the exception of biofuels. Switching to biofuels may create engine-related challenges around lube oil. In diesel engines running on conventional fuels, one of the functions of the lube oil is to neutralise SOx produced when marine fuel oil burns. Without neutralisation these oxides are corrosive to engine piston liners, which can have a negative impact on engine performance and efficiency. However, a small amount of acidic oxides can be beneficial in cleaning the piston and liner surfaces, improving the adherence of the lube oil to the surface. A complete absence of the acid, resulting from a sulphur-free fuel (such as biofuels) can lead to polishing of the surfaces resulting in the breakdown of the lubricating oil film (SwedishClub, 2015).

The engine efficiency improvements from the other fuels have not been quantified, and most likely do not correspond to the scale of CO_2 emission reductions needed to play a significant role in reaching the IMO ambition.

5 Fuel and technology packages

Key points:

- Three possible future 'packages' of fuels, technologies and operational measures are defined. Fuel pathways are stipulated. Selections are made based on the potential, applicability and availability of the technologies and fuels, together with views on likely uptake from stakeholders.
- **Package 1 'early pursuit of zero carbon fuels'**
    - Ammonia (deep-sea shipping) and hydrogen (short-sea shipping[49]) for some new build vessels from 2025, ramping up to all new-build ships by 2035. Transitioning from grey to blue to green fuels over 2025-2035 period.
    - Medium take up of energy efficiency technologies and operational measures. A 10% speed reduction is assumed for slow steaming. No onboard CCS.
- **Package 2 'moderate uptake of interim and drop-in fuels'**
    - From 2025, HFO and MDO use is assumed to be increasingly substituted with drop-in biofuels (FAME, HVO). LNG transitions to bio methane (BioLNG) from 2030 onwards.
    - Medium take up of energy efficiency technologies and operational measures. A 20% speed reduction is assumed for slow steaming. No onboard CCS.
- **Package 3 'initial maximisation of vessel decarbonisation measures'**
    - Focuses on maximising technology use with a later transition to alternative fuels.
    - High take up of energy efficiency technologies and operational measures. A 30% speed reduction is assumed for slow steaming. Onboard CCS applied to 50% of new ships (using carbon-containing fuels) post-2030, ramping up to 100% of new ships post 2040
    - Ammonia and methanol for some new build vessels from 2025, ramping up to 50% new-build ships by 2035. Transitioning from grey to blue to green fuels over 2025-2035 period. Increased use of LNG, then transitioning to BioLNG from 2030 onwards, reaching 50% of new build ships by 2050.

Section 4 described the vessel and engine technologies, operational improvements and alternative fuels that could contribute to decarbonising the shipping sector. The GHG abatement efficiencies and costs shown in that section were at the vessel level. To move forward to assess the aggregate impact of technologies and fuels at the fleet level, and thus estimate the sectoral GHG emission reductions in the context of meeting the IMO's ambition, section 5 considers three possible future 'packages' of technologies and fuels.

This section first provides a decision process for selecting fuels and technologies for the packages (section 5.1) and then describes the three packages in section 5.2.

As has been noted in the preceding sections, many of the vessel and engine technologies are already in widespread use, although there is the potential for increased use, or more complete exploitation of the potential, for some. The main options for achieving the 2050 ambition of the IMO, therefore, depend on the adoption of alternative fuels in the future.

[49] The European Commission defines short-sea shipping as "the maritime transport of goods over relatively short distances, as opposed to the intercontinental cross-ocean deep sea shipping" (https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Short_sea_shipping_(SSS)). For the current study the term is used to distinguish smaller vessels with shorter ranges from the large vessels with transoceanic capability. For the vessel categories analysed in this study, divided into small, medium and large sub-categories, this generally means the small sub-category.

5.1 Selection of fuels and technologies for the packages

5.1.1 Fuel selection

Fuel pathways were selected based on stakeholder feedback, GHG reduction potential and the need to reach the IMO 2050 GHG reduction ambition, cost-effectiveness, and with the intention to reflect different plausible pathways to decarbonisation. For this reason, not only green production pathways but grey and blue production pathways were included in the selection for hydrogen and ammonia. The final candidate fuels selected for the packages are summarised in Table 5-1. The emissions data included in the table have been derived as averages of multiple references (where available) and, as such, represent those for an average engine. In practice, the emissions (for engines using carbon-containing fuels) will vary depending on the engine cycle and design.

The emissions values for several of the fuels, particularly the blue and green versions, are from a Ricardo analysis using lifecycle analyses of the production pathways, including the embedded emissions in the renewable electricity generation plant (if appropriate). As these pathways are expected to improve over time, the well-to-wake (WTW) emissions values also reduce. Therefore, Table 5-1 includes estimated WTW emissions for both 2020 and 2050 (values for fuels not calculated in this manner are assumed to remain constant).

Table 5-1 Final candidate fuel pathways selected for packages

Fuel	Production pathway		Well-to-Wake (WTW) emissions (g CO_2eq/MJ)	
			2020	2050
HFO		*Reference pathway*	87.2	87.2
Hydrogen	*Grey*	*Steam reforming from natural gas*	98.5	90.1
	Blue	*Natural gas and CCS**	21.5	19.2
	Green	*Renewable electrolysis*	22.2	7.7
Ammonia	*Grey*	*Natural gas*	98.9	98.9
	Blue	*Natural gas and CCS**	20.9	20.9
	Green	*Renewable electrolysis*	22.2	7.7
Methanol	*Grey*	*Natural gas*	98.1	98.1
	Green	*Synthetic (renewable)*	22.2	7.2
LNG		*Global average*	83.8	83.8
BioLNG		*Average of liquid manure**, municipal organic waste, sewage sludge and maize*	24.6	27.5
FAME		*Waste cooking oil*	23.2	23.2
HVO		*Waste cooking oil*	20.4	20.4

**Assumes production pathway with carbon capture and storage with 90% carbon capture efficiency*

***Pathway includes positive effect of preventing methane emissions by storage and use of biogas instead of releasing to the atmosphere. Basic calculations and conversions have been completed by Ricardo Plc for comparability. Sources: HFO* (Lindstad and Rialland, 2020)*, Grey hydrogen* (Ricardo, 2019)*, Grey ammonia* (DECHEMA, 2017)*, Grey methanol* (Winebrake, 2018) (Nyári, 2018)*, LNG* (Thinkstep, 2019) *, BioLNG, FAME and HVO* (Verbeek, 2015) *and* (JRC, EUCAR and Concawe, 2020)*. Blue hydrogen/ammonia and Green hydrogen/methanol/ammonia (Ricardo calculations based on lifecycle analysis of production pathways)..*

5.1.2 Technology selection

In order to differentiate between the technologies and operational measures, a decision matrix was developed. The matrix includes three main equally weighted criteria:

1. Readiness Level:

This is based on the TRL of the technologies/ measures, as determined from literature and from consultation with stakeholders as to whether the technologies are already widely implemented. The majority of the design measures were confirmed as widely applicable to different vessel types and already widely implemented, with the exception of air lubrication and interceptors. Similarly, propeller design measures were also confirmed as already widely implemented, and, in general, ship design is already optimised to have the largest propeller diameter possible. Whilst the power assistance measures are not already widely implemented, the technology has been piloted. Engine aftertreatment technologies were also found to be widely implemented. Onboard carbon capture remains theoretical with a lack of practical application. The ratings were applied as follows:

- A rating of 0 refers to measures that should already be included in the baseline or a lack of data
- A rating of 1 refers to measures with TRL less than 5
- A rating of 2 refers to TRL of 5/6/7
- A rating of 3 refers to TRL of 8/9

2. Likely adoption rate:

This is based on the expectation of the use of the technology/measure and interest expressed by stakeholders.

- A rating of 0 refers to technologies already included in the baseline or a lack of data
- A rating of 1 refers to low likely adoption and stakeholder interest
- A rating of 2 refers to moderate likelihood of adoption and stakeholder interest
- A rating of 3 refers to high likely adoption rate.

3. Cost-effectiveness:

This is based on cost-effectiveness ($/ tonne CO_2 abated) calculated with the savings in CO_2 emissions over the lifetime of the vessel (assumption: 30 years) divided by the cost of implementing the technology on the vessel. These have been calculated assuming an average annual tonne-miles delivered and energy consumption values derived from analysis of the 2018 EU MRV data. The “average ship size” that these values correspond to is approximately 60,000 DWT. The ratings are applied as follows:

- A rating of 0 shows a lack of data
- A rating of 1 if cost-effectiveness estimated to be more than $50/tonne CO_2,
- A rating of 2 if cost-effectiveness estimated to be between $10/tonne CO_2 and $50/tonne CO_2,
- A rating of 3 if cost-effectiveness estimated to be less than $10/tonne CO_2 or negative.

The selection of each technology and operational measure into each package is based on the combined criteria scores. Technologies that had a decision matrix score total of under 5 were not included in any packages. Technologies that are considered to be widely implemented already, but with little continued used, are not included in the technology/fuel packages as they considered to be current technology. These are assumed as included in the new build ships in the baseline analysis.

The results of the decision matrix are in Table 5-2; for a more detailed breakdown of the raw values and criteria scores assigned to inform fuel and technology package development, see Appendix 8 (A.8).

Table 5-2 Maritime decarbonisation technology and operational measure decision matrix.

Technology/Measure		Criteria: Readiness level	Criteria: Likely adoption rate	Criteria: Cost-effectiveness	Final Score
Vessel design measures	Optimum ship size dimensions	3	3	0	6
Vessel design measures	Construction weight	3	3	0	6
Vessel design measures	Hull dimensions (form optimisation)	3	3	3	9
Vessel design measures	Bulbous bow retrofit	3	2	3	8
Vessel design measures	Bow thruster tunnel optimisation	3	2	3	8
Vessel design measures	Hull coatings	3	2	3	8
Vessel design measures	Interceptors	3	0	3	6
Vessel design measures	Ducktail waterline extension	3	1	0	4
Vessel design measures	Air lubrication	3	1	2	6
Vessel design measures	Ballast reduction and trim optimisation	3	3	3	9
Power assistance	Flettner rotors	3	2	2	7
Power assistance	Towing kites	2	1	2	5
Power assistance	Sails	3	1	3	7
Power assistance	Solar panels	3	2	1	6
Power assistance	Shore power supply	3	2	0	5
Propulsion devices	Large area propellers (LAP)	3	2	3	8
Propulsion devices	Contra rotating propellers (CRP)	3	1	2	6
Propulsion devices	Podded thrusters	3	2	2	7
Propulsion devices	Ducts (PID)	3	2	2	7
Propulsion devices	Pre-swirl (PID)	3	2	3	8
Propulsion devices	Post-swirl fins and rudder bulbs (PID)	3	2	2	7
Engine / aftertreatmen	Fuel injection valve improvements (slide valves)	3	0	0	3
Engine / aftertreatmen	Common rail fuel injection	3	0	0	3
Engine / aftertreatmen	Water in Fuel Emulsion (WiFE)/Water Injection	3	0	0	3
Engine / aftertreatmen	Hybrid diesel-electric	3	0	0	3
Engine / aftertreatmen	Early Intake Valve Closing (Miller cycle)	3	0	0	3
Engine / aftertreatmen	Waste heat recovery (WHR)	3	2	1	6
Carbon capture & storage (CCS)		2	1	2	5
Vessel operational measures	Speed reduction	3	3	3	9
Vessel operational measures	Advanced port logistics	3	2	3	8
Vessel operational measures	Optimisation of vessel capacity utilisation	3	2	3	8
Vessel operational measures	Advanced autopilots	3	2	3	8
Vessel operational measures	Voyage planning and weather routing	3	3	3	9
Vessel operational measures	Autonomous shipping	2	1	3	6
Vessel operational measures	Power demand management e.g. lighting	3	3	3	9
Vessel operational measures	Engine efficiency measurements	3	3	3	9
Vessel operational measures	Hull cleaning	3	3	3	9
Vessel operational measures	Propeller cleaning and polishing	3	3	3	9

5.1.3 Cost-effectiveness ranking

Figure 5-1 to Figure 5-6 show the cost-effectiveness of the different fuels and technologies, as used in the derivation of the cost-effectiveness ratings in Table 5-2. These cost-effectiveness values have all been derived for an average ship size, using assumptions for the vessel lifetime and the tonne-miles delivered per year. For the vessel and operational technologies, the values derived in this way include the changes to the vessel capital costs, but do not include the reductions in lifetime fuel costs (as fuel cost savings have the potential to swamp the implementation costs). An exception to this is for the onboard carbon capture and storage (CCS) technology under the engine technologies in Figure 5-4. In this case, the implementation of the technology also results in an increase in fuel consumption (and hence fuel costs) because of the demands of the CCS system. Therefore, the cost-effectiveness is shown both excluding and including the additional fuel costs. For the alternative fuels, the assessment was based on the increased price and CO_2 savings per unit of fuel. As for the results shown in Figure 4-3, this analysis used the fuel price projections for 2030.

The cost-effectiveness values presented in the following charts are shown in order of increasing cost-effectiveness value (i.e. increasing cost to achieve the same reductions in emissions) to assist in the identification of the “better” and “less good” options. As shown in Table 5-2, however, this is not the only criterion used in the selection of the technologies to include in the packages. The ducktail waterline extension technology is not included in Figure 5-1 as no cost data were identified and it is applicable only to a limited range of vessels (RoRo ships and ferries). The “optimum ship size and hull dimensions” and “construction weight” technologies are both shown as having zero cost per tonne CO_2. These two technologies were identified as being widely applicable and are already widely employed in vessel design, so they were considered as being able to be implemented at low cost compared to the other technologies.

Figure 5-1: Cost-effectiveness ranking for vessel design measures

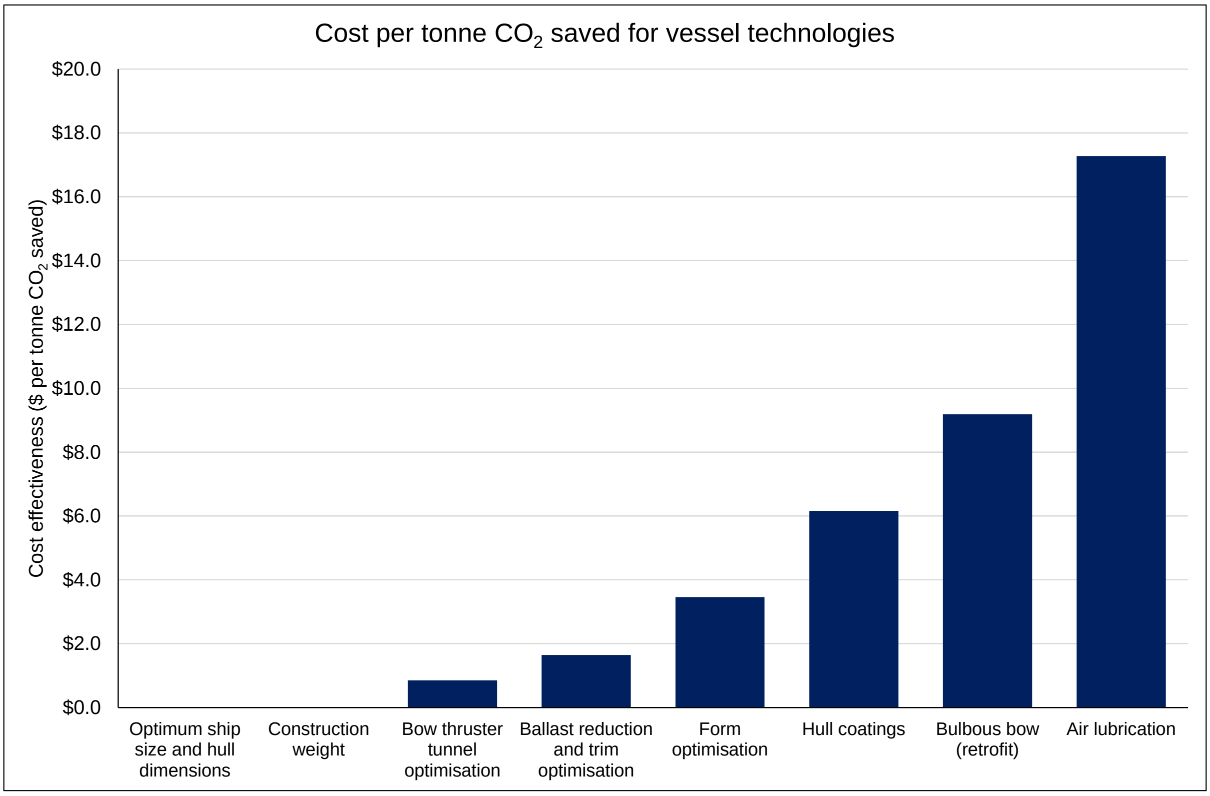


Figure 5-2: Cost-effectiveness ranking for power assistance measures

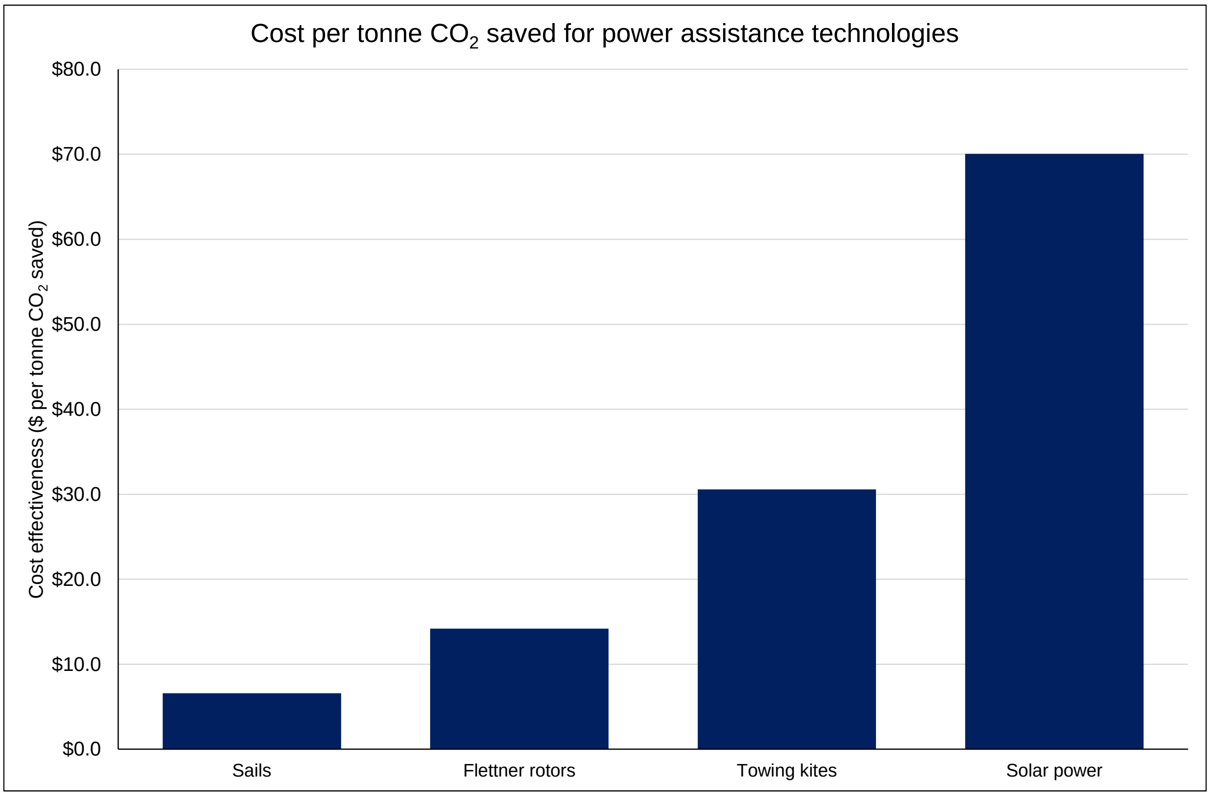


Figure 5-3: Cost-effectiveness ranking for propulsion technologies

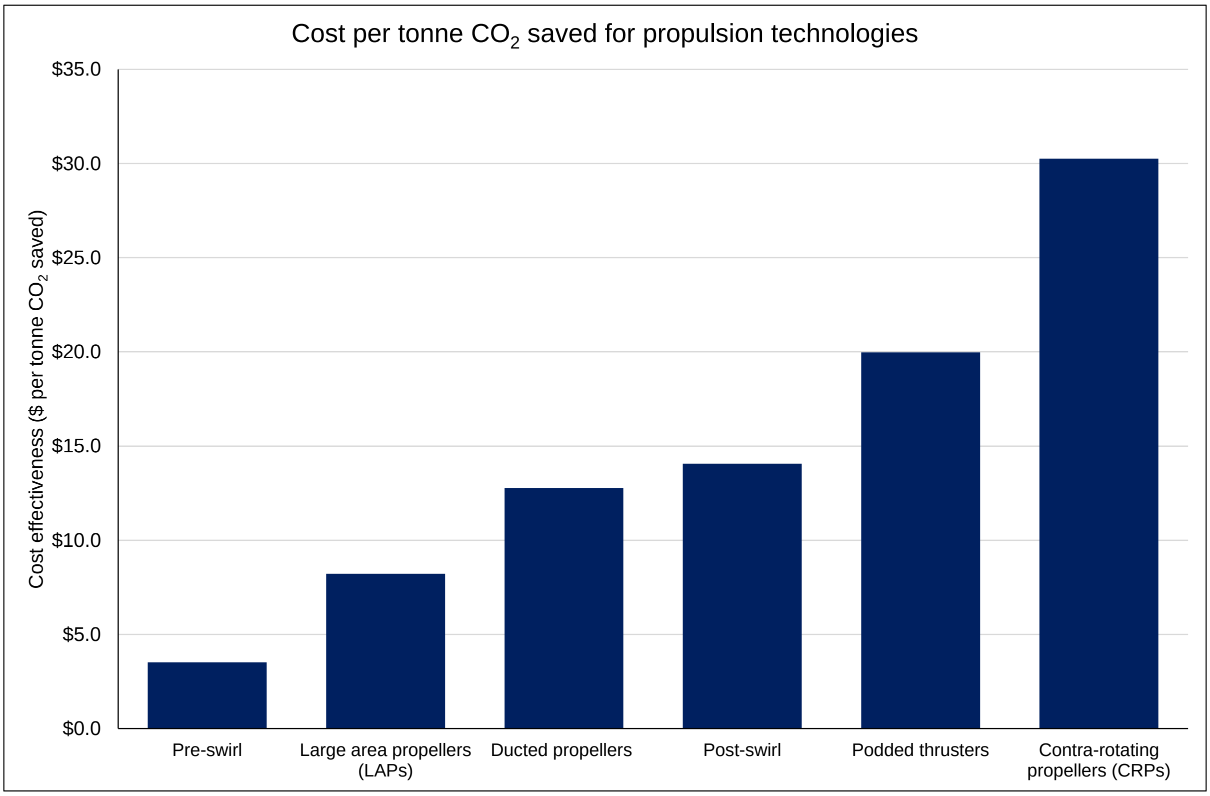


Figure 5-4: Cost-effectiveness ranking for engine technologies

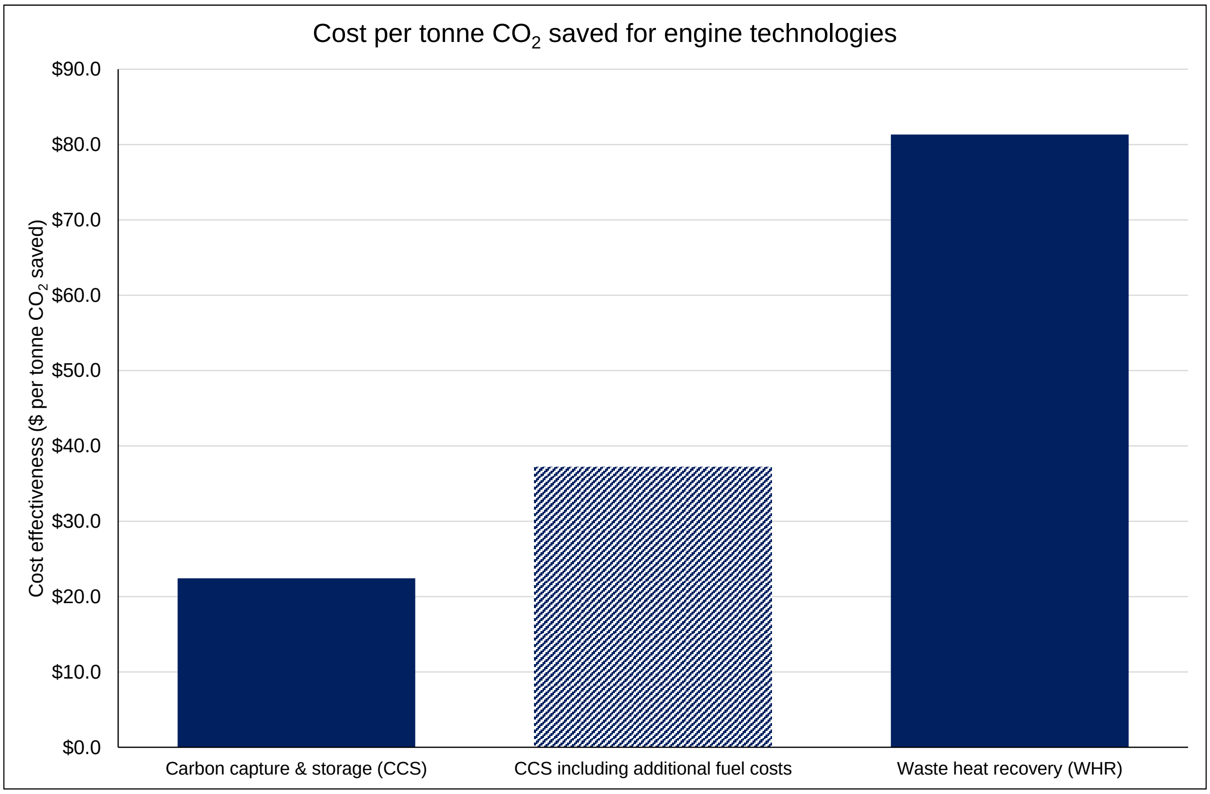


Figure 5-5: Cost-effectiveness ranking for voyage optimisation measures

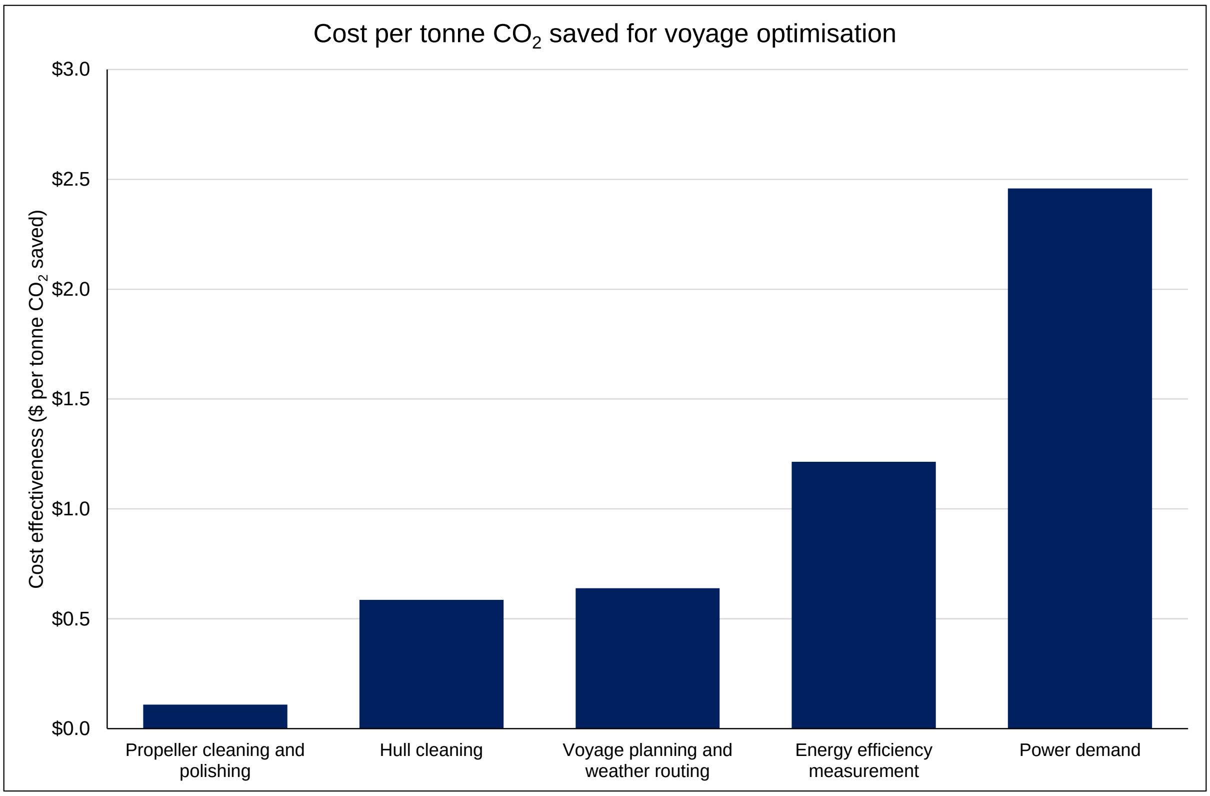
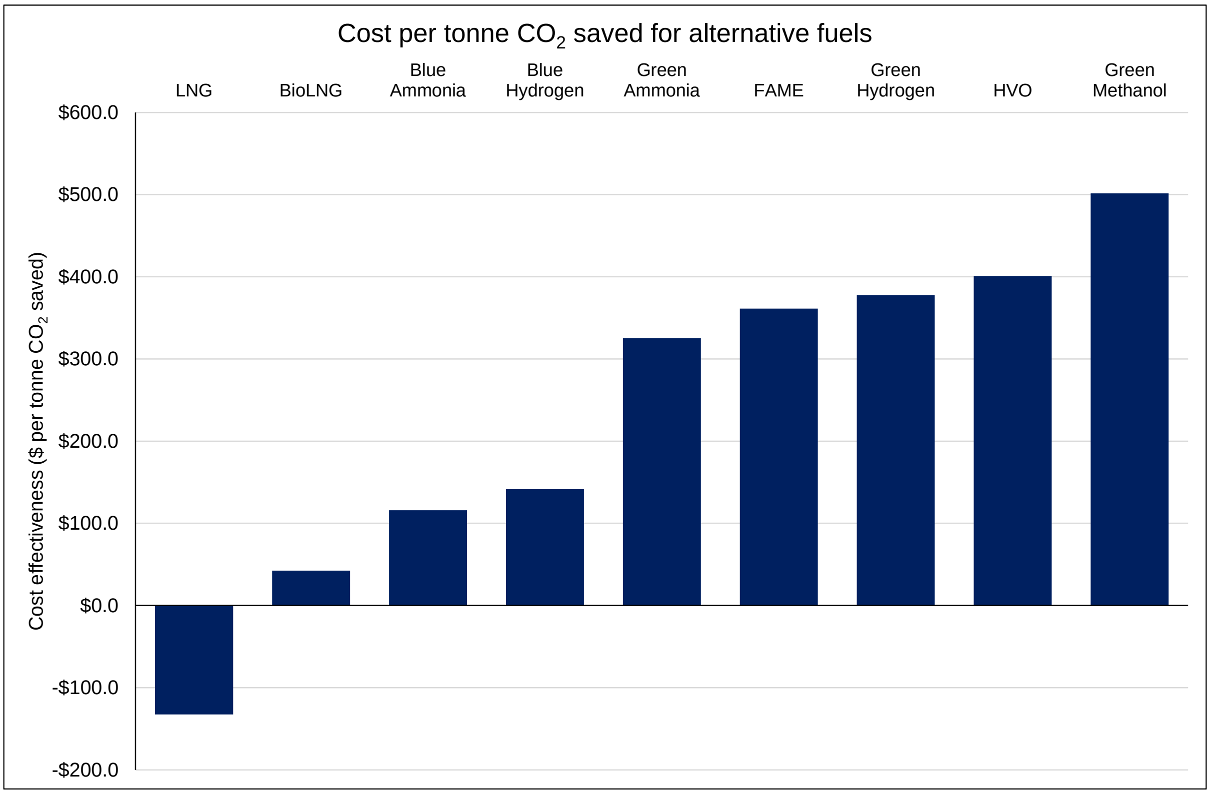


Figure 5-6: Cost-effectiveness ranking for alternative fuels



5.2 Package definition

Three packages of technologies and fuels have been defined for analysis. These packages are driven by the potential contributions of technologies (also including operational measures) and alternative fuels to deliver the decarbonisation of the sector. A summary of the three packages is shown in Figure 5-7.

Figure 5-7 Overview of three technology/fuel packages developed for analysis

Package 1	Package 2	Package 3
Characterised by **an early pursuit of carbon-free alternative fuels**	A **moderate uptake of an interim alternative fuel** (represented by LNG) **in the short-term**	**Maximum use of decarbonisation measures** while using conventional fuels.
Introduction of new build ships using grey **hydrogen** and grey **ammonia**, and battery electric (coastal shipping) from 2025. Followed by a transition from grey to blue fuel pathways and to green from 2035 onwards. **Medium take up** of energy efficiency technologies and operational measures. A **10% speed reduction** is assumed for slow steaming. No onboard CCS.	From 2025, HFO and MDO use is assumed to be increasingly substituted with drop-in biofuels **(FAME, HVO)**. LNG transitions to bio methane (bio-LNG) from 2030 onwards. **Medium take up** of energy efficiency technologies and operational measures. A **20% speed reduction** is assumed for slow steaming. No onboard CCS.	Conventional fuels, **HFO and MDO,** with a **later transition to reduced carbon alternative fuels** using pathways that provide some reductions in emissions Gradual transition to use of bio-LNG, green methanol and green ammonia. **High take up** of energy efficiency technologies and operational measures. A **30% speed reduction** is assumed for slow steaming. Onboard CCS post 2030.

5.2.1 Package 1 – Early pursuit of zero-carbon fuels

The package is characterised by an early pursuit of carbon-free alternative fuels (hydrogen and ammonia). This package reflects the view expressed by some stakeholders that the adoption of interim alternative fuels such as LNG would be a diversion from the focus on achieving the comprehensive decarbonisation of the industry as soon as possible.

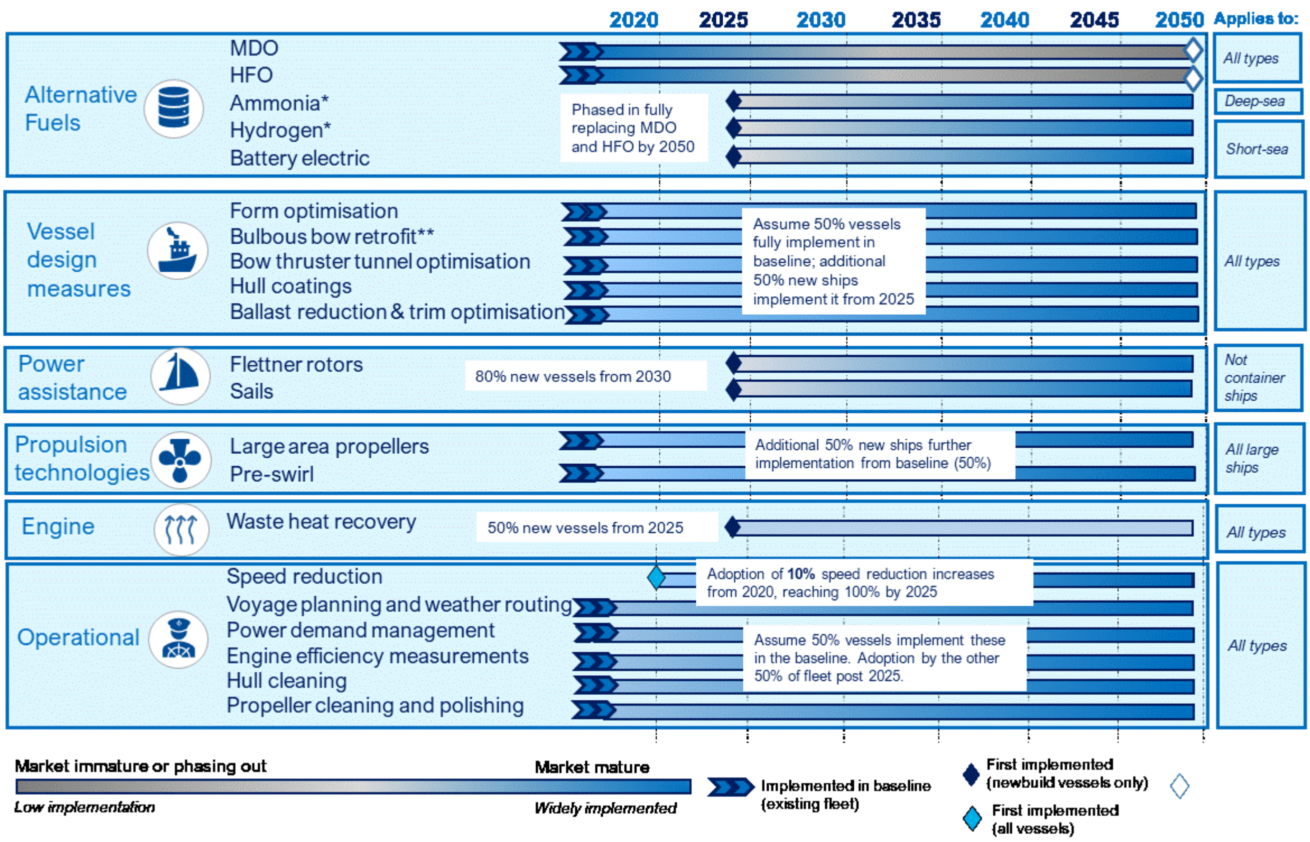
This package focuses on the highest scoring decarbonisation measures. It includes vessel design measures with the highest decision matrix scores (8/9) and power assistance measures with highest scores (7). It assumes 50% Flettner rotor implementation and 50% sail implementation post 2025. This package also includes the highest scoring propulsion devices (8) which consist of large area propellers and pre-swirl devices. Although, post-swirl fins and rudder bulbs also scored 8, these were not included as they are more expensive than the other PIDs. WHR is included. The highest scoring operational measures are included (9), and a 10% speed reduction is assumed for slow steaming.

Given the focus of this package is on the early pursuit of low carbon green fuels to reduce GHG emissions, onboard CCS is not included in this package.

The key parameters and timeframes corresponding to package 1 for the modelling are shown in Figure 5-8.

The application of the different vessel technologies included in the modelling of this package are shown in Table 5-3. The package also includes assumptions around the production pathways used for hydrogen and ammonia. These are summarised in Table 5-4.

Figure 5-8 Overview of timeline and components of Package 1.



**Note: Ammonia and hydrogen first transition using the grey production pathways in 2025, followed by blue (CCS) and finally green pathways from 2035 onwards. **Bulbous bow retrofit is only in Ro-Ros, ferries and containers*

Table 5-3: Application of vessel technologies under Package 1 to different vessel types and sizes

	Form optimisation	Ballast reduction and trim optimisation	Bow thruster tunnel optimisation	Hull coatings	Interceptors	Ducktail waterline extension	Optimum ship size and hull dimensions	Construction weight	Flettner rotors	Sails	Large area propellers (LAPs)	Contra-rotating propellers (CRPs)	Pre-swirl	Post-swirl	Carbon capture & storage (CCS)	Waste heat recovery (WHR)
Tankers	Yes	Yes	Yes	Yes					Yes	Yes	Large vessels only		Large vessels only	Large vessels only		Yes
Bulk carriers	Yes	Yes	Yes	Yes												Yes
Container vessels	Yes	Yes	Yes	Yes							Large vessels only		Large vessels only	Large vessels only		Yes
General cargo vessels	Yes	Yes	Yes	Yes					Yes	Yes						Yes
LNG carriers	Yes	Yes	Yes	Yes					Yes	Yes						Yes
LPG carriers	Yes	Yes	Yes	Yes					Yes	Yes						Yes
RoRo vessels	Yes	Yes	Yes	Yes					Yes	Yes						Yes
Cruise ships	Yes	Yes	Yes	Yes					Yes	Yes						Yes

Table 5-4 Fuel specifications for the modelling of Package 1

Fuel	Applicability	Additional specification for the modelling
Ammonia from-2025 build year	Deep sea shipping	Assumed to use three pathways; *grey* ammonia followed by *blue* ammonia then transitioning to *green* ammonia
Hydrogen from-2025 build year	Short sea shipping	Assumed to use three pathways; *grey* hydrogen transitioning to *blue* hydrogen, then transitioning to *green* hydrogen by 2050.
Battery from-2025 build year	Coastal shipping	Assumed to use 100% renewable electricity by 2050.

Overall the assumed timeline of implementation for the fuels for package 1 is as follows:

- **2020** - Assumes 72% HFO, 28% MDO for all ship categories except LNG carriers (100% LNG).
- **2025** - Assumes grey hydrogen and grey ammonia in use (2025-2030)
- **2030** - Assumes grey hydrogen and grey ammonia start to transition out, (2030-2035), blue hydrogen and blue ammonia transition in (2030-2035)
- **2035** – Assumes blue hydrogen and blue ammonia start to transition out (2035-2040), green hydrogen and green ammonia transition in (2035-2050).
- **2050** – Assumes by 2050, 100% green hydrogen and 100% green ammonia use

5.2.2 Package 2 - Moderate uptake of interim and drop-in fuels

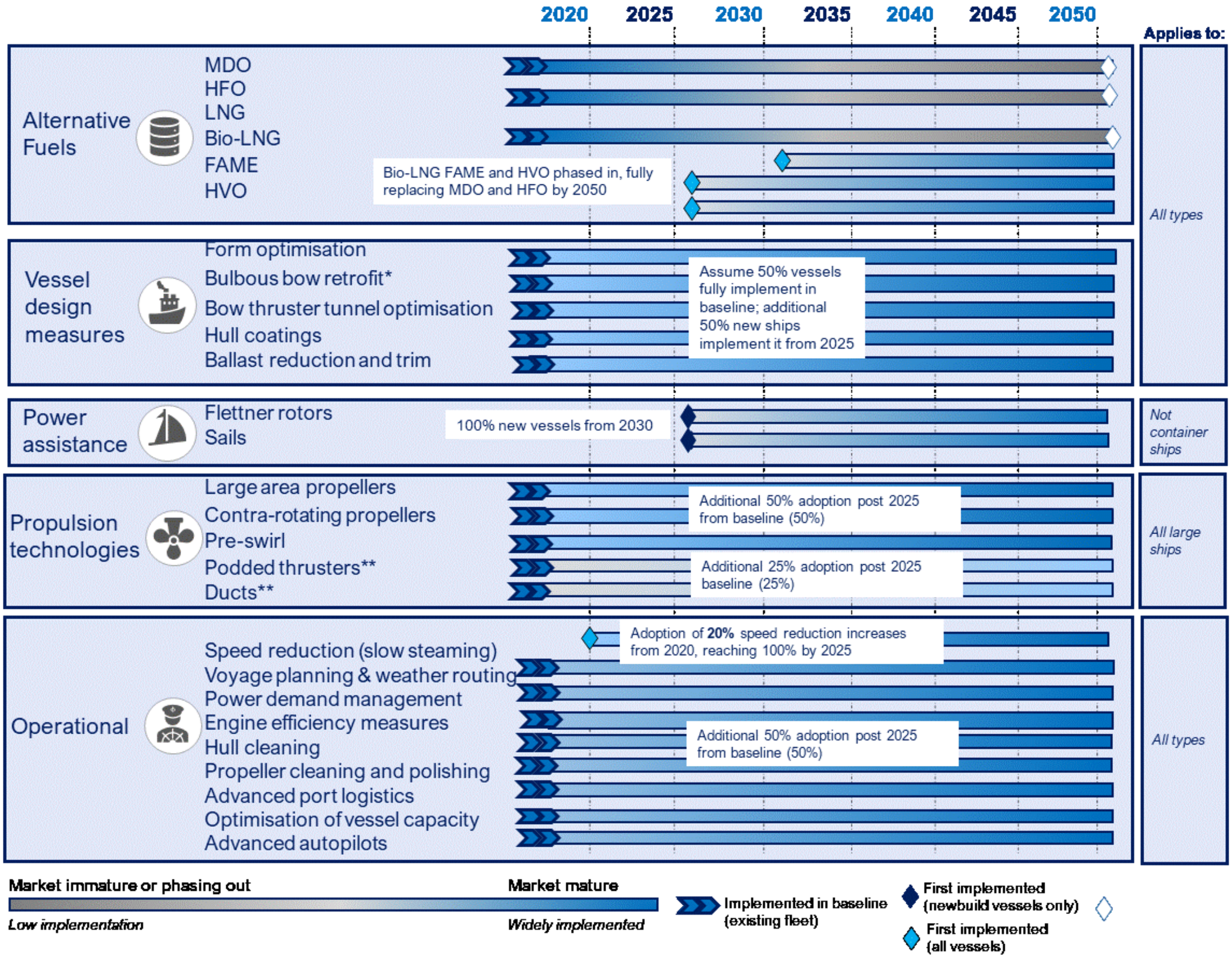
This package represents a moderate uptake of an interim alternative fuel (represented by LNG) in the short-term and continuing to increase to 2040. From 2025 the HFO and MDO use is assumed to be increasingly substituted with drop-in biofuels (FAME, HVO). This is followed by a later transition to BioLNG in the 2040s to displace the LNG, with its use dependent on the build of ships using dual-fuel engines. The significant increase in the use of LNG (and, subsequently, BioLNG) could bring a risk of increased methane emissions through methane slip. However, during the study, stakeholders have indicated that latest gas-fuelled engine designs have significantly reduced methane slip. This is particularly true of low-speed engines (and emissions from medium-speed engines may increase under lower load conditions when employing slow steaming); an increased use of LNG may provide a drive towards increased use of low-speed engines.

In terms of technologies, this package focuses on the high-to-moderate scoring technologies. Similarly to package 1, it includes vessel design measures with decision matrix scores (8/9), and power assistance measures with highest scores (7) and same assumption for Flettner rotor and sail implementation post 2025. However, with respect to propulsion devices this package also includes those scoring 7, and includes contra rotating propellers (CRPs), podded thrusters and ducts. The highest scoring operational measures are included (9) as well as three additional measures scoring 8; advanced port logistics, optimisation of capacity utilisation, and advanced autopilots.

In contrast to package 1, a 20% speed reduction is assumed for slow steaming. Given the reduced effectiveness of waste heat recovery with significant speed reductions, waste heat recovery is not included in this package. Given the focus of this package on pursuing interim and drop-in fuels to reduce GHG emissions, onboard CCS is assumed to not be needed in this package.

The key parameters and timeframes corresponding to package 2 for the modelling are shown in Figure 5-9. The application of the different vessel technologies included in the modelling of this package are shown in Table 5-5. The package also includes assumptions around the production pathways used for LNG, BioLNG, FAME and HVO. These are summarised in Table 5-6.

Figure 5-9 Overview of timeline and components of Package 2.



** Bulbous bow retrofit is only in Ro-Ros, ferries and containers. **Not compatible with other propulsors*

Table 5-5: Application of vessel technologies under Package 2 to different vessel types and sizes

	Form optimisation	Ballast reduction and trim optimisation	Bow thruster tunnel optimisation	Hull coatings	Interceptors	Ducktail waterline extension	Optimum ship size and hull dimensions	Construction weight	Flettner rotors	Sails	Large area propellers (LAPs)	Contra-rotating propellers (CRPs)	Pre-swirl	Post-swirl	Carbon capture & storage (CCS)	Waste heat recovery (WHR)
Tankers	Yes	Yes	Yes	Yes			Yes		Yes	Yes	Large vessels only	Large vessels only	Large vessels only			
Bulk carriers	Yes	Yes	Yes	Yes			Yes									
Container vessels	Yes	Yes	Yes	Yes			Yes				Large vessels only	Large vessels only				
General cargo vessels	Yes	Yes	Yes	Yes			Yes		Yes	Yes	Medium and large vessels only	Medium and large vessels only				
LNG carriers	Yes	Yes	Yes	Yes			Yes		Yes	Yes	Yes	Yes				
LPG carriers	Yes	Yes	Yes	Yes			Yes		Yes	Yes	Yes	Yes				
RoRo vessels	Yes	Yes	Yes	Yes			Yes		Yes	Yes						
Cruise ships	Yes	Yes	Yes	Yes			Yes		Yes	Yes						

Table 5-6 Fuel specifications for the modelling of Package 2

Fuel	Applicability	Additional specification for the modelling
LNG	All LNG vessels	Assumed to use g*lobal average* pathway.
BioLNG	All LNG vessels	Assumed to use *liquid manure* pathway
Biofuels	All vessel types	Assumed to use *waste cooking oil feedstock* pathway for both FAME and HVO.

Overall the assumed timeline of implementation for the fuels for package 2 is as follows:

- **2020** – Assumes 50% conventional fuel (HFO), 50% Grey LNG (gas-only and dual-fuel vessels) (LNG) for new vessels from 2020
- **2025** – Assumes FAME and HVO start to be used to replace HFO (equal 50/50 split), gradual transition from 2025-2045. By 2045 fully replaced HFO. Initial use of BioLNG in some vessels.
- **2030** – BioLNG starts to be used more widely; gradual transition from 2030-2050.
- **2045** – Assumes by 2045 100% FAME and HVO replacement of HFO
- **2050** – By 2050, 100% BioLNG replacement of LNG, together FAME and HVO replace 100% of HFO

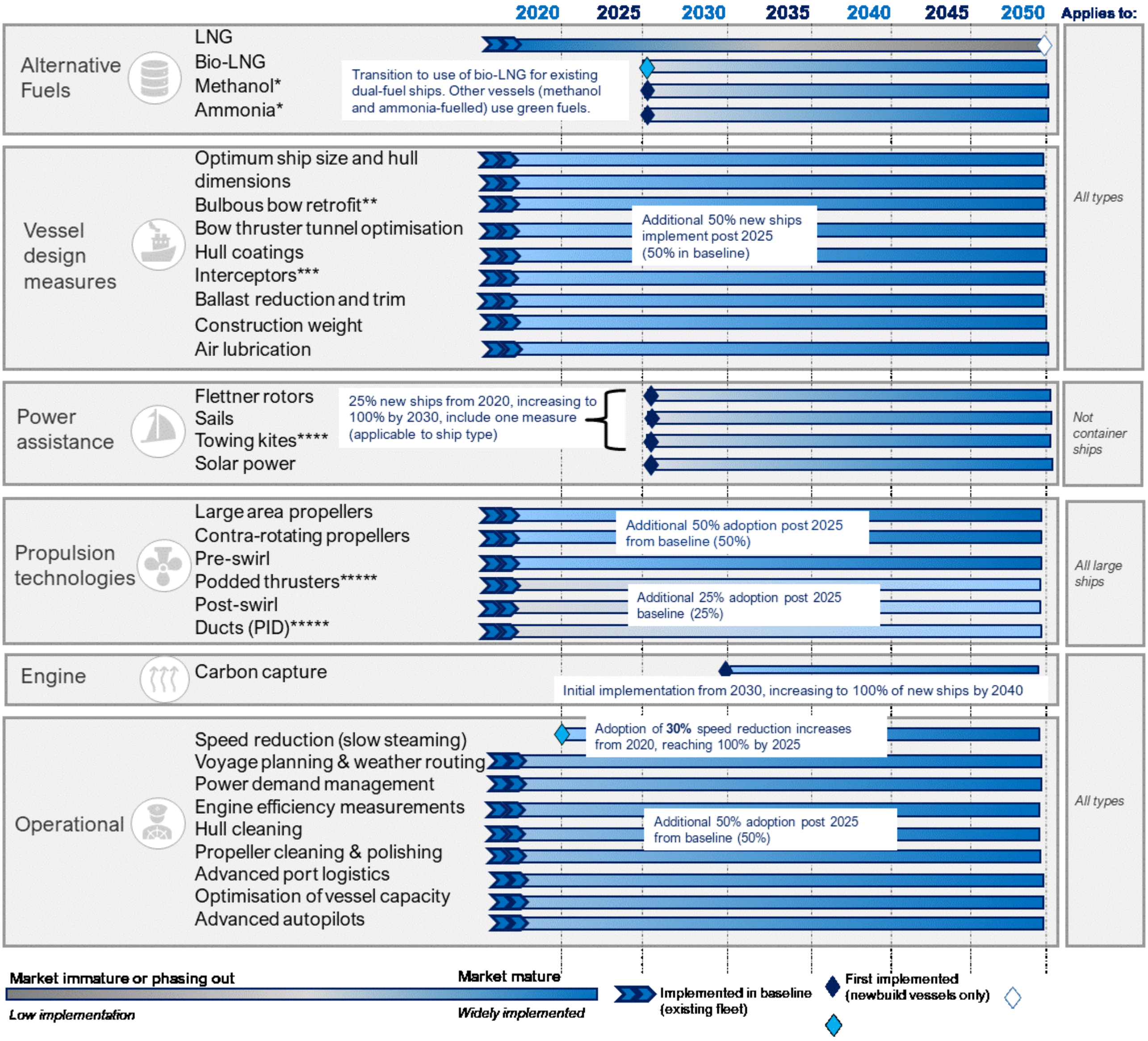
5.2.3 Package 3 – Initial maximisation of vessel decarbonisation measures

This package represents an emphasis on the maximum use of fuel efficiency technologies to deliver maximum reductions in emissions while using conventional fuels. The package then includes a later transition to reduced carbon alternative fuels, and includes fuel pathways for LNG, ammonia and methanol, subsequently followed by a transition to “green” versions of the same fuel types. The initial deliveries of new vessels using ammonia and methanol is modelled as starting in 2025 and increasing linearly over time to reach maximum percentages (25% of all new vessels using ammonia, 25% using methanol and 50% using LNG) by 2035. Although it is possible that one of the reduced carbon liquid fuels, methanol and ammonia, will be taken up more widely (they both require new engine types and fuel systems, methanol is easier to handle as it is a liquid at room temperature, but ammonia offers greater emissions savings, at least at the vessel exhaust), they are modelled as having an equal share due to the uncertainty as to which may end up dominating.

In terms of technologies, this package focuses on maximising technology use, therefore it includes all technologies with scores of 6/7/8/9 in the decision matrix. In addition to the measures deployed in package 2, package 3 also harnesses measures including air lubrication, towing kites and solar panels. A 30% speed reduction is assumed for slow steaming, and similar to package 2, given the reduced effectiveness of waste heat recovery with significant speed reductions, waste heat recovery is not included in this package. However, despite the score assigned to it, onboard CC is included in this package due to the longer continued use of conventional carbon containing fuels: the package assumes initial deployment of new ships with carbon capture in 2030, with penetration increasing over time so that all new ships (using carbon-containing fuels) are equipped from 2040.

The key parameters and timeframes corresponding to package 3 for the modelling are shown in Figure 5-10. The application of the different vessel technologies included in the modelling of this package are shown in Table 5-7. The package also includes assumptions around the production pathways used for LNG, BioLNG, ammonia and methanol. These are summarised in Table 5-8.

Figure 5-10 Overview of timeline and components of Package 3



** Note: Ammonia and methanol first transition using the grey production pathways in, followed by blue (CCS) (ammonia only) and finally green pathways from 2035 onwards.** Bulbous bow retrofit is only in Ro-Ros, ferries and containers. *** Only in cruise ships and Ro-Ros. **** Tankers and bulk carriers only. ******Not compatible with other propulsors*

Table 5-7: Application of vessel technologies under Package 3 to different vessel types and sizes

	Form optimisation	Ballast reduction and trim optimisation	Bow thruster tunnel optimisation	Hull coatings	Interceptors	Ducktail waterline extension	Optimum ship size and hull dimensions	Construction weight	Flettner rotors	Sails	Large area propellers (LAPs)	Contra-rotating propellers (CRPs)	Pre-swirl	Post-swirl	Carbon capture & storage (CCS)	Waste heat recovery (WHR)	Air lubrication
Tankers	Yes	Yes	Yes	Yes			Yes	Yes	Yes	Yes	Large vessels only	Large vessels only	Large vessels only	Large vessels only	Yes		Yes
Bulk carriers	Yes	Yes	Yes	Yes			Yes	Yes							Yes		Yes
Container vessels	Yes	Yes	Yes	Yes			Yes	Yes			Large vessels only	Large vessels only	Large vessels only	Large vessels only	Yes		Yes
General cargo vessels	Yes	Yes	Yes	Yes			Yes	Yes	Yes	Yes	Medium and large vessels only	Medium and large vessels only	Medium and large vessels only	Medium and large vessels only	Yes		Yes
LNG carriers	Yes	Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes		Yes
LPG carriers	Yes	Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes		Yes
RoRo vessels	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes					Yes		Yes
Cruise ships	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes					Yes		Yes

Table 5-8 Fuel specifications for the modelling of Package 3

Fuel	Applicability	Additional specification for the modelling
LNG	All LNG vessels	Assumed to use g*lobal average* pathway
BioLNG	All LNG vessels	Assumed to use *liquid manure* pathway
Ammonia	All vessel types	Assumed to use three pathways; *grey* ammonia followed by *blue* ammonia then transitioning to *green* ammonia
Methanol	All vessel types	Assumed to use two pathways; *grey* methanol followed by *green* methanol

Overall the assumed timeline of implementation for the fuels for package 3 is as follows:

- **2020 –** Assumes 72% HFO, 28% MDO for all ship categories except LNG carriers, which are 100% grey LNG.
- **2025 -** Grey ammonia starts to be used in 2025 but transitions out and is replaced by blue ammonia (2025-2035). Grey methanol starts to be used in 2025 but starts to transition out and be replaced by green methanol by 2040 (2025-2040). BioLNG starts to be used, gradual replacement of LNG from 2025-2050
- **2035 -** Blue ammonia starts to transition out (2035-2040), green ammonia transitions in (2035-2040). Grey methanol starts to transition (2035-2040).
- **2040 -** By 2040, 100% green methanol and 100% green ammonia
- **2050 -** By 2050, 100% BioLNG replacement of LNG, 100% green methanol and green ammonia.

5.2.4 Technologies and fuel sensitivity studies

The three packages described above differ both in the technologies assumed to be implemented in new vessels and in the range of alternative fuels used. To give further insight into the effects of these different elements of the packages, two additional sensitivity analyses have been performed. These are:

- Package 1A:
  - Early pursuit of zero-carbon alternative fuels as in Package 1
  - Same maximisation of vessel decarbonisation technologies as in Package 3
- Package 2A:
  - Use of interim lower-carbon fuels and drop-in fuels as in Package 2
  - Same maximisation of vessel decarbonisation technologies as in Package 3

The results of these analyses are presented in Section 7.5.

6 Modelling methodology

This section describes the approach taken to modelling the impacts of the different fuel and technology packages on the fleet, fuel consumption, emissions and costs. Key points:

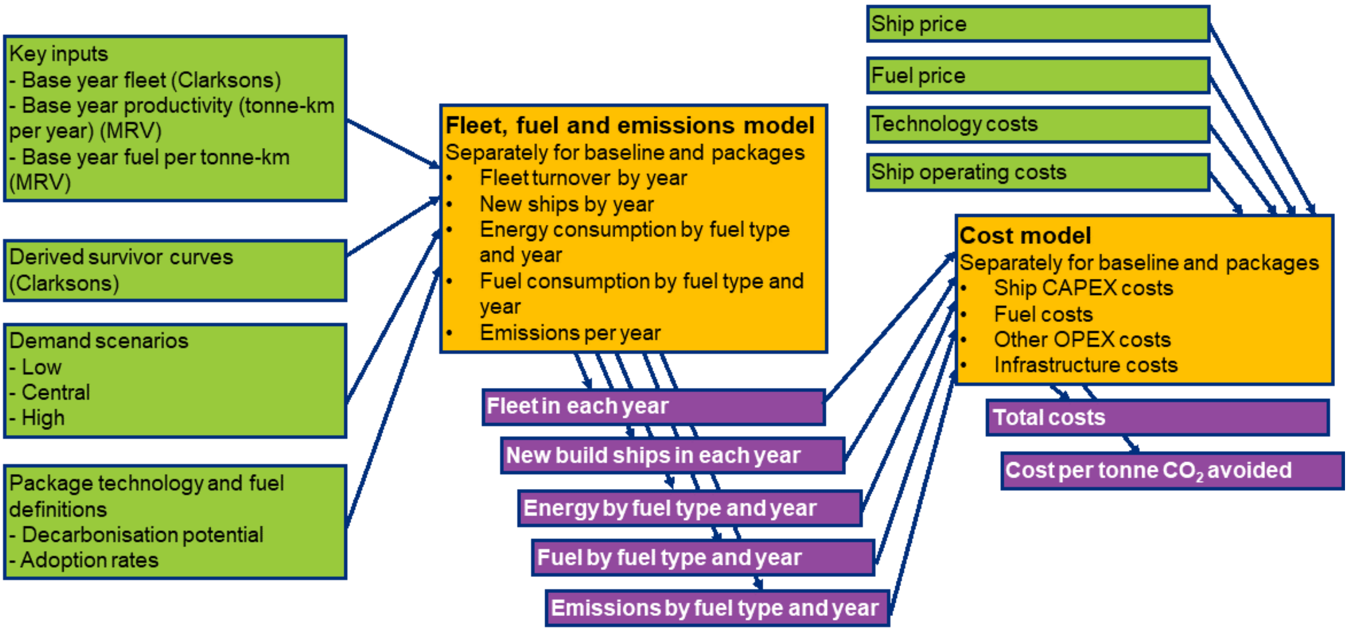
- A global vessel fleet model has been constructed, with a baseline set (low, central, high) of maritime transport demand scenarios following selected pathways from the IMO's 4th GHG study. The central scenario sees demand in tonne-miles nearly double by 2050 from 2020.
- The future fleet has been estimated matching both the demand profile of the scenarios as well as accounting for turnover of the vessel fleet. The fleet turnover is calculated separately for each vessel category utilising recent historical vessel lifetimes. Vessel productivity decline with age is accounted for.
- Under the central demand scenario, we estimate the fleet size will need to grow to accommodate the increased demand from ~49,000 ships in 2020 (~47,000 existing ships and ~2,000 newly built ships) to ~71,000 ships by 2050 (comprising ~67,000 built since 2020, and ~4,000 ships from prior to 2020 remaining in the fleet). Under the low and high demand scenarios, the fleet size in 2050 is 18% lower and 21% higher than in the central scenario, respectively.
- Baseline CO_2 emissions estimated in the central demand scenario to grow by ~22% between 2020 and 2050 (grow by 53% in the high demand scenario; decline by 13% in low demand).
- The packages are implemented in the model by changes to the fuel efficiency and fuel used by newly built ships, and the emissions characteristics of the fuel used by new and existing ships. The impact of the fuel and technology packages are taken as the difference from the baseline.
- The cost impacts of the packages account for alternative fuel costs (future price reductions are forecast), vessel capital and operating costs. The net change in fuel production infrastructure costs (capital and operating) are estimated. Cost-effectiveness of the packages is derived.

The analysis to estimate the decarbonisation potential and associated costs for the three packages was performed using two components of a model. The two components were:

i. Estimating fleet changes and emissions impacts
ii. Estimating cost impacts

As well as the fuel and technology packages, the model also calculates a baseline case, allowing the impacts of the packages to be derived as the difference from the baseline. To address uncertainty in the possible future maritime transport demand, the baseline and packages are estimated for three demand scenarios (low, central and high). The two components of the model are linked by the fleet (numbers of ships constructed and in the fleet), fuel consumption (by fuel type) and emissions. Figure 6-1 shows an overview of the complete modelling structure used in this study, including the interaction between the two components.

Figure 6-1: Structure of modelling framework



This section describes the methodology deployed for the modelling in both components. The results of the modelling are shown in Section 7.

6.1 Fleet and emissions

The fleet and emissions modelling consists of a number of discrete steps, as listed in Table 6-1.

Table 6-1: Steps in the fleet and emissions modelling

Step	Step name	Summary
Baseline definition		
1	Future demand scenarios	Definition of future maritime transport demand under different growth assumptions
2	Base year fleet	Definition of the numbers of vessels by type and size in the base year
3	Survivor curves	Derivation of a set of functions defining the percentage of vessels built that survive to a given age before being demolished
4	Vessel productivity	Derivation of average annual productivity (tonne-miles delivered per annum) by vessel type and size
For each demand scenario		
5	Future year fleet	Calculation of the vessel fleet numbers by type and size, as driven by the demand scenarios
6	Baseline fuel consumption and emissions	Calculation of the fuel consumption and emissions under the baseline assumptions
For each demand scenario and fuel and technology package		
7	Impacts of technologies and alternative fuels on emissions	Calculation of the fuel consumption and emissions under the assumptions for the future technology development and alternative fuel use under the three packages

These steps are described in additional detail, with examples of the intermediate results, in the following subsections.

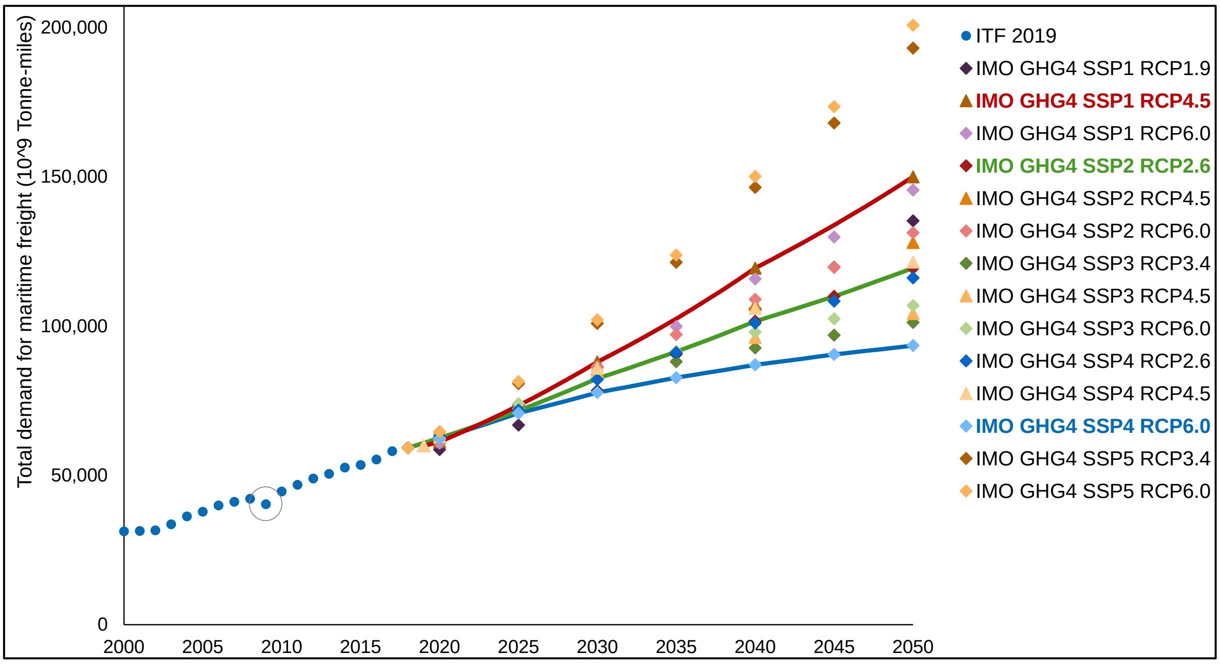
6.1.1 Future demand scenarios

A key input to the analysis of the development of the future fleet and emissions is the demand scenario. This specifies, for each vessel type and hence the nature of the transport of the goods, the global demand in tonne-miles. Three scenarios were included, representing low, central and high demand growth scenarios. These were selected from the IMO fourth greenhouse gas study (IMO, 2020). As mentioned in Section 1.1, the conclusions from the IMO study indicate expected growth in CO_2 emissions to 2050 of between 90% and 130% of the 2008 value, based on a limited set of the scenarios considered in the study. The different scenarios are defined in terms of the assumptions on future socioeconomic development (known as "Shared Socioeconomic Pathways" (SSP)) and the atmospheric greenhouse gas concentration development (known as "Representative Concentration Pathways" (RCP)). The scenarios on which the IMO report bases its headline '90% to 130%' change statement are those associated with RCP 2.6 (limiting global temperature increase to below 2°C). However, beyond the executive summary of the IMO report, a fuller range of future maritime demand scenarios consistent with additional pathways, from RCP 1.9 (1.5°C global temperature rise) to RCP 6.0 (2.8°C global temperature rise, is provided. From reviewing the demand projections provided, the following projections were selected for the low, central and high demand scenarios for this study.

Low	SSP4, RCP6.0 ("Inequality, a road divided" + "2.8°C medium baseline, high mitigation")
Central	SSP2, RCP2.6 ("Middle of the Road" + "2.0°C low GHG emissions")
High	SSP1, RCP4.5 ("Sustainability, Taking the High Road" + "2.4°C, medium-low mitigation")

The total demand under these three projections, together with those for other scenarios in the IMO report are shown in Figure 6-2.[50]

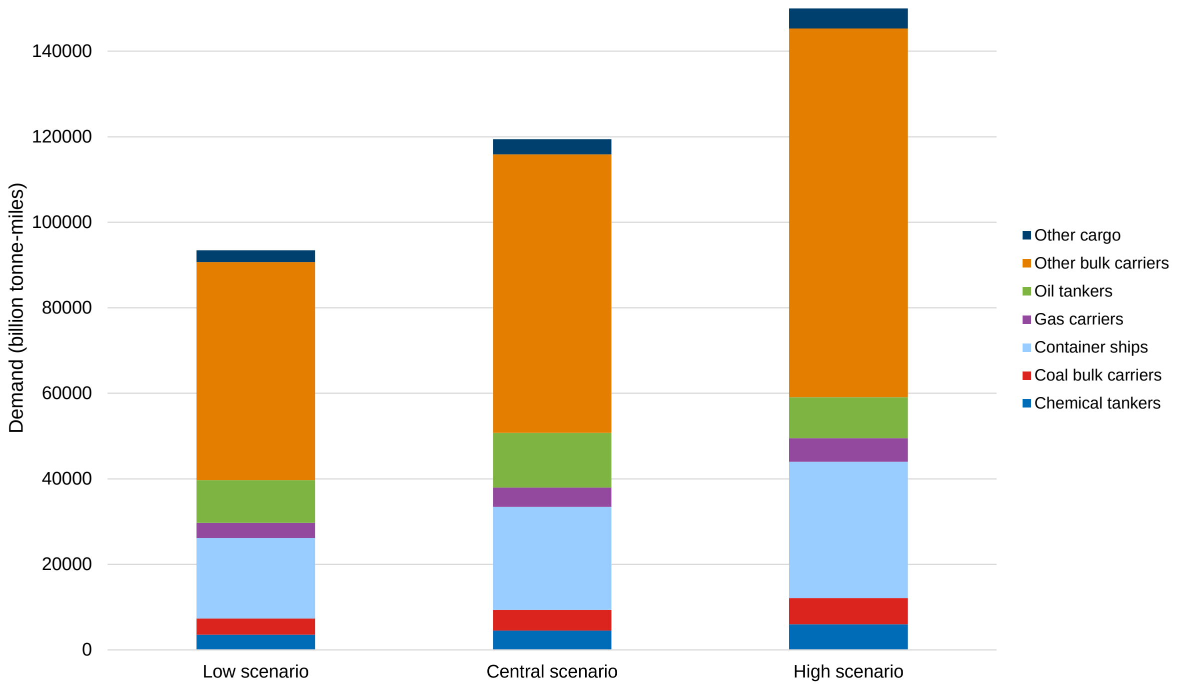
Figure 6-2: Low, central and high demand projections selected, together with other demand scenarios from the IMO fourth greenhouse gas study report



[50] The scenarios selected from those shown in Figure 6-2 represent reasonable bounds on future demand growth, rather than representing scenarios that are more likely than others. The IMO report also included two further scenarios (based on SSP5) with demand levels above the selected "high" scenario; however, it was felt that these represented an overly high level of demand and, therefore, they were not included in the scenarios modelled.

The split of demand between different vessel types under these three scenarios are shown for 2050 in Figure 6-3. By 2050, the greatest levels of demand are met by non-coal bulk carriers and container ships. It is notable that, although the total demand for maritime transport is highest under the high demand scenario, the demand for the transport of oil is lower than under the central scenario. This is because the cases are based on different global SSPs, with the high scenario being based on one with lower global demand for oil products (SSP1 rather than SSP2).

Figure 6-3: Split of total demand between vessel types in 2050



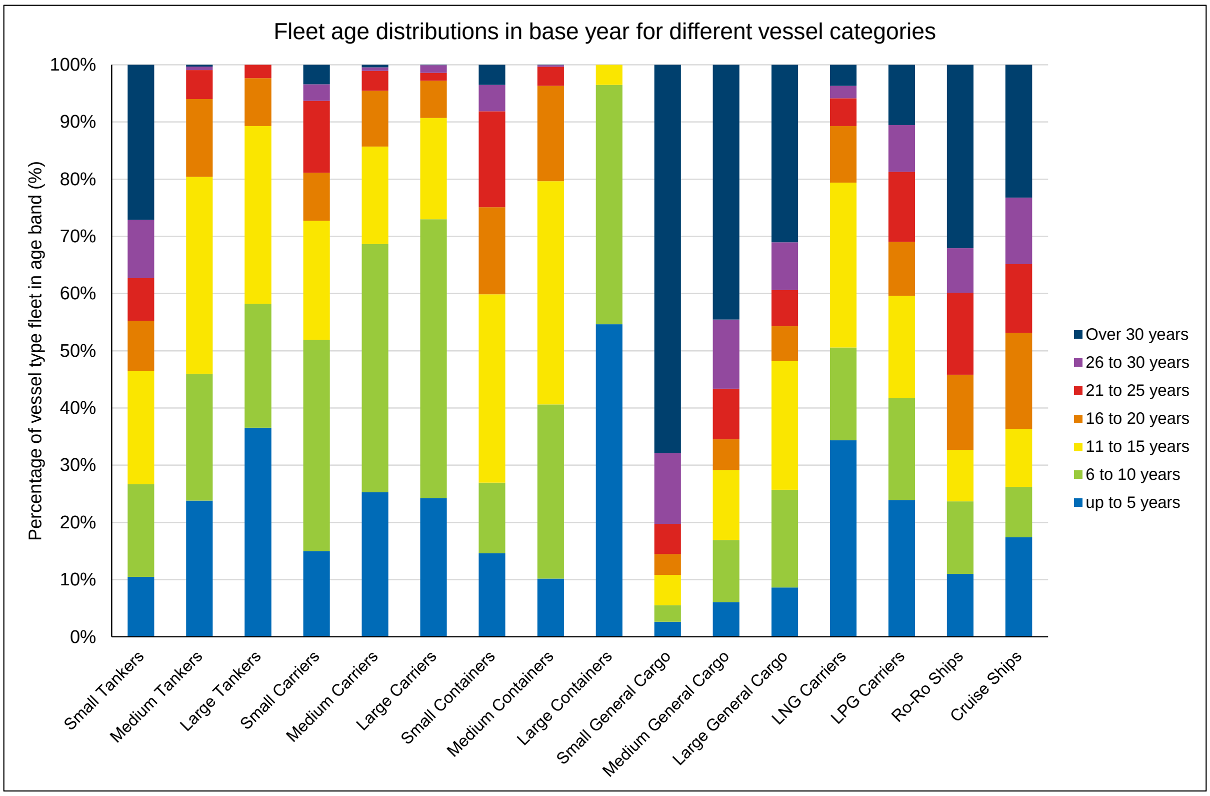
6.1.2 Base year fleet

The baseline calculations in this model started from a description of the global maritime fleet in 2020 (the base year for the fleet analysis). This defined the numbers of ships in each category (and size sub-category) and age; these were obtained by analyses of the current fleet using data from the Clarksons World Fleet Register (Clarksons Research, n.d.). The vessel categories included in the model are shown in Table 6-2, including the total fleet size at the start of the base year; Figure 6-4 shows the distribution of ages in these categories.

Table 6-2: Definition of vessel size sub-categories and numbers of vessels in the base year

Vessel category	Size sub-category	Vessel sizes included	Number of vessels at the start of 2020
Tankers	Small	Up to 40,000 DWT	10,052
	Medium	40,000 to 100,000 DWT	2,170
	Large	Over 100,000 DWT	383
Bulk carriers	Small	Up to 50,000 DWT	4,431
	Medium	50,000 to 100,000 DWT	5,848
	Large	Over 100,000 DWT	1,793
Container ships	Small	Up to 4,000 TEU	3,255
	Medium	4,000 to 13,000 TEU	1,730
	Large	Over 13,000 TEU	399
General cargo ships	Small	Up to 1,000 DWT	4,192
	Medium	1,000 to 2,500 DWT	4,300
	Large	Over 2,500 DWT	4,820
LNG Carriers			597
LPG Carriers			1,480
Ro-Ro Ships			836
Cruise Ships			465
Total fleet			**46,751**

Figure 6-4: Age distributions for the different vessel categories in the base year

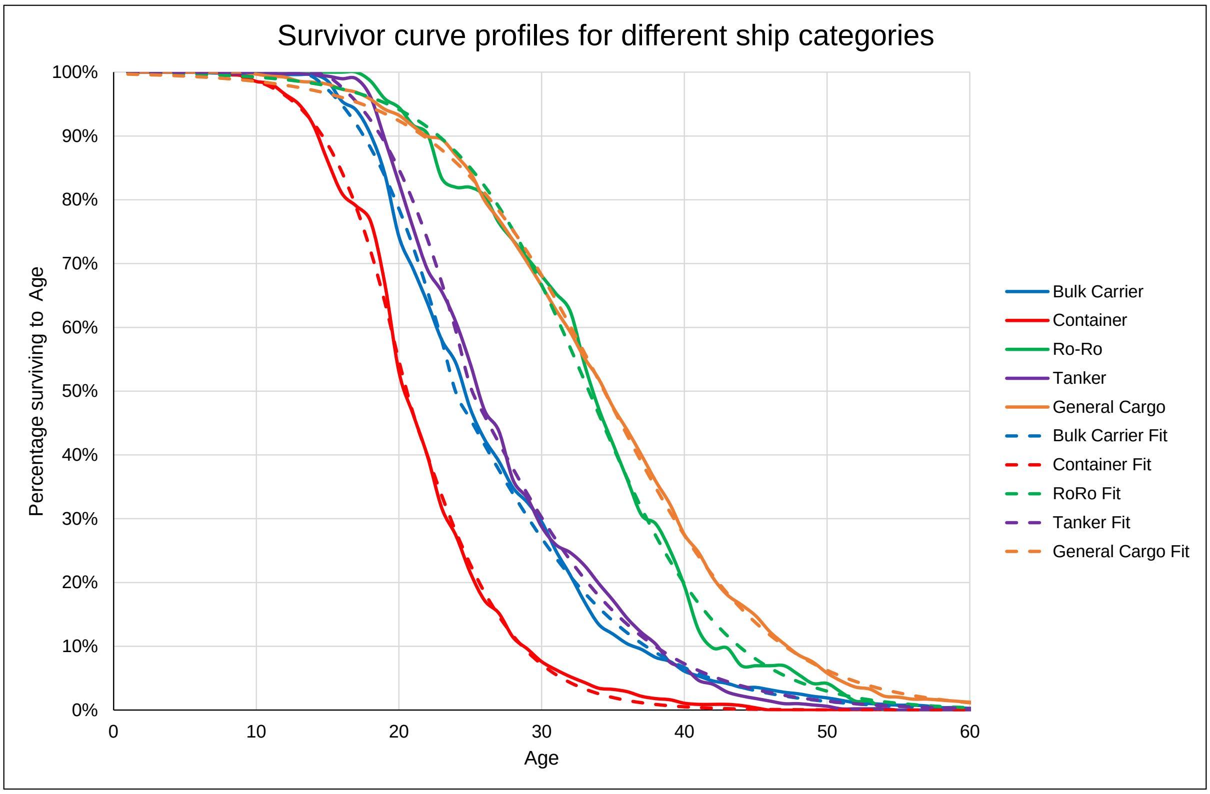


For tankers and bulk carriers, the fleets are comparatively young, with larger numbers of vessels in the "younger" age bands. This is consistent with a stable situation with vessels being constructed on a broadly steady basis and then retired gradually over time. Large container ships (over 13,000 TEU) are a more recent development, and so this age profile analysis shows almost all vessels are very young (up to 10 years) .A few vessel categories, such as the small general cargo category, show a dominance of older ships; this may indicate a limitation of the data source or a long vessel lifetime having led to a reduced demand for new vessels.

6.1.3 Survivor curves

The modelling of the packages under future scenarios requires an estimate of the future fleet characteristics, giving the number of vessels by category (and size) and age in each year between the base year and 2050. A fleet turnover model is applied to achieve this aim. For each year, this identifies the fraction of the fleet from the previous year that would survive to the new year and, hence, the fraction that would be retired (i.e. demolished). To do so, the model applies a set of survivor curves that specify the percentage of the fleet that survive to different ages. These curves were derived from vessel demolition data obtained from the Clarksons' World Fleet Register (Clarksons Research, n.d.). The analysis of the demolition data produced distributions of the ages to which vessels survived; these were then fitted with logistic curves to produce the functions applied in the model. The main curves used are shown in Figure 6-5. In Figure 6-5, the solid lines show the original data (percentage of vessels surviving to beyond a given age, based on the ages in the demolition data), with the fitted curves shown as dashed lines.

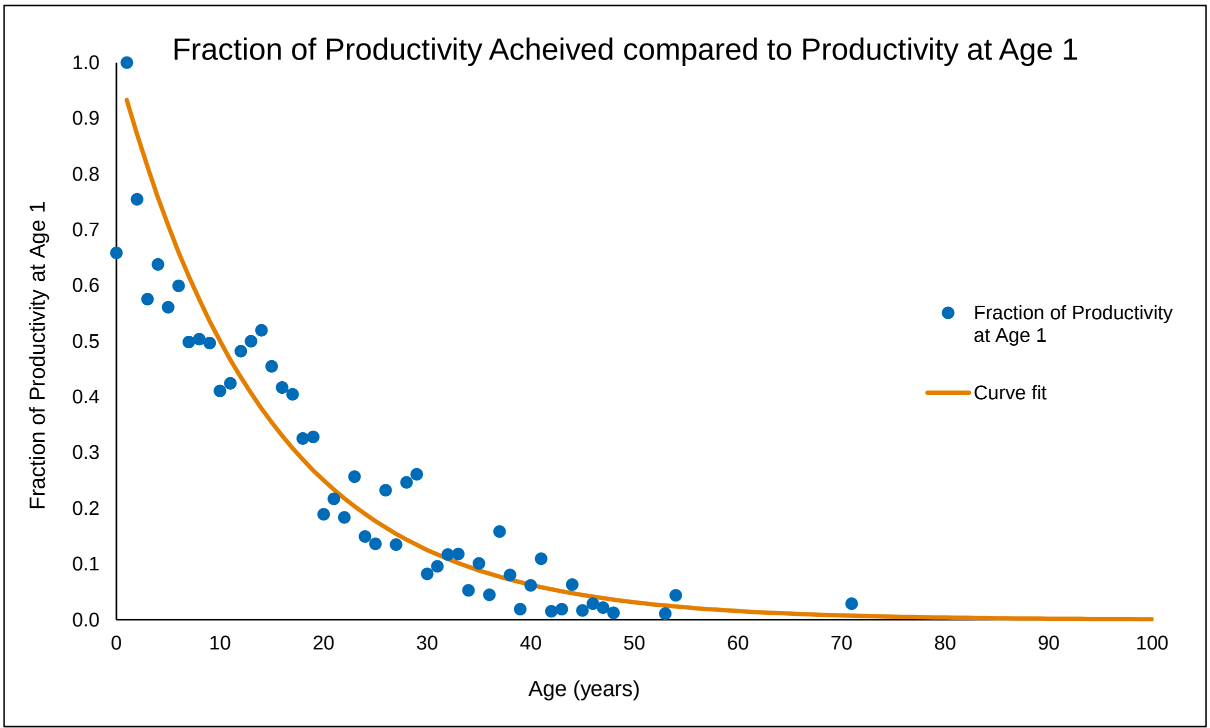
Figure 6-5: Survivor curves developed for key vessel categories



6.1.4 Vessel productivity

Once the number of ships that survive to operate in the next year has been calculated, their capacity to deliver cargo is calculated using a set of productivity curves. To estimate the productivity (in tonne-miles per year for a vessel), the data published through the THETIS-MRV portal[51] were analysed to develop distributions of productivity against age and size of vessel. Data were available (with sufficient information) for almost 10,000 vessels to include in this analysis. The analysis of the fleet average productivity as a function of vessel age showed a strong dependence, as shown in Figure 6-6.

Figure 6-6: Productivity curve showing strong dependence on vessel age



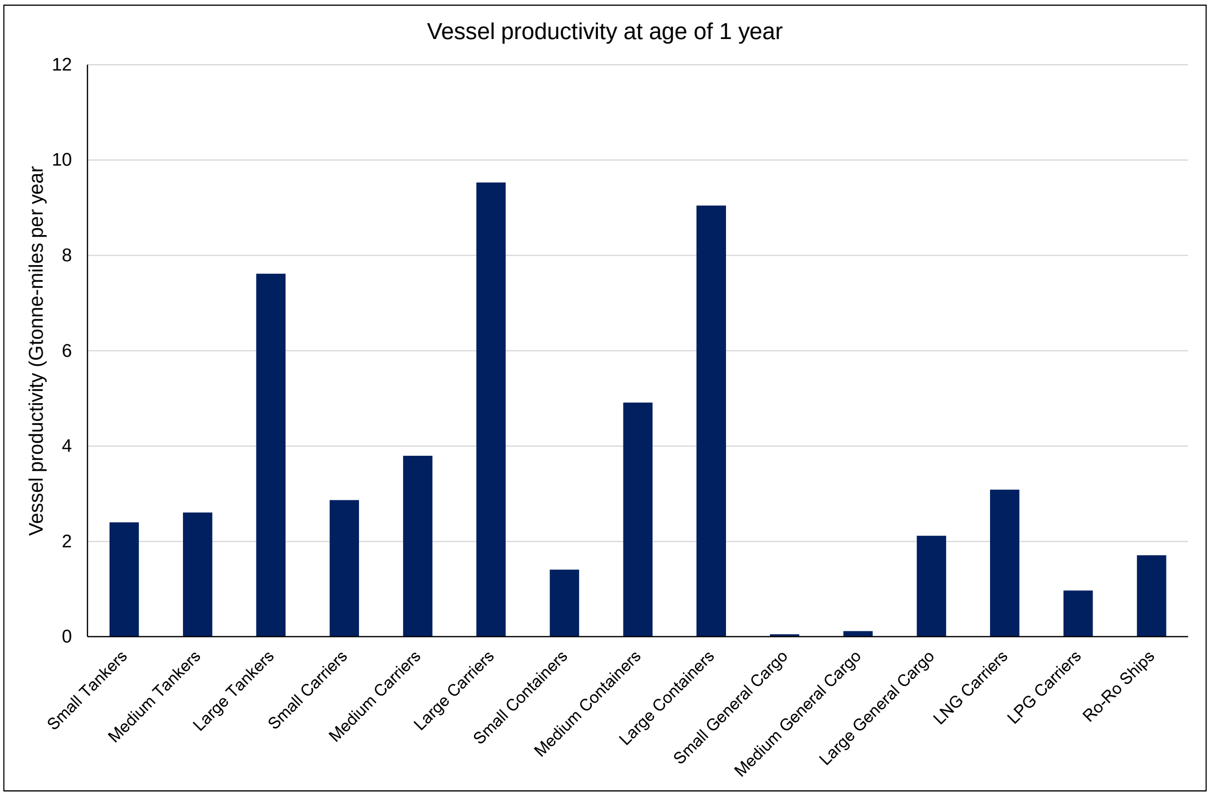
The curve shown in Figure 6-6 was used to model the reduction the productivity of the vessels as they aged; their productivity at age of 1 year was based on the average values by ship category from the THETIS-MRV data; they were then adjusted to ensure a balance between the number of vessels in the fleet in the base year and the demand (total tonne-miles) required to be transported.[52]

The resulting age-dependant productivity of each vessel type is shown in Figure 6-7 for vessels of age one year. As expected, the largest ship categories (large tankers, large bulk carriers and large container ships) have the highest productivity values, with the smaller vessels having lower productivity. The small and medium general cargo vessels can be seen to have very low productivity values (the numbers of such vessels in the modelled fleet is comparable to other categories, so their contribution to the overall demand is also small).

[51] https://mrv.emsa.europa.eu/#public/eumrv. These EU level data are the most detailed information available, and have been assumed to be representative of global vessel productivity.

[52] The fleet data, productivity data and demand were derived from different sources, so some manual adjustment was required to ensure consistent operation of the model.

Figure 6-7: Calculated productivity (tonne-miles delivered per year) at a vessel age of 1 year



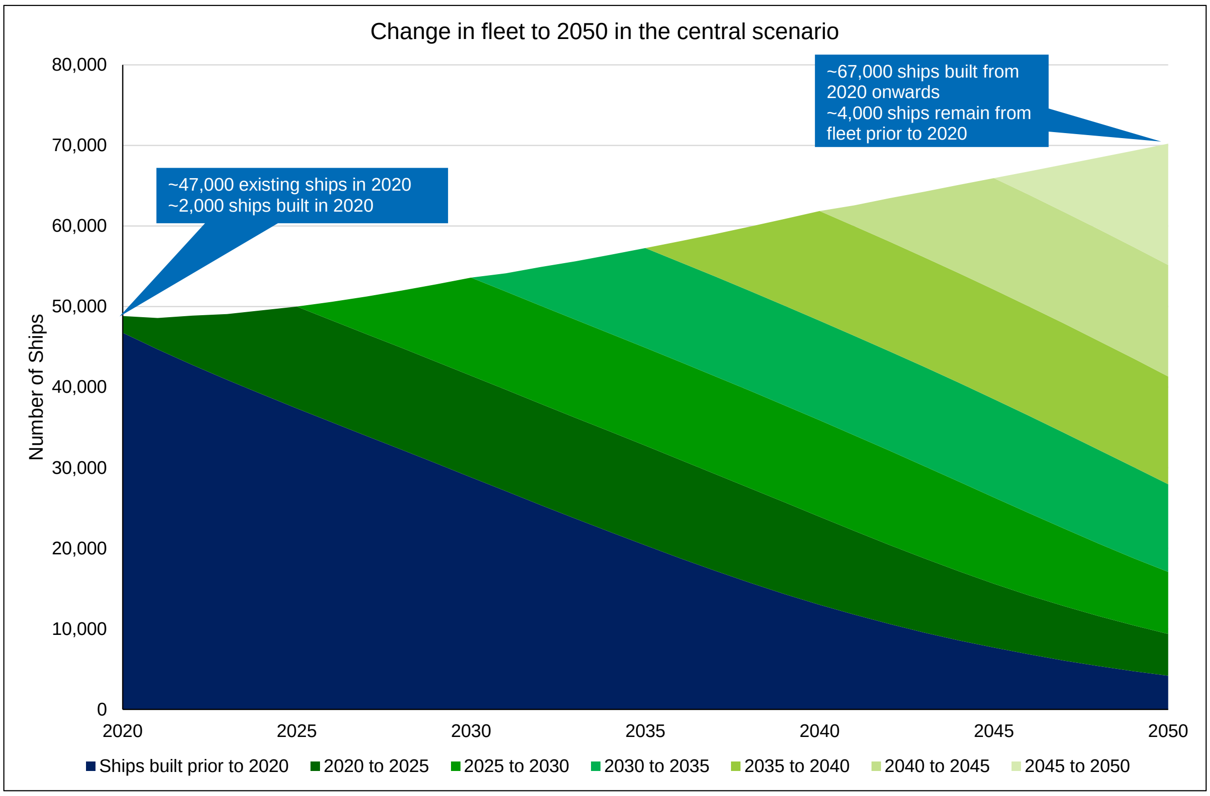
6.1.5 Future year fleet

The fleet in operation in future years (defined by the number of vessels in each category, including the age profiles) are calculated using a fleet turnover model that, in each year, calculates the number of vessels (and their capacity to transport goods) that survive from the previous year and the number of new vessels that must be built to enable the fleet to meet the transport demand.

The combination of the fleet size (including the age profile) surviving to the future year and the productivity data shown in Figure 6-6 and Figure 6-7 determine the capacity of the existing fleet to transport goods. The gap between this capacity of the existing fleet and the demand for that year gives the capacity that must be met by new vessels. The productivity at age zero is then used to determine how many new vessels are required to be delivered during the year to ensure that the transport demand is met.

As a result of this calculation process, the maritime fleet in a future year consists of a number of vessels from the base year fleet (with this number reducing over time) and a number of vessels built after the base year. This is an important output as the differentiation between existing and new vessels is critical to the assumptions of the three technology and fuels packages related to which are the new vessels that are able to be equipped with new technologies, or to use new fuels. Figure 6-8 shows the increase in the size of the future fleet and how it consists of different numbers of ships built in different years.

Figure 6-8: Fleet development (total number of vessels) to 2050 under the central scenario, showing those built prior to and after 2020



As can be seen, the number of vessels in a band of delivery years (e.g. 2025 to 2030) increases over the five years of the band, then decreases gradually out to 2050 as the application of the survivor curves takes effect.

6.1.6 Baseline fuel consumption and emissions

Using the calculated fleet in the future year, and the number of tonne-miles delivered in each vessel category, the model calculates the fuel consumption and CO_2 emissions. This calculation relies on a set of fuel consumption per tonne-mile values derived from the data from the THETIS-MRV portal. The calculated fuel consumption values are converted to energy consumption figures to simplify the application of the alternative fuels under the three technology and fuels packages.

For each vessel category and each future year, the demand met (in tonne-miles) is multiplied by the relevant energy consumption value for that category to give the total energy consumed by the fleet (in that vessel category). For the baseline cases, the energy efficiency values for new build vessels are held constant for vessels delivered from 2020 (i.e. vessels built after 2020 are assumed to have the same efficiency as those built in 2020). This reflects the assumption that the historic improvements in efficiency for new vessels are the result of the introduction of improved technologies, along similar lines to those implemented under the packages; projecting continuing improvements in the baseline would lead to double counting of efficiency improvements under the packages. This approach is known as a "technology freeze" model assumption. The fuel consumption is calculated separately for each fuel type, so that the total fuel consumption by fuel type can be determined and so that the CO_2 emissions can be calculated using standard emissions factors for the different fuels. In addition to CO_2 emissions, the model also calculates CO_2-equivalent (CO_2e) emissions, which include the impacts of methane (CH_4) and nitrous oxide (N_2O) emissions, factored by the relevant ratios of global warming potential. The CO_2e

emissions are calculated applied separately for well-to-wake[53] (WTW) and tank-to-wake (TTW) emissions so that the effects of the different fuel pathways can be identified as well as the different fuel types. The assumptions behind the definition of the different fuel types and pathways was presented in Section 4. The emissions factors for 2020 used in the model are shown (based on mass of CO_2 or CO_2e emissions per energy content to ease comparisons between the different fuel types) are shown in Table 6-3. As shown previously in Table 5-1, for some of the "green" fuels, the WTW emissions are higher than the equivalent "blue" fuels in 2020; these are expected to reduce over time as the embedded emissions in the renewable electricity generation plants reduce, thus giving them lower emissions than the "blue" variants in future years.

Table 6-3: Summary of fuel CO_2 emission factors for 2020 used in model

Fuel	CO_2 TTW (g/MJ)	CO_2e TTW (g/MJ)	CO_2e WTW (g/MJ)
HFO	77.5	77.6	87.2
MDO	75.1	76.1	93.5
LNG	57.3	59.6	78.1
BioLNG	57.3	59.6	27.5
Hydrogen (Grey)	0.0	0.0	92.4
Hydrogen (Blue)	0.0	0.0	21.5
Hydrogen (Green)	0.0	0.0	22.2
Ammonia (Grey)	0.0	0.0	100.6
Ammonia (Blue)	0.0	0.0	20.9
Ammonia (Green)	0.0	0.0	22.2
Methanol (Grey)	69.1	76.1	98.1
Methanol (Green)	69.1	76.1	22.2
FAME	75.5	76.5	13.8
HVO	70.7	71.6	8.1

For fuel types with different pathways (hydrogen, ammonia and methanol), the TTW emissions are the same for the different pathways, as the fuel loaded into the tank is chemically identical in each case. For hydrogen and ammonia, these values are zero, as they do not produce any CO_2 on combustion; all the WTW emissions relate to the production process.

Figure 6-9 shows the calculated global emissions from 2020 to 2050 under the three baseline scenarios. The baseline calculations assume that no new technology is introduced into newly built vessels after 2020, so all vessels delivered after that date have the same characteristics as those built in 2020. The overall fleet continues to improve (efficiency) as the newest vessels form a greater portion of the fleet.

[53] Well-to-wake emissions include the emissions associated with the production of the fuel, as well as those from the combustion in the ship's engines, while tank-to-wake emissions include only those from combustion.

Figure 6-9: Emissions of CO_2e from 2020 to 2050 under three baseline (technology freeze) scenarios

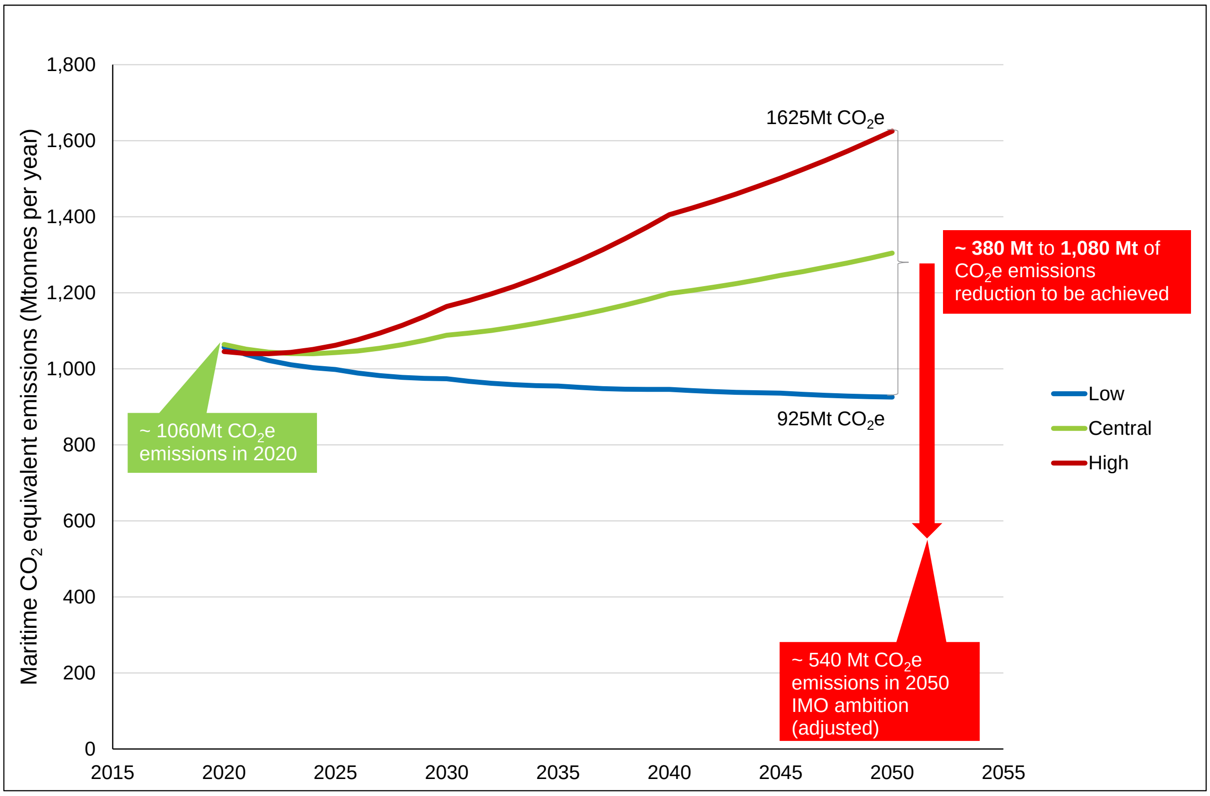


Figure 6-9 shows calculated CO_2e emissions in 2020 of approximately 1,060 Mtonnes. This is approximately 15% higher than the value for 2018 reported by IMO in their fourth greenhouse gas study (IMO, 2020). The reasons for this difference in emissions could include:

- Difference in base year (although the effect of this would be expected to be small as the data in the IMO study does not indicate a rapid rise in emissions approaching 2018);
- Differences in scope and assumptions behind the allocation of vessel types to deliver the identified demand;
- Differences in modelling of fuel consumption by different vessel types.

The current modelling uses data from the EU THETIS-MRV database from 2018 and 2019 to estimate the fuel consumption of different vessels. The IMO study uses different data to estimate fuel consumption; as a result, this effect probably has the greatest impact on the differences in the calculated fuel consumption and emissions.

The IMO third greenhouse gas study (International Maritime Organization, 2014) reported CO_2e emissions in 2008 of 940 Mtonnes. The achievement of the ambition of, at least, a 50% reduction in emissions by 2050 would imply emissions from international shipping of no more than 470 Mtonnes. As the current study has calculated higher emissions in the base year than those in the IMO fourth greenhouse gas study, it is sensible to compare the achievements of the measures against a target for 2050 that is also increased by a similar percentage. Therefore, the results of the analyses are compared against a 2050 target of no more than 540 Mtonnes CO_2e.

6.1.7 Impacts of technologies and alternative fuels on emissions

The calculation process described above is applied for the baseline and package cases. The impacts of the different packages are then identified as the difference (in fuel consumption, emissions, etc.) between the baseline and the package results.

The implementation of the packages in the calculations consists of three separate elements:

- Vessel-based technologies
- Operational improvements
- Alternative fuels

For the vessel-based technologies, the fleet turnover calculation, described in Section 6.1.5, retains the age profile of the fleet in the future years. For each future year, this allows the percentage of the operating fleet that was delivered in each previous year to be identified. Each vessel-based technology is specified by an initial year of introduction into new-build vessels, and the percentage of new vessels that it is applied to. Using the numbers of vessels built in each year, as described in Section 6.1.5, the percentage of the operating fleet in the future year equipped with the technology can be calculated. This percentage is then used, with the defined efficiency improvement for the technology, to calculate the reduction in energy requirements for the fleet in that year.

The resulting increased penetration of the different technologies into the operating fleet (over any penetration in the baseline), under the three packages, is illustrated in Figure 6-10 to Figure 6-12.

Figure 6-10: Penetration of technology into the in-service fleet under Package 1

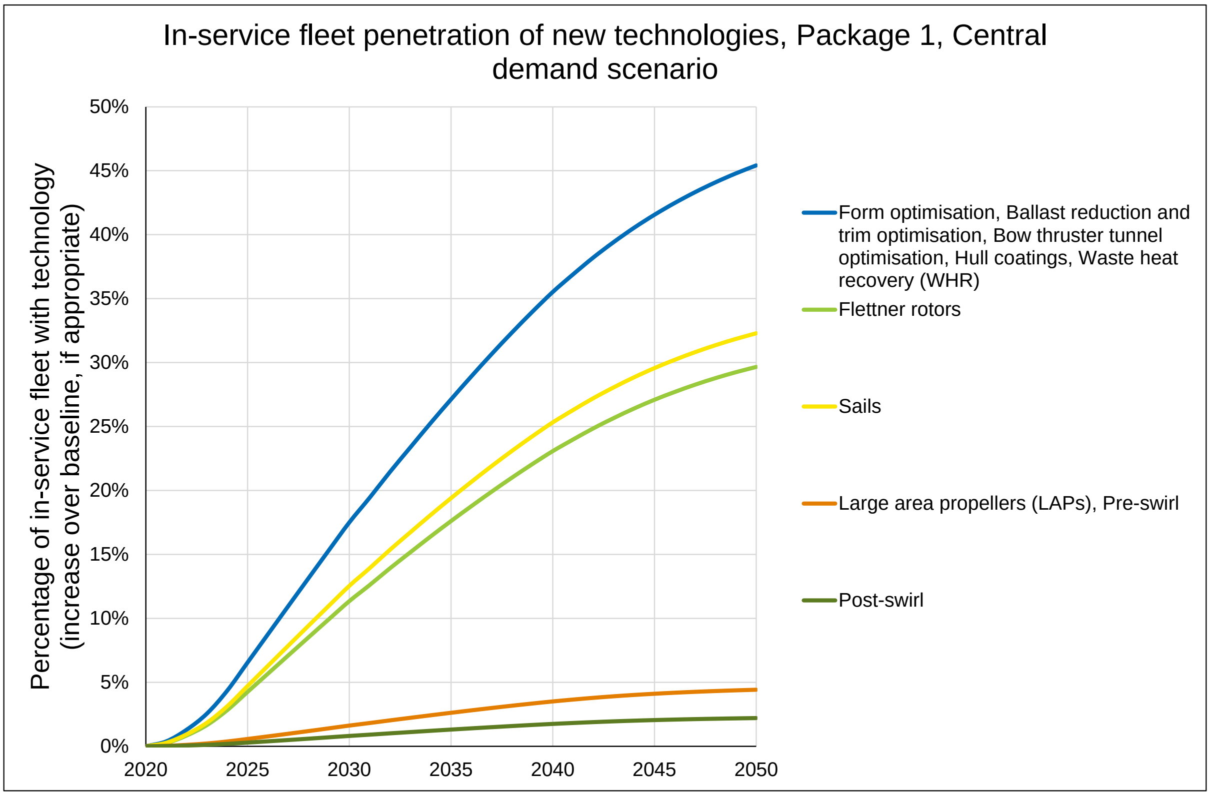


Figure 6-11: Penetration of technology into the in-service fleet under Package 2

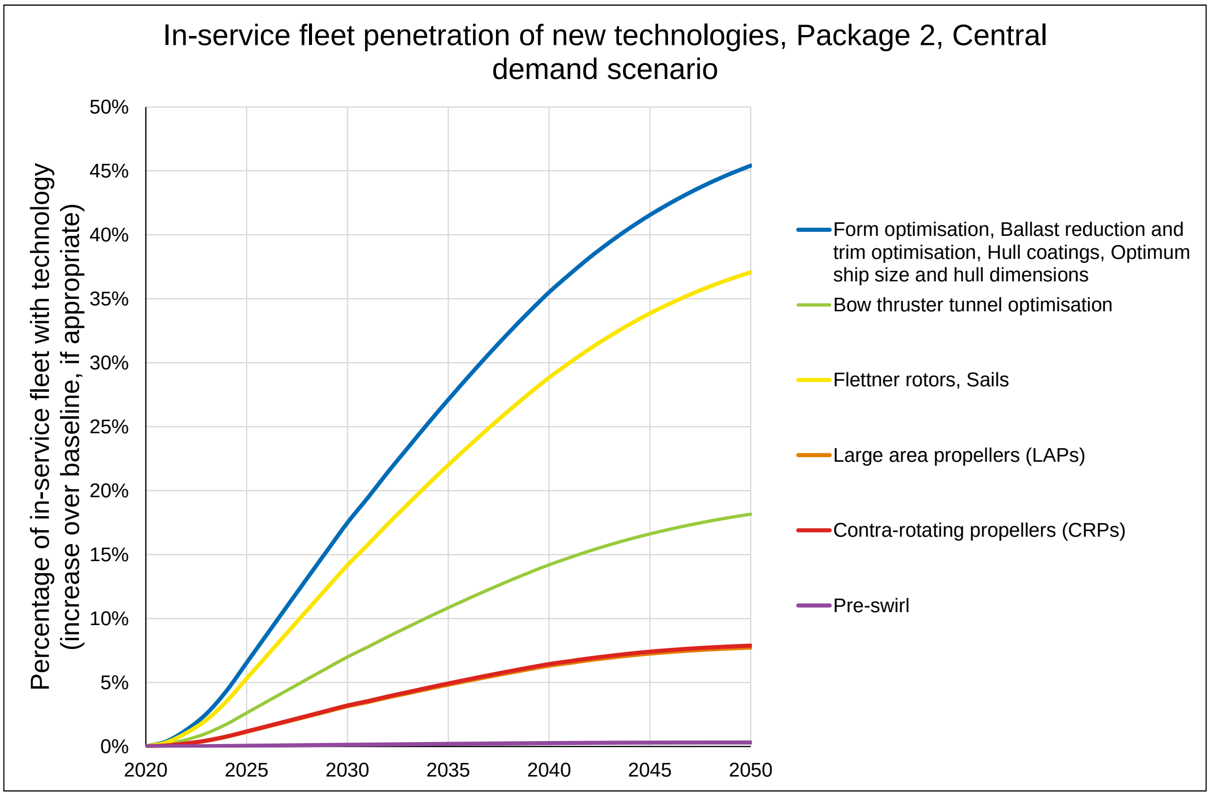
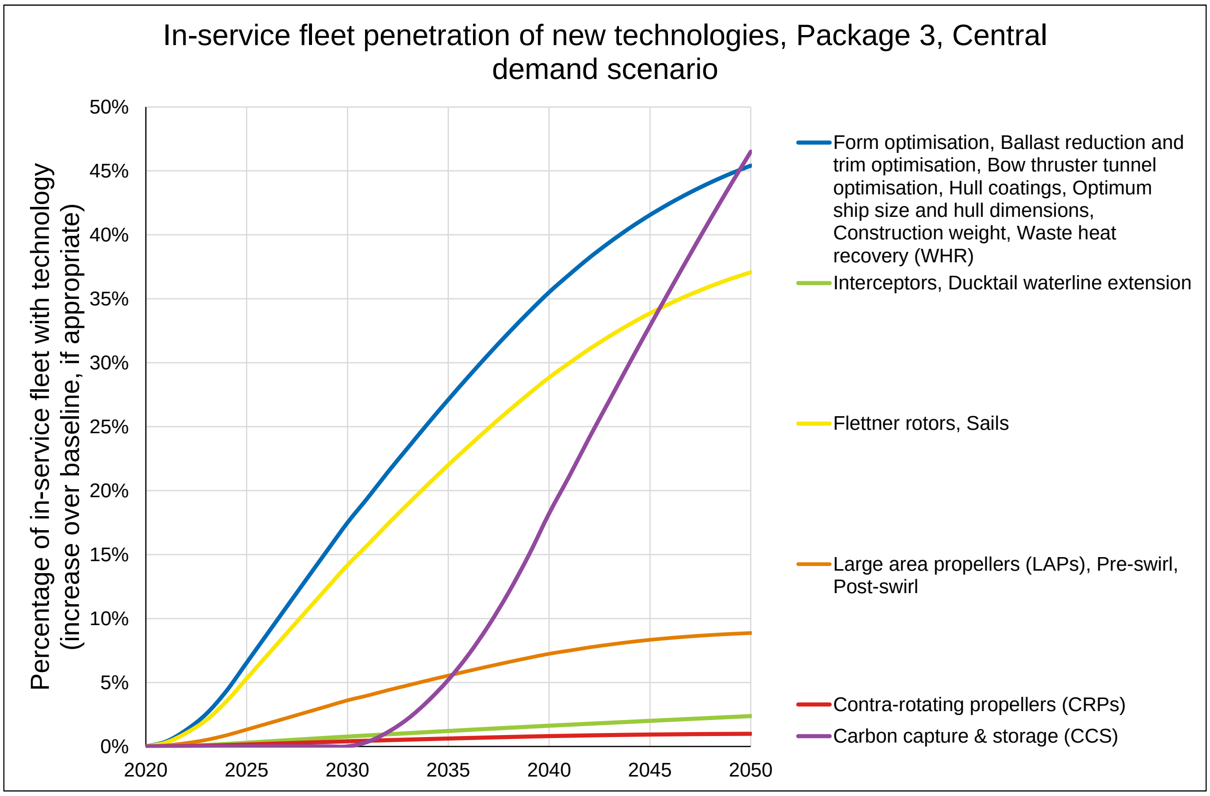


Figure 6-12: Penetration of technology into the in-service fleet under Package 3



As several technologies are given the same initial implementation dates and applicability, some curves in these charts represent multiple technologies, as shown. The highest levels of fleet penetration achieved by 2050 are just over 45% under each package.

Operational improvements are assumed to be available to all operating vessels in the future year, not just those built after a given year. Therefore, the energy reductions resulting from the take-up of the improvement are applied across the full fleet (factored by the assumed percentage take-up in the future year).

The take-up of alternative fuels is dependent on the ability of the vessel to use that fuel, which also depends on its build year (in a similar way to the vessel-based technologies). Therefore, the calculated fleet in each future year is also defined by the fuel used (HFO, MDO, LNG, ammonia, etc). The approach described above for calculating the fuel consumption from the energy consumption is then applied separately by each fuel type. In doing so, it is assumed that the fuel type does not change the energy needed for the vessel to deliver a tonne-mile, this energy requirement having been reduced by any vessel-based technologies and operational improvements included in the package.

6.2 Costs

The cost modelling takes the results for the vessel fleet, fuel consumption and emissions calculations described in Section 6.1 and applies estimated values for vessel and infrastructure capital and operational costs, to derive overall costs in each year under the baseline and fuel and technology package cases. As for the fleet and emissions modelling, the cost impacts of the packages were calculated as the difference between the total costs under the package and those under the baseline.

The methodological steps in the cost modelling are summarised in Table 6-4 and described in the following subsections.

Table 6-4: Steps in cost modelling

Step	Step name	Description
1	Fuel specification	Define fuel specification, including price projections to 2050, for all fuel types
2	Define vessel prices	Define the prices for the different vessel types, including the impact of the inclusion of the different technologies under the package cases
3	Calculate vessel capital costs	Calculate total capital costs, including costs of capital (e.g. interest on loans) for the fleet, by vessel type
4	Calculate vessel operating costs	Calculate annual operating costs for the fleet, by vessel type
5	Calculate fuel production infrastructure capital costs	Based on the calculated demand for fuels of each types, calculate the number of production plants required and their associated capital costs
6	Calculate fuel production infrastructure operating costs	For the number of plants calculated to be required for each fuel type, calculate the annual operating costs
7	Calculate port refuelling infrastructure costs	Based on the calculated demand for the fuels of different types, calculate the refuelling infrastructure required and the associated costs (capital and operating)
8	Calculate port CO_2 handling costs	Based on the calculated CO_2 captured by on-board CC systems, calculate the costs for offloading and handling the fuel in ports
9	Calculate total costs and cost-effectiveness	The cost modelling uses the emissions results from the fleet and emissions modelling to output cost-effectiveness values (net cost per tonne CO_2 reduction).

6.2.1 Fuel specification

This first step specifies the assumptions on the prices for the different fuel types out to 2050. Illustrative current (or recent) prices for the different fuel types considered in the study are shown in Section 4.1. The modelling of future costs needs to account for future prices of fuels. Since many of the fuel pathways considered are in their infancy from a TRL perspective, it would be overly cautious and an overestimate to assume these prices (e.g. green hydrogen/ammonia) would not drop over time. Therefore, estimates of future fuel prices have been developed in order to calculate the fuel costs over time. The prices have been developed in constant 2020 US dollars (i.e. not including the effects of general inflation). To ensure that the price projections for the different fuel types are all developed in a consistent manner, IHS Markit (under a separate contract to Concawe) developed a set of price projections, using prices from multiple regions for current prices and their own knowledge and intelligence to derive the expected future development of these prices. The exceptions were for BioLNG and green methanol, for which IHS Markit were not able to provide price projections. In these two cases, previous Ricardo price projections for LNG and BioLNG, and for grey methanol and green methanol, were used to derive price deltas, which were added to the IHS Markit projections for LNG and grey methanol, respectively. To provide the inputs to the modelling, the fuel price projections were averaged across the three regions for which they were provided. The averaging weighted the values provided for the three regions using data for deliveries of oil products to international marine bunkers from the IEA. The weighting factors calculated were:

- Northwest Europe 31%
- US Gulf Coast 17%
- South East Asia 52%

The price projections for the different fuels, averaged across the regions as described and converted to $/GJ, are shown in Table 6-5. The narrative accompanying the fuel price projections is included in Appendix A.10

Table 6-5: Fuel price values used in the cost modelling (values in $/GJ)

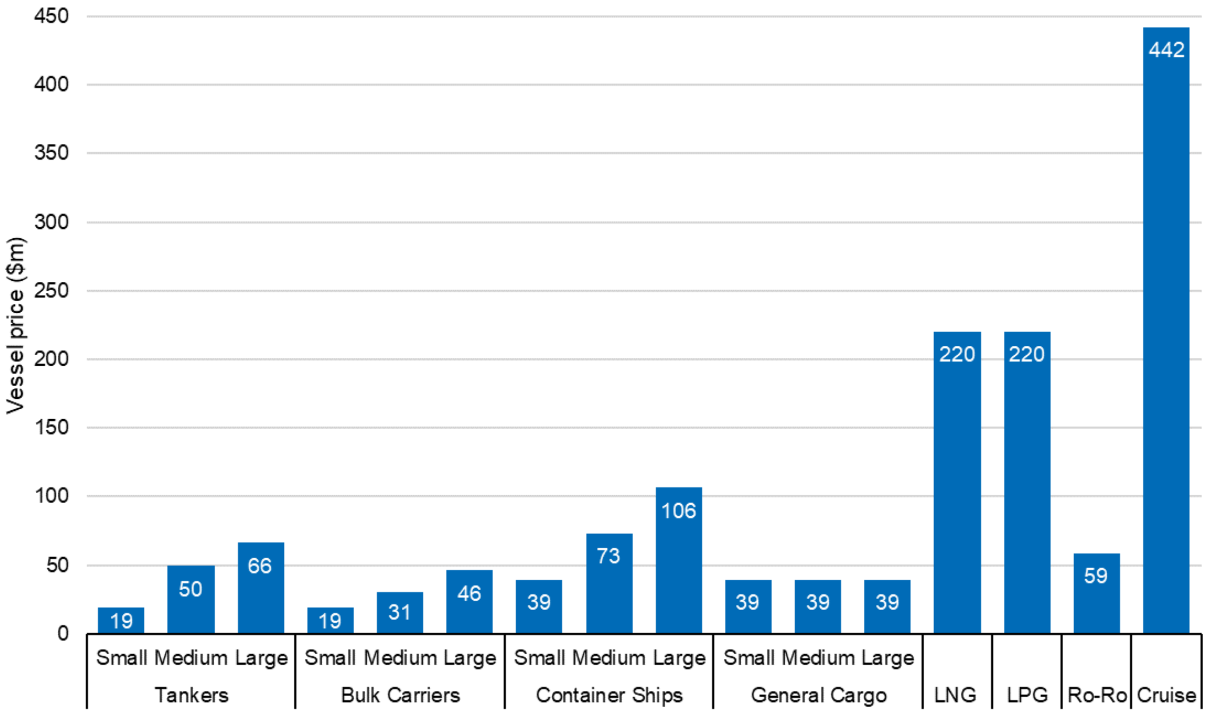
Fuel		2020	2030	2040	2050
HFO		$8.22	$10.99	$10.39	$9.27
MDO		$8.61	$12.61	$12.08	$11.08
LNG		$6.78	$8.29	$9.28	$9.42
BioLNG		$10.52	$41.29	$42.28	$42.42
Methanol	Grey	$13.65	$19.52	$19.61	$19.13
Methanol	Green	$48.35	$39.59	$30.27	$26.44
Ammonia	Grey	$13.40	$21.05	$21.71	$23.14
Ammonia	Blue	$15.93	$24.27	$23.36	$24.46
Ammonia	Green	$36.58	$36.43	$31.61	$29.43
Hydrogen	Grey	$12.34	$13.99	$14.65	$14.80
Hydrogen	Blue	$17.62	$19.57	$20.66	$20.66
Hydrogen	Green	$41.17	$24.73	$19.99	$18.49
FAME		$34.74	$33.34	$30.76	$27.19
HVO		$39.94	$37.91	$34.40	$30.62

All prices are based on those provided by IHS, with the exception of BioLNG and green methanol. These are based on the IHS values for LNG and grey methanol, adjusted using deltas derived from in-house Ricardo analyses.

6.2.2 Define vessel prices

The prices for new vessels have been developed using analyses of vessel price data from the Clarksons World Fleet Register (Clarksons Research, n.d.). A regression analysis was performed on these data against vessel size (in DWT, or TEU for container ships) to derive the new vessel prices as functions of vessel size. These functions were then used to derive average prices for vessels in each category (and size sub-category), based on the average size of vessel in the category. The prices used in the cost analysis are shown in Figure 6-13.

Figure 6-13: Average new build vessel prices used in the cost analysis



The prices derived in this manner were used for the calculation of capital costs in the baseline cases (assuming that the vessel prices would remain constant over time, consistent with the technology freeze assumption applied in the baseline case).

For the calculations including the fuel and technology packages, the estimated costs of including the technologies in the vessels, as described in Section 4.2 to Section 4.7, were added to the baseline vessel prices for inclusion in the capital cost calculations (for vessels delivered in years following the assumed adoption of the technology). In cases where a range of costs were identified for the technology, an average value was used; the costs were included as identified, no learning factors were applied.

6.2.3 Calculate vessel capital costs

As the modelling calculated costs for each year from 2020 to 2050, the capital costs are also annualised. The total capital costs consist of two elements:

- Vessel purchase cost
- Costs of capital

The annualised vessel purchase costs are calculated by spreading them evenly over an average vessel lifetime. The vessel lifetimes used, derived from the same analyses used to derive the survivor curves described in Section 6.1.3, are shown in Table 6-6. Lifetimes for vessel types not included in this table were set to those for the nearest equivalent vessel type (e.g. tanker for LNG carrier).

Table 6-6: Vessel average lifetimes used in capital cost analyses

Vessel type	Average lifetime (years)
Bulk Carrier	26.3
Container	21.4
Cruise	35.5
RoRo	33.3
Tanker	27.1

The costs of capital (representing, for example, interest on loans) were derived as additional capital costs associated with the weighted average cost of capital in the sector. The same rates as mentioned in section 3.3 were applied.

6.2.4 Calculate vessel operating costs

The total vessel operating costs included in the analysis include:

- Crew costs
- Stores
- Lubricant costs
- Maintenance costs
- Insurance
- Administration
- Fuel costs
- Port charges

The annual costs for crew, stores, maintenance, insurance, administration and lubricants were derived from benchmark reports published by Moore Stephens (Dec 2017)[54] and the BCG Shipping Benchmarking Initiative[55].

The port charges were calculated using averages of charges for a number of international ports, published by the Hong Kong Maritime Department[56], multiplied by an estimated number of port visits by the fleet. For each vessel type, a typical route portfolio was assumed, according to the most representative routes for each vessel type and size (Baltic dry index routes, EEX tanker index routes and World Shipping Council trade routes as a proxy for container routes). As such, the modelling of port charges does not take account of any changes in those charges as the nature of the fuels supplied change over time under the different packages.

The fuel cost calculations use the total fuel consumed by each type of fuel, multiplied by the assumed price for those fuels in each year, as described in Section 6.2.1.

6.2.5 Calculate fuel production infrastructure capital costs

The three technology and fuels packages include future transitions to alternative fuels (hydrogen, ammonia, FAME, BioLNG, etc.); these also include transitions in the production pathways of some of those fuels (from grey fuels in the short term to green production pathways in the longer term). The

[54] http://greece.moorestephens.com/MediaLibsAndFiles/media/greeceweb.moorestephens.com/Documents/1-Richard-Greiner.pdf

[55] https://www.bcg.com/industries/transportation-travel-tourism/shipping--benchmark-initiative/benchmarks

[56] https://www.mardep.gov.hk/en/publication/pdf/port_bm_study.pdf

consumption of these alternative fuels implies a need for increased production, which will require investment in the construction of those facilities.

Under normal commercial considerations, it would be expected that the investment costs of those new facilities would be recovered through the higher prices for the fuels. Therefore, to account for both the infrastructure investment costs and the increased fuel prices in the final cost calculations could be considered as double counting.[57] Nonetheless, it is valuable to understand the implications of the uptake of the different alternative fuels for the industry's investment requirements in fuel production infrastructure, so these costs were calculated as described in this section (impacts on fuel distribution and bunkering infrastructure were not included in this analysis). The results are presented in 7.3.

The calculations of the total capital expenditure (CAPEX) on fuels production infrastructure considers the annual demand for the alternative fuels (as calculated by the fleet and emissions modelling) and determines how many additional fuel production plants would be required to meet the demand. The calculation includes the expected lifetime for the plant, with new plants being built to maintain total production capacity to meet demand as plants are decommissioned (or equivalently, existing plants renewed). The cost calculations also take account of the corresponding reduction in demand, and hence production capacity requirements, of conventional fuels (HFO and MDO), leading to some offsetting of the additional capital costs of the alternative fuel plants.

The capital cost data for the different fuel types have been obtained from a range of sources, as shown in Table 6-7. The data identified cover a range of different plant sizes (and capacities), which leads to some uncertainties in comparing the different values, so the costs are also shown divided by the total lifetime production capacity to improve this. The lifetime production capacities were derived in total energy (GJ) terms, again to enable comparisons between the plants for different types of fuels. The capital expenditure per GJ of fuel produced values for the different fuels are also compared in Figure 6-14.

[57] Whilst adding plant investment and operation to fuel price would lead to double counting the capex and opex of the operator, this is not necessarily the case for any infrastructure which is shared and/or developed by public authorities in case needed (pipelines, new storage facilities at port, etc.)

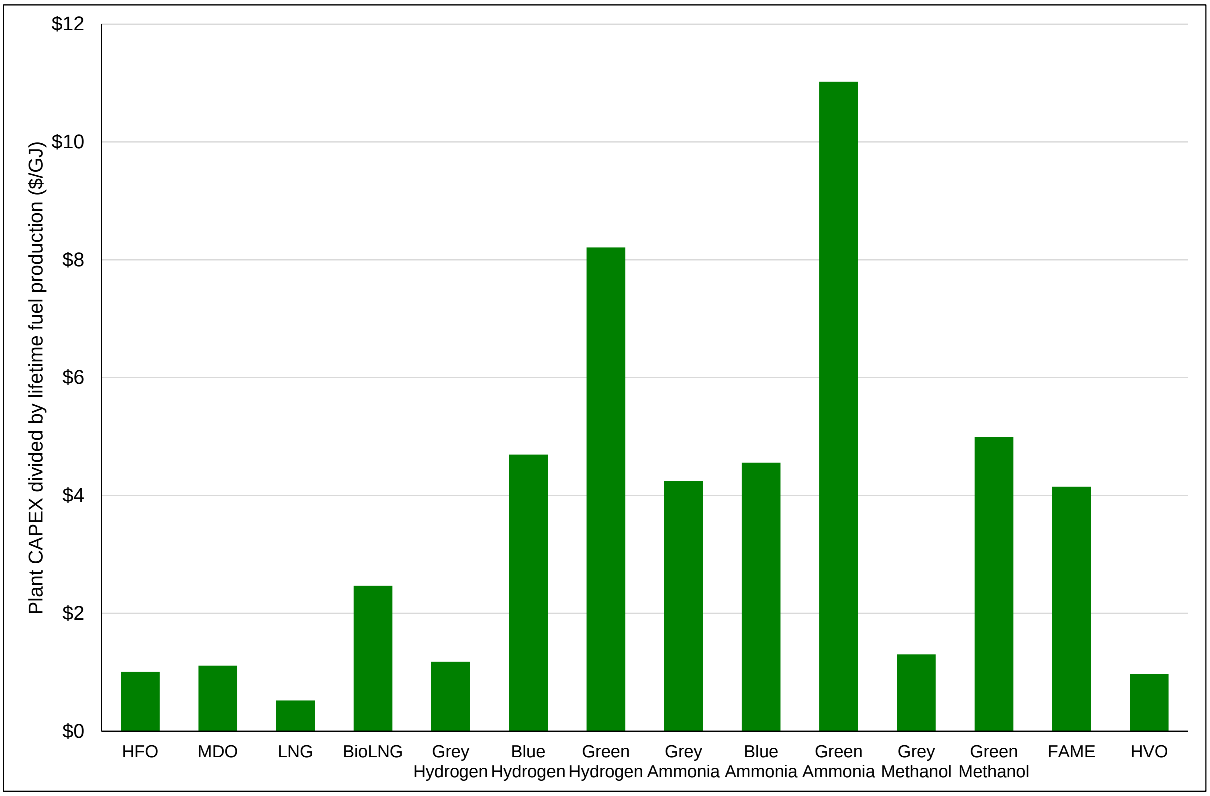
Table 6-7: Fuel (including alternative fuels) plant CAPEX values for infrastructure cost calculations

Fuel type	Fuel pathway	Example plant capacity (Mt/yr)	Example plant CAPEX ($m)	Example plant CAPEX/total energy ($/GJ)	References
HFO	Conventional	1.47	1190	$1.01	(FuelsEurope, 2018) (JWEnergy, 2017)
MDO	Conventional	3.91	3720	$1.11	(FuelsEurope, 2018) (JWEnergy, 2017)
LNG	Global average LNG	10.00	10000	$0.52	(CBC, 2020) (OffshoreEnergy, 2015)
BioLNG	Liquid manure (closed digestate storage)	0.01	14	$2.05	(Navigant, 2019)
Grey Hydrogen	Steam reforming natural gas	0.08	223	$1.18	(IEAGHG, 2017)
Blue Hydrogen	Natural gas and CCS	0.04	411	$4.69	(IEAGHG, 2017)
Green Hydrogen	Hydrogen - Electrolysis (renewable energy)	0.04	719	$8.21	(FCH2 JU, 2017) (Morgan, 2013)
Grey Ammonia	Conventional natural gas feedstock - EU electricity mix	0.44	705	$4.24	(Brown, 2017)
Blue Ammonia	Natural gas and CCS	0.21	357	$4.56	(Morgan, 2013)
Green Ammonia	100% renewable production	1.20	5,000	$11.02	(Morgan, 2013)
Grey Methanol	Natural gas	1.50	1166	$1.30	(ADI analytics, 2017)
Green Methanol	Synthetic methanol - Power to fuel	3.6	10,718[58]	$4.99	(ADI analytics, 2017)
FAME	Waste cooking oil	0.25	581	$4.15	(ECOFYS, 2013)
HVO	Waste cooking oil	0.50	321	$0.97	(TOTAL, 2019)

All values converted to 2020 USD. A more detailed breakdown can be found in Appendix A.9

[58] This value includes $1,854 million quoted in the reference, plus the scaled value for an equivalent capacity green hydrogen plant.

Figure 6-14: Capital costs for different fuel production infrastructure expressed as $/GJ



The fuel types with the greatest capital cost (per GJ of fuel produced) are the green hydrogen and ammonia plants, with the plants for the blue fuels also significant. This contrasts with the costs for the methanol plants and grey hydrogen (based on steam reforming of natural gas), all of which are similar in magnitude to the conventional fuels. It is important to note that the production of green methanol requires the production of green hydrogen as part of the process; therefore, the significantly lower value for green methanol in Table 6-7 and Figure 6-14 indicate some uncertainties (particularly in the green methanol data) due to the limited range of sources of data available and suggest some caution should be used in relation to these results.

6.2.6 Calculate fuel production infrastructure operating costs

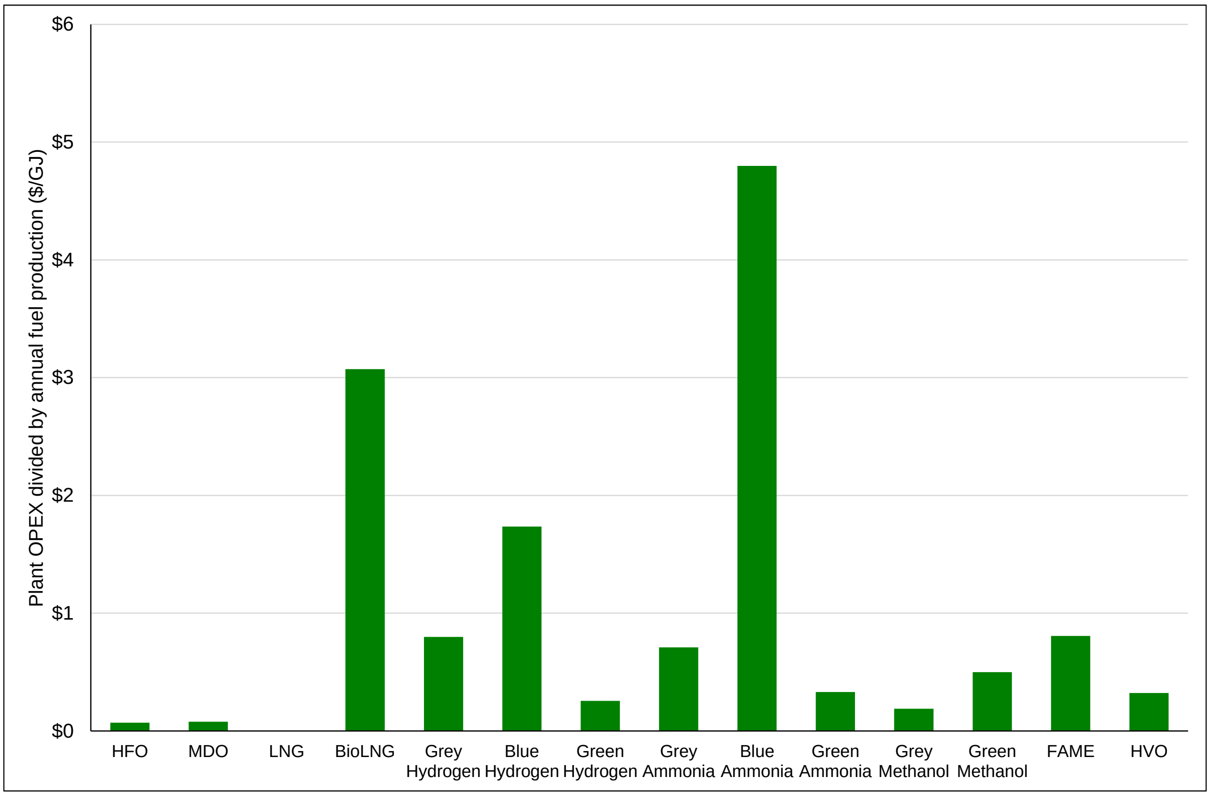
The calculation of the fuel production infrastructure operating costs follows a very similar approach to that for the capital costs. Similar sources have been used to identify the annual operating costs for the different plant types. For the cost modelling, the costs per GJ of fuel produced were multiplied by the annual demand for the fuels, to produce a total annual operating cost for the fuel production infrastructure by fuel type.

The cost inputs are shown in Table 6-8, with the calculated annual operating costs per GJ of fuel produced for the different fuel types compared in Figure 6-15.

Table 6-8: Fuel (including alternative fuels) plant OPEX values for infrastructure cost calculations

Fuel type	Fuel pathway	Example plant capacity (Mt/yr)	Example plant OPEX ($m/yr)	Example plant OPEX/total energy ($/GJ)	References
HFO	Conventional	1.47	4.15	$0.07	(FuelsEurope, 2018) (JWEnergy, 2017)
MDO	Conventional	3.91	12.96	$0.08	(FuelsEurope, 2018) (JWEnergy, 2017)
LNG	Global average LNG	10.00	0.56	$0.0012	(OffshoreEnergy, 2015)
BioLNG	Liquid manure (closed digestate storage)	0.01	0.86	$3.07	(Navigant, 2019)
Grey Hydrogen	Steam reforming natural gas	0.08	7.55	$0.80	(IEAGHG, 2017)
Blue Hydrogen	Natural gas and CCS	0.04	7.60	$1.74	(IEAGHG, 2017)
Green Hydrogen	Electrolysis (renewable energy)	0.04	1.12	$0.25	(FCH2 JU, 2017) (Morgan, 2013)
Grey Ammonia	Conventional natural gas feedstock - EU electricity mix	0.44	5.89	$0.71	(Brown, 2017)
Blue Ammonia	Natural gas and CCS	0.21	18.80	$4.80	(Morgan, 2013)
Green Ammonia	100% renewable production	1.20	7.50	$0.33	(Morgan, 2013)
Grey Methanol	Natural gas	1.50	5.62	$0.19	(Nyári, 2018)
Green Methanol	Synthetic methanol - Power to fuel	3.60	1,072	$0.50	(ADI analytics, 2017)
FAME	Waste cooking oil	0.25	7.53	$0.81	(ECOFYS, 2013)
HVO	Waste cooking oil (standalone plants)	0.50	7.07	$0.32	(TOTAL, 2019)

Figure 6-15: Operating costs for different fuel production infrastructure expressed as $/GJ



On a per unit energy basis, the BioLNG, blue hydrogen, blue ammonia and green methanol fuel types have a significantly higher production cost than the other fuel types. That for LNG is significantly lower.

As noted above, the costs of building and operating the fuel production infrastructure were implicitly included in the overall cost results through the fuel prices and, therefore, the costs as described here were not added to the total, but are presented separately to assist in understanding the implications for the fuel supply industry. As noted above in relation to the capital costs, the different fuel production infrastructure costs were derived from different sources, and based on different sizes of plants. Although they have been expressed in costs per unit of energy, to improve comparability, there is still significant uncertainty in the different values presented.

6.2.7 Calculate port refuelling infrastructure costs

The fuel price projections presented in Section 6.2.1 are those for the fuel as sold by the producers. As such, they do not include the additional costs related to the provision of the new refuelling infrastructure at the ports. As the alternative fuels may require more complex storage and transfer facilities than for conventional fuels (particularly for those that are stored at high pressures and/or low temperatures, such as hydrogen and ammonia), the additional facilities may have significantly higher costs. Unlike the fuel production infrastructure costs, which are expected to be recovered through the fuel prices, the refuelling infrastructure costs are in addition to the fuel prices and, therefore, are included in the total cost calculations.

The calculation identified the quantity of the alternative fuel that needs to be supplied in each year; the increase in the fuel demand in each year was used to identify the additional global refuelling capacity that was required. The assumed facility lifetime was used to identify the refuelling capacity that will be decommissioned and, hence, will need to be replaced (unless the demand is reducing, in which case not all of the decommissioned capacity will need to be replaced).

Available sources were reviewed to identify estimated costs for the provision of refuelling facilities for alternative fuels at example ports. These were converted to a cost per GJ of fuel supplied (with the capital costs amortised over the estimated lifetime of the facility), which were multiplied by the additional refuelling capacity required in each year to give the associated costs. For presentation, these additional costs were then added to the fuel costs as described in Section 6.2.1.

The estimated values for the provision of port refuelling infrastructure, together with the sources on which they were based, are shown in Table 6-9.

Table 6-9: Assumed costs for refuelling infrastructure for alternative fuels

Fuel type	Bunker capacity (tonnes/annum)	Port facility lifetime (years)	CAPEX ($ million)	OPEX ($ million per year)	Source
HFO	1,000,000	30	10.00	0.50	No detailed data found. Estimated value to provide some balancing cost reductions.
MDO	1,000,000	30	10.00	0.50	Assumed same as HFO
LNG	1,935,000	30	53.27	5.03	LNG bunkering financing opportunities (Ocean Shipping Consultants, 2016[59])
BioLNG	1,935,000	30	53.27	5.03	Assumed same as LNG
Hydrogen	255.5	30	23.00	0.92	Feasibility of hydrogen bunkering (ITM Power, 2019[60])
Ammonia	255,500	20	41.00	1.33	A blueprint for commercial-scale zero-emission shipping pilots (Energy Transitions Commission, 2020[61])
Methanol	255,500	20	8.00	0.17	Same source as Ammonia
FAME	1,000,000	30	10.00	0.50	Assumed same as HFO
HVO	1,000,000	30	10.00	0.50	Assumed same as HFO

6.2.8 Calculate port CO_2 handling costs

As described in Section 4.6, in addition to the additional vessel costs for its implementation, the introduction of on-board carbon capture under Package 3 will result in additional port costs for offloading and onward transport of the captured CO_2. As also noted in Section 4.6, a study[62] for BEIS was used to identify an average cost of $21.62 per tonne CO_2 handled by ports.

[59] http://www.anave.es/images/seguridad/eu_lng_bunkering_financing_opportunities_osc.pdf

[60] https://northsearegion.eu/media/9385/feasibility-of-hydrogen-bunkering-final-080419.pdf

[61] https://www.globalmaritimeforum.org/content/2020/11/The-First-Wave-%E2%80%93-A-blueprint-for-commercial-scale-zero-emission-shipping-pilots.pdf

[62] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/761762/BEIS_Shipping_CO2.pdf

To calculate the overall costs, the quantity of CO_2 captured by on-board carbon capture systems was calculated from the results of the emissions modelling and then multiplied by the value above.

For presentation, the additional operating costs associated with the handling of the captured CO_2 were combined with the other vessel operating costs.

6.2.9 Calculate total costs and cost-effectiveness

The different cost elements described in the preceding sections were integrated into a set of total costs for each demand scenario and each technology and fuels package (including the baseline). The additional costs related to the packages were then calculated as the difference between the results for the package and the equivalent results for the baseline scenario.

All costs were calculated separately for each year between 2020 and 2050. Discounting was then applied to the calculation of the total costs when summed over the period from 2020 to 2050, to reflect different views on the future value of money, interest rates, etc., to derive the net present value (NPV) results. The main results presented in this report are derived using a discount rate of 10%; additional sensitivity results are also presented for a discount rate of 5%.

By combining the total costs and the total emissions savings under each of the packages, cost-effectiveness values, in $/tonne CO_2, were calculated to provide an overall comparison of the three packages. These were again summed over the period from 2020 to 2050, with discounting applied, to calculate the NPV. By default, the calculations of cost-effectiveness included discounting of both the costs (reflecting the future value of money) and the emissions savings (reflecting perceptions that early emissions savings are more valuable than later savings), with the same discount rate applied to both. However, opinions in literature vary as to whether emissions savings should be discounted in this way, so the model also calculates cost-effectiveness values with the costs discounted and the emissions savings not discounted.

7 Decarbonisation potential and costs of fuel and technology packages

This section describes the results of the analyses of the different fuel and technology packages on the future emissions, the levels of decarbonisation achieved and their associated costs and cost-effectiveness. Key points relating to vessel technologies and fuel consumption:

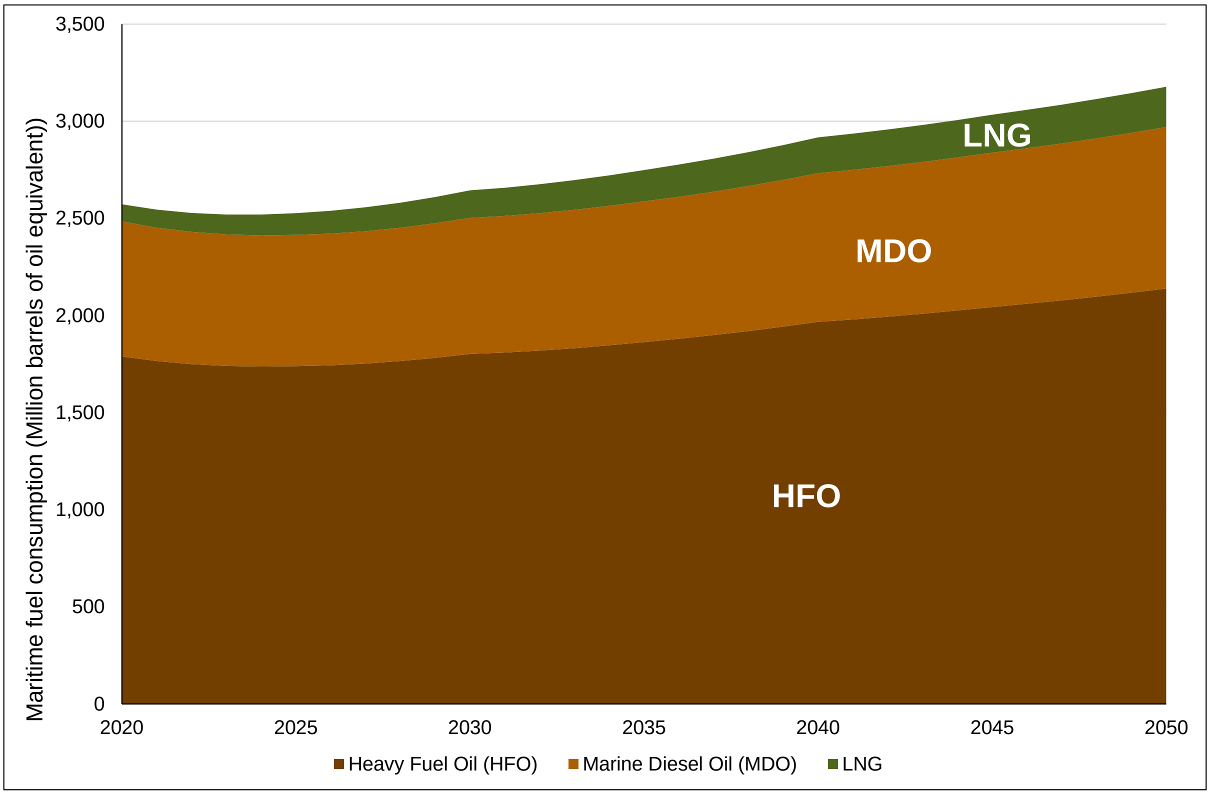
- Fuel consumption in the central baseline scenario (two thirds HFO, one quarter MDO, 10% LNG) is estimated to increase by around 20% by 2050 compared to 2020 despite the demand growing much more strongly, showing the effects of energy efficiency gains in the fleet.
- In contrast, also under the central baseline scenario, the total fuel consumption of package 1 drops by about 8% by 2050 and is made up of ~72% ammonia, ~12% hydrogen, and ~16% conventional fuels (HFO/MDO/LNG)
- Package 2 total fuel consumption in 2050 is about 12% lower than in 2020. This package sees methane (LNG, BioLNG) increase to just over half of total fuel consumption by 2050, with LNG dominating until the late 2030s before giving way to drop-in substitute BioLNG. The remainder is assumed to be split between drop-in biofuels HVO and FAME.
- The increased emphasis on energy efficiency measures in package 3 means it has the lowest total fuel consumption (about 23% lower in 2050 than in 2020). Its fuel mix remains dominated by conventional fuels until 2040. By 2050, the mix is ~50% BioLNG, ~20% each of ammonia and methanol and remainder HFO/MDO.
- Under the central demand scenario, baseline CO_2e emissions rise to 1,300 Mtonnes by 2050
- Under all packages, CO_2e emissions in 2050 are reduced to between 260 and -20 Mtonnes on a well-to-wake basis, better than the IMO ambition
- Packages 1 and 3 also meet the IMO ambition for 2050 when emissions are compared on a tank-to-wake basis, with emissions of 160 and 290 Mtonnes; TTW emissions for Package 2 are approximately 800 Mtonnes
- Package 3 is the least cost solution, reaching \$39 / tonneCO_2e WTW in a mid-demand scenario
- Package 2 is the highest cost solution driven by high fuel costs, reaching \$113 / tonneCO_2e WTW in a mid-demand scenario
- Cost-effectiveness figures are highly sensitive to discounting or not discounting the CO_2e in the analysis. The same is true for the discount rate for both costs and CO_2e (this report provides a range of ratios.)

The fleet and emissions modelling, described in Section 6.1, has been applied to the calculation of the fuel consumption and emissions under the three demand scenarios and the three technology and fuels packages (plus the baseline cases).

7.1 Fuel consumption

The overall development of the fuel consumption by the global maritime fleet under the central baseline scenario is shown in Figure 7-1. To enable the consumption of the different fuels to be combined into a single chart, they are presented as million barrels of oil equivalent (Mboe) values.

Figure 7-1: Baseline fuel consumption to 2050 under the central scenario

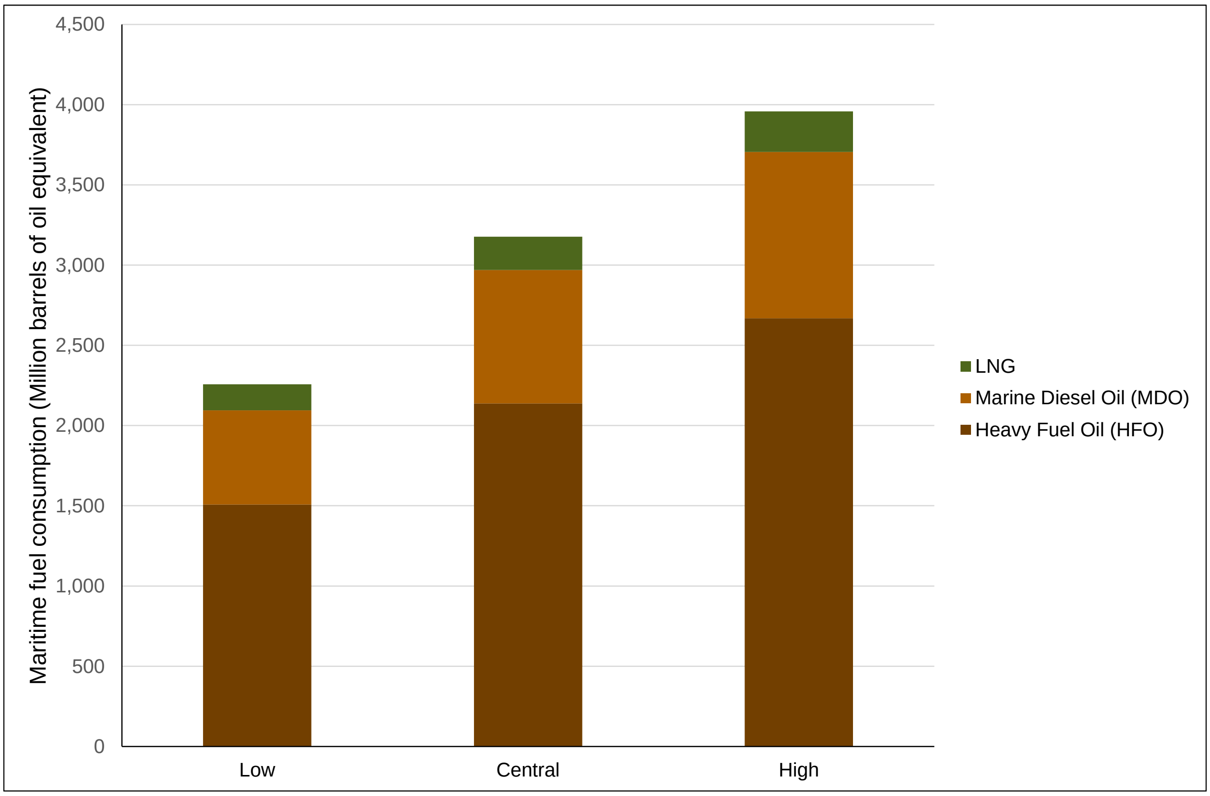


Source: Ricardo calculation based on central scenario projection and modelling described in Section 6

Under the baseline scenarios, the fuel efficiency of new vessels built after 2020 remain at the same levels as those built in 2020. Therefore, the lower rate of growth in the fuel consumption in Figure 7-1, compared to the rate of growth in demand under the central baseline (as was shown in Figure 6-2) is due to the increased fleet penetration of the 2020-technology vessels over time. For reference, the central scenario demand (Figure 6-2) has an average annual growth rate between 2020 and 2050 of 2.2%, while the fuel consumption increases by 0.7% per annum on average.

A comparison of the fuel consumption under the three baseline scenarios is shown in Figure 7-2.

Figure 7-2: Comparison of 2050 fuel consumption under three baseline scenarios



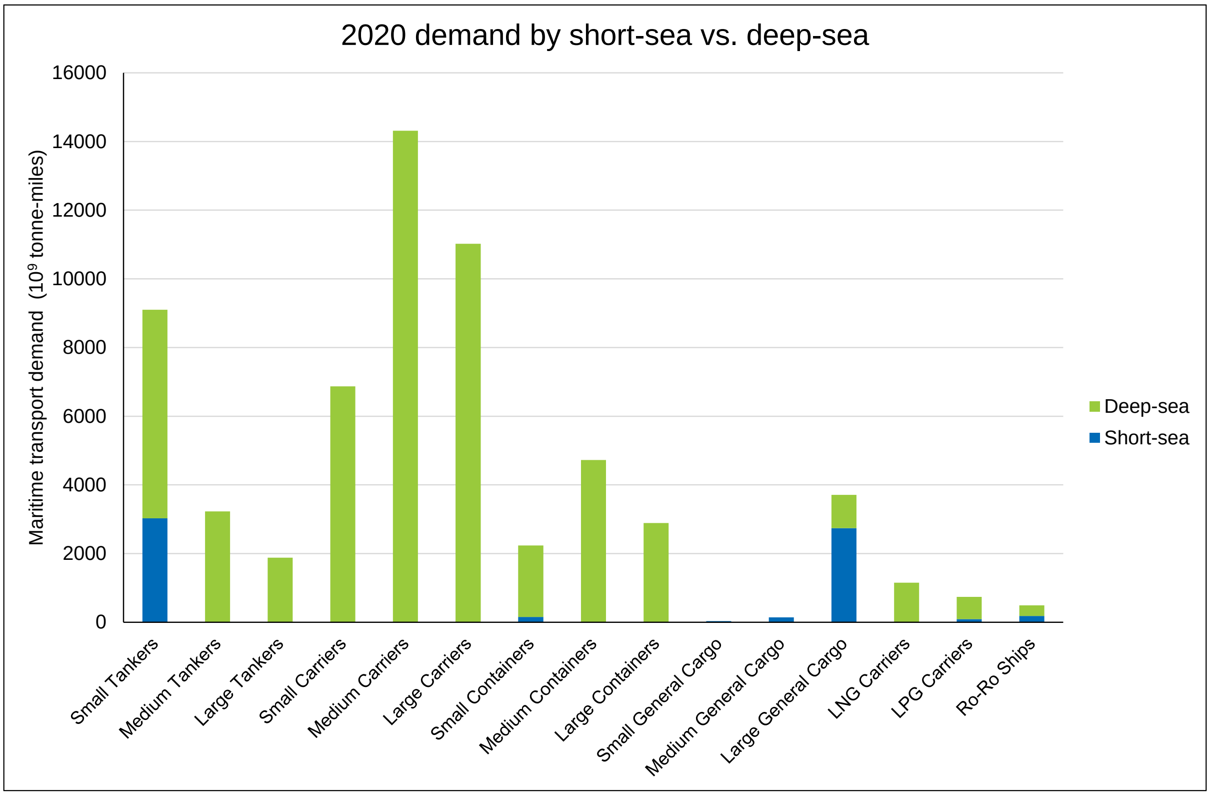
Under the central scenario, the total fuel consumption in 2050 is approximately 3,180 Mboe; this decreases by 29% to 2,260 Mboe under the low demand baseline, and increases by 25% to 3,960 under the high demand baseline. The proportions of the three fuel types remain approximately constant across the three baselines (because the demand is defined at a vessel type level for each of the three baselines, there are small variations in the fuel proportions under the different baselines, but they are less than 1% across all three baselines).

As expected, the inclusion of the technology and fuels packages leads to significant changes in the fuel consumption over time, both in terms of total consumption and the distribution across the different fuel types. Of significance is that, under package 1, the alternative fuels adopted were split between hydrogen (for short-sea shipping) and ammonia (for deep-sea shipping). The reasons for the allocation of the fuels in this manner was to distinguish between vessels that (mostly) travel short distances between ports and, hence, have frequent opportunities to refuel, and those that travel long distances and must be able to hold sufficient fuel for a long journey. Although the difference between short-sea and deep sea shipping is primarily associated with the nature of the vessel operation, the short-sea operations are mostly fulfilled by smaller vessels and deep sea operations by larger vessels. The European Community Shipowners' Associations (ECSA) has indicated that vessels used in short-sea operations are generally below 10,000 tonnes DWT[63]; the analysis presented here has adopted the same threshold.

Using the threshold of 10,000 tonnes DWT, the demand in 2020 can be analysed to identify, under each vessel category, the fraction of the demand (in tonne-miles) met by vessels below the threshold (classified as 'short-sea') and above it (classified as 'deep sea'), as shown in Figure 7-3.

[63] https://www.ecsa.eu/images/NEW_Position_Papers/ECSA_SSS_Download%201.pdf

Figure 7-3: Split of demand in 2020 by above and below 10,000 DWT, to identify short-sea and deep sea demand



Using this threshold, the short-sea operations are met using mostly small tankers and small, medium and large general cargo vessels, with small additional contributions from small container vessels and ro-ro ships. Calculated using these allocations for package 1, and the splits defined previously for the different alternative fuels under packages 2 and 3, the resulting fuel consumption under the three packages are shown, for the central demand scenario, in Figure 7-4 to Figure 7-6. Under the three packages, the fuel consumption in 2050 is reduced from the 3,180 Mboe of the central baseline to between 2,000 Mboe and 2,400 Mboe, reductions of 26% to 37% relative to the baseline.

Figure 7-4: Fuel consumption to 2050 under the central scenario for package 1

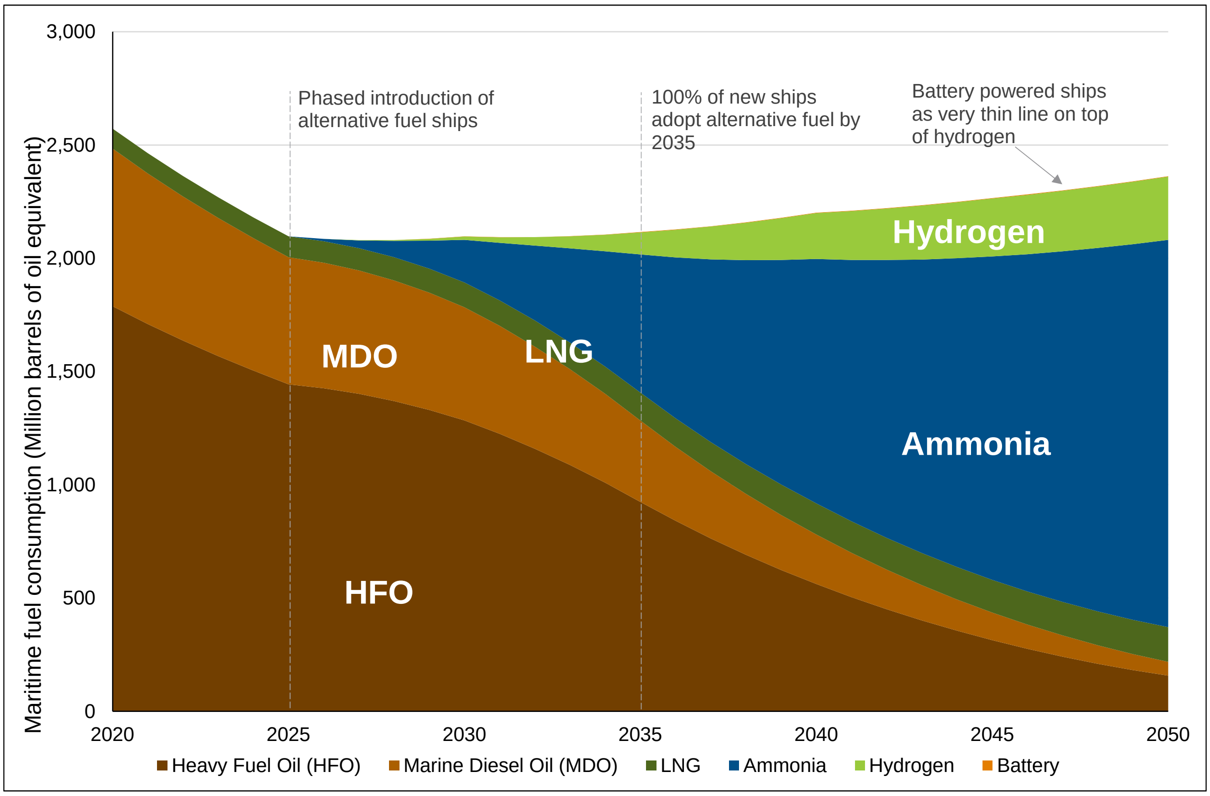


Figure 7-5: Fuel consumption to 2050 under the central scenario for package 2

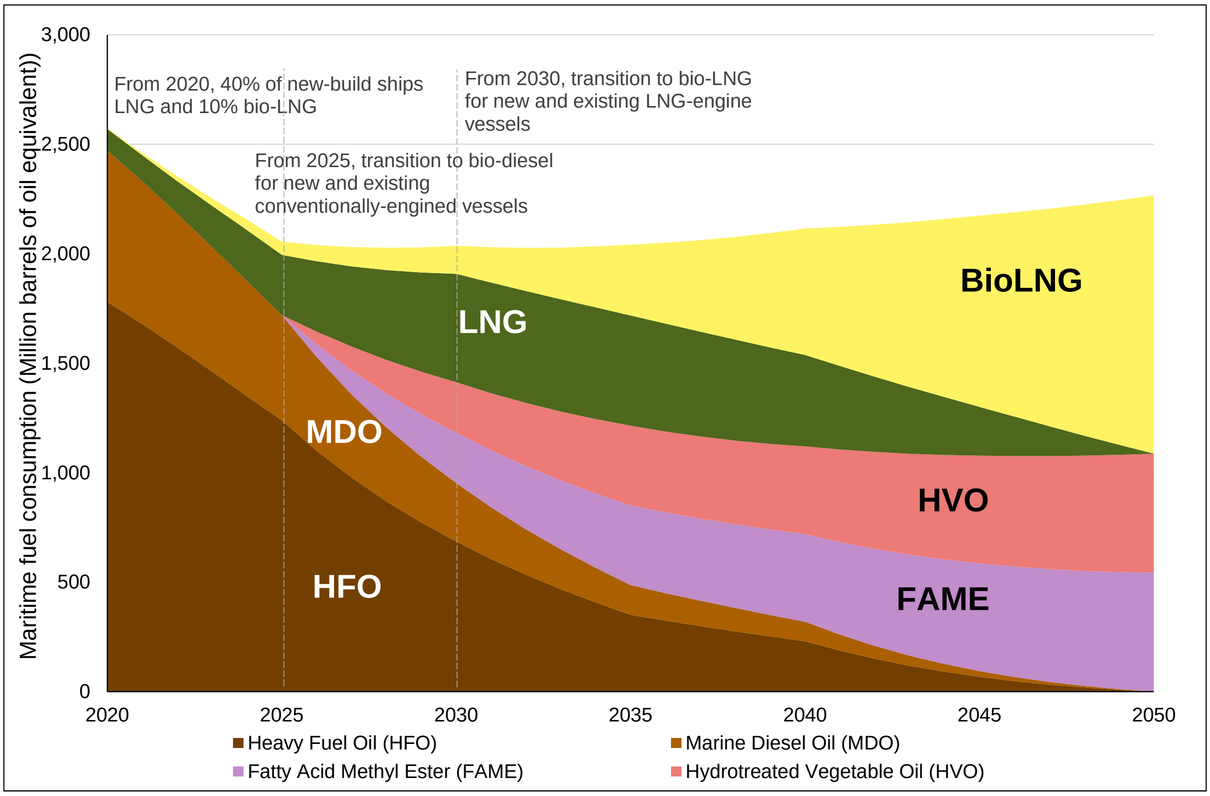
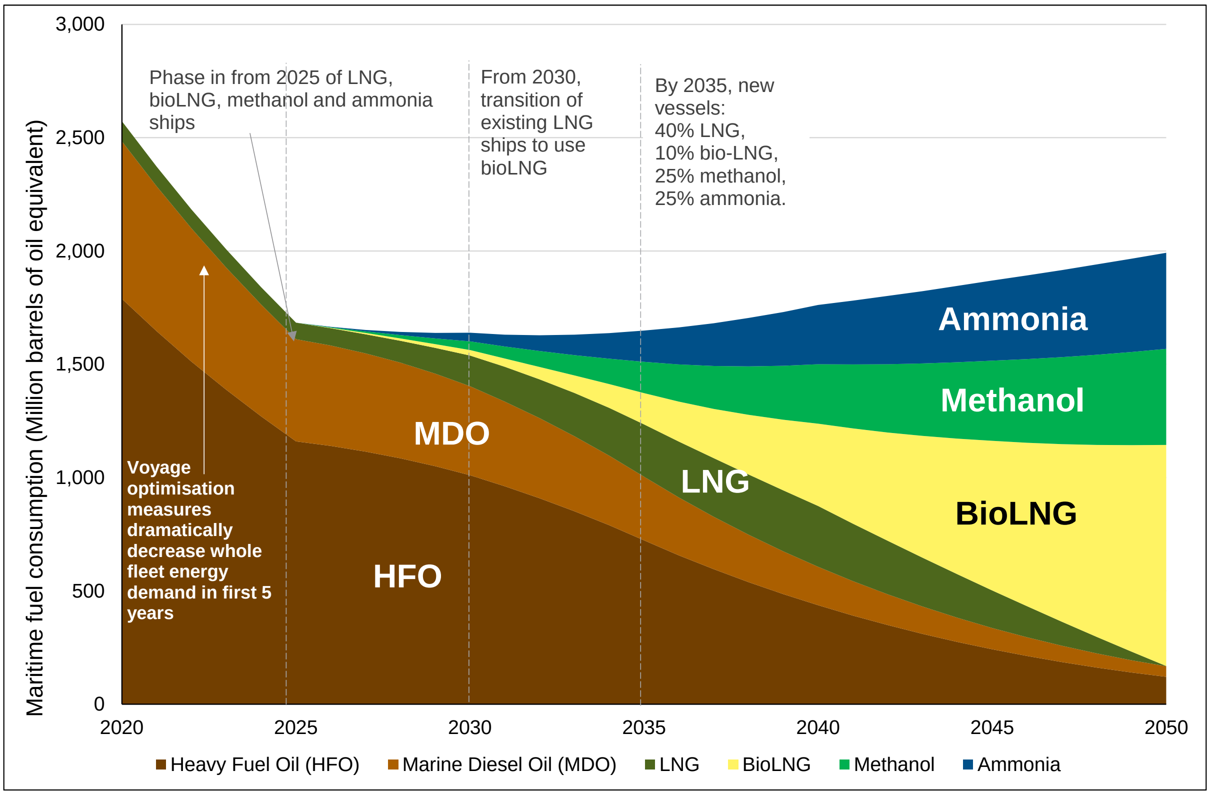


Figure 7-6: Fuel consumption to 2050 under the central scenario for package 3



Under **package 1** (Figure 7-4), there is a significant drop in fuel consumption between 2020 and 2025 as the technology improvements (including the operational improvements) impact the fleet fuel efficiency. Beyond 2025, the technology improvements continue to penetrate the fleet, but they do not provide sufficient efficiency improvements to offset the increase in demand and the total fuel consumption begins to increase again. From 2025, there is a gradual increase in the use of alternative fuels by the fleet, represented in package 1 by ammonia (for deep-sea vessels) and hydrogen (for short-sea vessels). Deep-sea vessels account for a greater proportion of the total maritime energy consumption, so the consumption of ammonia is significantly greater than that of hydrogen (on an energy basis), although there is still a considerable consumption of hydrogen by 2050. Under this package, by 2050, the consumption of conventional fuels (HFO and MDO) has reduced by 91% relative to the value in 2020; at this point alternative fuels make up almost 91% of the total fuel consumption. LNG carriers, which use LNG in the baseline scenario, are assumed to continue to use LNG under this package. The small growth of the use of LNG in Figure 7-4 is due to the growth in demand for the transport of LNG. A third alternative fuel included in this package is electricity, deployed by battery-electric vessels. The expectation is that, despite the advances in battery technology, these will still only be used by relatively small vessels on local (generally coastal) operations. The energy consumed by battery-electric vessels remains very small (their consumption is presented as a thin red line on top of the other fuels).

Under this package, the pathways assumed for the hydrogen and methanol fuels change over time, evolving from grey (fossil fuel-based), through blue (fossil fuel-based, with carbon capture during production) to green (using renewable resources) pathways. Figure 7-7 and Figure 7-8 show how the quantities of fuel required vary between the different pathways.

Figure 7-7: Split of hydrogen consumption under package 1 by grey, blue and green (million barrels of oil equivalent per year)

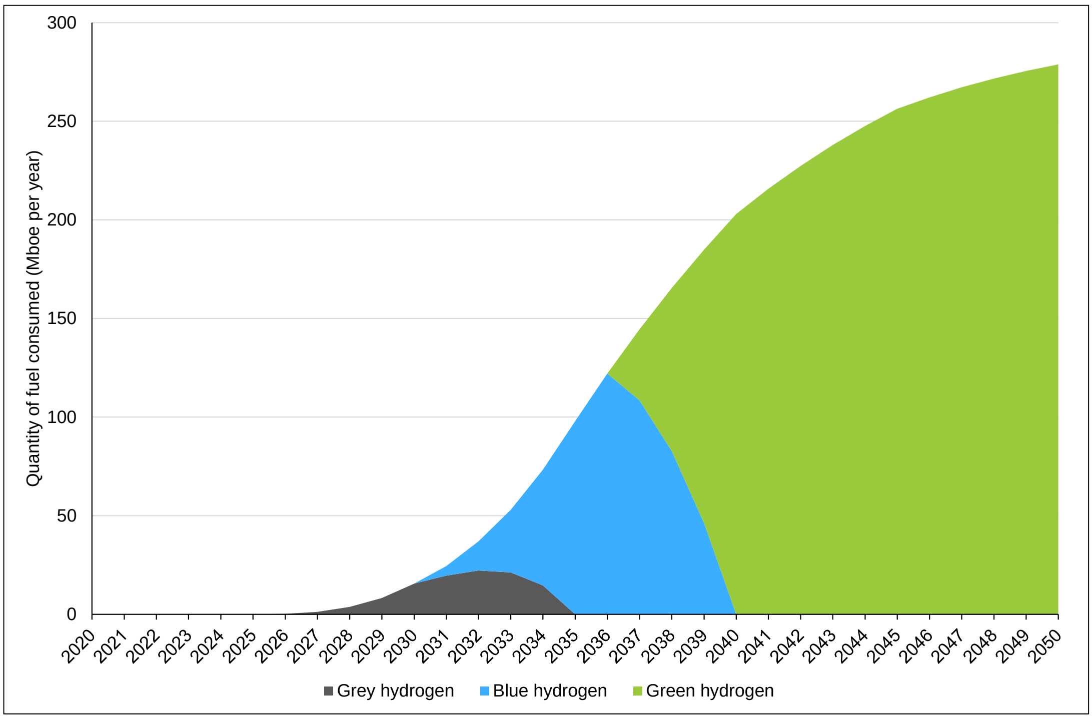
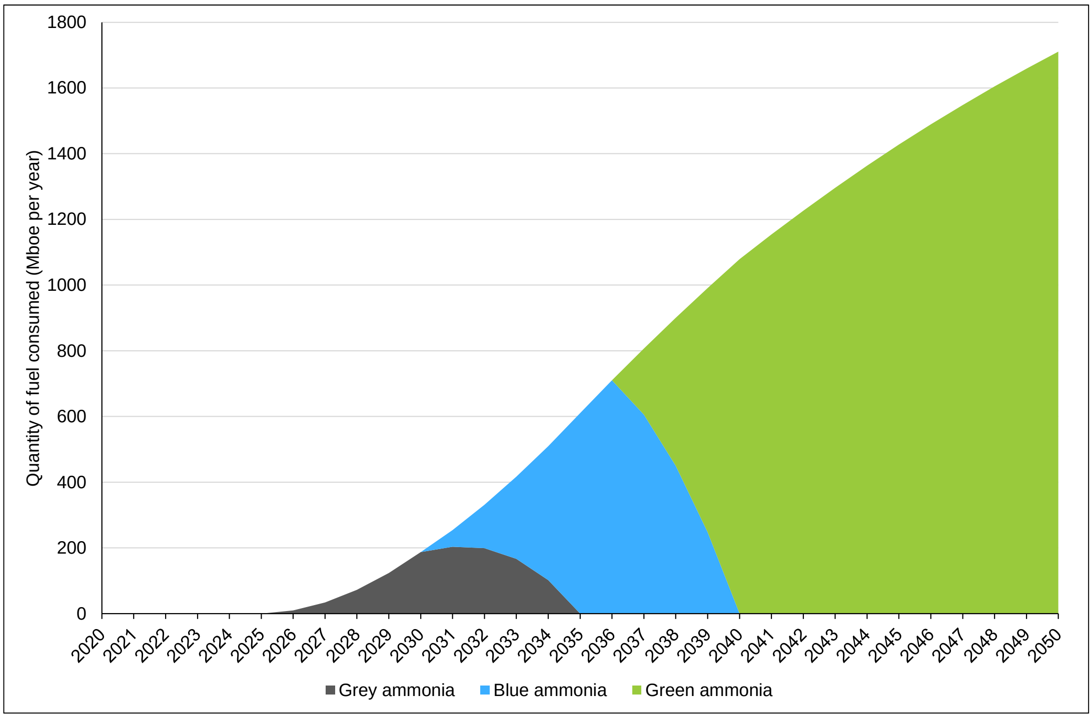


Figure 7-8: Split of ammonia consumption under package 1 by grey, blue and green (million barrels of oil equivalent per year)



For both of these fuels, the demand is quite small during the period that only grey fuel is available, As demand picks up, the fuel supply also transitions to blue fuel, leading to a larger total demand for blue fuel than grey fuel, even though the blue fuel transitions to green in a relatively short timeframe. The demand for the green fuels is then considerable, leading to annual demands for green hydrogen and ammonia in 2050 of about 280 and 1,710 Mboe, respectively. The transition from blue fuel to green fuel will result in increased fuel costs for vessel operators; the inclusion of this transition in the modelling, based around the lower GHG emissions, assumes some form of driver for this transition, most likely regulatory.

Under **package 2 (**Figure 7-5**)**, there is a slightly greater reduction in fuel consumption from 2020 to 2025, but with an expanding use of LNG and BioLNG fuel, as specified in the definition of the package. From 2025 onwards, the liquid biofuels (FAME and HVO) start to replace conventional fuels on a drop-in basis, and LNG and BioLNG further increase their contribution. By 2030, the consumption of conventional fuels (HFO and MDO) has reduced by 62% relative to 2020, with alternative fuels (including LNG) now representing 53% of total fuel consumption. From 2030 onwards, BioLNG starts to completely replace the remaining LNG and, similarly, FAME and HVO replace the remaining HFO and MDO so that, by 2050, 100% of fuel consumption is alternative.

Under **package 3 (**Figure 7-6**)**, the fuel consumption in the early years after 2020 is impacted by the higher penetration of vessel and operational technologies under this package. By 2025, the consumption of conventional fuels has decreased by 35% relative to 2020. This is a significant reduction in a short timeframe and depends on a widespread adoption of the operational measures, particularly slow steaming and vessel capacity utilisation. Although both measures are already adopted to some extent, strong policy signals and coordinated action would be likely to be required to achieve such significant changes in a short time. By 2050, the total fuel consumption is 37% lower than in the baseline case. However, this package includes the use of carbon capture technology on vessels using carbon-containing fuels, with an associated 20% fuel consumption increase. Without that fuel consumption increase, the fuel consumption under package 3 would be 45% lower than the baseline case (but would not have the same level of CO_2 reduction as can be achieved with the carbon capture).

Similarly to package 1, the split of methanol and ammonia fuel demand by pathway is shown in Figure 7-9 and Figure 7-10.

Figure 7-9: Split of methanol consumption under package 3 by grey and green (million barrels of oil equivalent per year)

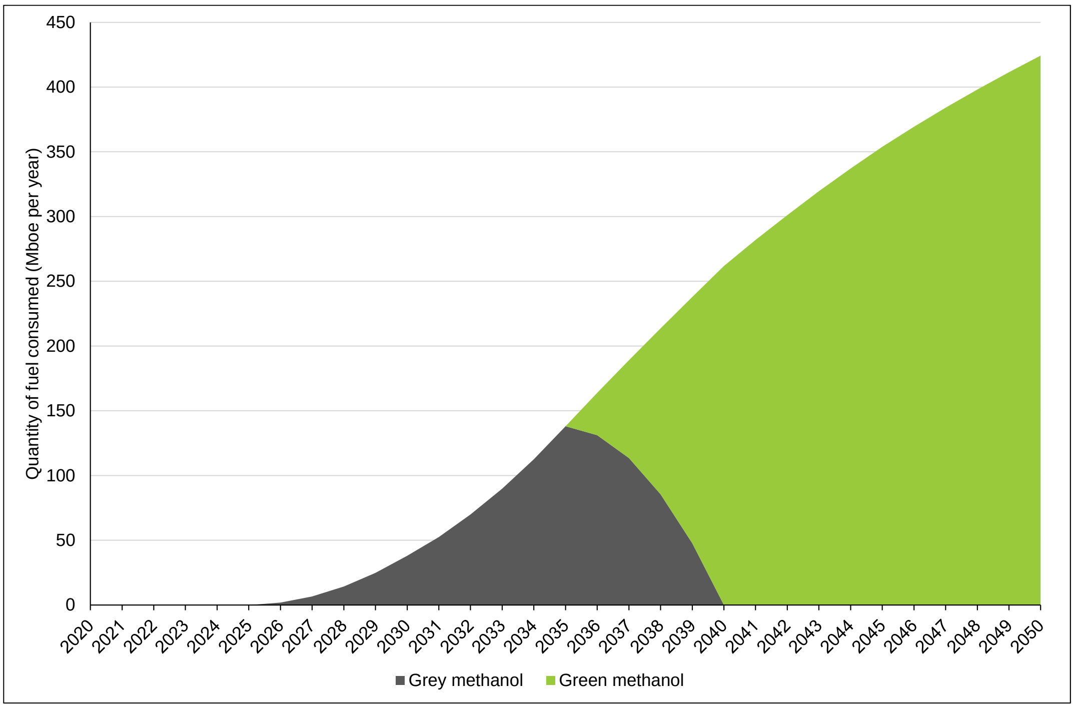
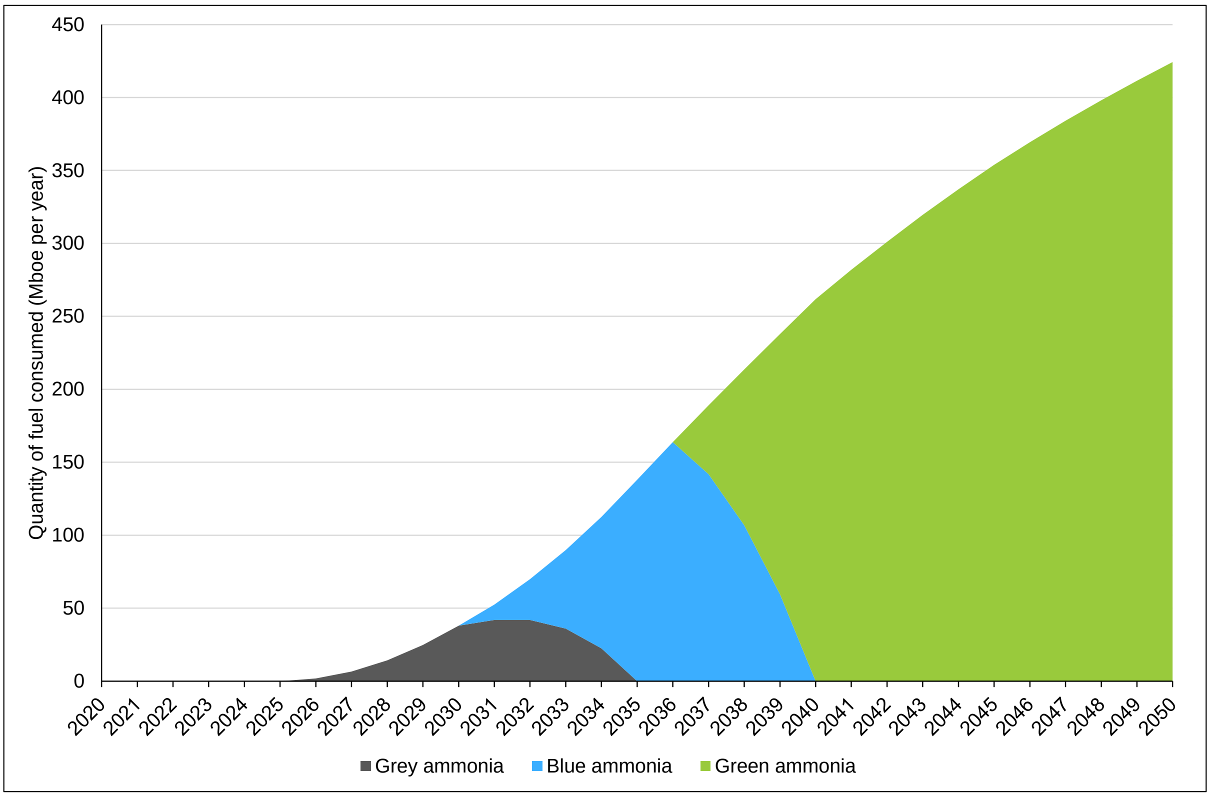
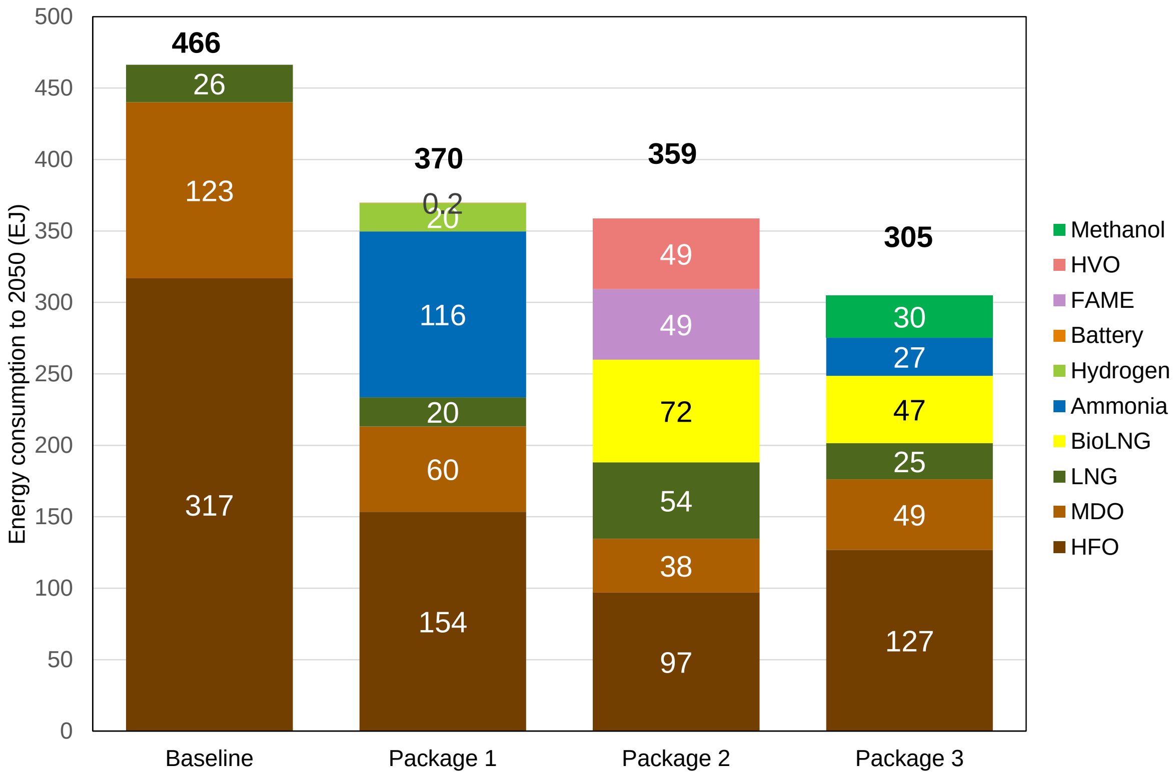


Figure 7-10: Split of ammonia consumption under package 3 by grey, blue and green (million barrels of oil equivalent per year)



A comparison of the different fuel splits for the three packages, and the baseline case, under the central demand scenario, aggregated over the 2020 to 2050 period, is shown in Figure 7-11.

Figure 7-11: Fuel demand per fuel and technology package by fuel type for central demand scenario (cumulative 2020-2050)



7.2 Emissions

Whilst the previous subsection has commented on the fuel consumption impacts of the packages, the key focus of this study is on measures to reduce greenhouse gas emissions from maritime transport to 2050. The CO_2e emissions to 2050 under the three baseline scenarios were presented in Figure 6-9.

The trajectories to 2050 range from a small reduction relative to 2020 under the low baseline scenario to a 53% increase under the high scenario. As was shown in Figure 6-9, the achievement of the IMO ambition for 2050 implies reductions of between 380 Mtonnes and 1,080 Mtonnes CO_2e in 2050, depending on the growth scenario assumed.

To present the trajectories in CO_2e emissions under the three packages, it is important to consider the production pathways assumed for the fuels. A "green" alternative fuel (produced using renewable energy, for example) will give considerably greater reductions in total emissions than a "grey" fuel (an alternative fuel produced from fossil fuel feedstock). Accordingly, the following charts show the emissions under the three packages, presenting both the CO_2e emissions from the ship itself (known as tank-to-wake, or TTW) and the full emissions including those from the fuel production (well-to-wake or WTW).

Figure 7-12: Total CO_2e emissions (TTW and WTW) to 2050 under package 1

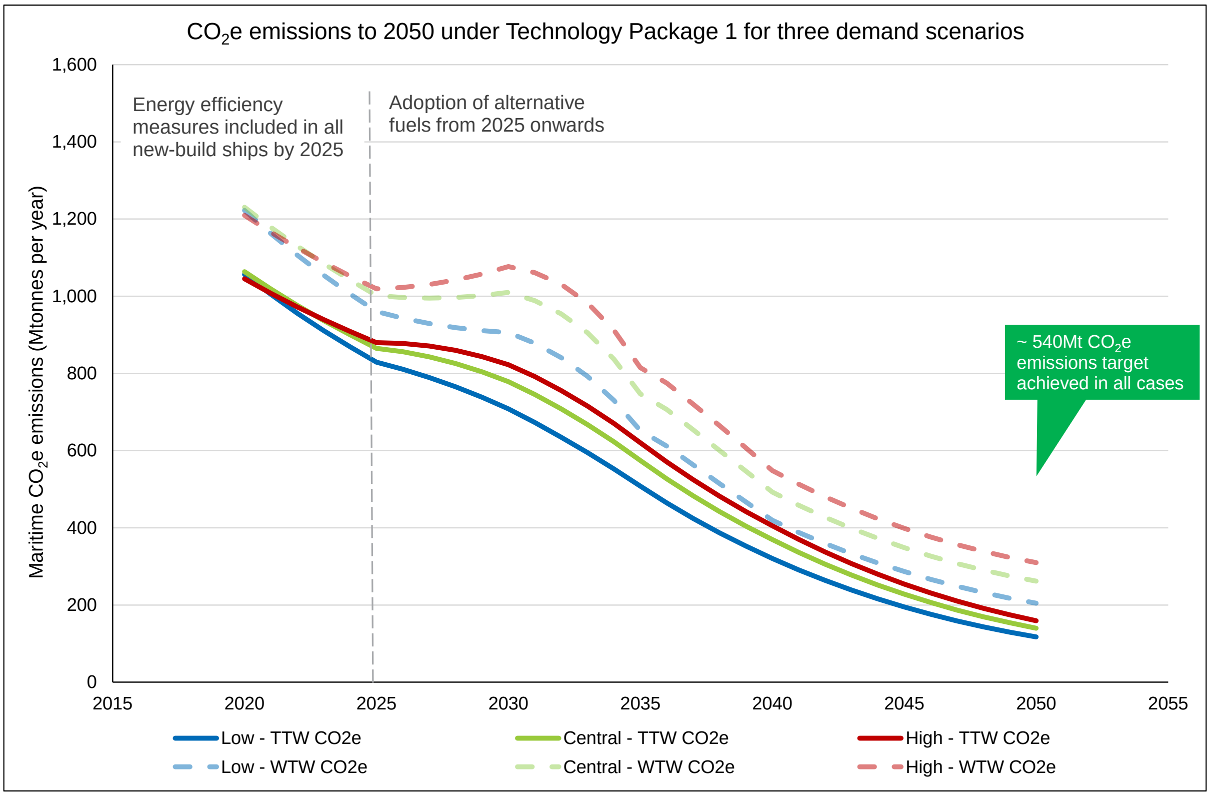


Figure 7-13: Total CO_2e emissions (TTW and WTW) to 2050 under package 2

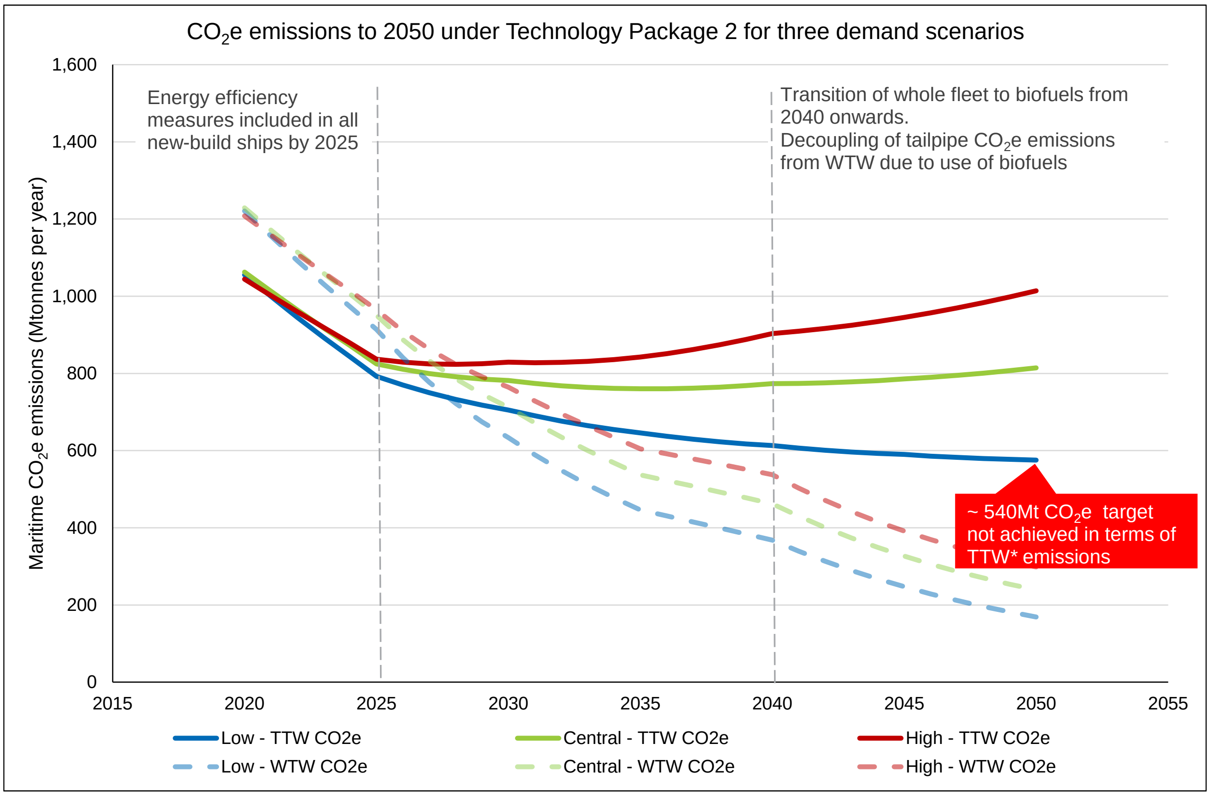
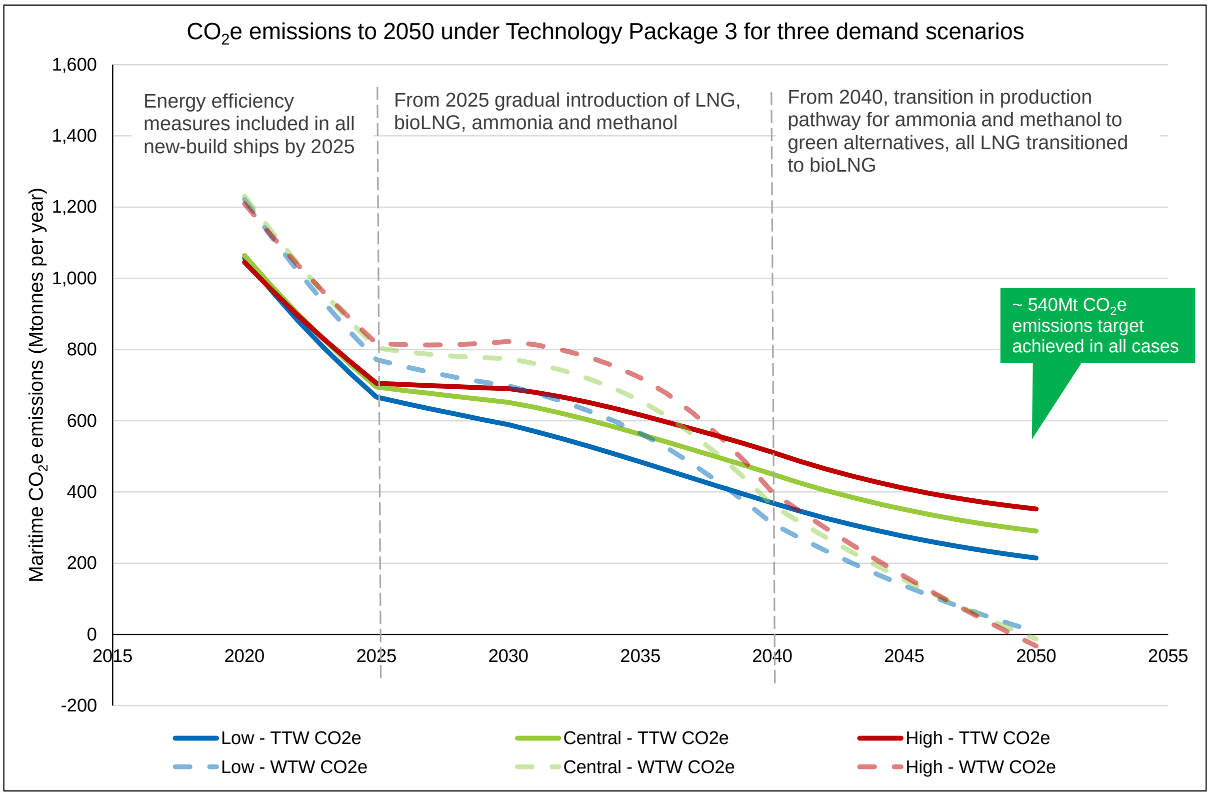


Figure 7-14: Total CO_2e emissions (TTW and WTW) to 2050 under package 3[64]



Under **package 1**, the TTW and WTW emissions follow broadly similar trends , with a gradual reduction from current levels to significantly lower levels by 2050, under all three baseline demand scenarios. The WTW emissions show an increase in the period from 2025 to 2030, as “grey” alternative fuels start to be used (with relatively high WTT emissions). As these grey fuels are replaced by blue and then green variants, the WTW emissions reduce towards the low levels in 2050. Under this package, the global emissions in 2050 are less than 200 Mtonnes CO_2e, less than half of the ambition of the IMO[65].

Under **package 2**, the TTW emissions are reduced relative to the baseline by the use of the technologies and the alternative fuels (particularly methane, in the form of LNG and BioLNG) by over 31% under each of the three baseline demand scenarios. However, this is limited by the fuels employed all being carbon-containing (and hence producing CO_2e emissions on combustion), together with some methane slip when using LNG or BioLNG, and hence insufficient to meet the IMO ambition in each case. Viewing the results from a WTW perspective, however, provides significantly greater reductions, as the CO_2 emissions produced on combustion are offset to a large extent by the absorption of CO_2 during their production, giving low WTW emissions. This could alternatively be summarised as fuels being ‘CO_2 neutral’ in package 2, rather than the ‘zero carbon’ fuels in package 1. From this perspective, the global WTW CO_2e emissions in 2050 are between 170 and 300 Mtonnes, well under the IMO ambition under all three baseline demand scenarios.

The results for **package 3** show reductions in TTW emissions similar to those from package 1 by 2050. As noted above, under this package the reduction achieved in fuel consumption through vessel technologies is offset partially by the fuel consumption increase due to the use of carbon capture

[64] Negative emissions occur by 2050 on a WTW basis, due to the use of green carbon-containing fuels (with the caron content having been captured from the atmosphere during production), combined with on-board carbon capture technology that removes most of the CO_2 from the ship’s exhaust.

[65] As specified, the IMO ambition relates to the exhaust emissions from the ships, rather than the full well-to-wake emissions associated with the fuels consumed. However, as the supply of alternative fuels transitions towards a greater degree of renewability (green fuels), much of the additional benefit is seen in the WTT emissions. Therefore, in this study, the results of the calculations for both TTW and WTW are compared to the IMO ambition.

technology on-board ships. The CO_2e emissions show much stronger reductions as much of the emission is captured by this technology. When considering WTW emissions, the achievement of small negative net emissions can be seen under each of the baseline demand scenarios. This is caused by the low WTT emissions of the green fuels, combined with the capture of the CO_2 emissions from the carbon-containing fuels (BioLNG and green methanol) from the ship exhaust. Overall, the process results in a net capture of CO_2 from the atmosphere through the complete fuel production and combustion process.

As noted previously, the IMO ambition on CO_2 emissions is framed as a 50% reduction relative to 2008 levels by 2050. For comparison with this ambition, Table 7-1 shows the changes in emissions in 2030 and 2050 relative to 2008 levels for each of the packages under each baseline scenario. Also included are the baseline results; for these, and the TTW results for package 2 in 2050, there is an increase in emissions relative to 2008[66].

Table 7-1: Changes in CO_2e WTW emissions relative to 2008 (TTW values in parentheses)

	Baseline	Package 1	Package 2	Package 3
Low scenario				
2030	9% (4%)	-13% (-25%)	-39% (-25%)	-33% (-37%)
2050	4% (-2%)	-80% (-88%)	-84% (-39%)	-99% (-77%)
Central scenario				
2030	22% (16%)	-2% (-17%)	-31% (-17%)	-25% (-31%)
2050	46% (39%)	-74% (-85%)	-77% (-13%)	-101% (-69%)
High scenario				
2030	30% (24%)	4% (-13%)	-26% (-12%)	-21% (-27%)
2050	82% (73%)	-70% (-83%)	-71% (8%)	-103% (-63%)

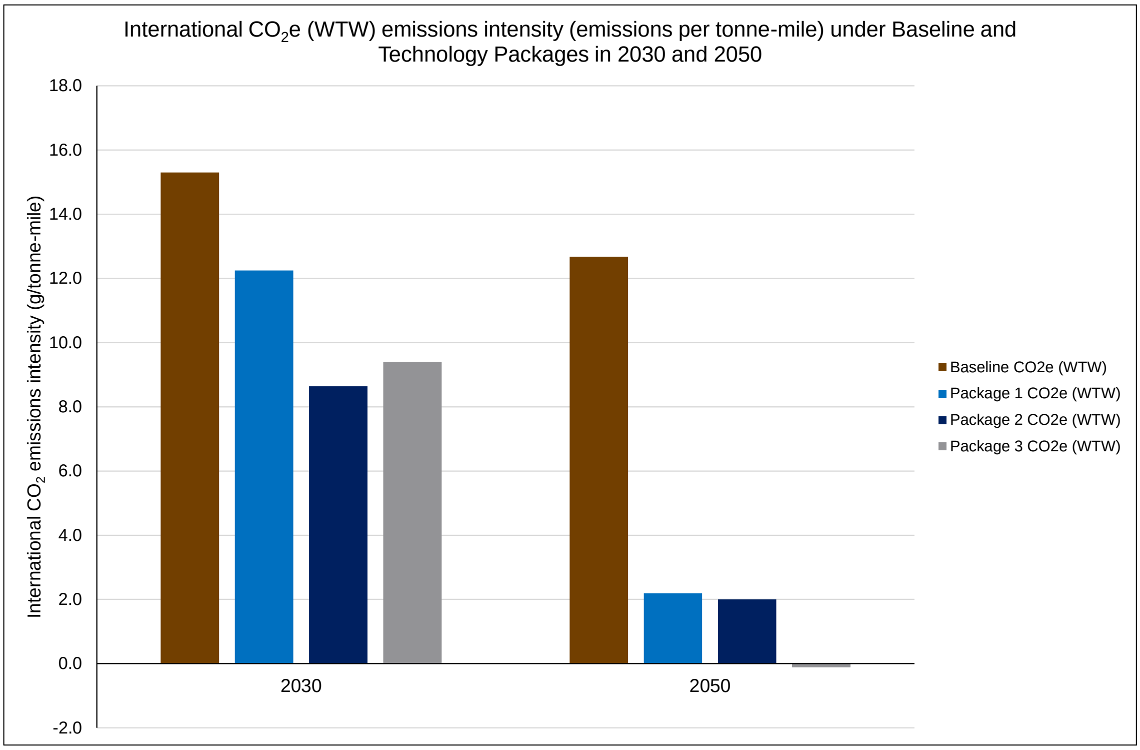
The results show that all three packages meet the IMO ambition on a WTW basis in 2050, with package 3 showing reductions of over 100%, indicating a net absorption of CO_2, as described above. Packages 1 and 2 show reductions of over 80% under the low scenario and 74% or 77% under the central scenario. Under the high scenario, the emissions reduction under package 1 remains above 80%, but that for package 2 reduces to 70%.

Table 7-1 also includes the emissions reductions calculated on a TTW basis. For some cases, particularly under package 2, these show considerably lower reductions than on the WTW basis as the fuels contain carbon and much of the overall reduction occurs in the fuel production phase.

Figure 7-15 compares the CO_2e emissions on a WTW basis between the baseline and three packages under the central demand scenario, with results shown for 2030 and 2050. Reductions are evident for the three packages in 2030, but the most significant reductions do not appear until 2050, when the full transition to alternative fuels (particularly green fuels) is achieved.

[66] For these comparisons, the WTW emissions values for 2008 were derived from the TTW values (as reported in the IMO Third Greenhouse Gas Study (International Maritime Organization, 2014)) were factored by the same WTW and TTW emissions factors for HFO as used in the calculations being reported here. For both WTW and TTW emissions, the 2008 emissions from the IMO report were scaled up for consistency with the calculations described in this report.

Figure 7-15: WTW CO_2e emissions intensity in 2030 and 2050 for the baseline and three packages under the central scenario



In addition to the overall CO_2 (including CO_2e) results, an important parameter for the maritime industry is the carbon intensity, expressed as grams of CO_2 emitted per tonne-mile transported. Table 7-2 shows the changes relative to 2008 levels, again including both WTW and TTW values. The carbon intensity values were calculated using the emissions for 2008, published in the IMO third greenhouse gas study (International Maritime Organization, 2014), combined with demand values for the same year published in the International Transport Forum's Transport Outlook (International Transport Forum, 2019). Under the baseline cases, despite the assumption of a technology freeze for new ships at 2020 levels, reductions in carbon intensity of over 50% are achieved by 2050, as a result of the latest technology vessels contributing a greater part of the fleet; these are, however, short of the initial IMO strategy target of 70%. Under the fuel and technology packages, with the additional technologies and the alternative fuels, the reductions achieved by 2050 are all over 90% relative to 2008 on a WTW basis. On a TTW basis, package 1 also exceeds 90% reductions by 2050, with package 3 approaching the same threshold; package 2 barely meets the initial IMO strategy target of 70%.

Table 7-2: Changes in CO_2e WTW emissions intensity relative to 2008 (TTW values in parentheses)

	Baseline	Package 1	Package 2	Package 3
Low scenario				
2030	-41% (-44%)	-53% (-59%)	-67% (-59%)	-63% (-66%)
2050	-53% (-56%)	-91% (-94%)	-93% (-72%)	-100% (-90%)
Central scenario				
2030	-38% (-41%)	-50% (-58%)	-65% (-57%)	-62% (-65%)
2050	-48% (-51%)	-91% (-95%)	-92% (-69%)	-100% (-89%)
High scenario				
2030	-38% (-41%)	-50% (-58%)	-65% (-58%)	-62% (-65%)
2050	-49% (-51%)	-91% (-95%)	-92% (-70%)	-101% (-89%)

The results presented above show significant reductions in emissions to 2050 through the impacts of the changes in fuels and technologies under the three packages. Figure 7-16 to Figure 7-18 show the contributions of vessel technologies and fuels to the reductions achieved and how these vary over time. For Package 3 (Figure 7-18), the contribution of carbon capture is separated out from the other technologies.

Figure 7-16: Contributions of technology and fuels to WTW emissions reductions under Package 1

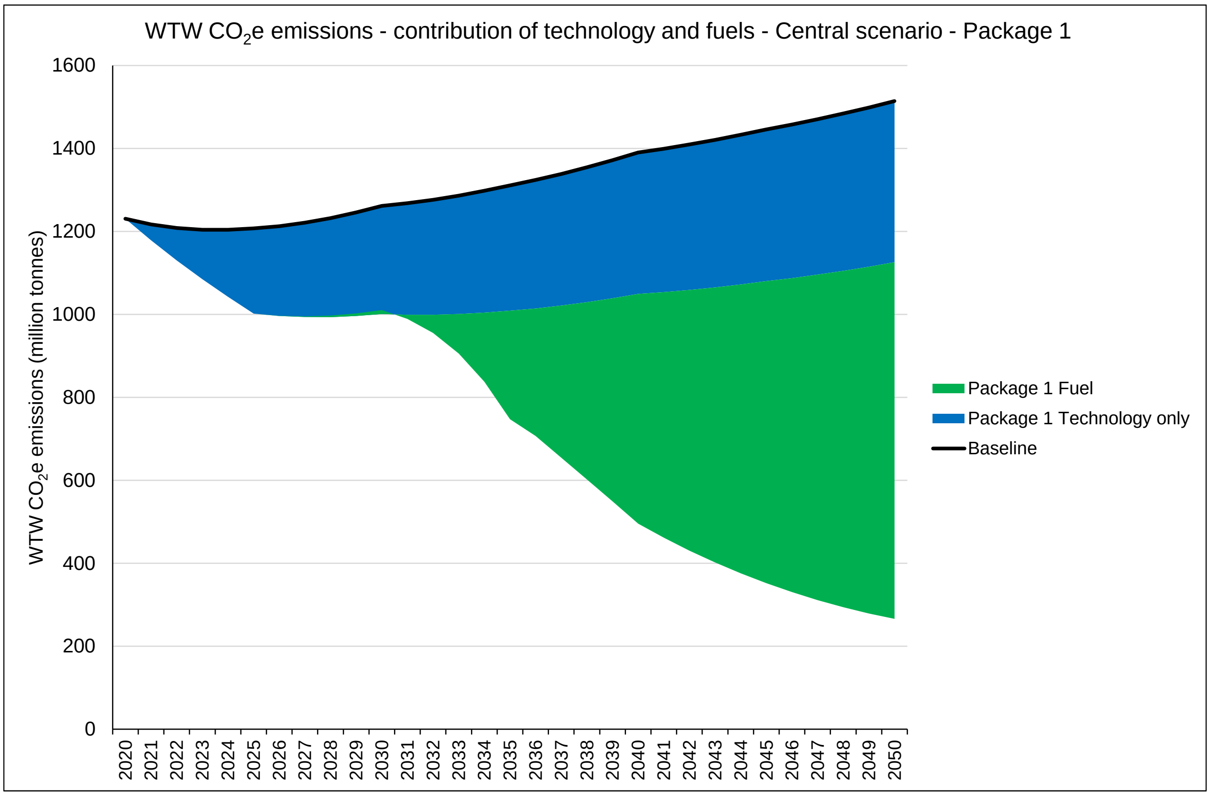


Figure 7-17: Contributions of technology and fuels to WTW emissions reductions under Package 2

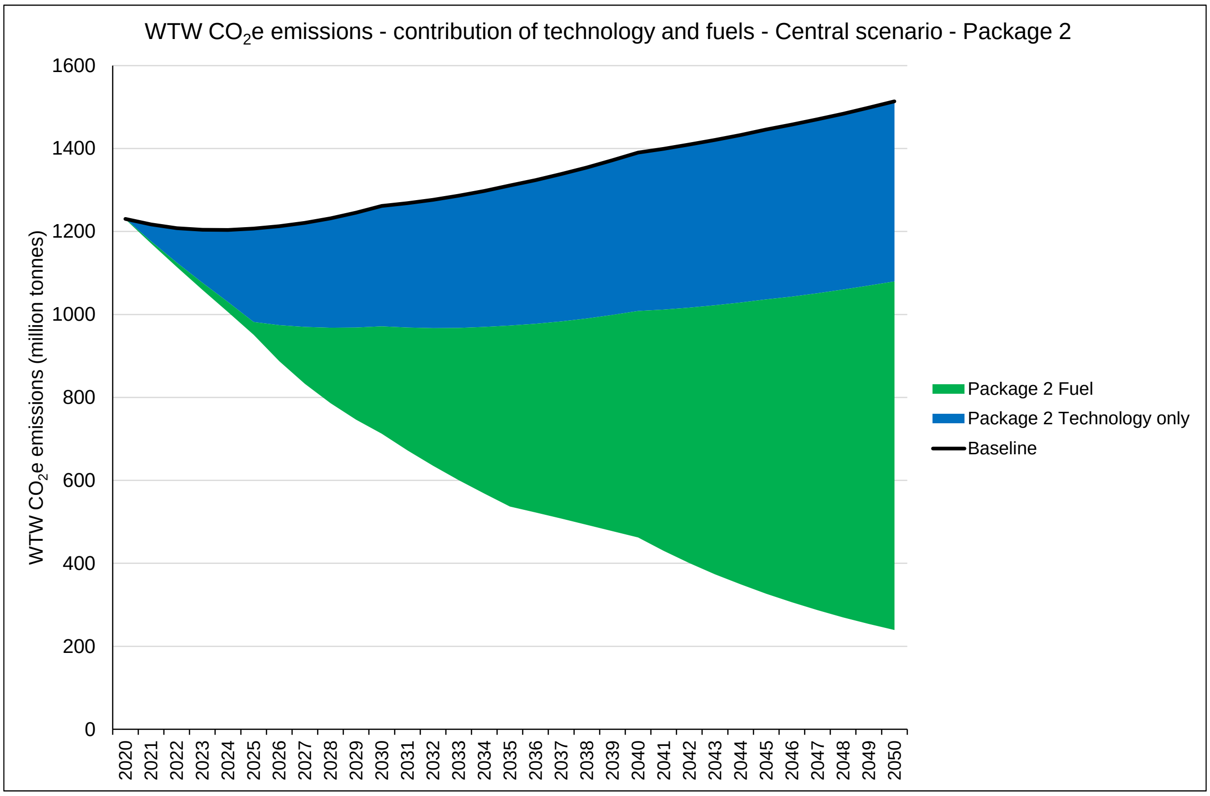
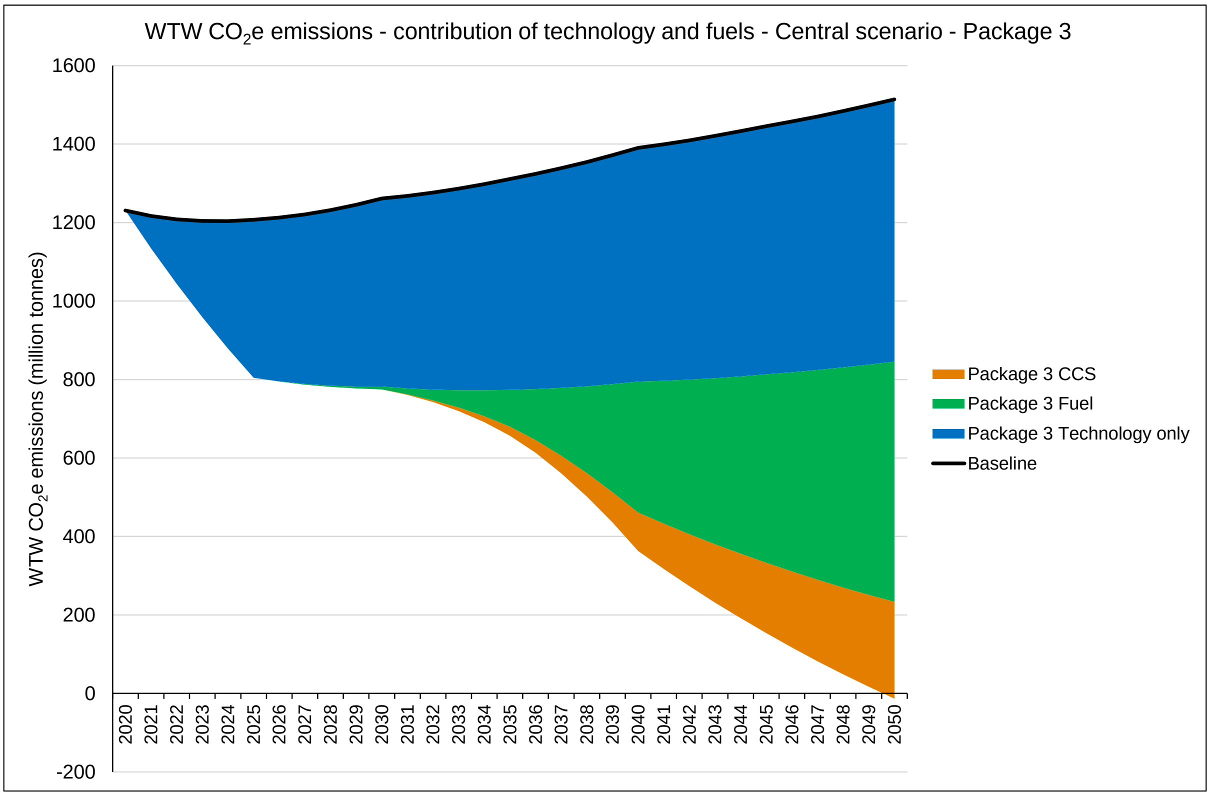


Figure 7-18: Contributions of technology and fuels to WTW emissions reductions under Package 3



For each chart, the emissions under the central baseline are shown as a black line close to the top of the chart. The emissions reductions are then represented by the shaded areas below that line. Under each package, the contribution of technology, largely operational measures, is dominant in the initial years, followed by a steady increase in the reduction due to technology, but a more rapid rise in the reduction due to alternative fuels. Under Package 3, the contribution of on-board carbon capture to emissions reductions also increases noticeably from 2025 onwards. Under this package, the emissions reductions delivered by technology and fuels (i.e. excluding carbon capture) in 2050 is slightly greater than that delivered under Package 1. **This would suggest that the more cost-effective technologies implemented in Package 1 deliver nearly all the improvements available from the technologies identified.** The percentage contributions to the emissions reductions achieved in 2050 are compared for the three packages in Table 7-3.

Table 7-3: Percentage contributions to total TTW CO_2e emissions reduction by technology and fuel for the three packages

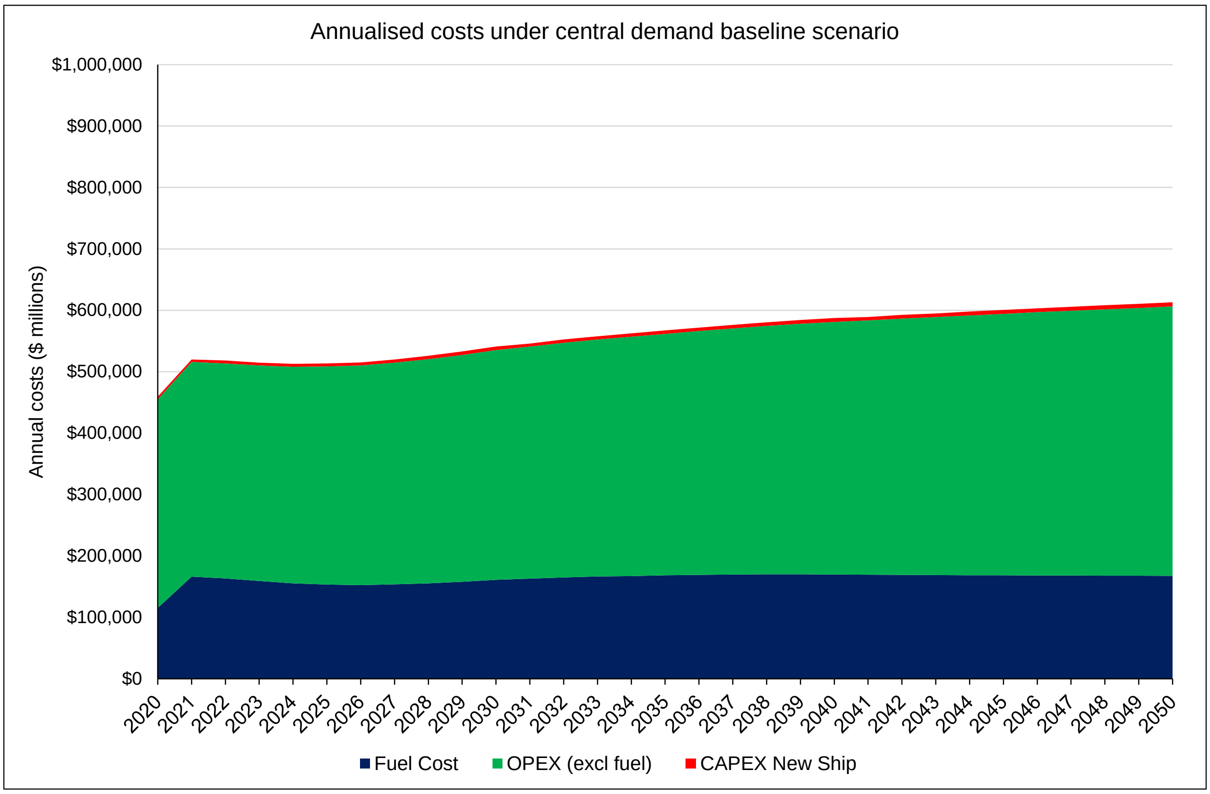
	Package 1	Package 2	Package 3
Technology	31%	34%	44%
Fuel	69%	66%	40%
Carbon Capture	-	-	16%

Under Packages 1 and 2, the splits of the contributions between technology and fuels is broadly similar at one third / two thirds. For Package 3, the contribution from technology and carbon capture increases, with a commensurate reduction in the contribution from fuel.

7.3 Costs associated with the fuel and technology packages

The evolution of the calculated costs under the central baseline, separated by fuel costs, operating costs (excluding fuel) and capital costs, are shown in Figure 7-19.

Figure 7-19: Annualised costs under the central baseline scenario



The operating costs include port charges, canal dues, cargo handling, crew, stores, lubricants, maintenance, insurance, and administration costs. The capital costs include the capital costs of new ships by ship category as well as the capital costs of the additional technologies applied (e.g. carbon capture). Under this baseline, the total costs for the sector are forecast to increase by approximately 30% between 2020 and 2050, driven primarily by the increased transport demand in the forecast. In 2020, operating costs (excluding fuel) account for fuel costs account for approximately 72% of annual costs with fuel costs accounting for approximately 27%. Capital costs (annualised) account for less than 1% of total costs. These percentage splits remain approximately constant through to 2050 under this baseline scenario.

For comparison, Figure 7-22 to Figure 7-22 show the evolution of the calculated costs under Packages 1 to 3 applied to the same baseline.

Figure 7-20: Annualised costs under Package 1 on the central demand baseline

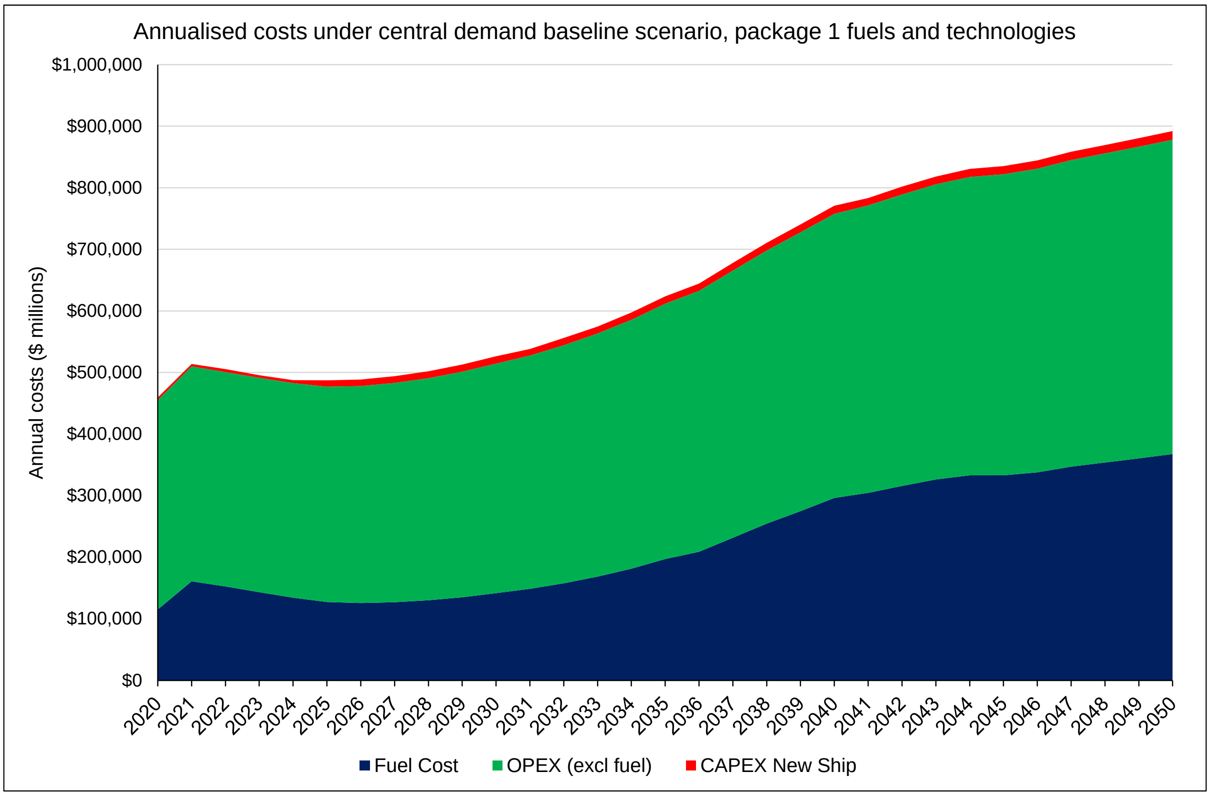


Figure 7-21: Annualised costs under Package 2 on the central demand baseline

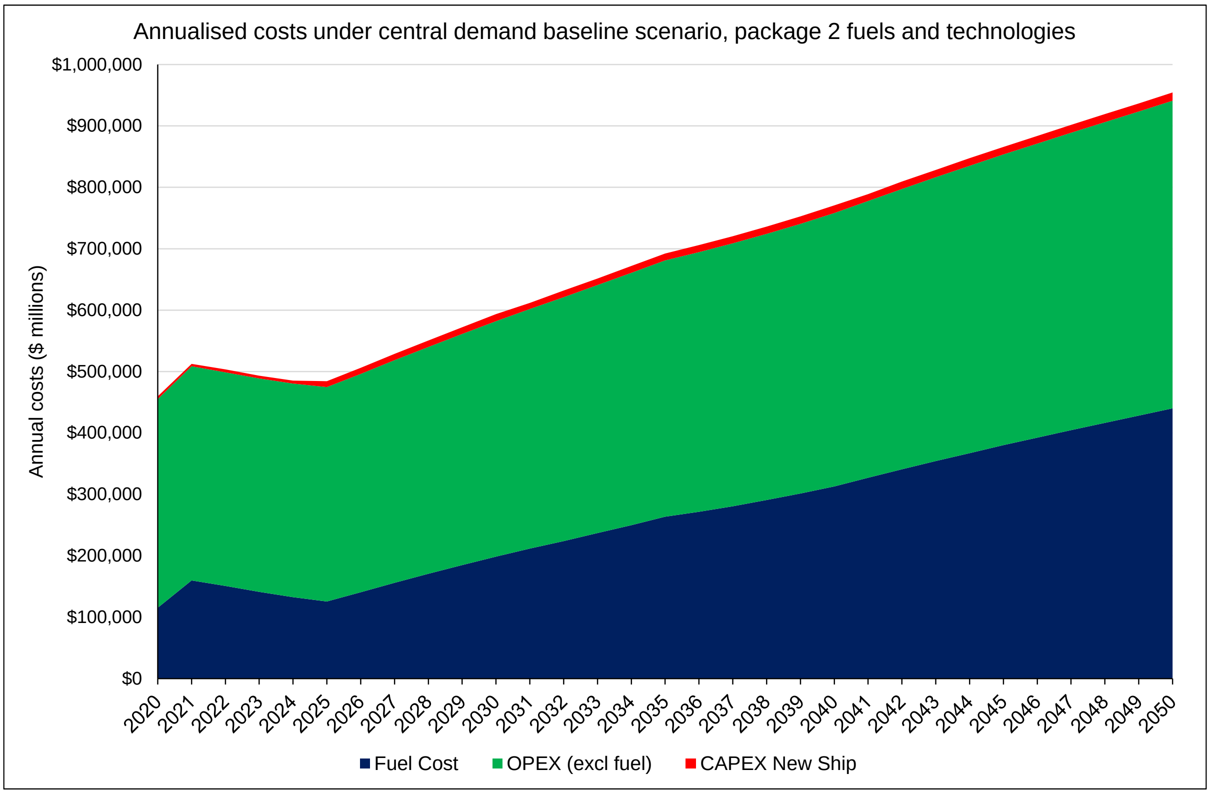
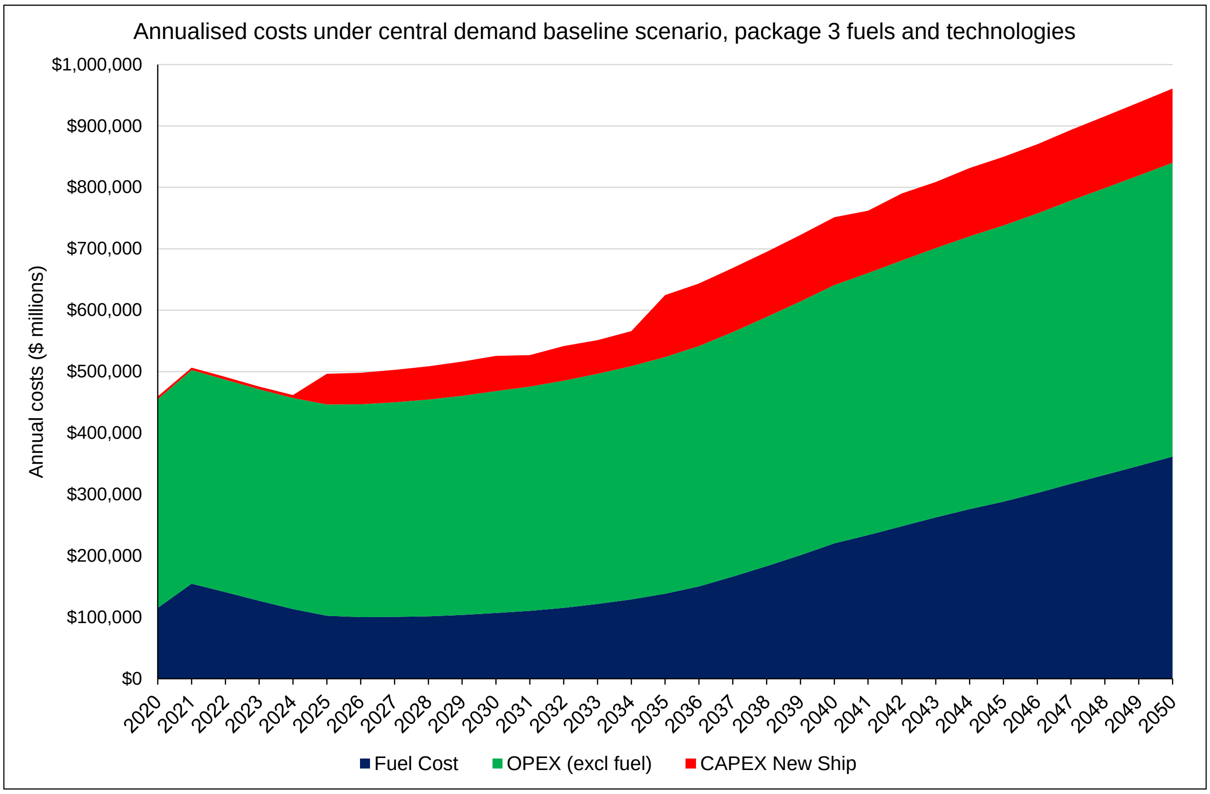


Figure 7-22: Annualised costs under Package 3 on the central demand baseline



All three packages show total costs having a greater increase to 2050 (up to 116% increase over 2020 for Package 3) than the baseline. The operating costs (excluding fuel) increase by a slightly greater amount for package 3 than under the baseline, but the fuel costs increase significantly, reaching 41% of the total costs by 2050. For this package, the increase in the capital costs is very evident, reaching 12% of the total costs by 2050. In contrast, packages 1 and 2 show only marginal increases in capital costs.

Figure 7-23 to Figure 7-25 show the change in annualised costs for each of the three packages relative to the central baseline.

Figure 7-23: Change in annualised costs relative to the central baseline for Package 1

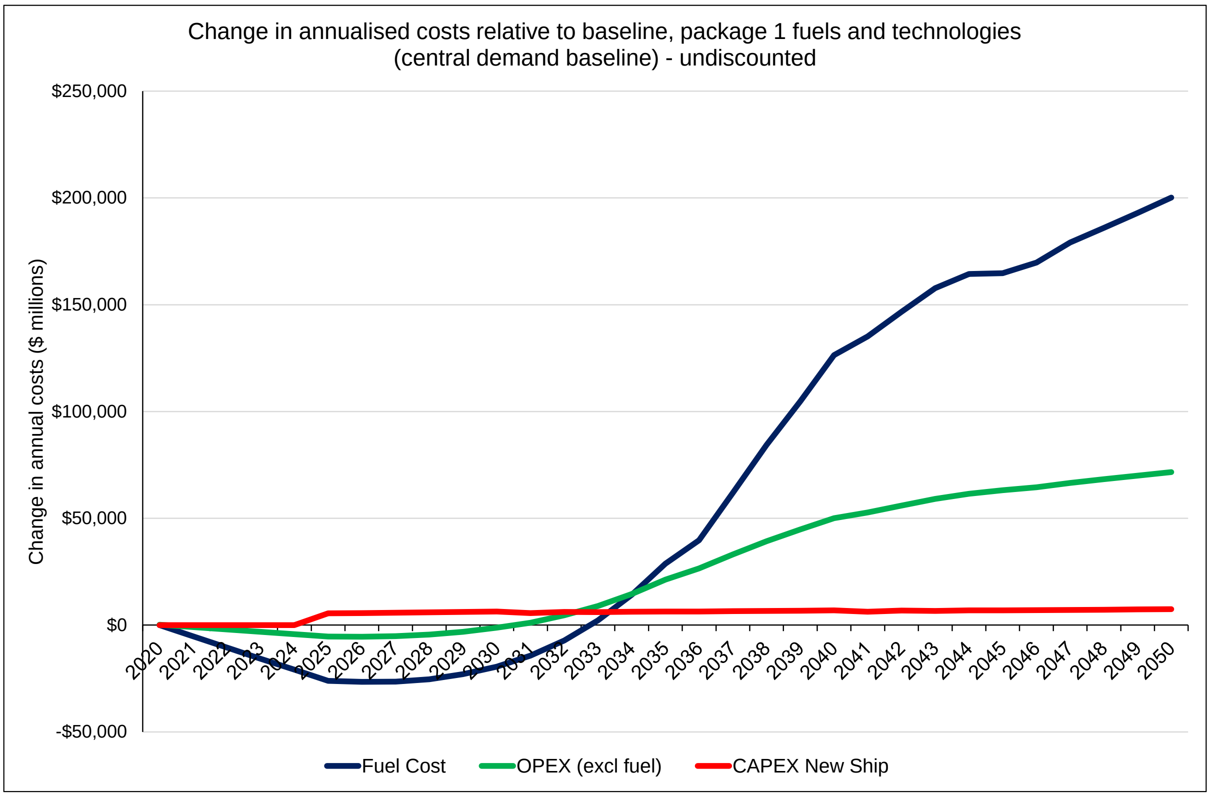


Figure 7-24: Change in annualised costs relative to the central baseline for Package 2

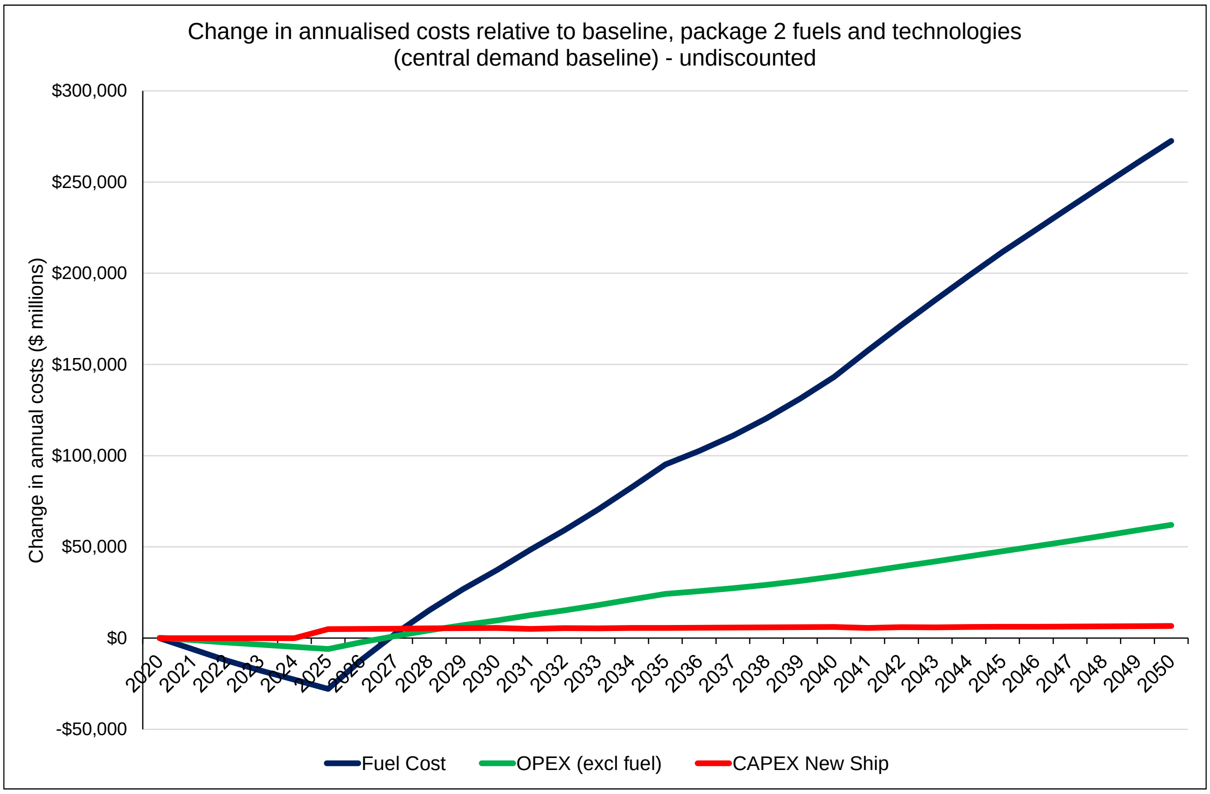
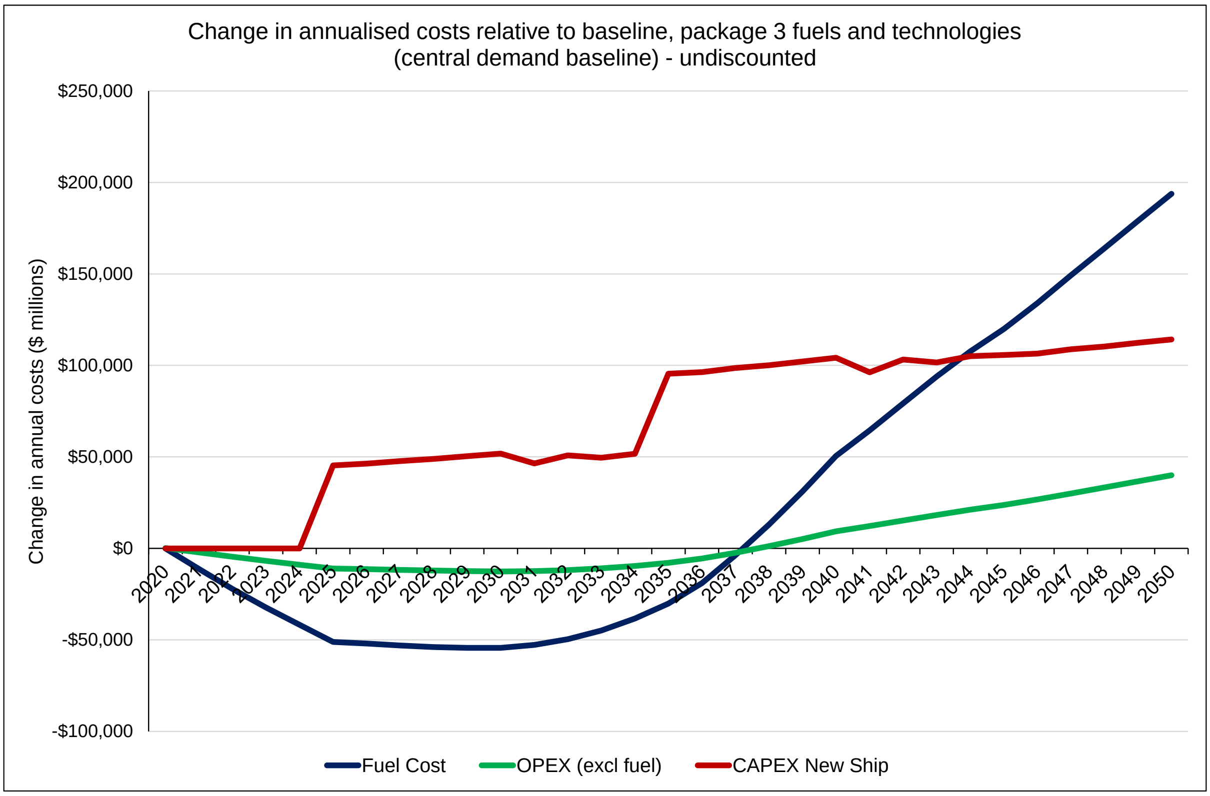


Figure 7-25: Change in annualised costs relative to the central baseline for Package 3



Under each package, the early improvements in vessel efficiency, mainly driven by operational measures, lead to an initial reduction in fuel costs. The fuel costs subsequently rise (to be substantially greater than the baseline) as alternative fuels, particularly the 'green' variants, are adopted. The operating costs (excluding fuel) also show a small rise above the baseline out to 2050. Under Packages 1 and 2, the capital costs also show a small increase over the baseline as the result of the adoption of new technologies on new vessels; this increase is substantially greater under Package 3 due to the focus of that package on the early adoption of new vessel technologies.

Total costs have been calculated by summing the fuel costs, operating costs and capital costs of new ships and new technologies over a period of 30 years, with discounting of future costs applied to derive net present values (NPV). The primary discount rate applied here is 10%, reflecting an industry focus of the cost analysis; additional results are also presented for a discount rate of 5%, reflecting a public sector focus.

Table 7-4 shows the results of the total costs for the baseline package and the three fuel and technology packages at various discount rates under the central demand scenario. Results for package 2 show the highest costs compared to the baseline while package 1 shows the lowest costs compared to the baseline scenario.

Table 7-4: Net present values (2020-2050) of total costs by package for the central demand scenario

Discount rate	Baseline ($ billion)	Package 1 ($ billion)	Package 2 ($ billion)	Package 3 ($ billion)
10%	5,539	5,774	6,027	5,720
5%	8,912	9,764	10,248	9,713

Table 7-5 shows the breakdown of the changes in NPV by fuel and technology package compared to the baseline by cost component. The fuel costs are calculated using the fuel prices shown in Table 6-5.

Table 7-5: Changes in NPV by fuel and technology package relative to the baseline at 10% and 5% discount rates for the central demand scenario

Package	Fuel cost ($ billion)	OPEX (exc. Fuel) ($ billion)	CAPEX ($ billion)	Total change in NPV ($ billion)
10% discount rate				
Package 1	+113	+83	+39	+235
Package 2	+364	+91	+34	+489
Package 3	-186	-46	+413	+181
5% discount rate				
Package 1	+517	+260	+75	+852
Package 2	+1,024	+246	+66	+1,336
Package 3	-47	-23	+871	+800

The outcome of the total costs for the three packages show increases in total costs of between 4% (for Package 1) and 9% (for Package 2) of the baseline value (when discounted at 10%). The fuel price assumptions for packages 1 and 2 through to 2050 are the key determinants of the package total costs[67], while the capital cost assumptions in package 3 is the driving force behind its total costs. This is illustrated for the 10% discount rate results in Figure 7-26.

[67] It is worth noting that the results for package 2 are sensitive to the price assumption for BioLNG; as noted in Section 6.2.1, this was derived slightly differently from most other fuels as IHS Markit did not provide a price projection for it

Figure 7-26: Change in NPV at 10% discount rate by fuel and technology package for the central demand scenario compared to the baseline

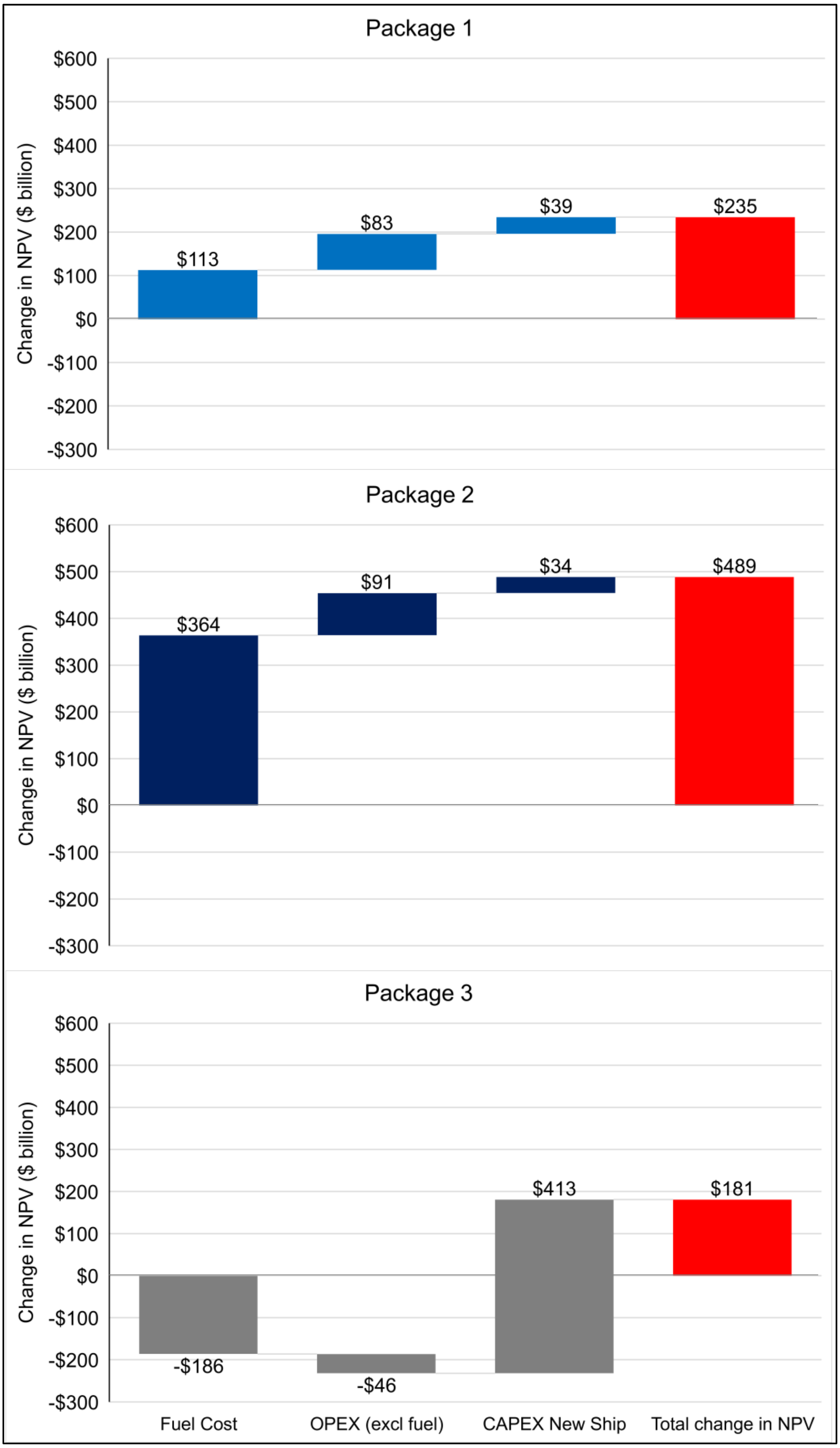
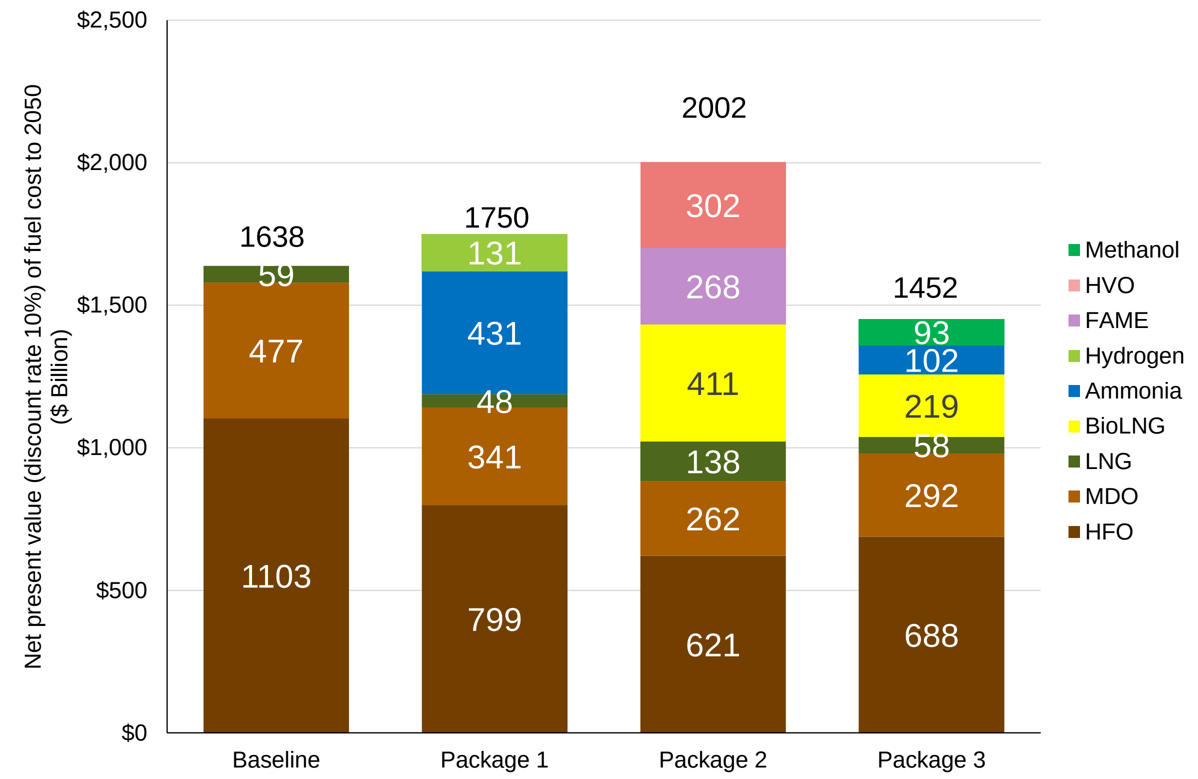


Figure 7-27 shows how the fuel costs for each package are built up from the fuel mix. The volumes of fuel needed in each package was shown in section 7.1. The high fuel cost change in package 2 can be mainly attributed to the high proportion of Bio LNG, FAME and HVO and their anticipated high prices.

Figure 7-27: Net present value of aggregated fuel costs from 2020 to 2050 per package by fuel type for central demand scenario



7.4 Cost-effectiveness of the fuel and technology packages

As described in section 7, and in particular as illustrated in Figure 7-12, Figure 7-13 and Figure 7-14 for the three packages respectively, the CO_2 and CO_2e emissions can be compared to the baseline (on both a TTW and WTW basis) for each package. The differences divided by the total discounted costs provide then the cost-effectiveness for each fuel and technology package in \$/tonneCO_2e. The results for the default calculation based on discounting both the costs and the emissions savings (using savings in WTW CO_2e) are shown in Table 7-6.

Table 7-6: Net present value of cost-effectiveness of the three different packages to 2050 (\$/tonneCO_2e)

	10% discount rate	5% discount rate
Package 1	$73	$120
Package 2	$113	$149
Package 3	$39	$83

Package 2 is the least cost-effective (highest cost per tonne CO_2e) under both discount rates, with package 3 being the most cost-effective.

For comparison, the IMO fourth GHG study (IMO, 2020) presents higher values for the marginal abatement costs in 2050, with values of about \$260/tonne CO_2e and \$410/tonneCO_2e, depending on the scenario. These values differ from those presented in this report in that they are for 2050 (rather than cumulative to 2050) and are undiscounted. For the technology and fuel packages presented here, the undiscounted cost-effectiveness values (cumulative to 2050) are approximately \$160/tonneCO_2e for package 1, \$180/ tonneCO_2e and \$130/tonneCO_2e for package 3.

7.4.1 Sensitivity calculations

In addition to the "default" calculation, using WTW CO_2e and with both costs and emissions savings discounted at the same rate (emissions savings are discounted to reflect the additional benefits on short-term reductions relative to the longer-term), additional sensitivity cases have also been calculated, to reflect alternative views on the application of discounting to emissions savings and on the use of TTW or WTW emissions. These sensitivity cases are defined in Table 7-7.

Table 7-7: Definition of sensitivity cases for cost-effectiveness calculations

Case	Emissions calculation	Discounting applied to emissions?
Default	WTW	Yes
Sensitivity 1	WTW	No
Sensitivity 2	TTW	Yes
Sensitivity 3	TTW	No

The changes in emissions and costs for these sensitivity cases are shown, for a discount rate of 10%, in Table 7-8.

Table 7-8: Changes in CO_2e and cost by package for central demand scenario, including sensitivity cases

	Emissions scope (change in CO_2e)	Discount rate applied to emissions	Package 1	Package 2	Package 3
Changes in CO_2e emissions			(Mt)	(Mt)	(Mt)
Default	WTW	10%	3,202	4,312	4,680
Sensitivity 1	WTW	N/A	18,626	21,984	23,762
Sensitivity 2	TTW	10%	3,131	2,358	3,822
Sensitivity 3	TTW	N/A	17,859	10,349	17,978
Discounted costs (change in NPV)			(\$ billion)	(\$ billion)	(\$ billion)
	Change in Total Cost (NPV)	10%	235	489	181

Combining the costs and emissions savings presented in Table 7-8 gives the cost-effectiveness values shown in Table 7-9.

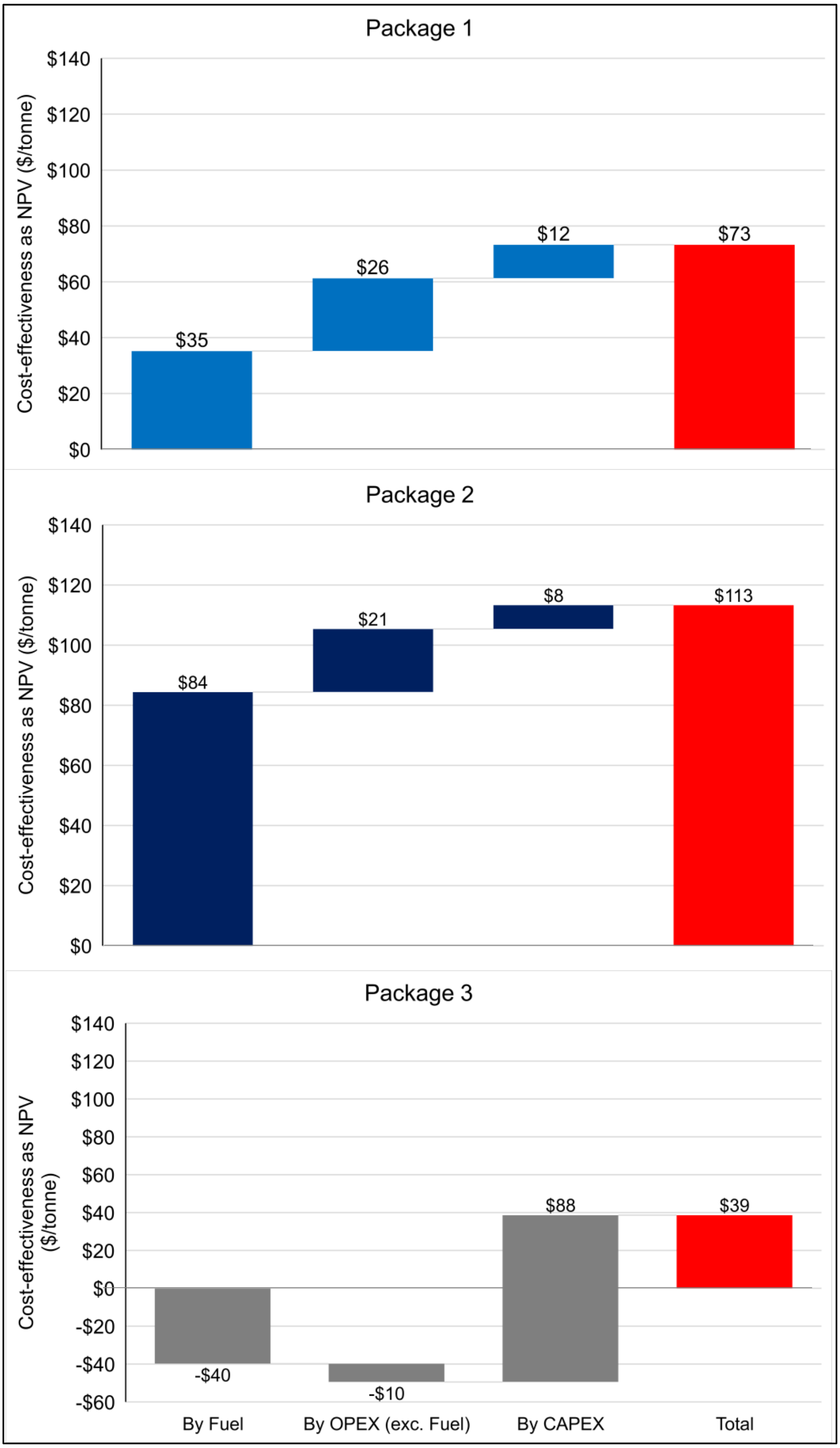
Table 7-9: Cost-effectiveness for central demand scenario, including sensitivity cases

	Emissions scope (CO_2e)	Discount rate applied to emissions	Package 1 ($/tonne$CO_2e$)	Package 2 ($/tonne$CO_2e$)	Package 3 ($/tonne$CO_2e$)
Default	WTW	10%	$73	$113	$39
Sensitivity 1	WTW	N/A	$13	$22	$8
Sensitivity 2	TTW	10%	$75	$207	$47
Sensitivity 3	TTW	N/A	$13	$47	$10

Package 2 consistently has the highest calculated abatement costs overall. This highlights the fact that BioLNG, HVO and the use of FAME through to 2050 is costly and only slightly more effective on carbon reductions than Package 1 (on a WTW basis). The sensitivity cases with the emissions savings not discounted show lower cost-effectiveness values (by a factor of about 5 for each package when considering WTW emissions), but do not impact the relative magnitude of the results for the three packages.

As Figure 7-28 shows, the highest abatement cost is reflected in package 2 at $113 per tonne$CO_2$ (WTW). Package 3 is the least costly package (Figure 7-26) and the abatement costs for this package are $39 per tonne CO_2e (WTW) for the central demand scenario. Note that all analysis above is based on a 10% discount rate and the cost-effectiveness would increase at lower discount rates and vice versa for higher discount rates. The changes in NPV results for the various discount rates are shown in Table 7-5 above.

Figure 7-28: Cost-effectiveness of each package (as $/tonne$CO_2$ WTW abated, both 10% discount rate), central demand scenario



7.5 Fuel and technology sensitivity analysis results

7.5.1 Fuel and emissions calculations

As noted in Section 5.2.4, additional sensitivity analyses were performed to provide further insight into the changes in emissions and costs due to the technologies and fuels, and to enable an easier comparison of the differences due to the different fuel assumptions between the packages. These sensitivity analyses applied the technology assumptions from Package 3 (including the use of on-board carbon capture) with the fuel assumptions from Package 1 (forming Package 1A) and Package 2 (forming Package 2A).

The calculated fuel consumption from 2020 to 2050 under the central demand scenario is shown for each sensitivity package in Figure 7-29 to Figure 7-31, with a summary of the cumulative total, split by package and fuel type, in Figure 7-32. Like other figures in this section, the results for Package 3 (Figure 7-31) are unchanged from those presented earlier in the report.

Figure 7-29: Fuel consumption to 2050 under the central scenario for Package 1A

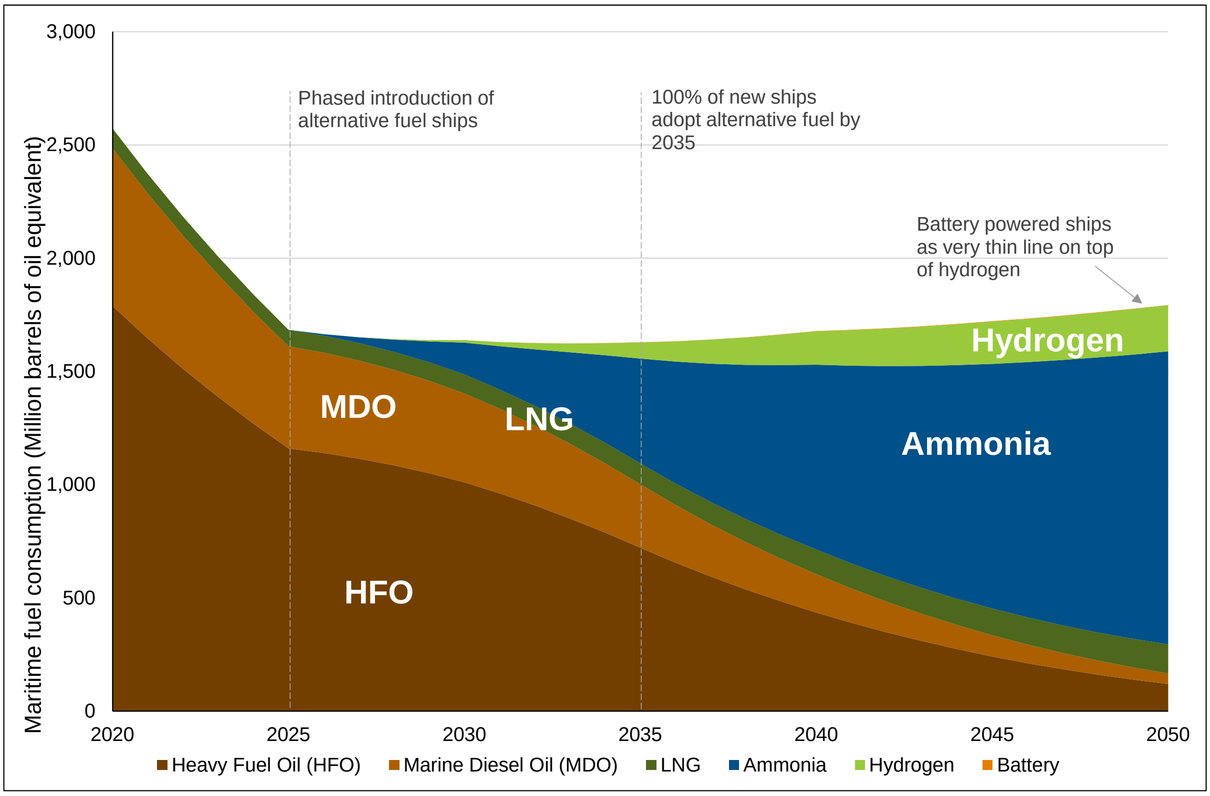


Figure 7-30: Fuel consumption to 2050 under the central scenario for Package 2A

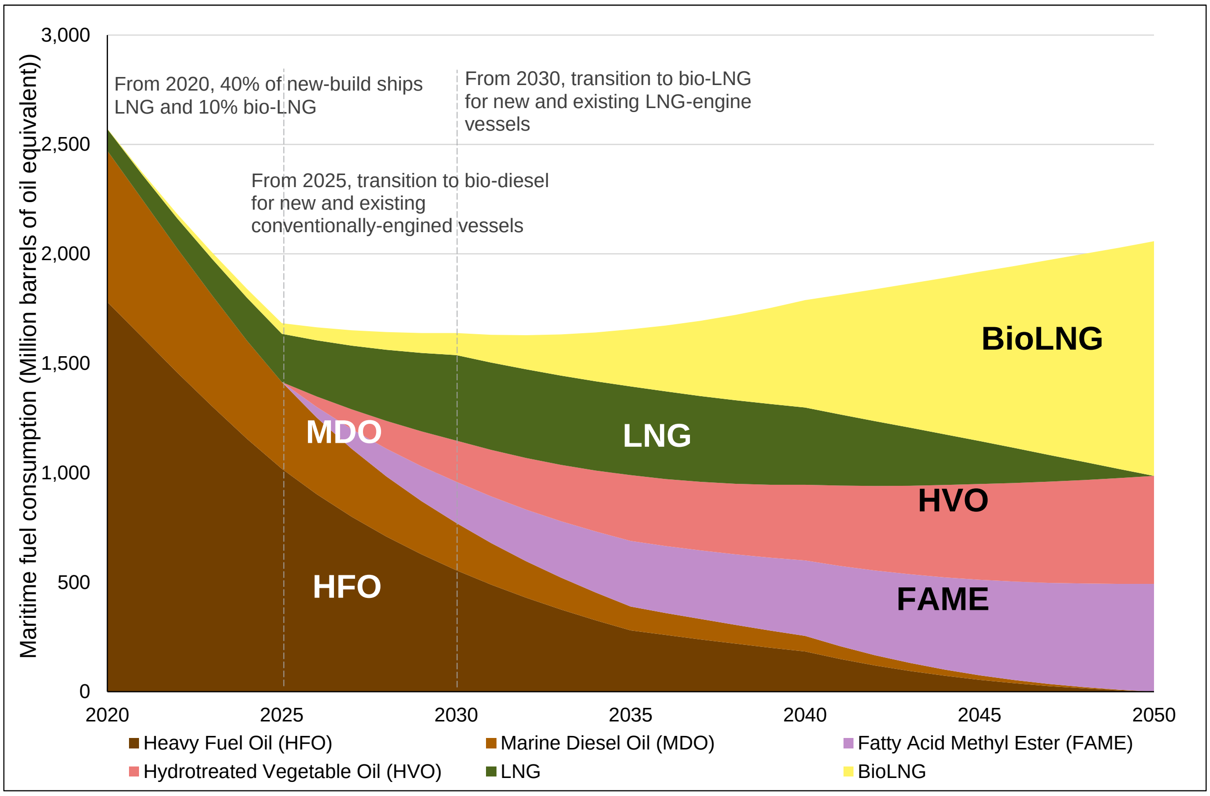


Figure 7-31: Fuel consumption to 2050 under the central scenario for Package 3

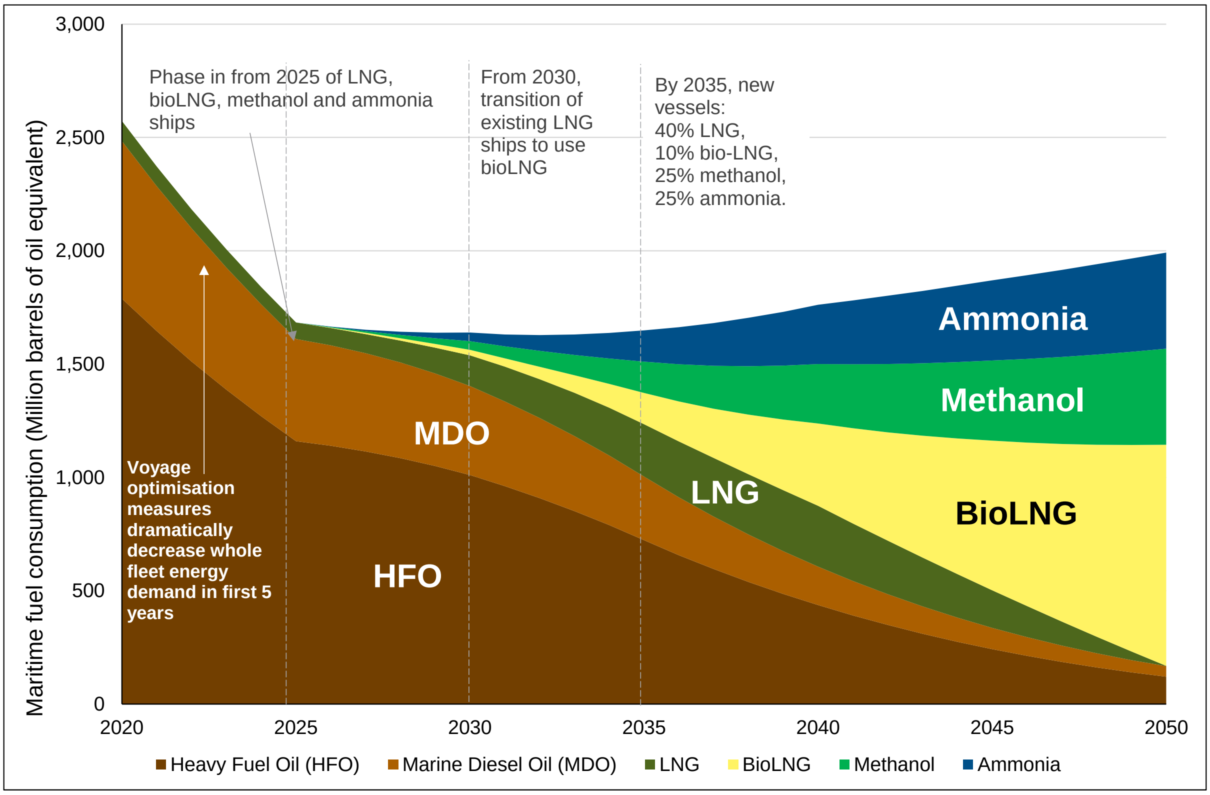
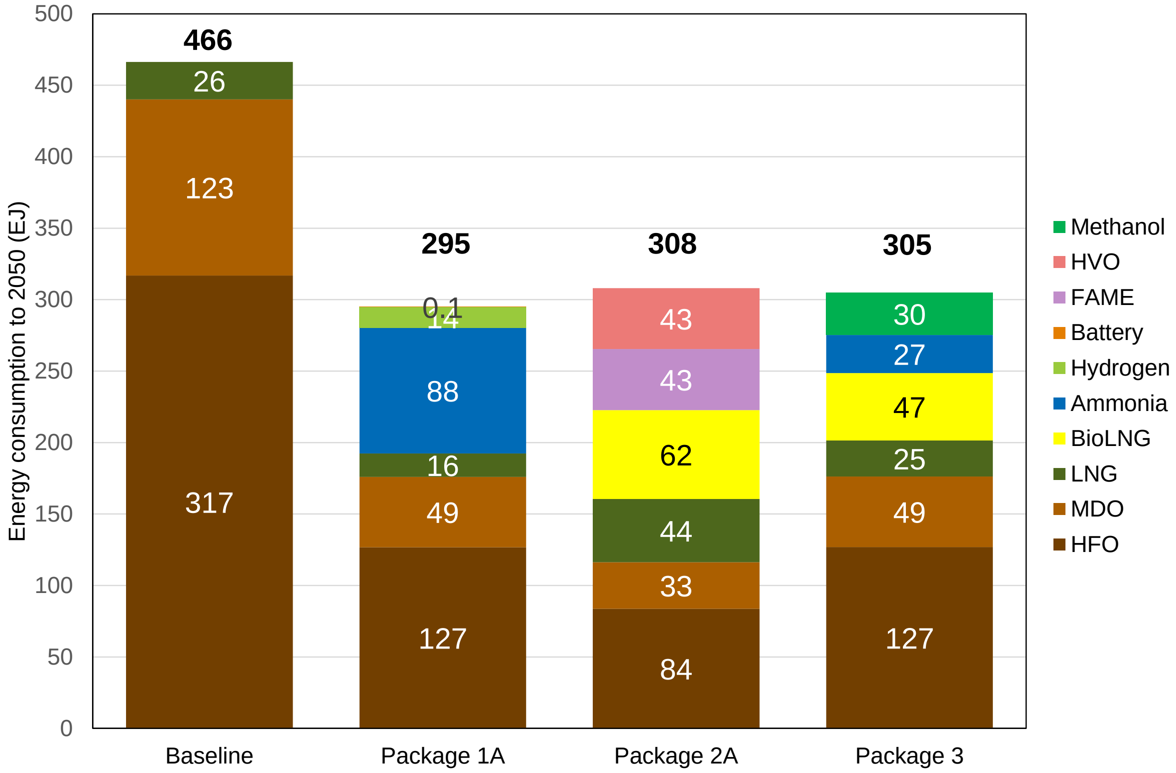


Figure 7-32: Fuel demand per fuel and technology package by fuel type for central demand scenario (cumulative 2020-2050)



Compared to the main calculation (Figure 7-11), the fuel consumption reduces from 370 EJ (Package 1) to 295 EJ (Package 1A) and from 359 EJ (Package 2) to 308 EJ (Package 2A). The fuel consumption for Package 3 is unchanged.

Although Packages 1A, 2A and 3 all implement the same vessel technology and operational assumptions, there are small differences in the fuel (energy) consumption. This results from the inclusion of on-board carbon capture in each package. The different packages include different proportions of carbon-containing and zero-carbon fuels; on-board carbon capture is not used on vessels fuelled by zero-carbon fuels, so the energy consumption penalty associated with it is applied to different proportions of the fleet. There is, therefore, a greater use of carbon capture in Package 2A than Package 3 and, similarly, a greater use in Package 3 than Package 1A.

The CO_2e emissions profiles to 2050 under the three packages are shown in Figure 7-33 to Figure 7-35.

Figure 7-33: Total CO_2e emissions (TTW and WTW) to 2050 under package 1A

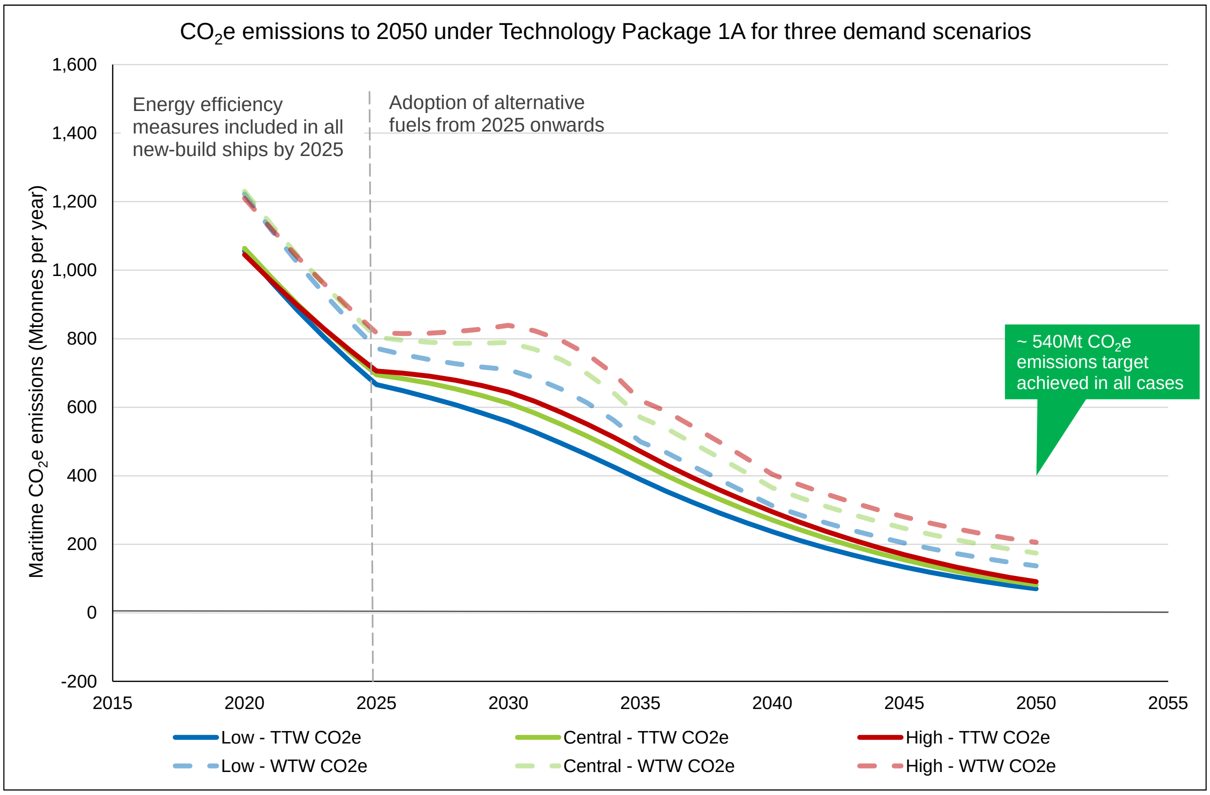


Figure 7-34: Total CO_2e emissions (TTW and WTW) to 2050 under package 2A

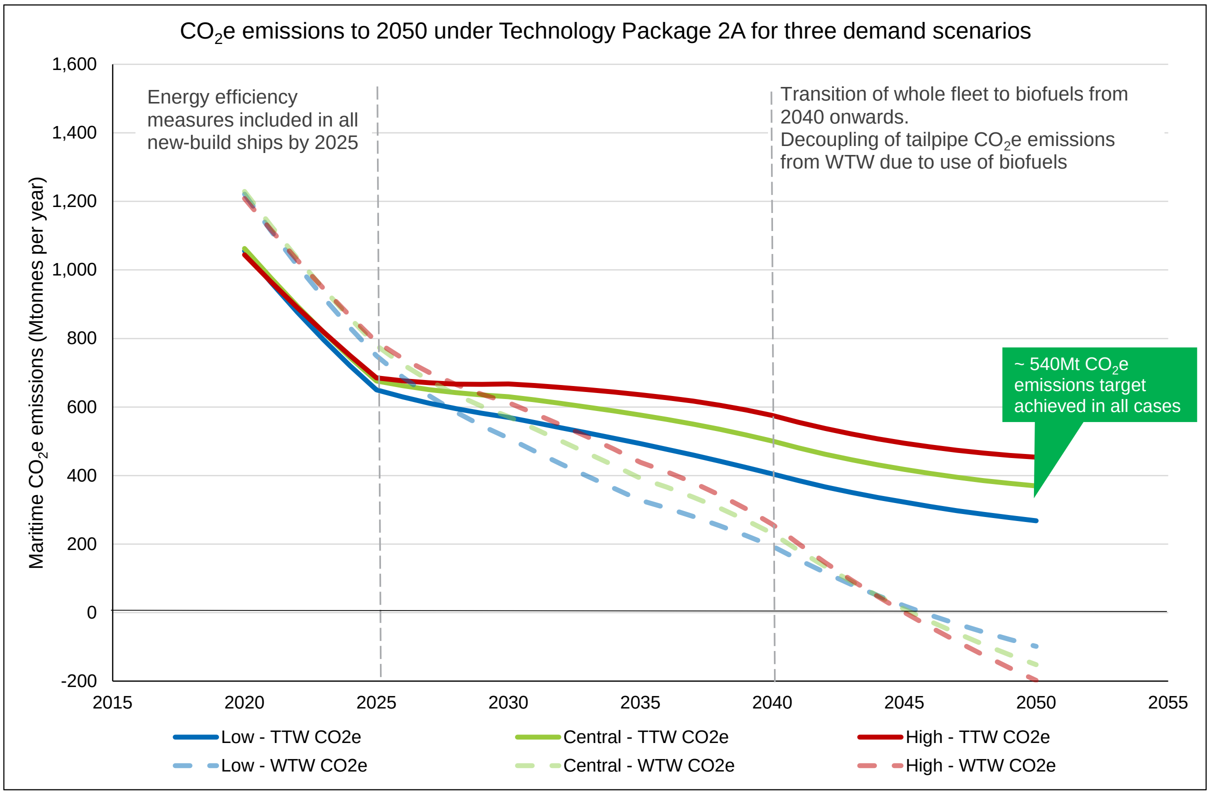
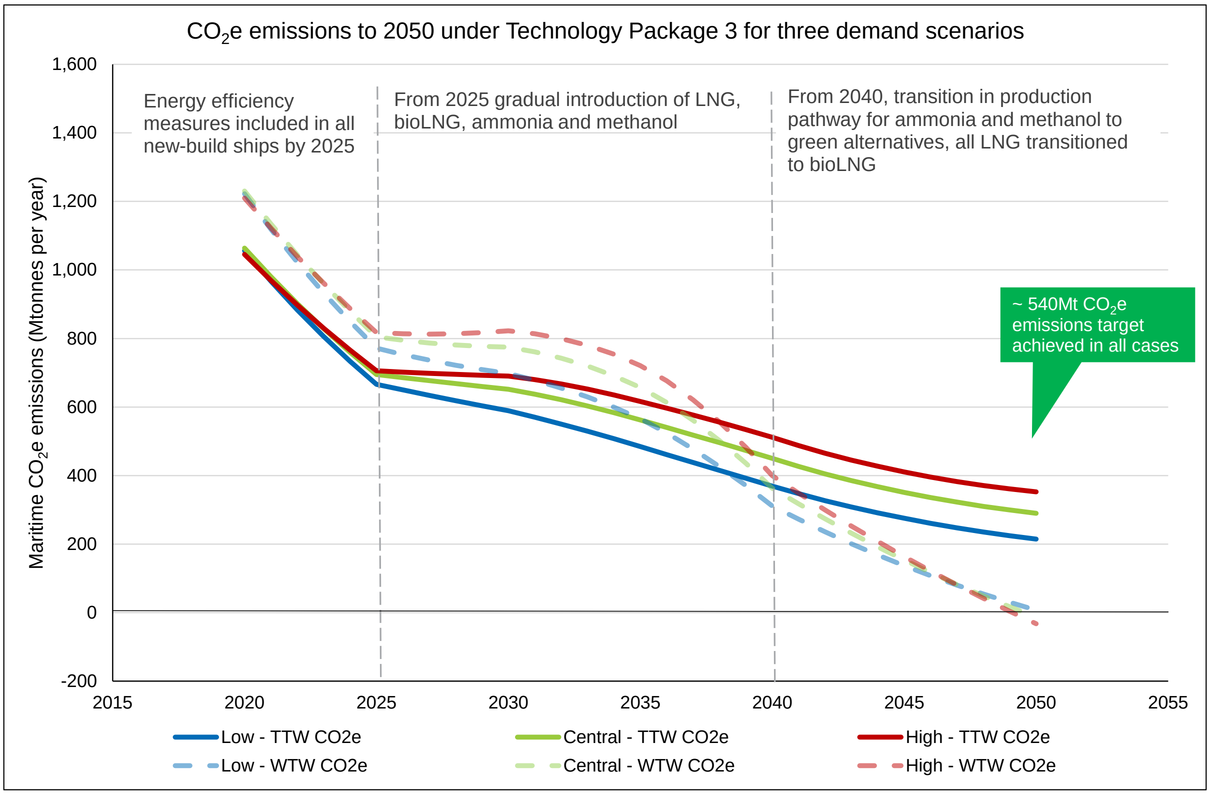


Figure 7-35: Total CO_2e emissions (TTW and WTW) to 2050 under package 3



Under these sensitivity assumptions of maximising the energy efficiency technology uptake, all three packages are estimated to meet the IMO ambition on a TTW basis by 2050. Packages 2A and 3 show negative WTW emissions by 2050 as they are using low-carbon fuels combined with carbon capture in the vessel exhaust. Package 1A does not achieve the negative emissions as, by 2050, the fuel used is predominantly zero-carbon, so there is little use and, consequently, little benefit from on-board carbon capture (leading to the lower energy consumption in Figure 7-32). The cost analyses do not apply the costs of carbon capture systems on vessels using zero-carbon fuels, so the overall vessel costs are also lower under this package.

The changes in WTW and TTW CO_2e emissions from 2008 to 2030 and 2050 are shown, for the baseline and packages 1A, 2A and 3 under the low, central and high demand scenarios, in Table 7-10.

Table 7-10: Changes in CO_2e WTW emissions relative to 2008 (TTW values in parentheses)

	Baseline	Package 1A	Package 2A	Package 3
Low scenario				
2030	9% (4%)	-31% (-41%)	-51% (-39%)	-33% (-37%)
2050	4% (-2%)	-87% (-93%)	-110% (-71%)	-99% (-77%)
Central scenario				
2030	22% (16%)	-24% (-35%)	-45% (-33%)	-25% (-31%)
2050	46% (39%)	-83% (-91%)	-115% (-61%)	-101% (-69%)
High scenario				
2030	30% (24%)	-19% (-31%)	-41% (-29%)	-21% (-27%)
2050	82% (73%)	-80% (-90%)	-119% (-52%)	-103% (-63%)

By 2050, all three (sensitivity) packages meet the IMO ambition of a 50% reduction in emissions relative to 2008 with a significant margin on both a TTW and WTW basis under the low and central demand scenarios. Under the high demand scenario, packages 2A and 3 meet the 50% reduction ambition by a small margin on a TTW basis, but a significant margin on a WTW basis. The use of different fuels under the three packages continues to give different emissions reductions, but the spread across the three packages on a TTW basis is significantly lower than in the main analysis (comparing to the results in Table 7-1).

Table 7-11 similarly shows the changes in emissions intensity relative to 2008 for the baseline and three sensitivity packages under each demand scenario.

Table 7-11: Changes in CO_2e WTW emissions intensity relative to 2008 (TTW values in parentheses)

	Baseline	Package 1A	Package 2A	Package 3
Low scenario				
2030	-41% (-44%)	-63% (-68%)	-73% (-67%)	-63% (-66%)
2050	-53% (-56%)	-94% (-97%)	-104% (-87%)	-100% (-90%)
Central scenario				
2030	-38% (-41%)	-61% (-67%)	-72% (-66%)	-62% (-65%)
2050	-48% (-51%)	-94% (-97%)	-105% (-86%)	-100% (-89%)
High scenario				
2030	-38% (-41%)	-61% (-67%)	-72% (-66%)	-62% (-65%)
2050	-49% (-51%)	-94% (-97%)	-105% (-86%)	-101% (-89%)

By 2050, all three packages show reductions of over 90% on a WTW basis and of over 85% on a TTW basis. In 2030, the reductions are lower, but still exceed 60% relative to 2008 on both a WTW and TTW basis.

Figure 7-36 shows the reductions in WTW emissions associated with technology, fuels and carbon capture systems under packages 1A, 2A and 3; Table 7-12 then summarises the percentage contributions in TTW emissions in 2050. As expected from the previous results, carbon capture provides only a small contribution to the emissions reductions under Package 1A (as the majority of new vessels use zero-carbon fuels by this time), with technology and fuel having an approximately even contribution to the emissions reductions. Under packages 2A and 3, carbon capture contributes about 20%, with technology and fuels again having an approximately even split of the remaining reductions.

Figure 7-36: Contributions of technology (blue), fuels (green) and carbon capture (orange) to WTW emissions reductions under Package 1A (top), 2A (middle) and 3 (lower) from the baseline

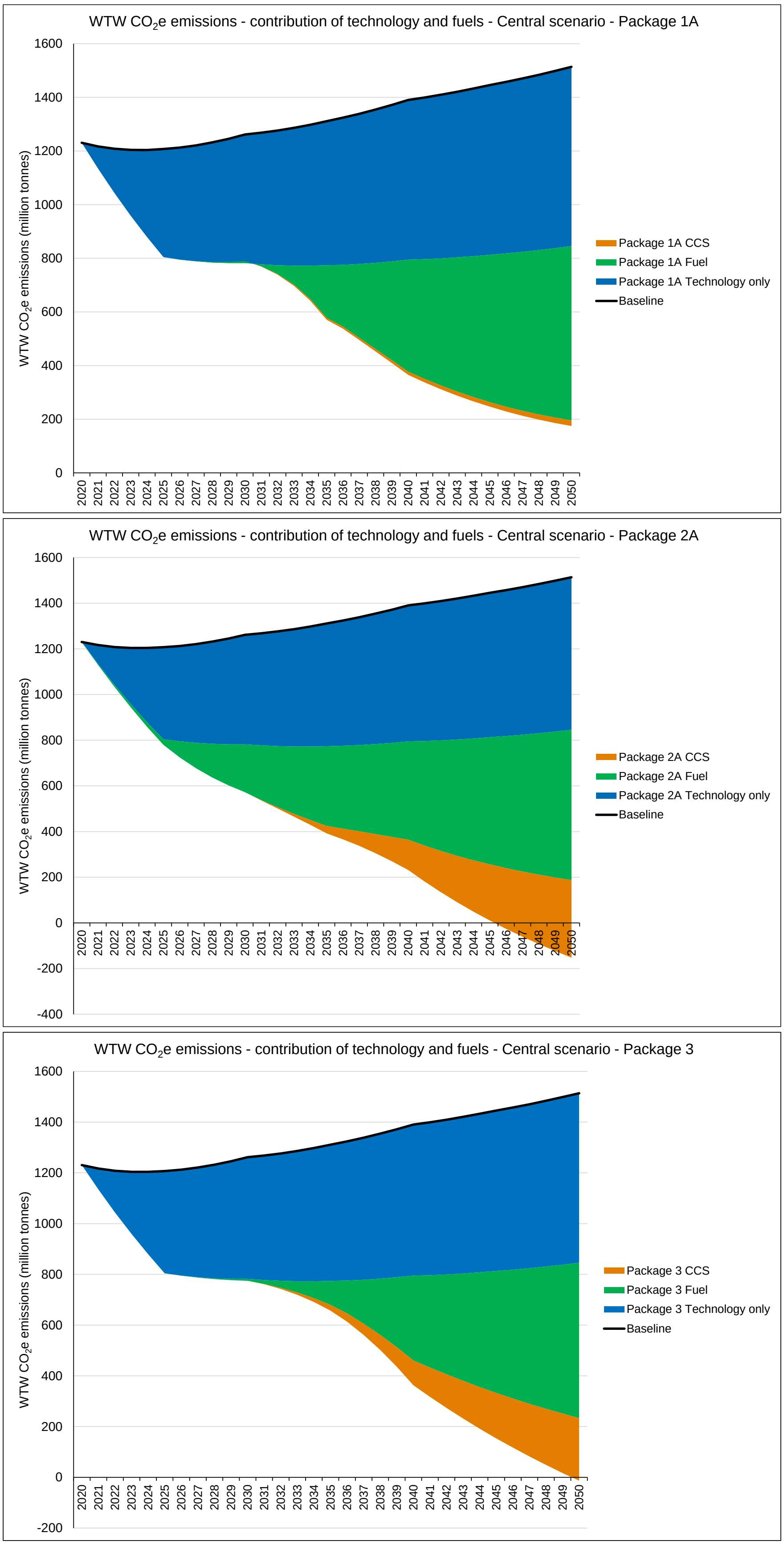


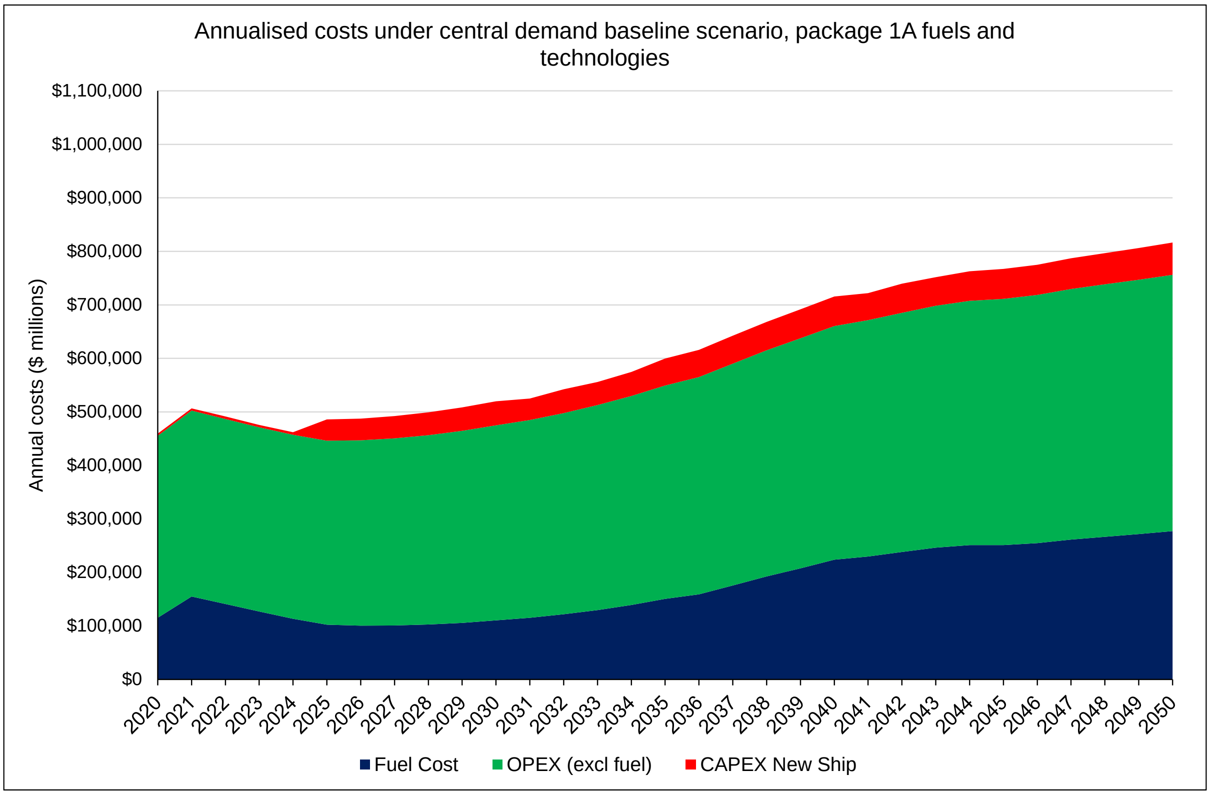
Table 7-12: Percentage contributions to total WTW CO_2e emissions reduction by technology and fuel for the three packages

	Package 1A	Package 2A	Package 3
Technology	50%	40%	44%
Fuel	48%	40%	40%
Carbon Capture	2%	20%	16%

7.5.2 Cost calculations

The costs associated with the emissions reductions achieved under packages 1A and 2A have been calculated using the same approach and assumptions as for the main analysis. Figure 7-37 shows the development of costs to 2050 under Package 1A, split by fuel cost, OPEX and CAPEX.

Figure 7-37: Annualised costs under Package 1A on the central demand baseline



Unlike Package 1 under the main analysis (Figure 7-20), CAPEX now shows a significant increase in costs under Package 1A, due to the inclusion of the additional vessel technologies. However, OPEX still forms the dominant cost under this package.

Similar cost profiles are shown for packages 2A and 3 in Figure 7-38 and Figure 7-39 (the latter being a copy of Figure 7-22 as shown for the main analysis).

Figure 7-38: Annualised costs under Package 2A on the central demand baseline

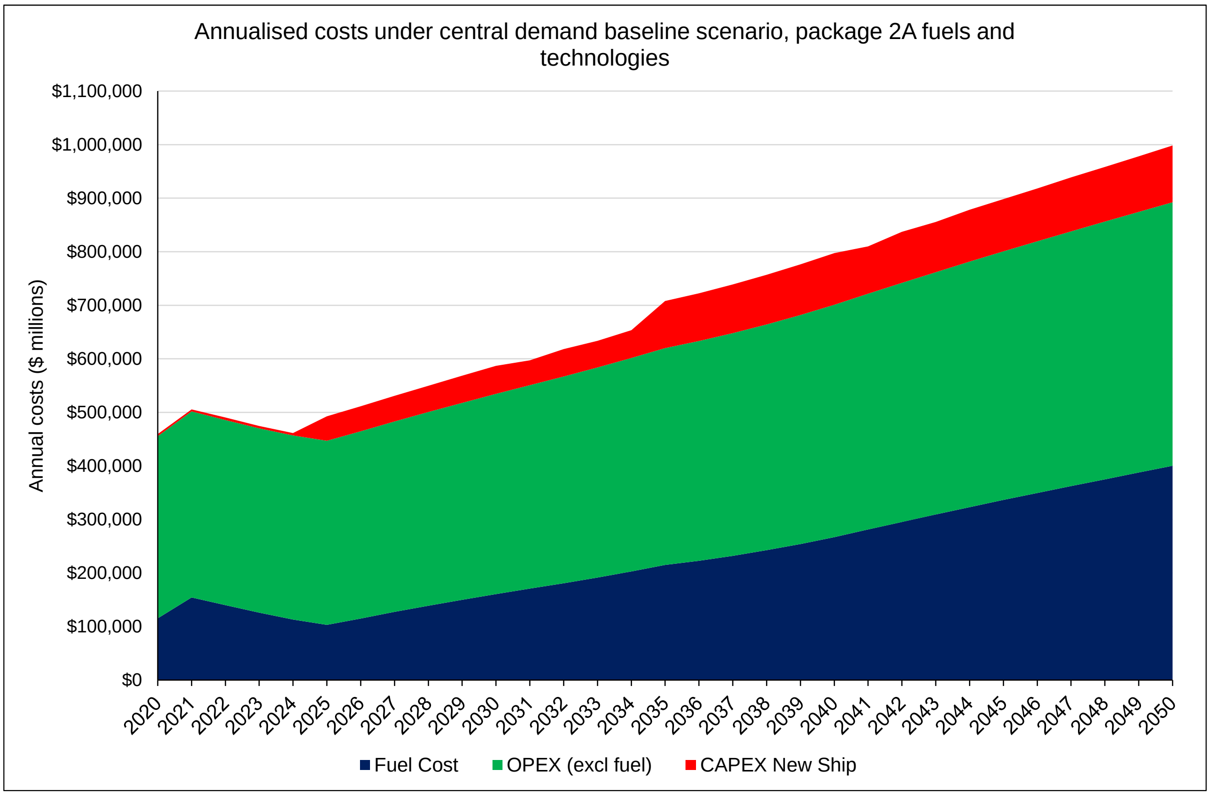
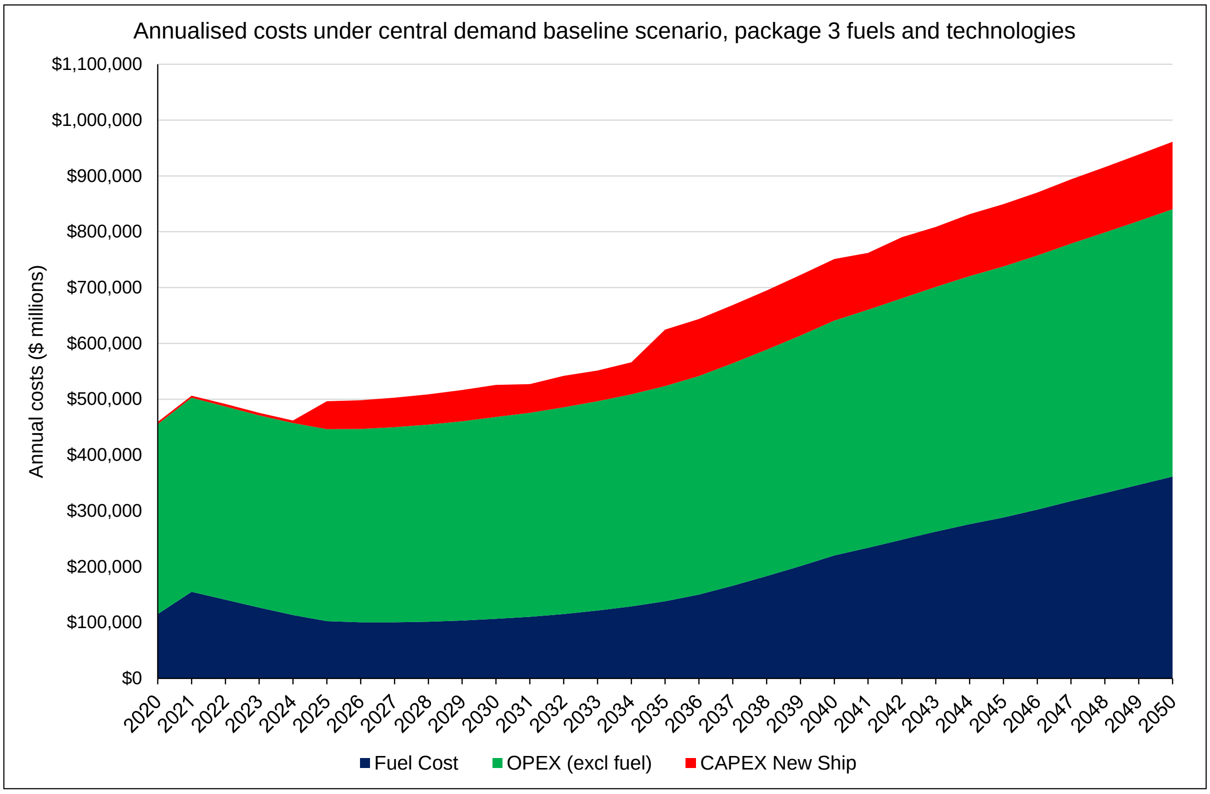


Figure 7-39: Annualised costs under Package 3 on the central demand baseline (repeat of Figure 7-22)



Under packages 2A and 3, the costs associated with technology are significantly higher than under Package 1A, reflecting the much higher use (and associated costs) of carbon capture technology under that package.

The changes in costs relative to the baseline are shown for the three packages in Figure 7-40 to Figure 7-42. For each package, the fuel costs are initially lower than under the baseline as the fuel efficiency technologies and operational measures have a greater impact than the demand growth, but increase to be the highest cost element by 2050.

Figure 7-40: Change in annualised costs relative to the central baseline for Package 1A

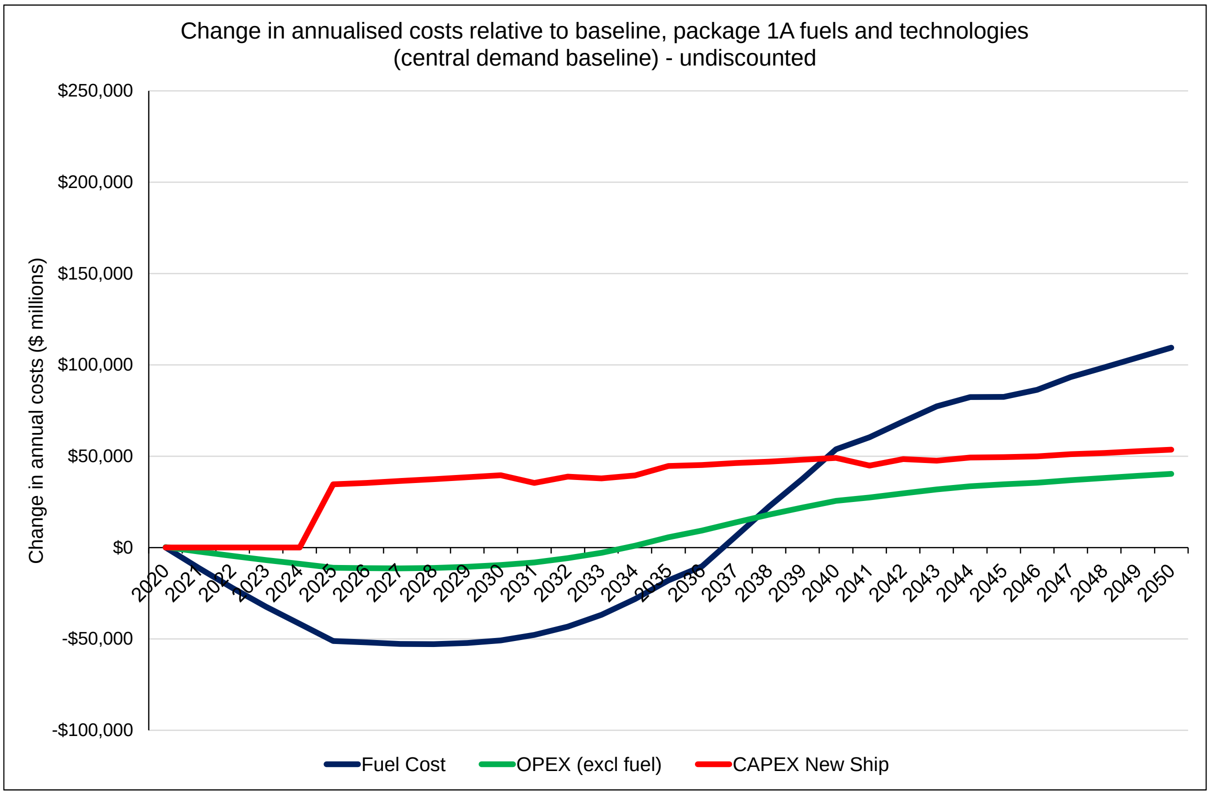


Figure 7-41: Change in annualised costs relative to the central baseline for Package 2A

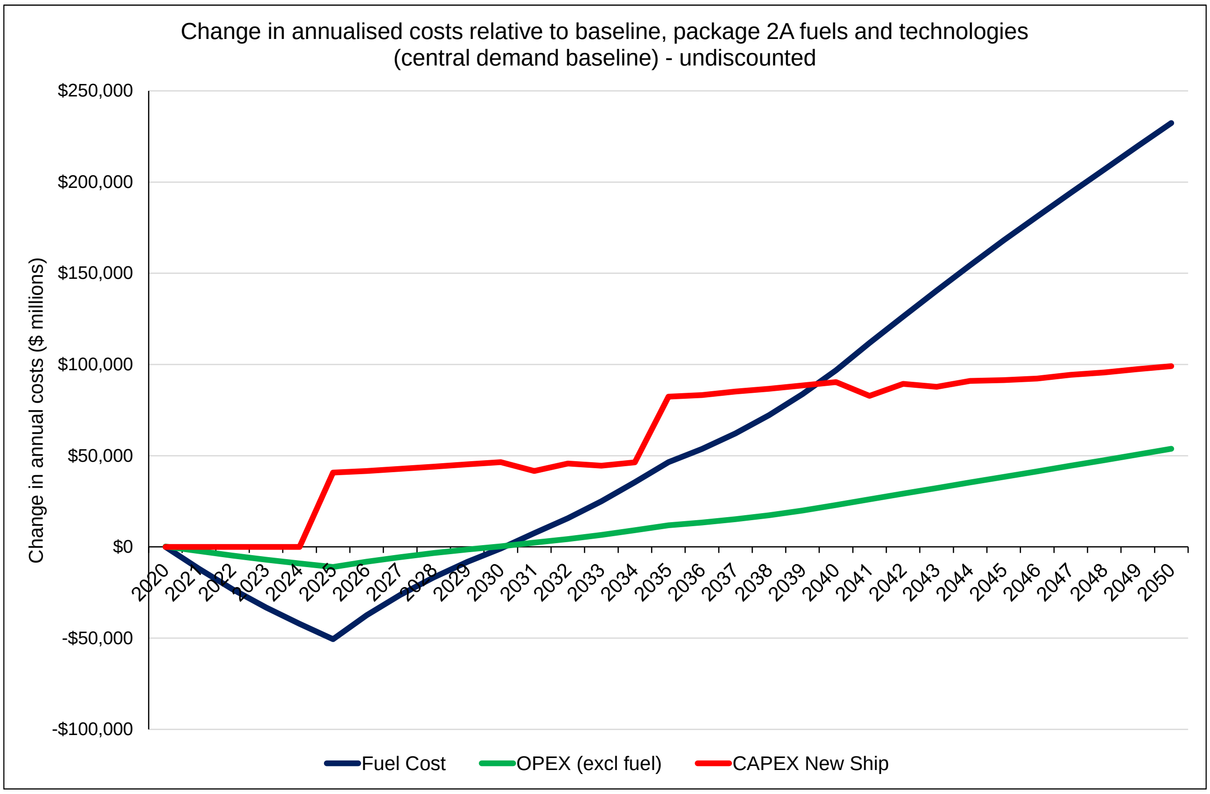
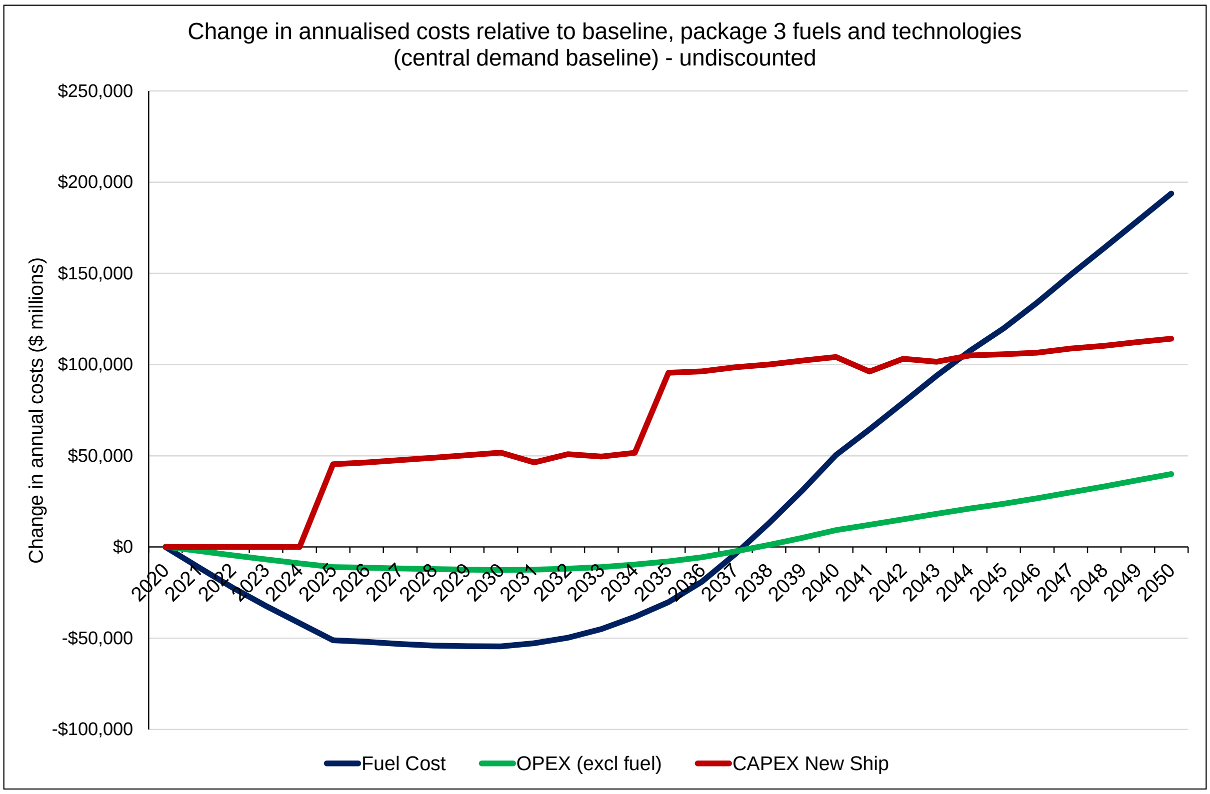
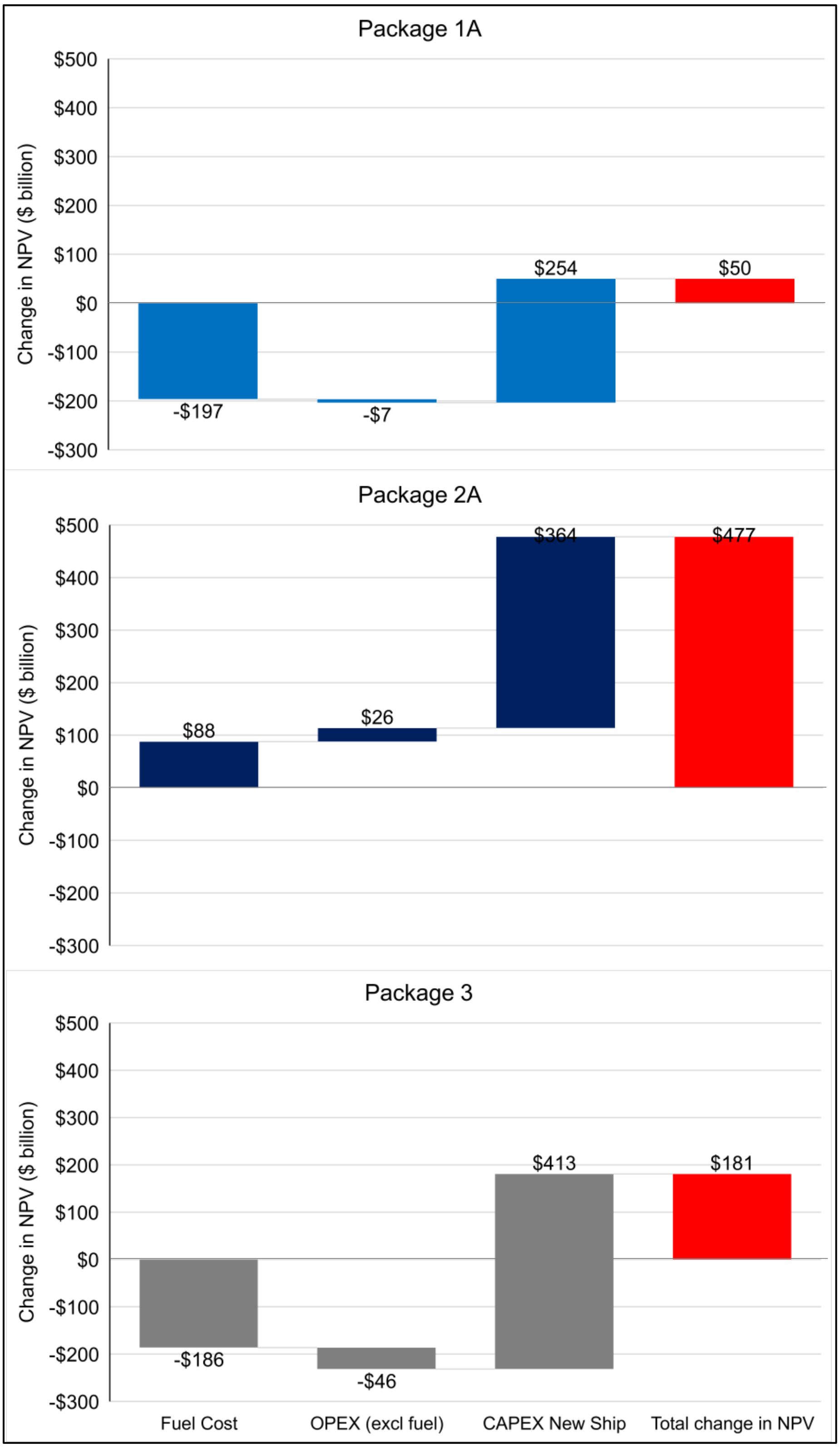


Figure 7-42: Change in annualised costs relative to the central baseline for Package 3 (repeat of Figure 7-25)



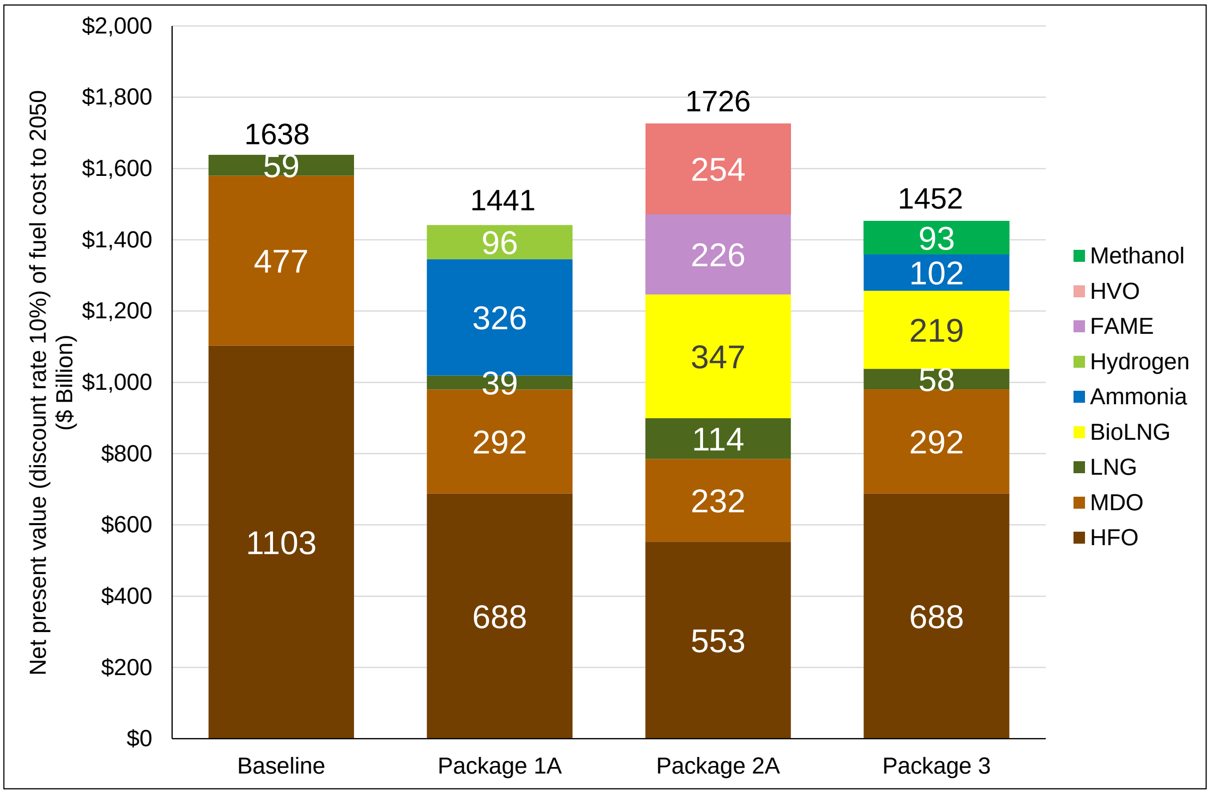
As expected from the inclusion of the additional vessel technologies, packages 1A and 2A show a significantly greater contribution of technology to the overall costs than packages 1 and 2 (Figure 7-23 and Figure 7-24). The overall impacts of the three packages on the NPV of costs to 2050, again split by fuel, OPEX and CAPEX, are shown in Figure 7-43.

Figure 7-43: Change in NPV at 10% discount rate by fuel and sensitivity technology package (packages 1A, 2A, 3) for the central demand scenario compared to the baseline



To provide more insight into the fuel cost element of the total costs (as shown in Figure 7-43), the split of the fuel costs amongst the different fuel types for the baseline and the three sensitivity packages are shown in Figure 7-44 (note that the fuel costs are not discounted for this figure, unlike those in Figure 7-43).

Figure 7-44: Net present value of aggregated fuel costs from 2020 to 2050 per sensitivity package by fuel type for central demand scenario



Compared to the results from the main analysis (Figure 7-27), the increased use of vessel technologies under packages 1A and 2A results in a reduced fuel consumption in later years and hence a reduced cost associated with the alternative fuels. As a result, the conventional fuels (HFO, MDO and LNG) form a slightly greater proportion of the total fuel cost from 2020 to 2050 (and hence the NPV of those costs) than for packages 1 and 2 (as shown in Figure 7-27). Package 1A and package 3 have the same costs associated with the consumption of conventional fuels HFO and MDO. These two packages share the same technology assumptions and same phase-out of new vessels using conventional fuels, although they have different assumptions for the alternative fuels that replace them. In contrast, package 2A has an increased take-up of new vessels using LNG and BioLNG before 2030, leading to a reduction in the use of HFO and MDO.

7.5.3 Cost-effectiveness calculations

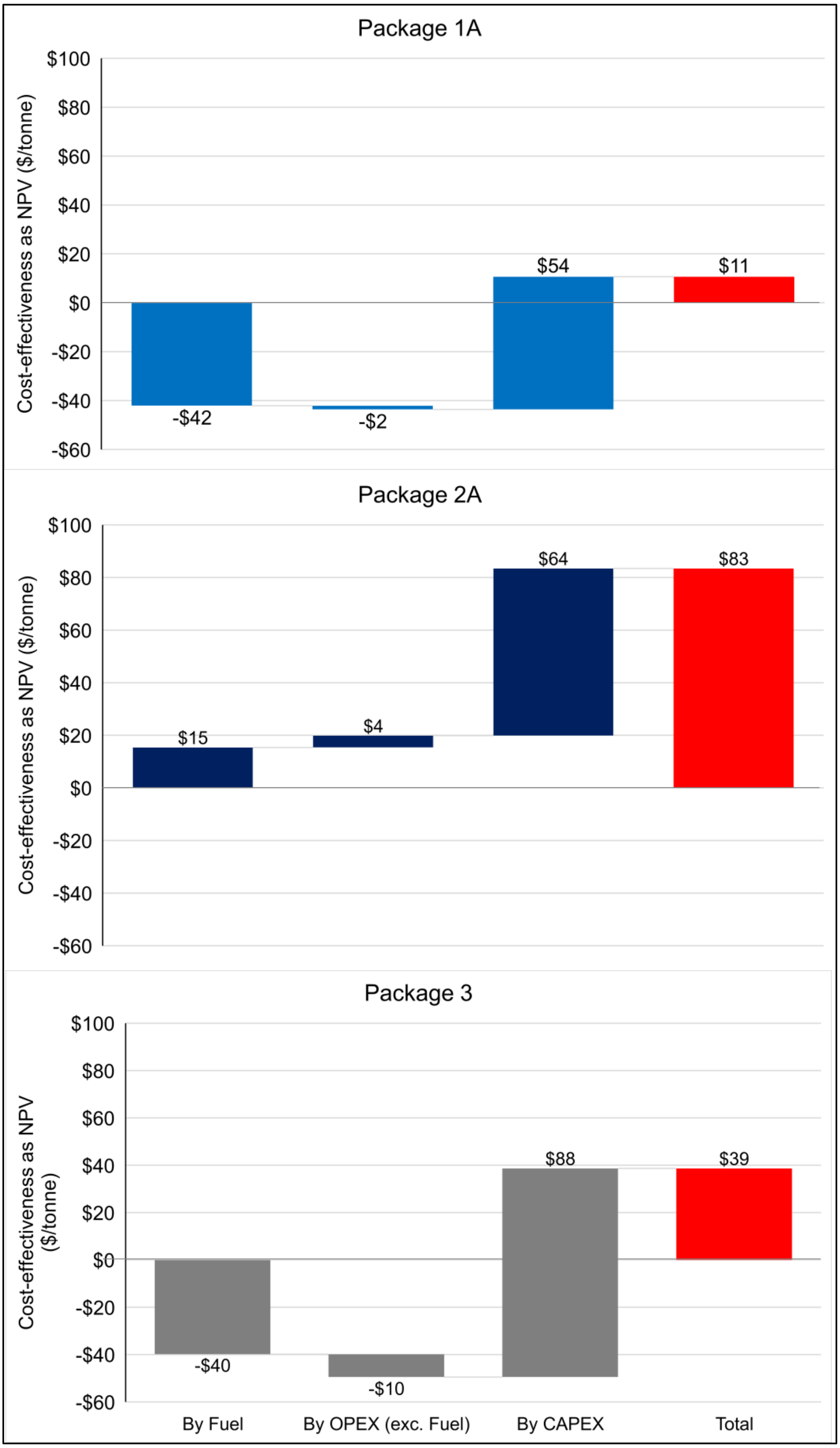
The cost-effectiveness of the packages has been calculated using the same approach as for the main analysis. Table 7-6 summarises the NPV of the cost-effectiveness to 2050 of all five packages (including packages 1, 2 and 3 from the main analysis as well as packages 1A and 2A from this sensitivity analysis) under both 10% and 5% discount rates.

Table 7-13: Net present value of cost-effectiveness of the different packages to 2050 ($/tonne$CO_2$e)

	10% discount rate	5% discount rate
Package 1	$73	$120
Package 1A	$11	$47
Package 2	$113	$149
Package 2A	$83	$120
Package 3	$39	$83

Package 2A can be seen to have slightly lower cost per tonne CO_2e abated than Package 2, but still greater than Package 3. In contrast, Package 1A can be seen to have much reduced cost per tonne values compared to Package 1, to such an extent that they are significantly lower than Package 3. As illustrated in Figure 7-45, this is largely due to a significant negative contribution to the cost per tonne from the fuel. This arises due to the significant reduction in fuel demand (due to the use of the additional vessel energy efficiency technologies) combined with a moderate increase in fuel price relative to the baseline (primarily due to ammonia fuel).

Figure 7-45: Cost-effectiveness of each package (as $/tonne CO_2 WTW abated, both 10% discount rate), central demand scenario



8 Risks and investment requirements

This section discusses the key risks to the successful achievement of the decarbonisation potential of the fuel and technology packages, including the associated investments required

Key points:

- **Risks and barriers**: Barriers include the scale-up of the production and supply of alternative fuels, current inadequate infrastructure, need for engine technology scale up, uncertainty leading to investment impasse, the lack of standards for the sustainability of alternative fuels production and the lack of regulation to drive the transition to alternative fuels. There also specific barriers facing different fuels and different technologies that will need to be overcome.
- **Investment requirements:** Investments in fuel production infrastructure are highest for package 1 which is driven by ammonia and hydrogen plant costs and specifically by green ammonia and green hydrogen plant costs post 2035. Both Package 2 and Package 3 show less than half that amount of investment needed to meet the fuel requirements in that package.

8.1 Barriers to successful deployment

The results of the modelling in this study – as well as several other contemporary literature sources – suggest it is technologically feasible, though challenging, to decarbonise the global shipping sector to the ambition level of the IMO. However, despite this technical feasibility we have not so far seen rapid decarbonisation at the rate and scale required. Hence, barriers to decarbonising the shipping sector remain. These will need to be addressed and overcome to reach the IMO 2050 ambition.

8.1.1 Overarching barriers

8.1.1.1 Availability of alternative fuels

For all three packages, the production and supply of alternative fuels will need to be substantially increased. Whilst the fuel types requiring increased supply varies by package, this supply barrier applies to all packages. Increasing the supply will require a large increase in alternative fuel production facilities or conversion of traditional refineries, appropriately located across world's key ports and trade routes to supply port refuelling facilities, to adequately supply the world's global fleet. A threshold level of demand is required to make this economic.

8.1.1.2 Fuel bunkering infrastructure

With the exception of 'drop-in' fuels (such as FAME and HVO that can be used in conventional two stroke diesel engines and BioLNG that can be used as a drop-in replacement for LNG), associated bunkering infrastructure and port refuelling facilities will need to be scaled up rapidly. An additional challenge may be that the required bunkering locations are currently not necessarily where alternative fuels are/will be produced. In Europe bunkering facilities for ammonia are closer to production facilities than in other regions. This may require additional transport of fuels, although the impact of this on the industry (e.g. costs) may not be significant. (Note that bunkering infrastructure costs are assumed to be recovered through increased fuel prices in the modelling presented in this report).

8.1.1.3 Engine technology

Although engine technology to accommodate alternative fuels such as hydrogen and ammonia is already under development by engine manufacturers, such as MAN and Wärtsilä, this will need to be scaled up once demonstrated. A threshold level of expected demand for vessels equipped with these types of engine is required to make this economic. This then has an interaction with the demand required for fuel suppliers to invest in production facilities (as noted in Section 8.1.1.1).

8.1.1.4 Investment impasse and lack of certainty

For global-scale investments to be made, a higher degree of certainty and a threshold level of demand is required to make large scale manufacture economic. Currently, this is not the case. There is an impasse, as customers and charterers are not willing to pay or co-fund lower emission solutions and there is lack of clarity on how the preferred fuel(s) will be chosen to allow for scale (Shell, 2020). An increased uptake of drop-in fuels, as analysed under Package 2, does provide a short-term way around this impasse. Bunkering providers and ship operators are waiting on each other to make the initial investments in net-zero ships and infrastructure, in turn preventing the growth in supply of fuels that will be eventually unavoidable. This impasse is exacerbated by the long lifespans that vessels have, requiring significant time for fleet turnover.

In general, there is a lack of certainty regarding how the sector will reach the IMO ambition across the maritime supply chain (e.g. fuels/technologies/offsetting). The technology and fuel neutral approach of the IMO regulation is designed to ensure a level playing field for the sector, however the result is that it does not increase certainty. It does not indicate *how* the sector will move towards decarbonisation. Further policies will be required to provide direction towards meeting the IMO 2050 ambition, but these policies will need (and are expected) to remain technology-neutral.

8.1.1.5 Price differential

The price differential between traditional marine fuels and alternative fuels remains a large barrier to successful deployment of all 3 packages. HFO is difficult to match in terms of commercial attractiveness and existing scale (Shell, 2020). Whilst decreasing the gap between alternative fuels and HFO requires additional financing and investments in research and scale-up, financiers do not have the risk appetite to fund unproven technologies or specific alternative fuels. Investors have no incentives to invest in companies with lower emission solutions as there is a lack of certainty around which solutions will be frontrunners. Stakeholders interviewed for this study have indicated that regulatory intervention or guidance, particularly regarding the adoption of alternative fuels, may be needed to achieve decarbonisation in line with the IMO ambition. The price differential is expected to be minimised with policy mechanisms and regulatory frameworks. Options include a bunker tax on fossil fuels or a levy on fuel carbon content, low carbon fuel standards, thresholds for renewable fuel content or a “cap and trade” scheme, but opinions about the most effective option vary.

8.1.1.6 Split incentives

For many of the technologies in the packages, because of the structure of the shipping sector, there is also a greater susceptibility to the “split incentive” problem (Rehmatulla et al, 2015). To date, some of the carbon reduction technologies that are cost-effective are not implemented to the scale expected. Split incentives need to be overcome. Furthermore, because the global fleet is owned by many small companies and multiple stakeholders are involved in ship operations, this can complicate decision-making around new technologies (Shell, 2020). Nevertheless, according to an interview with the Norwegian Shipowners Association, some charterers are willing to pay higher rates for more fuel efficient ships (Agnolucci, 2014). As for the container sector, a poll of twenty brokers showed that fuel efficiency was the single most important factor for the hiring of vessels on time charters, and that more efficient vessels obtain rate premiums compared to standard vessels (Agnolucci, 2014).

8.1.1.7 Sustainability of fuels and lack of robust certification

The final major barrier that needs to be overcome is the certainty of the sustainability and the way the fuel has been produced. Fuels that can be produced from fossil fuels or renewable energy (ammonia, hydrogen, methanol), will need to have reliable certification schemes to provide assurance that the chemically-identical fuel is from green sources. Biofuel (HVO, FAME) carbon reduction also hinges on feedstock sustainability, and this presents a major challenge as it is difficult to measure and track the indirect impacts of biofuels (such as indirect land use change). Therefore, there is a need for standards for the different fuels and pathways, including sustainability criteria, to be adopted by the IMO to provide guidance for organisations investing in alternative fuel production. Furthermore, there will be a need for a rigorous certification system in order to provide guidance to purchasers and to avoid rogue trading (e.g. grey ammonia labelled as green ammonia).

8.1.2 Package barriers

Beyond the overarching barriers, each package has more specific barriers associated with their fuel/energy carrier mix and these are summarised in Table 8-1. For package 1, the use of battery electric vessels will entail specific challenges, as lithium ion batteries require large quantities of mined material, which have both environmental and human rights considerations. Depleted lithium-ion cells can be harmful to the environment if not correctly recycled. As for ammonia in package 1 and package 3 this may in the longer-term be used in low temperature fuel cells. However, the necessary solid oxide fuel cell technology is not yet commercially available for marine application. For packages 2 and 3 the use of LNG requires that engines are developed to reduce methane slip (e.g. high pressure diesel cycle engines). The use of ammonia, hydrogen and methanol in packages 1 and 3 also requires the development of engines to operate on these alternative fuels. For package 2, the biofuels included (FAME, HVO) not only face barriers to deployment regarding sustainability of feedstock supply, but as high quality ‘drop-in’ fuels, will face competition for feedstocks for use in other difficult to decarbonise sectors, such as aviation, if feedstock availability (sustainable biomass) becomes a problem.

Table 8-1 Barriers to deployment mapped on to packages.

Fuel	Fuel related barriers	Applies to package:		
		1	2	3
LNG	Methane slip & lifecycle emissions, suitable bunkering infrastructure, cost	X	X	X
BioLNG	Need for BioLNG bunkering infrastructure, seasonal changes in waste quantities impacting availability		X	X
Ammonia	Production and supply, price parity, technology development of fuel cells, suitable bunkering infrastructure, cost, supply network infrastructure	X		X
Hydrogen	Green hydrogen production and supply, cost, and price parity, suitable bunkering infrastructure, cost, supply network infrastructure	X		
Methanol	Green methanol production and supply, suitable bunkering infrastructure			X
FAME	Ensuring sustainability of feedstocks, competition with other transport sectors		X	
HVO	Ensuring sustainability of feedstocks, competition with other transport sectors		X	
Battery electric	Limited range, cost, weight/size, end-of-life disposal	X		

Each package also has barriers associated with their technological and operational measures, and these are summarised in Table 8-2.

One barrier facing slow-steaming is that it has little further GHG reduction potential to be unlocked especially for the existing fleet as this is already widely practised. Furthermore, slow steaming leads to longer journey times, thus needing more ships to meet the same demand. When used as an alternative to “*rush and wait*”, slow steaming brings significant advantages and does not really introduce additional costs (except for investment in voyage management systems to make sure the ship arrives at the port at just the right time). However, if slow steaming reduces goods being transported to a point that means demand is not being met, there will be a need to invest in new ships. There are also some limitations with slow-steaming as some products need to be delivered quickly.

For the vessel technologies and propulsion technologies, the fact there is little remaining GHG reduction potential to still be harnessed presents a barrier. The packages also face the barrier of power variability because power assistance measures such as harnessing wind (e.g. Flettner rotors) and solar energy heavily depend on conditions and have significant deck space requirements. Package 1 faces the challenge of high capital investment of waste heat recovery (WHR), whilst the lack of current production-ready carbon capture systems is a challenge facing package 3.

Table 8-2 Technology related barriers to deployment

Technology category	Related barriers	Applies to package:		
		1	2	3
Vessel technology	Low GHG reduction potential to still be harnessed	X	X	X
Power assistance	Power variability depending on conditions, deck space requirements	X	X	X
Engine technologies	High capital investment of WHR	X		
Carbon capture	Not yet well developed, barriers to scaling up			X
Propulsion technologies	Low GHG reduction potential to still be harnessed	X	X	X
Voyage optimisation	Co-ordination/ information challenges regarding port logistics, legal issues around automation	X	X	X

8.2 Investment requirements for alternative fuels supply

In sections 6.2.5 and 6.2.6 the fuel production infrastructure capital costs and operating costs were described and referenced. This section presents the results of calculations using those assumptions to derive the investments needed to deliver the projected demand, taking into consideration the plant capacities[68] (Table 6-7). The investment and operating costs analyses for fuel production infrastructure are shown in the following total costs tables for a range of discount rates. The results are presented for the range of discount rates as the cost of capital in this new industry may vary due to green financing support; in addition the timeframe through to 2050 makes predictions on discount rates difficult.

Table 8-3: NPV (2020-2050) of total investment and operating costs at 10% discount rate

bn US $	Baseline	Package 1	Package 2	Package 3
Low demand	170	486	221	235
Mid demand	203	639	269	307
High demand	225	762	310	368

[68] This section focuses on the fuel production infrastructure. It does not include any increased investment in fuel transport or bunkering infrastructure.

Table 8-4: NPV (2020-2050) of total investment costs at 5% discount rate

bn US $	Baseline	Package 1	Package 2	Package 3
Low demand	255	1021	399	497
Mid demand	316	1383	502	670
High demand	356	1677	588	810

In Table 8-5 the split between OPEX and CAPEX proportion is illustrated for the central demand scenario at a discount rate of 10%. The OPEX in package 2 is relatively high (at 18%), followed by the OPEX for package 3 which is due to high operating cost assumptions for BioLNG in these scenarios. All input assumptions on the operating costs are listed in Table 6-8.

Table 8-5: NPV of investment costs by new plant OPEX and CAPEX at 10 % discount rate for central demand scenario

bn US $	Baseline	Package 1	Package 2	Package 3
TOTAL	203	639	269	307
OPEX	10	61	47	36
OPEX %	5%	10%	18%	12%
CAPEX	193	579	222	271
CAPEX %	95%	90%	82%	88%

With the inputs assumptions under section 6.2 in mind, the total capacity (in PJ/year) of new plants needed to be built in order to meet the demand is shown in Table 8-6 to Table 8-8.

All packages show still an initial investment requirement for conventional fuels and increased refining capacity until new investment in that sector is entirely substituted by new fuels after 2035.

Package 1 is very much driven by ammonia and hydrogen investment, initially into grey ammonia and hydrogen production which eventually is substituted by green ammonia and hydrogen plants in later years. For blue fuel production, there may be opportunities to reduce the investment costs by upgrading existing (grey fuel) production facilities with the relevant carbon capture and storage systems; similarly, there may be scope to reduce the costs for green fuel plants by replacing the reforming systems by electrolysis units. These potential reductions are not reflected in the costs calculations presented in this section, and therefore the costs should be considered upper bounds.

Table 8-6: New plant capacity to be installed to meet demand for fuel and technology package 1 in central demand scenario (total plant capacity in PJ per year)

	HFO	MDO	LNG	Ammonia (Grey)	Ammonia (Blue)	Ammonia (Green)	Hydrogen (Grey)	Hydrogen (Blue)	Hydrogen (Green)
2021-2025	1,415	1,002	960	-	-	-	-	-	-
2026-2030	2,359	1,337	-	656	-	-	47	-	-
2031-2035	1,238	167	-	75	2,343	-	9	1,484	-
2036-2040	-	-	-	-	423	4,332	-	250	2,610
2041-2045	-	-	-	-	-	1,474	-	-	705
2046-2050	-	167	-	-	-	1,179	-	-	469

In total, this package requires additional capacity of over 10 EJ/year of ammonia production (grey, blue and green combined) and over 6 EJ/year of hydrogen production capacity to be installed by 2050.

Package 2 requires rapid and large investments into LNG and Bio LNG plants, as well as into HVO and FAME production capacities post-2025.

Table 8-7: New plant capacity to be installed to meet demand for fuel and technology package 2 in central demand scenario (total plant capacity in PJ per year)

	HFO	MDO	LNG	Bio LNG	FAME	HVO
2021-2025	885	668	1,920	350	-	-
2026-2030	59	501	1,440	408	1,343	1,342
2031-2035	1,179	167	960	315	802	814
2036-2040	-	-	480	301	233	220
2041-2045	-	-	-	3,032	1,902	1,914
2046-2050	-	-	-	3,390	1,110	1,122

By 2050, nearly 8 EJ/year of BioLNG capacity is required to be installed, in addition to almost 5 EJ/year of new LNG capacity.

Package 3 requires investments post 2025 into BioLNG plants as well as into grey methanol production which will be substituted with green methanol from 2035. Similar for ammonia, the pathways change from grey to blue to green in 2025, 2030 and 2035 respectively.

Table 8-8: New plant capacity to be installed to meet demand for fuel and technology package 3 in central demand scenario (total plant capacity in PJ per year)

	HFO	MDO	LNG	Bio LNG	Methanol (Grey)	Methanol (Green)	Ammonia (Grey)	Ammonia (Blue)	Ammonia (Green)
2021-2025	-	334	480	-	-	-	-	-	-
2026-2030	2,595	1,504	480	145	239	-	241	-	-
2031-2035	1,592	334	960	310	627	-	25	842	-
2036-2040	-	-	1,440	383	-	1,576	-	153	1,565
2041-2045	-	-	-	2,096	-	501	-	-	499
2046-2050	-	-	-	2,765	-	358	-	-	363

This package requires an investment into over 3 EJ/year each of methanol and ammonia production capacity (combining grey, blue and green as appropriate) by 2050. It also implies investment in almost 6 EJ/year of BioLNG production capacity in the same timeframe.

8.3 Investment requirements for maritime industry

The major investments that take place on the vessel themselves are reflected in technology package 3 where large amounts of various carbon saving technologies are applied and, to a lesser extent, in packages 1 and 2. The technology types are listed in Sections 4.2 to 4.8. The following table shows the average additional costs by type of vessel post 2025. For package 3, a further increase in capital costs for carbon capture roll out is estimated from 2035 onwards.

Table 8-9: Average additional CAPEX per vessel by category from 2025 (and 2035 in package 3) in $millions

	Large tankers and bulk carriers	Small and medium container ships	Large container ships	Other small, medium vessels
Package 1 from 2025	3,176	1,426	2,426	2,176
Package 2 from 2025	2,851	1,551	2,101	1,851
Package 3 2025-2034	21,466	14,736	17,613	18,588
Package 3 from 2035	34,800	28,070	30,948	31,923

Table 8-10 shows the aggregated investments into new ships necessary over the three decades to 2050 (values are presented undiscounted; the total NPV is presented at a discount rate of 10%). The CAPEX for new ships for package 3 is particularly high as a large number of expensive technologies are applied to the fleet.

Table 8-10: Capital costs of newly built ships by package for the central demand scenario

Year	Number of newly built ships	CAPEX new ships ($ billion)			
		Baseline	Package 1	Package 2	Package 3
2020-2030	23,894	53	89	85	344
2031-2040	21,370	56	120	113	852
2041-2050	20,884	62	132	124	1,126
Total	66,148	-	-	-	-
NPV (10%)		52	91	86	465

The results show that the investment proportion for the marine operators and ship building industry heavily depends on the future pathways. Should conventional fuels persist longer than expected, then package 3 still saves large amounts of CO_2 by dealing with the emissions on board of the ship. The cost figures take into account (see package definitions in section 5) the implementation of CC in new vessels starting in 2030 and reaching 100% of new vessels by 2040 and is reflected in the high capital costs for new ships.

8.4 Summary of investment and operating cost implications

Pulling together the different capital cost elements described in the report, Table 8-11 summarises the additional investments (compared to the baseline) required in the maritime and fuels supply industries (all discounted using a 10% discount rate), separating the costs for the different parts of the industry. As described earlier in the report, it would be expected that the increased costs for the fuel supply industry (both capital investment and operating costs), including those for ports for storing and transferring fuel to vessels, would be recovered through the increased fuel prices. Therefore, it would be inappropriate to sum the different cost elements in these tables, as that would double-count those costs

Table 8-11: Summary of capital investment implications of the different packages compared to the baseline (discounted at 10%)

Change in discounted capital costs from baseline ($ billions)	Vessel capital costs	*Alternative fuel production investment*	*Alternative fuel port infrastructure investment*
Package 1	+$39	*+$386*	*+$8.4*
Package 2	+$34	*+$29*	*$0.0*
Package 3	+$413	*+$79*	*+$0.2*

Similarly, Table 8-12 summarises the operating cost changes for the maritime and fuels supply industries.

Table 8-12: Summary of operating cost implications of the different packages compared to the baseline (discounted at 10%)

Change in discounted operating costs from baseline ($ billions)	Vessel fuel costs	Vessel operating costs (exc. Fuel)	*Fuel production operating costs*	*Ports fuel infrastructure operating costs*
Package 1	+$113	+$83	*+$51*	*+$79*
Package 2	+$364	+$91	*+$37*	*+$0.5*
Package 3	-$186	-$46	*+$26*	*+$0.7*

The investment costs in vessel fleets and in fuel production infrastructure are of similar magnitudes (though both vary significantly between packages), while those in the ports infrastructure are significantly lower. There are greater variations in the operating costs, with large positive changes for vessel operating costs under packages 1 and 2, but negative ones under package 3. The fuel production costs are of a similar magnitude for all three packages, while the ports infrastructure operating costs are significant for package 1, but much lower for packages 2 and 3.

For packages 1 and 3, the additional investment required in production infrastructure for alternative fuels exceeds the additional costs of fuel to the vessel operators (and hence the income received by the fuel companies). This significant increase in investments compared to the baseline reflects the need for additional infrastructure for the production of all the alternative fuels, while much of the required production of conventional fuels in the baseline uses the existing infrastructure, so the reduction in the investment in conventional fuel production infrastructure under the packages is comparatively smaller.

9 Implications for the fuel production industry

This section discusses the implications of the results of the analyses for the oil and gas industry.

Key points:

- The oil and gas industry has a role in reducing uncertainties in the alternative fuel choices for the future
- The oil and gas industry could support proof of concept demonstrations
- There is a need to invest in fuel production infrastructure to ensure that future demand for fuel supply can be met (for Packages 1 and 3)
- There is a need for a robust certification system for green fuels

There is a role for refiners and fuel suppliers in this transition. They could help overcome some of these barriers through the following:

1. Reducing uncertainties around the alternative fuel choices

As previously described, maritime industry stakeholders are seeking further clarity/certainty about their alternative fuel choices and are looking for leadership on the selection of the "best" alternative fuels from the myriad options available. Fuel suppliers could help overcome this barrier through providing what clarity they can, via technical studies, on fuel options and through robust long-term strategies. Identifying leading fuel candidates is helpful. Detailed investigations of different fuels and pathways have shown a range of emissions reductions (including some increases on a well-to-wake (WTW) basis), but further insight from a production viewpoint would be beneficial. The changing fuel market and IMO regulations present strategic opportunities for fuel suppliers and refiners in the next few years. Those able to identify and secure demand can create a competitive advantage (Mckinsey, 2019). Publishing robust long-term strategies that clearly state refiners' and fuel suppliers' roles in the shipping transition will be important for not only their own navigation of the energy transition, but also for other actors, by increasing the certainty surrounding future fuel supplies (Bain & Company, 2019). Refiners could harness opportunities to invest in storage capacity, in order to manage more diverse fuel supplies (Mckinsey, 2019). Fuel suppliers could also help overcome the barriers to decarbonisation by leading the way and being involved in co-ordinated industry commitments and working to increase the reach of existing initiatives – such as the Getting to Zero Coalition, the Clean Cargo Working Group and others – by consolidating objectives and strengthening the coordination of various concurrent workstreams. This will also serve to decrease uncertainty around fuel options. This can encourage shipping companies to set decarbonisation targets and make related investments through activist shareholding (Shell, 2020)

Case study: Shell – Decarbonisation Strategy

- A founding member of the **Getting to Zero coalition** and an active participant in the **First Movers group** within the Global Maritime Forum
- Working to establish a consortium to develop a fuel cell trial on a commercial deep-sea vessel, pulling in partners **from across the value chain**
- Announced one of the largest green hydrogen projects in Europe, the **NorthH2 project,** in February 2020, with its consortium partners, Gasunie and Groningen Seaports
    - Project envisages the construction of wind farms in the North Sea
    - First turbines could be ready in 2027 and will be used for **green hydrogen** production, **producing up to 800,000 tonnes per year by 2040.**

Source: (Shell, 2020)

2. Providing proof of concept and investing in R&D

Providing proof of concept that a vessel can operate on an alternative fuel and have a (pre-determined/pre-arranged) refuelling point for its return journey can be a catalyst for more rapid progression and transition to alternative fuels. Refiners and fuel suppliers could increase research and development (R&D) investments and get involved in initiatives in partnership with ship operators and port authorities to not only demonstrate the feasibility of providing forerunner zero/low carbon fuels, such as hydrogen/ammonia/methanol/biofuels/LNG, at ports, but also their scaling up. Partnerships could be intensified through joint R&D across not only shipping, but other harder-to-abate sectors and the refining industry. Co-operation across the entire industry is required to develop robust solutions. Running end-to-end green pilot projects involving customers, charterers, operators, owners and ports on specific routes and vessel types will also be important. Smaller initiatives that establish infrastructure for large scale pilots should be combined and pilot requirements and results (e.g. routes and types of cargo suited to specific types of fuel) shared across the whole maritime supply chain, to inform all actors. Through greater cross-sectoral collaboration, the energy sector could play a role in contributing to a larger pool of capital and expertise and increase the likelihood that production and transportation infrastructure will be available once future fuels are commercially viable (Shell, 2020).

Case study: BP and Ørsted – Lingen Green Hydrogen Partnership

- BP and Ørsted will collaborate on a **50 MW electrolyser in Germany** in the first stage of a green hydrogen partnership. This could scale up to **500 MW.**
- Electricity is expected to be supplied from an Ørsted offshore wind farm to power the electrolysers.
- The **initial 50 MW phase will produce 9,000 tonnes of green hydrogen per year, enough to displace 20 % of the refinery's existing fossil-fuel-derived hydrogen.**
- **Excess hydrogen produced at Lingen could become the feedstock for synthetic fuel production.**

Source: (GTM, 2020)

3. Accommodating the increased alternative fuel demand

Although the technological improvements identified in this report can provide substantial improvements in energy efficiency, the results of the analyses to date indicate that alternative fuels will still be required to achieve the IMO's ambition for 2050. To accommodate the increased demand for alternative fuels, refiners could pursue solutions by adopting new processes and capabilities, such as the direct hydrogenation of bio streams, carbon capture and eventually co-processing or waste streams (at the refinery), the development of low-emission fuels, and the production of green hydrogen for use as fuel (Bain & Company, 2019). Fuel suppliers, terminal operators and other stakeholders could strategically invest in growth of fuel production facilities in close geographic proximity to supply port refuelling facilities, and adequately supply the world's global fleet. The lowest cost renewable energy sources should be considered. Solar PV and onshore wind are currently the cheapest sources of new-build generation for at least two-thirds of the global population (BNEF, 2020), and the costs of renewables are projected to continue to decline in the 2020s (EnergyPost, 2020).

These locations should ideally mirror key shipping trading lanes to minimise additional requirements to transport fuel to the ports. Fuel production could be scaled up if refiners and suppliers establish long-term strategic partnerships with ports. Similarly, refiners and fuel suppliers could play a part in the scaling-up of secure bunkering infrastructure of alternative fuels by establishing strategic partnerships with bunkering companies in the largest ports. Demand for green fuels could be not only met by actions taken by refiners and fuel suppliers, but also scaled up through refiners and fuel suppliers drawing up charterers' and customers' commitments that include long-term contracts and green procurement criteria (Shell, 2020).

Case study: Eni energy company – refinery conversions

Working on developing technologies to convert conventional fossil-fuel refineries into bio-refineries to produce high-quality, cleaner fuels has also resulted in patented innovative solutions.

Porto Marghera refinery

- The **first conventional refinery in the world to be converted into a bio-refinery**.
- Since 2014, about **360,000 tonnes** of vegetable oil are treated and converted annually
- In 2019 Eni launched feasibility studies of a Waste to Fuel plant at Porto Marghera with a FORSU processing capacity until **150,000 tonnes per year**

Gela refinery

- Operational in August 2019 and replaces the preceding large petrochemical plant
- Can process up to **750,000 tonnes annually** of waste vegetable oil, frying oil, fats, algae and waste by-products to produce quality biofuel.
- Conversion has cost **€294 million**, in addition to an estimated €73 million of investment in preparatory work.

Source: (Eni, 2020)

4. Provide 'Green' certification and fuel sustainability information

As the demand for ship owners/operators to know the provenance of the fuels they are purchasing increases, fuel suppliers and refiners could facilitate this. Specifically, where there are various possible production routes for the same fuel, knowing and verifying the upstream GHG emissions of the fuel will be important for shippers who are seeking to offer carbon-free transport. The market will also need a rigorous certification system in order to avoid rogue trading of e.g. grey ammonia labelled as green ammonia. The possible actions from fuel suppliers and refiners is that they could support the establishment of a robust certification system. Collaborating the IMO and key stakeholders in the maritime supply chain to adequately develop, test and prepare monitoring systems before demand for "green" alternative fuels is widely used on the market. Refiners also need to educate their customers about the fuels specifications they intend to supply and the ports where such fuels will be available (S&P Global Platts, 2019). Such a certification system would in any case be necessary if future policy measures or regulations place scrutiny on the fuel carbon content / associated GHG emissions.

10 Implications for the global maritime industry

This section discusses the implications of the results of the analyses for the maritime industry.

Key points:

- Vessel designers and builders have a role in ensuring that the best fuel efficiency technologies are available on future ships, including carbon reduction technology, and that they are ready for alternatively fuelled ships.
- Vessel owners and operators should seek options for funding the acquisition of more fuel efficient vessels, and/or those using alternative fuels, to assist in greening the future fleet

The analysis has shown that significant reductions in emissions are feasible for the global maritime industry out to 2050, but that there will be considerable changes required to the vessels and fuels if that potential is to be realised.

10.1 Vessel designers/builders

For vessel designers and builders, there is a need to ensure that the vessels that they design and produce incorporate the best available technology for energy efficiency. (Although not resolving the identification of the preferred zero/low carbon fuel, the reduced energy demand of a more energy efficient ship is a de-risking strategy for future price fluctuations.) The most energy efficient ships will require the lowest amounts of any energy source. In particular, the analysis has shown that meeting the IMO ambition for 2050 will require a shift to alternative fuels as well as the use of best available technologies. There is still debate on which fuel, or combination of fuels, will be the "best" option going forwards, but vessel designers will need to be able to incorporate the relevant engines and, perhaps more significantly, fuel storage and systems, to be able to take advantage of the decarbonisation offered.

This study has identified that the future decarbonisation may be met with different fuel types being used for different applications. For example, using ammonia for deep-sea shipping, hydrogen for short-sea shipping and battery-electric for coastal shipping. Designers and builders should consider how these different fuels will affect the design of the different ship types going forwards.

Another potentially key technology is the use of on-board carbon capture technology in conjunction with carbon-containing fuels. Currently, this technology is in its infancy, with only initial trials being performed. In the longer term, this technology could take on a much greater significance for reducing emissions while retaining carbon-containing fuels. For example, the IMO regulation on fuel sulphur content allows operators to use either very low sulphur fuels or to use sulphur dioxide capture technology ("scrubbers") when using higher sulphur fuels. Although there is currently no regulation on CO_2 emissions from ships of a similar nature, carbon capture devices might allow operators to meet such a regulation while continuing to operate on carbon-containing fuels. There is also a need to develop the business model for the subsequent treatment of the captured CO_2 (transfer at ports, storage or subsequent re-use in synthetic fuel production, etc.). It will be important to monitor the development of this technology to ensure that it can be incorporated in new vessels if the demand arises and the technology is proven. The need to invest in R&D for carbon capture would be removed if an early switch to zero-carbon fuels is made.

The need to incorporate these technologies (and fuels options) into new ships will bring additional costs for the industry. However, there are also potential opportunities for vessel designers and builders who are able to offer such capabilities in their ships at an early stage.

10.2 Vessel owners/operators

For vessel owners and operators, there are clear implications of additional costs in investing in new technologies (and fuel options on their vessels). These additional costs could challenge investment decisions, with possible implications for fleet renewal. Following the Paris agreement on climate change, there have been moves in some countries and regions to ensure that banks provide finance for "green" projects on preferential terms[69]. These moves may ensure that vessel owners can access the funding they require to invest in vessels with new technologies in the future.

Vessel owners and operators (and designers and builders) should also be involved in the coordinated industry initiatives referred to in Section 9, to ensure that the whole industry can contribute to a consistent response to the need for decarbonisation.

Vessel owners could invest in R&D programmes to develop and demonstrate zero- and low-carbon technologies implemented on specific vessel types (particularly the large bulk carriers, container ships and tankers identified by this study as contributing most to global emissions) to confirm the transferability of the technologies to real-world applications. Sharing the results of these projects would also contribute to a wider uptake of key technologies in the medium term.

Although the initial investment in new vessels may be increased as a result of the inclusion of new technologies, the resulting improvements in efficiency will reduce total fuel consumption and hence costs; the precise implications for this will depend on the particular fuel types used and any increases in prices as the fuel is transitioned from a grey to blue or green variety. Vessel operators will need to be aware of the implications of any fuel changes on their operating costs and also on decisions on their route structure. Discussions will be necessary with bunkering ports to ensure that the fuel for the vessels that they invest in will be available at all ports that they are likely to visit (or need to refuel at).

Further, the uptake of alternative fuels will have significant implications for vessel operating costs; the transition to such fuels will only occur if they are competitive with conventional fuels or through regulatory intervention. Owners and operators could provide support for regulatory measures to reduce price differentials and ensure the competitiveness of alternative fuels (or to minimise the cost impacts of any regulation-enforced transition).

[69] https://www.libf.ac.uk/news-and-insights/news/detail/2020/02/17/sustainable-finance-and-the-latest-banking-regulations

11 Regional developments and opportunities

This section provides context to the results at a regional level. Key points:

- Europe's ambition to be climate neutral by 2050, the European Green Deal and potential shipping sector inclusion in the EU ETS will drive industry and investors toward emission reductions in the sector. Existing funding schemes are in place to support decarbonisation initiatives.
    - Key projects include: NorthH2 project in the Netherlands, Green ammonia plants in Spain, and a 2.1 billion EUR carbon capture project in Norway.
- In the Middle East, climate policies are not as well developed as in Europe. However, there is an increasing trend of state-owned industrial companies proactively investing in cleaner fuels. A blue hydrogen economy is under consideration. Dubai and other Emirates are heavily investing in Solar and Hydro Electric power generation.
    - Key projects include: NEOM city related projects (hydrogen, ammonia, fuel cells), and biofuel projects (Uniper Energy DMCC biofuels for shipping, HVO production in Fujairah)
- Asia's climate policies are increasing in number and ambition. China, Japan and Korea now have zero emission targets and plans for 2060 and 2050 respectively, Multi-donor initiatives promoting low emission technologies and fuels are already in place. Asia is also gearing up to the scale up of hydrogen.
- Key projects include: Green ammonia consortium driving strategy and R&D projects (inc. Shell, Mitsubishi and Kanshair), as well as fuel cell development (Toshiba ESS & NEDO). CCS piloting has also been announced by Mitsubishi and Kawasaki Kisen Kaisha.

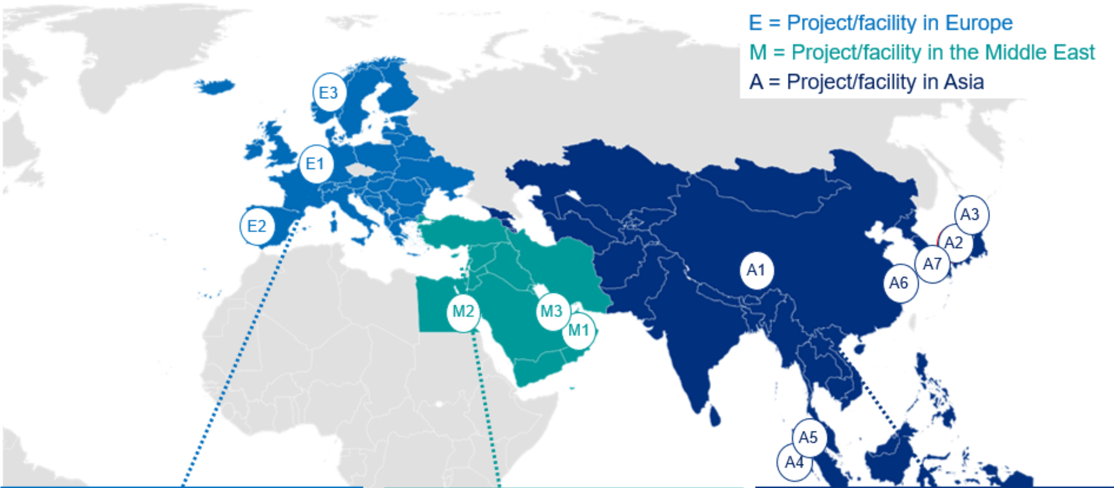
The IMO ambition to decarbonise the shipping sector will also present opportunities that will vary across major geographic regions. Different key regional policies, variation in technology access and project financing, along with business developments are summarised in Table 11-1.

Table 11-1 Regional developments related to decarbonisation of the shipping sector

Topic	Europe	Middle East	Asia
Policies as a driver	• The EU aims to be climate-neutral by 2050 – an economy with net-zero greenhouse gas emissions. • The European Green Deal will prove a key driver in ensuring demand for low carbon fuels/technology given the inclusion of international shipping in its targets and the promotion of a market for green maritime fuels. • This driver may be further increased if the shipping sector is included in the scope of the EU ETS and if the exemption of maritime fuel from tax is removed.	• Policy development and climate ambitions are not as well developed. • State-owned industrial companies are proactively investing in cleaner fuels • This region may become a net exporter of cleaner green electrofuels (e.g. ammonia and hydrogen)	• China and Japan now have zero emission targets and plans for 2060 and 2050 respectively, which will likely boost the supply of and demand for cleaner fuels (both electrofuels and biofuels). • India is yet to announce a target of achieving net zero emissions. • Fuels such as FAME and HVO may be required to minimise Scope 3 emissions from industry
Access to technology	• Green/ sustainable Finance (EU taxonomy and TCFD) are driving investors and industry toward emission reductions, including shipping • Several funding schemes are already in place to support decarbonisation initiatives (e.g. Project CHECK that focuses on long-distance shipping decarbonisation)	• Oil and gas heavy investment funds are being reinvested in renewables and alternative fuels • NEOM and other worldwide flagship large projects are attracting worldwide players (e.g. suppliers/ developers)	• Decarbonisation of the currently carbon intensive chemical sector, will likely impact the availability of alternative fuels and fuel options for ships • Multi donor initiatives (e.g. the World Bank and the Asian Development Bank) promoting and developing low emission technologies and fuels are already in place
Business	• Economies of scale are driving lower operating costs for green hydrogen and associated processes. Numerous hubs and large consortia are being created for this purpose • Converting existing infrastructure will likely provide a competitive advantage and save initial investment costs for traditional European industrial clusters	• In oil-rich countries, a blue hydrogen economy is being extensively studied as a viable means for transitioning. • The UAE and other Middle East countries are heavily investing in Solar and Hydro Electric power generation.	• Asia is also gearing up to the scale up of hydrogen. Japan was the first country to adopt a “Basic Hydrogen Strategy” targeting 300 kt of hydrogen production per annum. • This will likely be paired with hydrogen imports. Imports from Australia are attractive due to competitive prices and geographic location.

Emerging front-running alternative fuels will likely vary depending on region, and existing developments and pilot / scaled-up projects. Figure 11-1 captures some of these major projects and developments, mapping them by location.

Figure 11-1 Regional alternative fuel projects and developments



	Europe	Middle East	Asia
Hydrogen/ Ammonia/electric	E1 = H2 NorthH2 Eemshaven (NL) E2 = Green Ammonia: Fertiberia (2 sites) E3 = Batteries/ fuel cells for large ships: Eidesvik (NO)	M1 = H2: Oman's Sohar Port 3.5 GW M2 = H2 and Ammonia: Helios Green Fuels (4GW) Neom (S. Arabia), NEOM by 2025 M3 = Fuel Cell development on NEOM city projects	A1 = H2: Beijing Jingneng Inner Mongolia (5GW): 500 kt/y H2 A2 = Green Ammonia Consortium (Japan) leads strategy and R&D projects (Kanshai, Shell, Mitsubishi) A3 = Fuel Cells: Toshiba ESS & NEDO
Bio-LNG/ FAME/ HVO	• Legislation limits first generation biofuels (RED II) ~7% FAME. • More than 250 biofuel sites and 23,500 Ml /y • HVO: 3 billion lit/y (FR, IT, NL, ES) • Biogas:17k plants delivered 188 TJ; world leader for vehicle fuel	M3 = Uniper Energy DMCC (UED) work on carbon neutral fuels will provide maritime biofuels in Fujairah M3 = HVO: 400 kt/y UAE Fujairah Petrixo	A4 = Apical group with 5 vegetable oil refineries 7 Million t/y Indonesia A5 = Neste HVO production of 1000 kt/y in Singapore A6 = China is building floating storage and regasification units (FSRU)
Conventional/ Methanol/ CCS	E3 = Norwegian NOx Fund reducing emissions from ships customising industrial abatment devices (SCR, etc). A €2.1bn carbon-capture government proposed project has been approved by the state aid regulator • CCU benefits (use as feedstock) are catalysing new investments	• Saudi Arabia is in favour of promoting "circular carbon economy". • Uncertain impact of world climate policies (lower demand) on conventional fuel prices • Uncertain impact of clean finance initiative on investments for conventional fuels	A7 = Mitsubishi and Japan's Kawasaki Kisen Kaisha have announced CCS piloting for ships • Decarbonisation of the chemical sector (China/ Japan policies) will likely require CCS

12 Conclusions and recommendations

Meeting the IMO's 2050 decarbonisation ambition will need significant change in the shipping industry

This study was commissioned by the Oil and Gas Climate Initiative (OGCI) and Concawe, to investigate the "Technological, Operational and Energy Pathways for Maritime Transport to Reduce Emissions Towards 2050". The context for this study is the International Maritime Organization's level of ambition to reduce the total GHG emissions from international shipping by at least 50% in 2050 relative to 2008 levels, as well as reducing the carbon intensity of international shipping by at least 40% by 2030 and 70% by 2050 (again compared to a 2008 base year)[70].

The IMO's fourth greenhouse gas study, published in 2020, indicates that significant progress has been made, with global emissions in 2018 being almost the same as those in 2008. However, their future projections[71] of emissions from the sector in 2050, of between 90% and 130% of 2008 levels, miss the 2050 ambition by a considerable margin. To achieve the IMO ambition will require the introduction and large scale deployment of new technologies and/or alternative low-carbon fuels across international shipping.

Traditionally, demand for maritime transport is well correlated to global gross domestic product. Although projections for the future development show changes in the nature of goods transported – largely due to decarbonisation efforts in other sectors leading to a reduction in demand for transporting oil and coal, but a commensurate increase in demand for transporting raw materials and products – the majority continue to show strong growth in demand. The demand projections in the IMO's fourth greenhouse gas study show demand growth of 58% to 153% by 2050, relative to 2018, depending on the scenario.

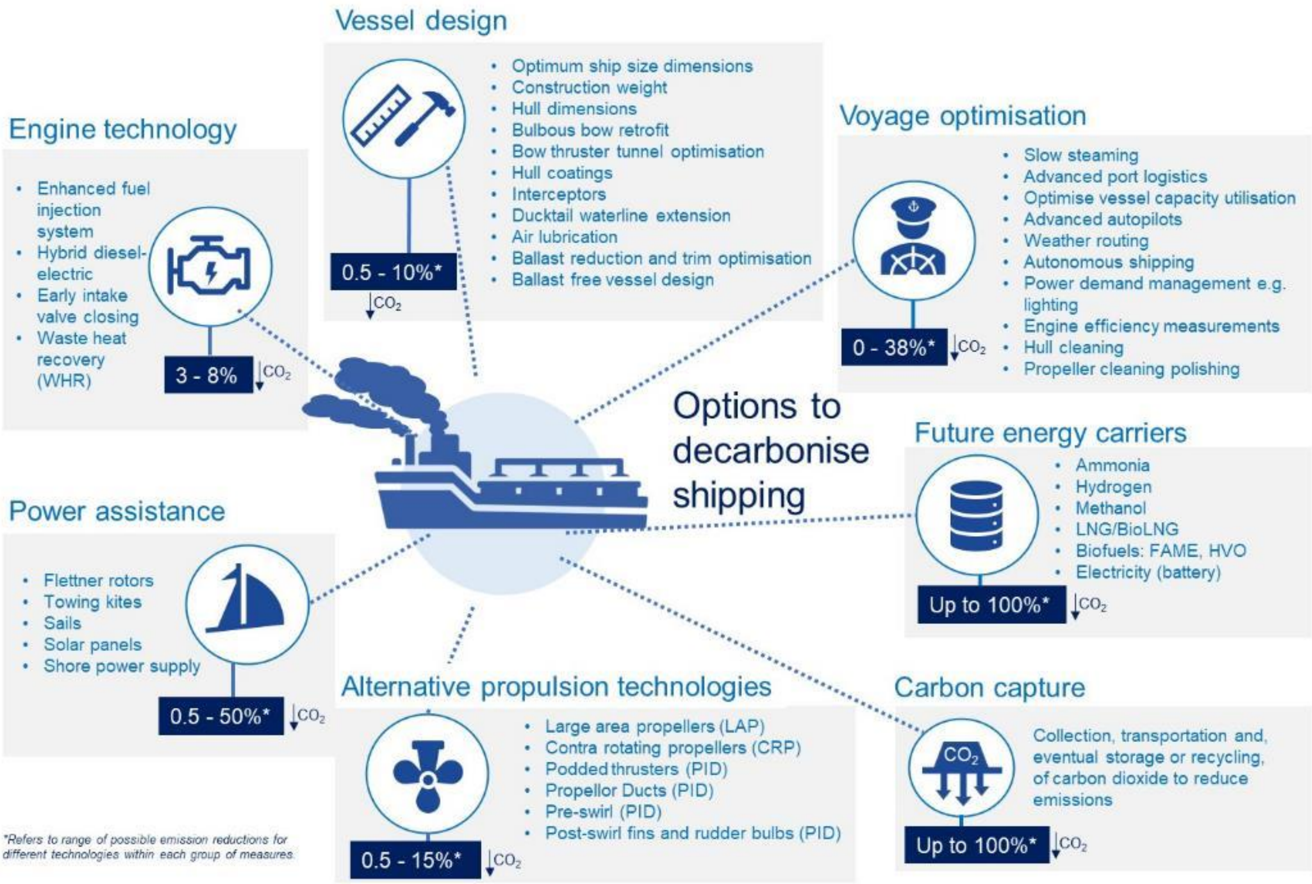
Historically, emissions of greenhouse gases from the maritime sector have been dominated by carbon dioxide (CO_2), with three vessel categories (bulk carriers, container ships and tankers) contributing the majority. In recent years, emissions of methane have increased strongly as more vessels using liquefied natural gas (LNG) as fuel have entered service. Whilst currently still small, these growing emissions of methane would become problematic without the ramp-up of technologies to better control the upstream and in-use methane releases.

Fuels, technologies and operational measures for decarbonising shipping have been selected into three 'packages' depicting possible pathways to reaching the IMO ambition

The study reviewed available literature, and interviewed multiple stakeholders, to identify the technologies and alternative fuels that are available to decarbonise international shipping. The different technologies and fuels are shown in the following figure.

[70] It should be noted that the IMO has started to discuss potential tightening of the ambition level, including a possible revision of the ambition in 2023.

[71] Projections without additional GHG abatement technologies or fuels other than already agreed policies and measures. The projections are principally driven by demand scenarios consistent with achieving a global temperature increase of less than 2°C



Each of these technologies has been assessed for its applicability (ship categories), availability (entry-into-service dates), carbon reduction potential and cost (capital and operating).

The different alternative fuels and technology options were combined into three “fuels and technology” packages for subsequent analyses of their impacts. These packages were characterised and fuels and technologies assigned as:

	Package 1	Package 2	Package 3
	Early pursuit of zero-carbon fuels (hydrogen and ammonia), with some limited adoption of new technologies	Moderate uptake of interim and drop-in fuels (LNG, BioLNG, FAME and HVO)	Initial maximisation of vessel decarbonisation measures, with later transition to lower carbon fuels (LNG, BioLNG, methanol, ammonia)
Future energy carriers	• Ammonia • Hydrogen • Electricity (battery)	• LNG/BioLNG • Biofuels: FAME, HVO	• Ammonia • Methanol • LNG/BioLNG
Vessel design	• Form optimisation • Bulbous bow retrofit • Bow thruster tunnel optimisation • Hull coatings • Ballast reduction & trim optimisation	• Form optimisation • Bulbous bow retrofit • Bow thruster tunnel optimisation • Hull coatings • Ballast reduction and trim optimisation	• Form optimisation • Bulbous bow retrofit • Bow thruster tunnel optimisation • Hull coatings • Ballast reduction and trim optimisation • Interceptors • Construction weight • Air lubrication
Power assistance	• Flettner rotors • Sails	• Flettner rotors • Sails	• Flettner rotors • Sails • Towing kites • Solar power
Propulsion technologies	• Large area propellers • Pre-swirl	• Large area propellers • Contra-rotating propellers • Pre-swirl • Podded thrusters • Ducts	• Large area propellers • Contra-rotating propellers • Pre-swirl • Post-swirl • Podded thrusters • Ducts
Engine	• Waste heat recovery		• Carbon capture
Operational	• Speed reduction • Voyage planning & weather routing • Power demand mgmt • Efficiency measurements • Hull cleaning • Propeller cleaning	• Speed reduction • Voyage planning / weather routing • Power demand mgmt • Efficiency measurements • Hull cleaning • Propeller cleaning • Advanced port logistics • Capacity optimisation • Advanced autopilots	• Speed reduction • Voyage planning / weather routing • Power demand mgmt • Efficiency measurements • Hull cleaning • Propeller cleaning • Advanced port logistics • Capacity optimisation • Advanced autopilots

In addition to the packages shown above, a sensitivity analysis was performed in which the alternative fuels assumptions of packages 1 and 2 were combined with the advanced technology assumptions of package 3, forming packages 1A and 2A.

A new model was developed to estimate the impacts that these packages would have on the future fleet, operations, CO_2e emissions and costs

An entirely new bottom-up modelling methodology was developed to assess the impacts that these fuel and technology packages would have on the future fleet, operations, emissions and costs. The modelling methodology started from a definition of the present day fleet and used as input three baseline scenarios (low, central, high) of future demand out to 2050 selected from the IMO's fourth GHG study. The model calculates:

- The future development of the fleet (number of vessels by build year) under each of the baseline scenarios, using a fleet retirement and growth/replacement approach;
- The future development of fuel consumption and emissions under the baseline scenarios, using derived fuel consumption and emissions per unit work (tonne-mile);
- The impacts of the fuel and technology package assumptions on the future fleet efficiency and fuel used (for the different fuel types);
- The impacts of the different types of fuels used on the emissions;
- The impact of the changes in the fleet definition (including the new technologies) on the vessel prices and hence the capital costs;
- The impact of the changes in the fuel consumption on the operating costs.

The impacts on the capital and operating costs of the fuel production infrastructure were also calculated. Although they are not included in the overall cost calculations, as they would be expected to be amortised through the increased fuel prices, these impacts are of importance to the oil and gas industry, who would be critical in ensuring the availability of the alternative fuels to meet the future demand.

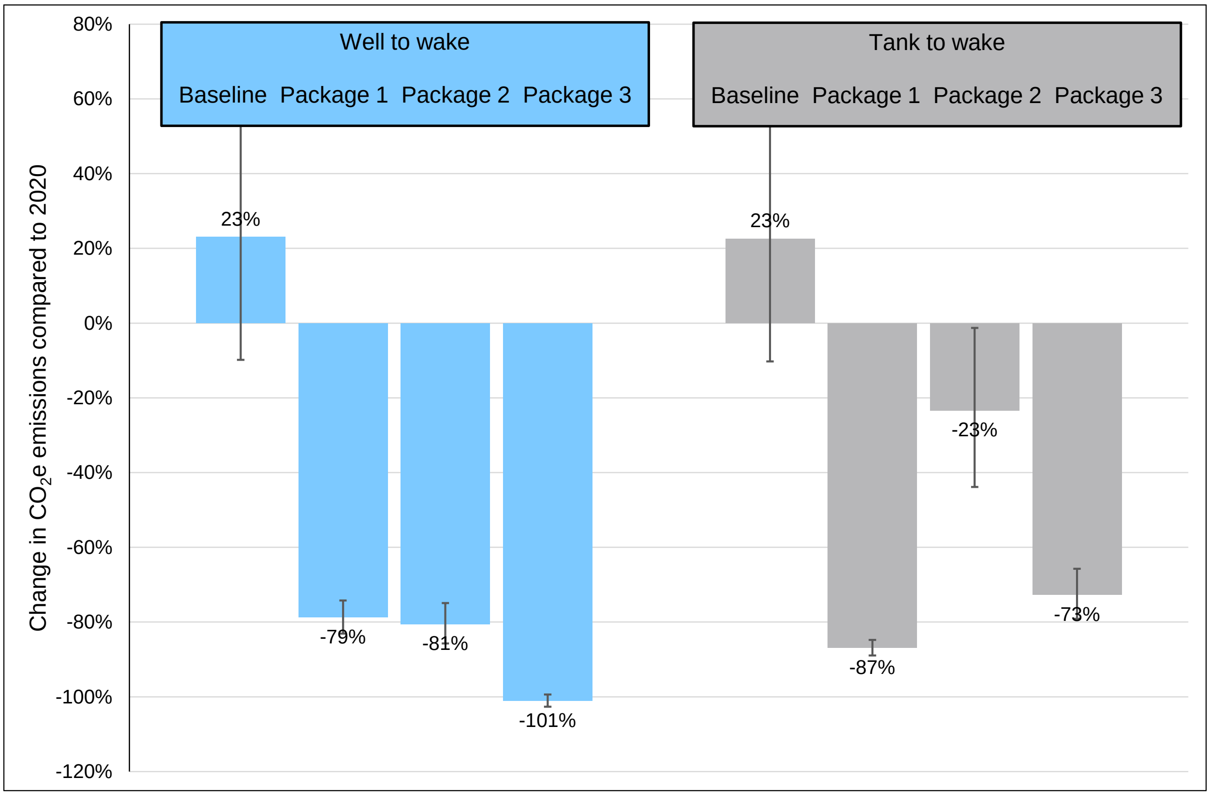
The IMO ambition is estimated to be met by all of packages 1, 2 and 3 when emissions are calculated on a well-to-wake basis; however only packages 1 and 3 would meet the ambition on a tank-to-wake basis

The results of the modelling showed that, by 2050, the emissions under the baseline scenario would be between 4% and 82% higher than in 2008, depending on the demand scenario assumed, compared to the IMO ambition of a 50% reduction (also relative to 2008). These increases in emissions were calculated on a “well-to-wake” (WTW) basis, as this represents the full impact on the global climate and is important when considering the impact of alternative fuels.

Under the three fuel and technology packages, these increases in emissions are replaced by significant decreases in most cases.

- Under package 1, emissions are reduced by over 70% relative to 2008 under all three demand scenarios, comfortably exceeding the IMO ambition.
- Under package 2, the reductions in emissions are very similar to those under package 1.
- Under package 3, the reductions in emissions relative to 2008 are close to or exceed 100% under all three demand scenarios. The package includes a transition to “green”, but carbon-containing, fuels and the use of on-board carbon capture technology. The combination leads to a net capture of CO_2 over the complete fuel production and combustion process, leading to a net negative emission and a reduction of over 100%. Carbon capture is therefore assumed to be available in time for this scale of deployment.

These changes in CO_2e emissions are shown in more detail for 2050, relative to 2020, in the following figure. Results are shown for both well-to-wake and tank-to-wake emissions, with the results for the central demand scenario shown as coloured bars and the range between the low and high demand scenarios represented by the error bars.



All three packages are estimated to exceed the IMO ambition on maritime decarbonisation by 2050, but this is only assured if the emissions are considered on a well-to-wake basis. The continued use of carbon containing alternative fuels under package 2 (as well as the associated methane slip of LNG/BioLNG; although, as noted in the report, the latest high-pressure diesel engines reduce methane slip to very low levels) still produces significant levels of emissions at the ship exhaust, even though they are offset by zero or negative emissions in the production ("well-to-tank") process. Consideration may need to be given to reformulating the IMO ambition on a well-to-wake basis to capture the decarbonisation benefits of such alternative fuels.

The reductions in CO_2e emissions shown above are accompanied by improvements in carbon intensity (CO_2e emissions per unit work, expressed as g/tonne-mile) of between 50% (Package 1) and 65% (Packages 2 and 3) in 2030, relative to 2008, and between 91% (Packages 1 and 2) and 101% (Package 3) in 2050. These changes in carbon intensity are relatively constant across the three demand scenarios.

The additional costs of implementing the packages are likely to be significant but vary between the packages

The overall costs of implementing the packages described above have been estimated. The total capital investment costs and operating costs to 2050 (both discounted to 2020 at a 10% discount rate) are presented in the next two tables, with the costs separated by the part of the industry affected.

Change in discounted capital costs from baseline ($ billions)	Vessel capital costs	*Alternative fuels production capital costs*	*Port capital costs for alternative fuel handling*
Package 1	+$39	*+$386*	*+$8.4*
Package 2	+$34	*+$29*	*$0.0*
Package 3	+$413	*+$79*	*+$0.2*

Change in discounted operating costs from baseline ($ billions)	Vessel fuel costs	Vessel operating costs (exc. fuel)	*Fuel production operating costs*	*Ports fuel infrastructure operating costs*
Package 1	+$113	+$83	*+$51*	*+$79*
Package 2	+$364	+$91	*+$37*	*+$0.5*
Package 3	-$186	-$46	*+$26*	*+$0.7*

In practice, the increased costs for the fuel supply industry (both capital investment and operating costs) would be expected to be recovered through increased fuel prices. Therefore, it would be inappropriate to sum the different cost elements in the cost tables above, as that would double-count those costs.

The capital investment costs in vessel fleets and fuel production infrastructure are of similar magnitudes (though both vary significantly between packages), while those for ports infrastructure are significantly lower. Under packages 1 and 3, the additional investment in fuel production infrastructure (compared to the baseline) significantly exceeds the increase in vessel fuel costs (and hence the increase in income for the fuel producers). This reflects the need for new production infrastructure for all alternative fuel production, while much of the conventional fuel required in the baseline will be produced by existing infrastructure. As a result, the saving in investment in conventional fuel production infrastructure (under the packages) is comparatively smaller.

There are greater variations in the operating costs, with large positive changes for vessel operating costs under packages 1 and 2, but negative changes under package 3. The increases in fuel production operating costs are of a similar magnitude for all three packages, while the ports infrastructure operating costs are significant for package 1, but much lower for packages 2 and 3.

The results of the emissions analyses indicate that the IMO ambition can be met (and, indeed, surpassed) with a high confidence under the assumptions described – that is to say that if the fuels are switched to as described, there is high confidence on the resulting emissions from using these fuels; there is however naturally a lower level of confidence in the calculated costs. In addition to the uncertainty inherent in the fuel price projections, the actual costs will be sensitive to decisions made in the future (for example, a high uptake of one alternative fuel type could lead to prices for different fuel types significantly different from those assumed for this study, which were based on projections assuming a more balanced marketplace)

Under the central scenario, the net present value of the accumulated total costs on the ships from 2020 to 2050 of packages 1 and 3 are estimated to be less than half the costs of package 2

The cost analyses show that the achievement of the emissions reductions will incur considerable costs. The total costs incurred are a combination of vessel capital costs, fuel costs and other vessel operating costs. These are calculated for each of the fuel and technology packages and the baseline; the impacts of the packages are then seen as the difference from the baseline. There are greater uncertainties associated with the projections of fuel costs than the other cost elements.

These costs are calculated as incurred over the full period from 2020 to 2050; net present values (NPV) are then calculated using assumed discount rates.

For a discount rate of 10%, the NPV of the total costs under the three packages, as compared to the baseline, under the central demand scenario vary between $181 billion and $489 billion:

Change in discounted costs from the baseline ($ billions)	Vessel capital costs	Fuel costs	Other operating costs	Total NPV
Package 1	+$39	+$113	+$83	+$235
Package 2	+$34	+$364	+$91	+$489
Package 3	+$413	-$186	-$46	+$181

Package 3 has the lowest total costs, and package 2 the highest. For packages 1 and 2, the total costs are dominated by the increased fuel costs (package 3 has reduced fuel costs compared to the baseline), while for package 3 vessel capital costs dominate (as expected as it has the highest level of additional vessel technologies applied of the three packages). The high fuel costs under package 2 are primarily related to the use of drop-in fuels, specifically BioLNG, FAME and HVO; this study identified higher projected fuel prices to 2050 for these fuels than other types. There is a higher level of uncertainty in the price projections for BioLNG as IHS Markit were unable to provide projections for it consistent with those for the other fuels; therefore, additional information was used when deriving the projection for BioLNG for this study.

The results of these calculations are sensitive to the discount rate used, but changes in discount rate do not affect the relative magnitudes of the results across the three packages. Reducing the discount rate to 5% increases the total NPV to between $800 billion and $1,340 billion.

Combining the calculated emissions reductions and the costs, with discounting at 10% applied to both emission savings and costs, gives cost-effectiveness values in $/tonneCO$_2$e:

Discounted cost-effectiveness ($/tonneCO$_2$e)	Vessel capital costs	Fuel costs	Other operating costs	Total NPV
Package 1	$12	$35	$26	$73
Package 2	$8	$84	$21	$113
Package 3	$88	-$40	-$10	$39

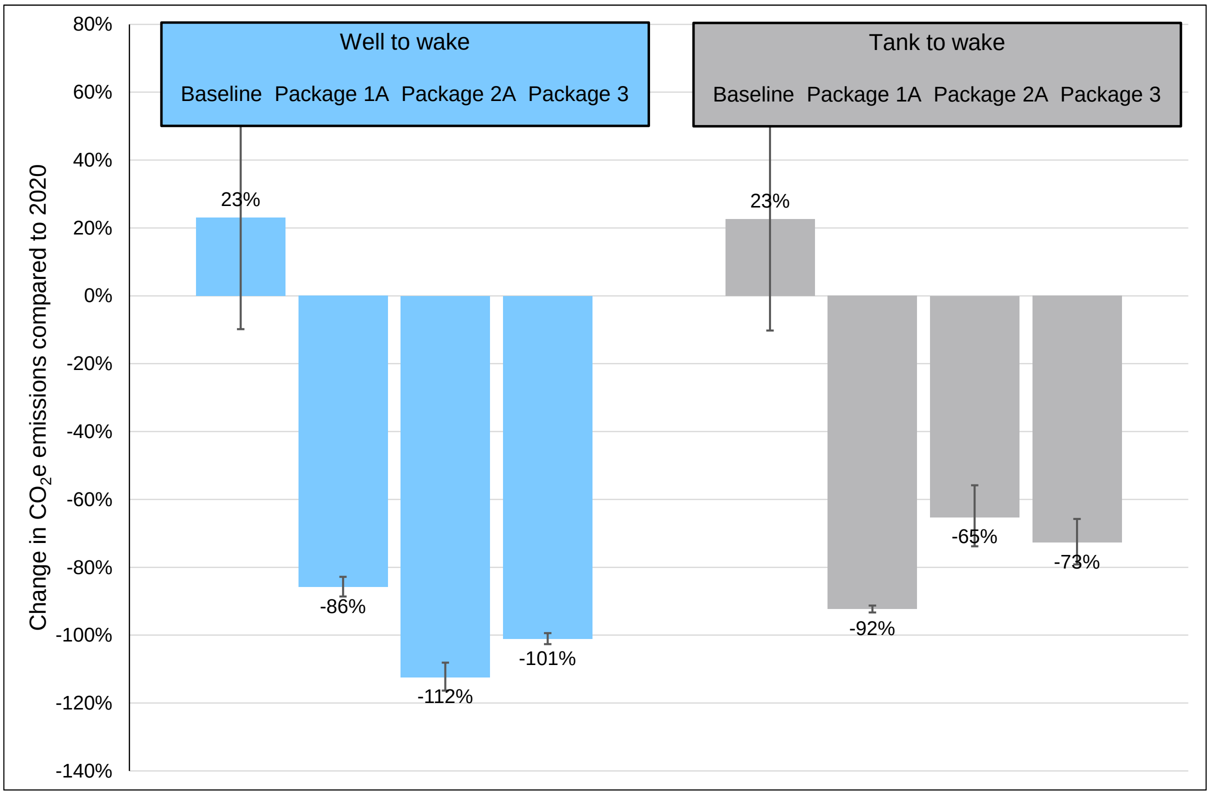
Again, these results are sensitive to the discount rate assumed, but changes in discount rate do not significantly affect the relative magnitudes across the packages. Reducing the discount rate to 5% increases the total NPV to between $83 and $149 per tonne CO$_2$e.

Under calculations in which the costs are discounted (at 10%), but the emissions savings are not discounted, the total NPV values reduce to between $8 per tonne CO_2e (package 3) and $22 per tonne CO_2e (package 2).

The calculated emissions reductions and costs vary significantly under a sensitivity analysis combining the advanced technology assumptions of package 3 with packages 1 and 2

A sensitivity analysis considered cases in which the alternative fuels assumptions of packages 1 and 2 were combined with the technology assumptions of Package 3 (referred to as packages 1A and 2A, respectively).

The increased deployment of vessel technologies under packages 1A and 2A (relative to packages 1 and 2) give increased emissions reductions, so that packages 1A, 2A and 3 all meet the IMO ambition on both a tank-to-wake and a well-to-wake basis. These reductions in emissions in 2050, relative to 2020, are shown in the figure below.



A significant additional technology that is included in packages 1A and 2A (that is not included in packages 1 and 2) is the use of on-board carbon capture. This has only limited impact on package 1A, as almost all fuel used by new vessels is zero-carbon by 2035 (the technology is assumed not to be incorporated in vessels that use zero-carbon fuels), but it has a significant impact on package 2A. As a result, package 2A has the greatest reduction in emissions of all three on a well-to-wake basis.

The inclusion of the additional vessel technologies in packages 1A and 2A (compared to packages 1 and 2) reduces the energy demand and hence the fuel costs. Under package 1A, this reduction in fuel costs is greater than the increase in vessel costs, leading to overall costs that are significantly lower than under package 1; under package 2A, however, the increased vessel costs are almost equal to the reduction in fuel costs, leading to a small reduction in total costs (when discounted at 10% discount rate).

The table below shows the overall cost-effectiveness (as $ per tonne CO_2 abated) of the main analysis packages and the sensitivity analysis packages aggregated over 2020 to 2050, as net present values using discount rates of 10% and 5%.

	10% discount rate	5% discount rate
Package 1	$73	$120
Package 1A	$11	$47
Package 2	$113	$149
Package 2A	$83	$120
Package 3	$39	$83

The sensitivity analysis packages (packages 1A and 2A) show significantly lower cost per tonne CO_2 abated than their corresponding packages 1 and 2 respectively in the main analysis with, in particular, very low values for package 1A. This is largely due to a significant negative contribution to the cost per tonne from the fuel costs, arising due to the significant reduction in fuel demand (due to the use of the additional vessel energy efficiency technologies) combined with a moderate increase in fuel price relative to the baseline (primarily due to ammonia fuel). Package 2A also shows a reduction in fuel consumption relative to package 2; however, the costs do not show such a large reduction due to the prices of the alternative fuels used in this package.

Barriers identified to the successful deployment of the fuels and technologies include:

- For all three packages, the production and supply of alternative fuels will need to be substantially increased
- By 2050, between 9 EJ and 12 EJ of alternative fuels will be required per annum; the infrastructure investment needed to achieve this is estimated at between $66 billion and $436 billion (combining capital and operating expenditure, between 2020 and 2050, discounted at 10%)
- The adoption of alternative maritime fuels depends on the availability of the associated infrastructure for their supply to vessels. With the exception of ‘drop-in’ fuels, associated bunkering infrastructure and port refuelling facilities will need to be scaled up significantly and rapidly. Given the increased number of fuel types included in the future projections, it might be challenging for all ports to offer all fuel types, in particular during transition. Therefore, vessel operators will need to pay attention to the availability of the fuels they require at the locations they need.
- Although engine technology to accommodate alternative fuels (such as ammonia) is already under development by engine manufacturers, this will need to be scaled up once demonstrated. Similarly, the development of fuel cells needs to scale up to the MW capacities needed, if fuel cells rather than engines will power the vessels (e.g. from hydrogen).
- Significant investments will need to be made in the developments of technologies (particularly those associated with the use of alternative fuels) and infrastructure. There is currently a lack of certainty regarding the specific fuels (and, perhaps to a lesser extent, technologies) that will be required. The industry needs greater clarity on these issues before committing to such investments.
- The price differential between traditional marine fuels and alternative fuels remains a large barrier to successful deployment of all three packages. While there is a clear desire on the part of stakeholders for the maritime sector to achieve the decarbonisation targets set by the IMO, the increased costs of the alternative fuels are a significant commercial barrier to a widespread uptake. Some regulatory intervention may be required to incentivise the uptake of alternative

fuels, including reducing the price differential and, hence, the commercial disadvantages of changing to the alternative fuels.

- Standards are required for the alternative fuels and pathways, including sustainability criteria.
- Marine fuels that can be produced from fossil fuels or renewable energy (ammonia, hydrogen, methanol), will need to have reliable certification schemes to provide assurance that the chemically-identical fuel is from green sources.
- Slow steaming has shown benefits to date in reducing emissions from shipping. However, there is little further benefit to be gained as it is already widely practised and the benefits for an individual vessel on a single voyage are offset by the reduction in productivity and, hence, the increased number of voyages (and, possibly vessels) necessary to meet the demand.

Recommended actions for supply of alternative fuels are:

Taking a lead on refining the choices of alternative fuels. The analysis has shown that a transition away from conventional fuels to alternative fuels will be needed if the maritime sector is to meet the IMO ambition by 2050. However, maritime industry stakeholders have indicated that there is a lack of clarity regarding the "right" or "best" options for such fuels, leading to difficulties in planning for future fleets and investments. The oil and gas industry should help in developing a roadmap for the future supply of alternative fuels to reach the IMO ambitions for the maritime sector. This needs to account for the well-to-wake emissions benefits, and account for the impacts of methane not just CO_2.

Supporting proof of concept demonstrations. Although all the alternative fuels described in this report are widely considered to be suitable for maritime transport, there has been only limited demonstration of their practicality for long-distance transport with the key vessel categories of bulk carriers, container ships and tankers. The oil and gas industry could support the design of infrastructure for alternative fuel proof of concept demonstrations, to provide confidence that the supply of these fuels can be scaled up to meet the potential future demand. This would also provide assurance to vessel owners regarding future acquisitions of vessels using these fuels. Taking this a step further, oil and gas industry players could (and have been) working at the vessel level with designers and builders to prove the concepts of working with alternative fuels on board.

Accommodating the increased demand for alternative fuels. This report has shown the scale of future demand for alternative fuels under different scenarios and fuel and technology packages. These have shown that significant scaling up of production and supply of these fuels, including a transition from the current "grey" pathways to "green" fuels (with "blue" fuels providing an opportunity for reduced emissions in the medium term). To ensure the availability of these alternative fuels in the future, investment in new production facilities, and ensuring the availability of the relevant feedstocks, will need to be planned.

Providing "green" certification and fuel sustainability information. The different pathways for the alternative fuels, giving "grey", "blue" and "green" versions, produce chemically-identical products. To provide assurance that an operator is purchasing, and using, sustainable fuels will need the introduction of a sustainability certification system. The oil and gas industry could take the lead in developing and implementing such a system as the market for, and supply of, alternative maritime fuels develops.

Supporting a reformulation of the IMO ambition. The benefits of green, but carbon-containing, fuels mainly occur in the production process, giving low or zero well-to-wake emissions. The industry could, through activities in the IMO, support a reformulation of the IMO ambition for 2050 to be focused on reductions in well-to-wake emissions, rather than tank-to-wake as at present, to be able to recognise the benefits of these alternative fuels.

Recommendations for the maritime industry are:

Vessel designers and builders to ensure that the vessels that they design and produce incorporate the best available technology for energy efficiency.

Vessel owners and operators should plan their future investments in new vessels to include the additional costs associated with decarbonisation technologies and low, or zero, carbon fuels. They could consider obtaining “green” finance from banks to support these investments.

Vessel operators could lobby for regulatory changes to support the uptake of alternative fuels. These fuels currently have a significant price premium over conventional fuels, which is expected to remain in place in the future. Regulatory support for alternative fuels may be needed to reduce the price differential and ensure that they are commercially competitive against conventional fuels. Support from the industry for such regulatory changes may enable their uptake to be accelerated.

As their fleets transition to alternative fuels, **vessel operators will need to ensure that the relevant fuels are available at the ports at which they need to refuel**. Early discussions with port operators are required to ensure that the necessary fuels infrastructure will be in place as they begin to use the new fuels.

A potentially key technology for maritime decarbonisation (if continuing to use conventional fuels as in package 3) is the use of on-board **carbon capture technology in conjunction with carbon-containing fuels**. The industry should monitor and support the development of this technology to ensure that it can be incorporated in new vessels if the demand arises. The need for carbon capture technology is avoided if a rapid switch to zero carbon fuels is made.

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A Appendices

A.1 Appendix 1 – Further analysis on the split incentive problem for shipping

When a Ship Owner hires out the use of their vessel to a Charterer, the responsibilities and costs incurred by each entity hinges on the contract between parties, the charter party. Whether there is an incentive for a Ship Owner to implement energy efficiency measures, is often highly dependent on the net daily charter-hire ($/day) the Charterer pays to the Ship Owner. In this way whether split incentive is an issue, depends on whether or not Ship Owners are rewarded through higher time charter rates for more efficient ships (Rehmatulla et al, 2015). For example, Agnolucci, Smith & Rehmatulla (2014) have shown that on average around 40% in the Panamax sector is recouped by Ship Owners through higher time charter rates (2008 – 2012). For £1000 saved on fuel, the Ship Owner sees an increase of £400 in the charter rate (Agnolucci, Smith, Rehmatulla et al, 2014). In this way there is an asymmetry between the Ship Owner and Ship Charterer financial gains. There are many different cost allocation combinations arising from different charter party contracts. Voyage and time charters divide responsibility for costs as seen in Table 2-2 and these differences can also led to a temporal dimension of conflicting or converging interests where the different parties strive to reduce their share of costs at different points in time. Normally, fuel costs are not covered by operating expenses but included in voyage expenses. Fuel costs are often responsible for a large portion of the of the voyage cost. Operational expenses usually involve crew costs, repair and maintenance costs and marine insurance.

Given these different combinations of cost responsibilities present, for the shipping sector the following main scenarios can occur (Rehmatulla et al, 2015):

1. **No split incentive**

There is no split incentive as the Principal (Charterer) pays for both the ship energy bill and the Principal can also implement the energy efficiency measure or technology. The Principal & Agent are responsible for energy efficiency operation, energy payments (fuel) and energy efficiency investment. This can occur when the Principle is a Bareboat Charterer responsible for energy efficiency and energy payments, and the Agent is a beneficial owner that simply supplies the bare ship. This is the case with Cargo Owner operated ships and can also occur when the Ship Owner is also the operator.

2. **Split incentive – Efficiency problem**

In this case the Principal (Charterer) is in charge of the ship energy bill but cannot select or implement the energy efficiency measure or technology. This is often the case for Time Chartered Ships. In the time charter, the Agent is the Ship Owner and provides the service of the ship. The Agent is responsible for determining the level of technological efficiency. The Principal demands the service of being supplied a ship but cannot improve the ships efficiency. The Principal bears the cost or benefit associated with the energy efficiency level but does not determine it. In this case, how well the charter rate reflects ship energy efficiency dictates how large the split incentive is.

3. **Split incentive – Usage problem**

This has also been referred to as the “reverse” split incentive. In this case, the Principal (Charterer) does not pay the energy bill nor can the Principal implement the energy efficiency measure or technology. In this way the Principal (Time Charterer) does not face the marginal cost of its own energy use and operational measures therefore there is no energy efficiency incentive. This can be the case in voyage-chartered ships.

Overcoming split incentives

Despite presenting a major barrier to the deployment of energy efficiency measures, technologies and alternative fuels in the shipping sector, split incentive challenges have not been investigated in great detail to date. However, these barriers have been investigated in the building & manufacturing industry. Third-party financing models from the built environment could be adapted for the shipping industry to enable significant capital costs to the Ship Owner or Ship Charterer to be overcome. The key to these financing mechanisms is that they incorporate measurement and verification technology into the financial package (Stulgis et al, 2014).

One such mechanism has been based on the Energy Service Companies (ESCO) model. The mechanism would be a Self-Financing Fuel-Saving Mechanism that could facilitate the adoption of fuel efficiency technologies by either long-term time-chartered ships or owner-operated ships. This could overcome split incentives by securing upfront capital investment cost of retrofit fuel efficiency technologies, from a third-party financier. The financier could recoup returns of fuel costs savings generated by the gains in fuel efficiency from the technology. Ship baseline performance statistics and consequent improvements would be used to calculate return rates. In this way, for Time – chartered ships, the Ship Owner can receive financing for improved measures without the fear of the additional investment costs not being recouped / passed on to the Charterer, as it would now be provided by a third-party. Another proposed mechanism could be use of third-party finance to enable vessels to convert to running primarily on LNG whilst retaining the ability to switch to conventional bunker fuels if necessary. Again, the cost is now passed to the third-party with the financiers receiving their returns by hedging against the pricing spread between low-sulphur bunker fuels and natural gas.

Finally, demand-side stakeholders within the industry (e.g. Charterers) have increasingly expressed their desire for more efficient vessels through a variety of market signals. For example, retailers including IKEA and WalMart, as part of the Clean Cargo Working Group are collaborating with leading container shippers to reduce their carbon footprints. In this way the Split incentive – Efficiency problem may be reduced through the Shipping Owner being incentivised to implement measures to avoid foregone revenue from the Charterers choosing to use an alternative ship. Although the benefit would still not be directly derived from the measure itself, the benefit would be retaining Charterers. This is the case for the tank and bulk charter market in particular, where Charterers are beginning to factor vessel efficiency into their commercial decision making. For example, as early as 2012, Cargill, Huntsman, and UNIPEC UK publicly announced they would no longer charter the least efficient ships in the global fleet.

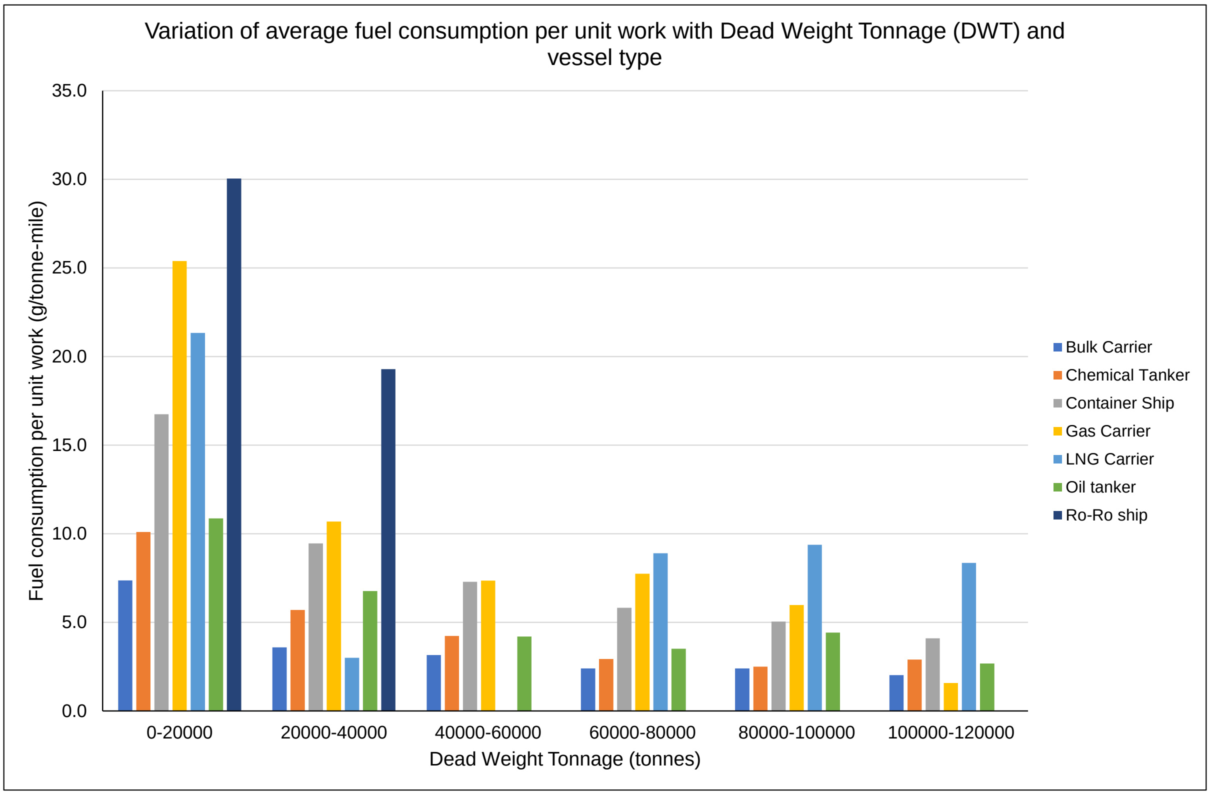
To what extent the split incentive problem has prevented the uptake of carbon reduction measures has not been quantified to date. Split incentives can also be exacerbated though lack of reliable information on costs and savings of a particular technology. An additional complexity to the split incentive problem in the shipping sector is that it most likely impacts technological, operational measures and uptake of alternative fuels differently. For operational measures such as weather routing, where the Charterer has operational control and also has fuel as a cost under their account, the split incentive problem may not be present. This is because the Charterer also has an incentive to save fuel. Technological measures with high levels of uncertainty can also compound the problem and are more likely to be a part of split incentives. The question of which new technology will be the most efficient and will work in the long-term makes residual value risk more contentious than it would otherwise be. In this way, each party aims to reduce risk. This can lead to Charterers trying to keep tenures as short as possible to leave the associated risk of the measure / potential gain with the Ship Owner, and Ship Owners being reluctant to pay the upfront capital costs for novel technologies.

A.2 Appendix 2 – Example detailed results from analyses of THETIS-MRV data

This appendix provides some additional results from the analyses of vessel fuel consumption data from the EU THETIS-MRV portal. In addition to the overall average fuel consumption per unit work presented in Section 3.2, the additional analyses have investigated the characteristics of the individual vessel categories and the variation by build year (or vessel age in 2019).

Figure 13-1 shows the variations of fuel consumption with ship size for the different vessel categories.

Figure 13-1: Average fuel consumption per unit work for a range of vessel categories and sizes



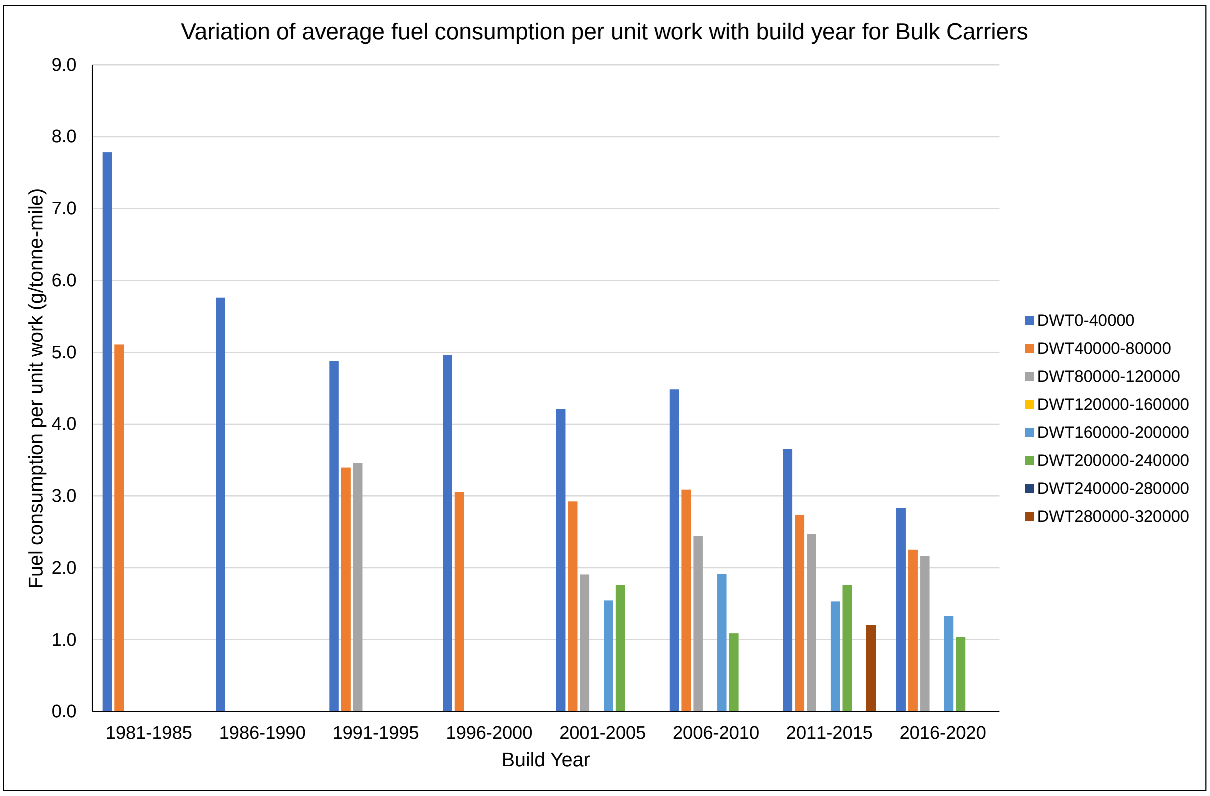
Source: Ricardo analysis using EU ship emissions MRV data and Clarksons World Fleet Register data

Figure 13-1 shows large differences between the fuel consumption per unit work, with gas carriers and Ro-Ro ships having the highest values (of up to 28 or 34 g/tonne-mile) and bulk carriers, chemical tankers and oil tankers generally having the lowest (of down to about 2.0). There are some anomalies present, such as the 80,000 to 100,000 DWT size category for chemical tankers. For most results, the averages shown have been calculated using data for multiple hundreds of ships; however, there are also some results that are based on very few ships, which can give rise to some of the anomalies seen (for example, the 80,000 to 100,000 DWT chemical tankers category includes only two ships).

For some ship categories, an increasing efficiency with vessel size is generally evident. For example, gas carriers, LNG carriers and oil tankers all show generally reducing fuel consumption per unit work with increasing DWT.

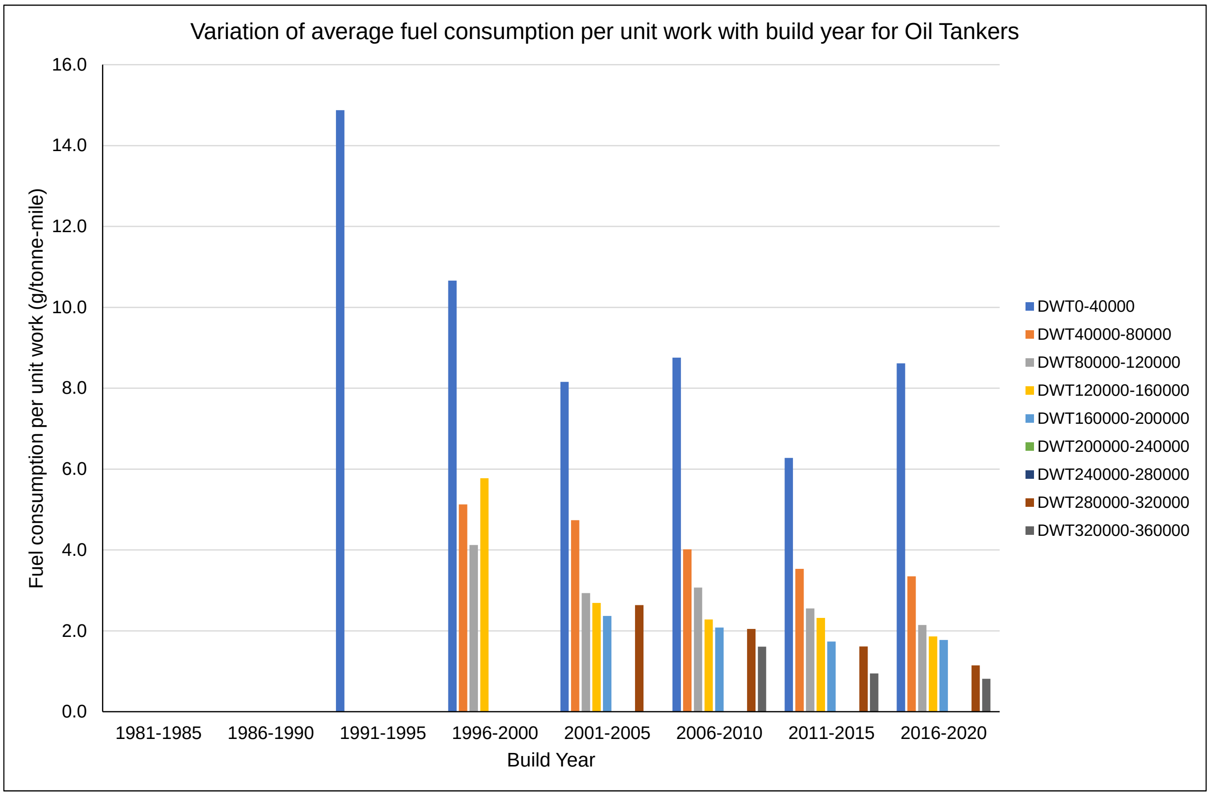
The combined use of the EU MRV data and the Clarksons World Fleet Register data allows the fuel consumption per unit work to be examined in greater detail, showing the development of the values with the build year of the ships. Figure 13-2 and Figure 13-3 show examples of these, for bulk carriers and oil tankers respectively.

Figure 13-2: Variation of average fuel consumption per unit work with build year and DWT for bulk carriers



Source: Ricardo analysis using EU ship emissions MRV data and Clarksons World Fleet Register data

Figure 13-3: Variation of average fuel consumption per unit work with build year and DWT for oil tankers



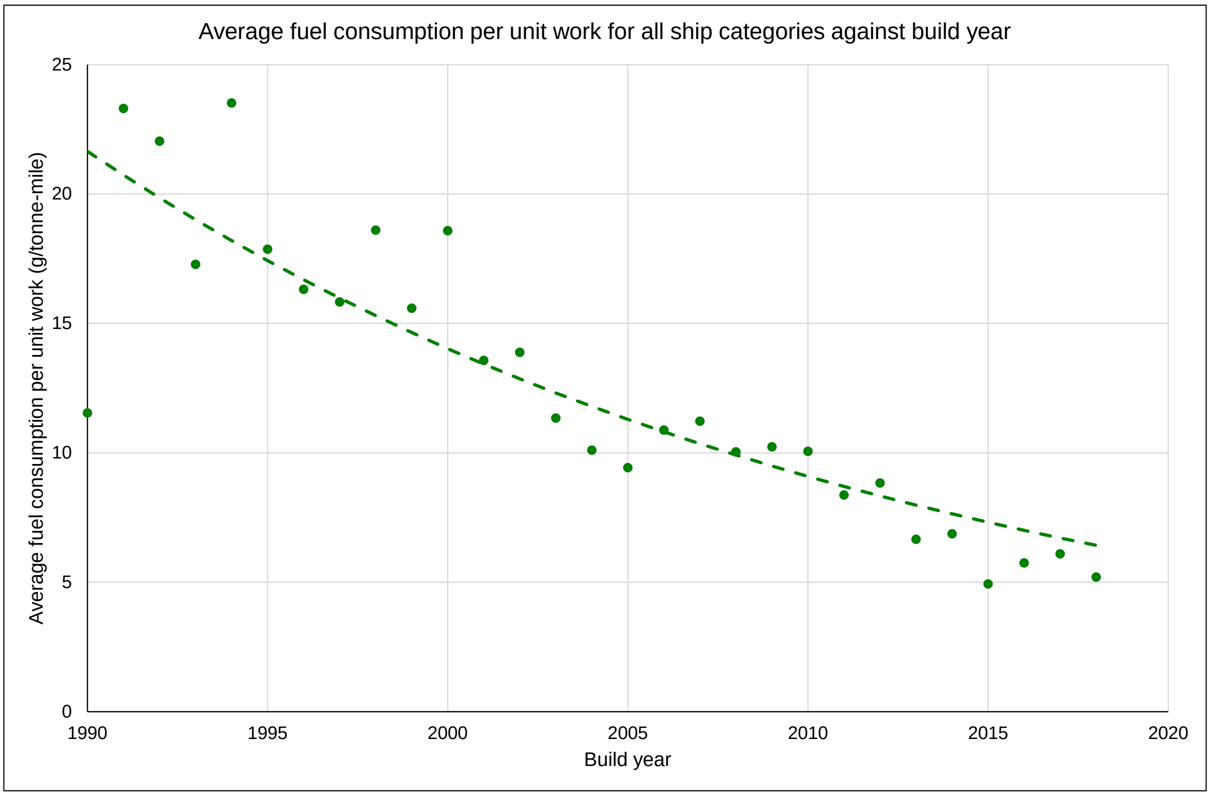
Source: Ricardo analysis using EU ship emissions MRV data and Clarksons World Fleet Register data

Some gaps are evident in the distributions, as the limited number of ships for which data are available becomes more evident as the data are analysed at a more refined level.. However, for cases where data are available across all build year groups, there is commonly evidence of a reducing fuel consumption over time, indicating the manner in which the incorporation of improved vessel design and other technologies has contributed to the improvements in fuel efficiency of new ships.

The results shown above, plus those for other ship categories, have been to define baseline fuel efficiency values, and their rates of improvement over time, which were applied to the modelling of the development of the global fleet (as new ships are built and enter into the fleet, replacing older ships) and the development of demand, to define baseline fuel consumption in future years.

Although the main analyses performed for this study considered the emissions by different ship types and sizes, it is constructive to consider the overall average emissions per unit work based on the build year of the ships. The results, with averages calculated using the emissions per unit work weighted by the total distance travelled by the ship in 2019, are shown in Figure 13-4.

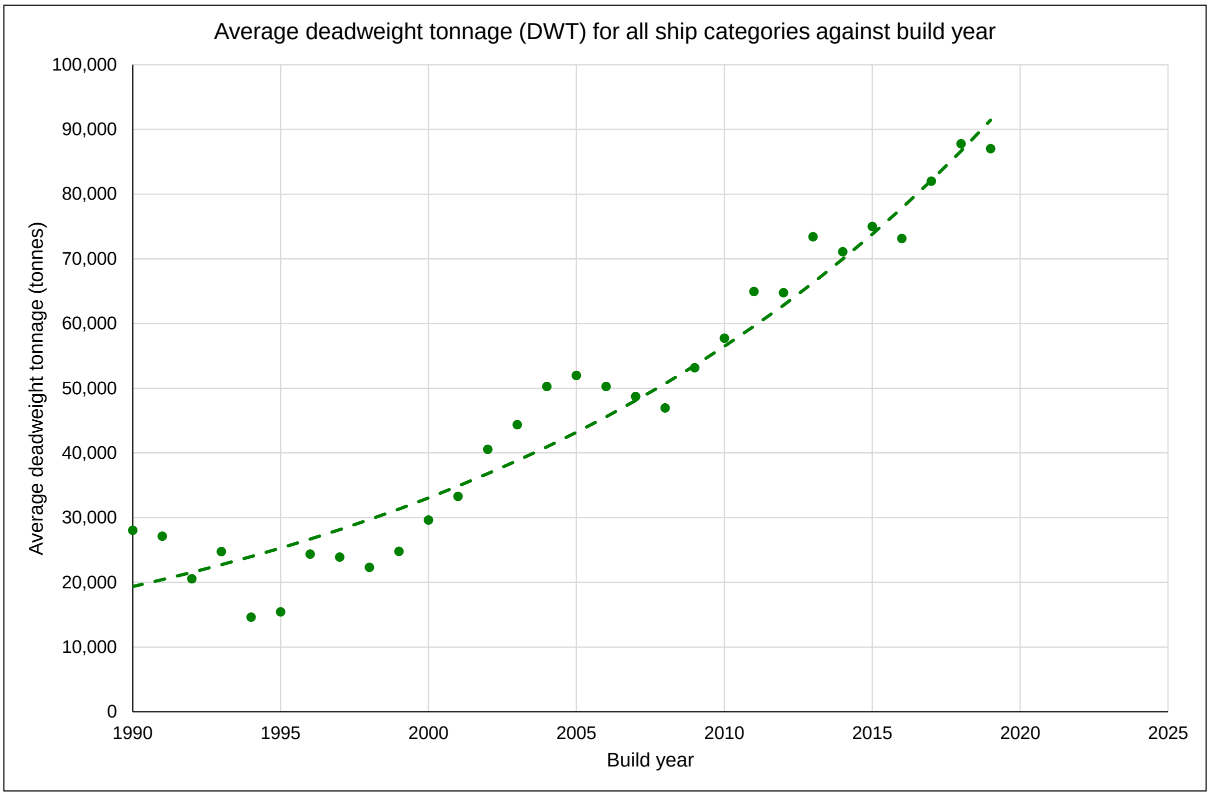
Figure 13-4: Overall average fuel consumption per unit work for the fleet in 2019 as a function of build year



Source: Ricardo analysis using EU ship emissions MRV data and Clarksons World Fleet Register data

The data shown in Figure 13-4 are limited to ships built from 1990 onwards, as the limited number of ships (for which data are available) with earlier build years led to very large levels of scatter. A consistent reduction in the fuel consumption per unit work is evident from the data points in Figure 13-4, and this is captured by the curve fitted to the data (using a best fit of a curve representing a constant percentage reduction each year). The curve shown represents a 4.2% annual reduction in the fuel consumption per unit work for newly built ships. This is a greater improvement rate than has been reported in other studies. For example, Scarbrough, Tsagatakis, et al. used an estimate of 1% per annum improvement based on a review of previous studies (Scarbrough, et al., 2017). The rate is also higher than has been reported for other modes; for example, ICAO has used assumptions of annual improvement rates of between 0.96% and 1.50% in their environmental trends assessments (Fleming & de Lepinay, 2019), while the IEA have identified average annual improvements of 1.85% for light duty road vehicles between 2005 and 2016[72], although this had slowed for 2017. A potential reason for the high rate of improvement calculated here is that, being based on the total fleet delivered in each year, it also includes the influence of a trend of increasing ship size over time. Figure 13-5 shows how average ship size, represented by DWT, has increased over the same period.

Figure 13-5: Overall average vessel size (DWT) as a function of build year



Source: Ricardo analysis using EU ship emissions MRV data and Clarksons World Fleet Register data

The curve fitted through the points in Figure 13-5 represents an annual increase of 5.5% in the DWT of newly delivered vessels; this would be expected to contribute to an improvement in fuel efficiency (expressed per unit of cargo transported) as larger vessels are, in general, more fuel efficient than smaller ones.

Significantly, the results shown in Figure 13-4 show that the ongoing reductions in fuel consumption are evident for ships built considerably before 2011, when the EEDI came into force for new ships. This may be seen as corroborating some views that have been expressed that to date the EEDI has had little impact on the fuel consumption of the fleet, which has been driven more by economic considerations (e.g. the cost of fuel) than by regulation.

The average build year of the ships whose data are shown in Figure 13-4 is 2009, giving an average age in 2019 of 10 years. Extrapolating these data forward, and assuming that the profile of distance covered by ships of a given age remains constant in the future and that, in the absence of further changes in policy or regulation, the annual improvement of newly built ships remains valid, in 2030 this estimates that the average fuel consumption per unit work of the fleet will be 58% lower than in 2008, while in 2050 it will be 81% lower than in 2008. There is clearly significant uncertainty around these assumptions, but these results indicate that the trajectory of ship technology improvements to date, if maintained, should be sufficient to meet the IMO ambition on the carbon intensity of the future fleet, as described in Section 1.1. The achievement of this continuing improvement in fuel consumption per unit

[72] https://www.iea.org/reports/fuel-consumption-of-cars-and-vans

work would imply the continued development of new vessel and engine technologies and their implementation in new ships. As discussed earlier in this report, the technologies identified during this study may not be sufficient to enable this trajectory to be continued, hence the requirement to consider alternative fuels to enable the targeted reductions in emissions to be achieved.

A.3 Appendix 3 – EEDI effectiveness

Whilst the average design efficiency of all ship types has improved substantially since the 1980s, changes in ships' design speeds and in power requirements to overcome resistance, can only explain a fraction design efficiency changes observed. Other aspects of ship design have been more important, such as hull, propeller and rudder design (Faber, Maarten, Vergeer, & Calleya, 2016). This period was then followed by a period of deterioration of average ship energy efficiency after 1999, but in more recent years ship efficiency has improved once again. Whilst some attribute EEDI amendments as the cause of the positive efficiency changes witnessed in recent years, others indicate these changes are actually the result of high fuel prices, rather than regulation (Faber, Maarten, Vergeer, & Calleya, 2016).

The role of EEDI may be reduced in the upcoming years due to past shipping sector trends such as the shipbuilding boom, which lasted for 10 years with a peak in demand for ordering of new ships in 2008. Because many technologies are fitted at the newbuild stage, the opportunity to reduce carbon emissions through the EEDI has declined since the boom came to end, given the reduced demand for new ships post 2008 (Stott, 2014). The average age of ships is approximately 22 years, therefore EEDI reductions in CO_2 emissions may occur far more slowly than anticipated, given fleet time lags in complete turn over (Chu Van, Ramirez, Rainey, Ristovski, & Brown, 2019).

Further amendments to the EEDI programme will bring forward phase 3 to 2022 and introduce stronger EEDI reduction levels for certain vessels, indicated in Table 13-1. However, these have been seen as controversial, with stakeholder feedback highlighting unequal targeting by sector.

Table 13-1: Amendments to EEDI regulation adopted in May 2019

Vessel Type	Size (DWT)	CO_2 reduction level*
Container Ships	10,000 to 14,999	15% to 30%
	15,000 to 39,999	30%
	40,000 to 79,999	35%
	80,000 to 119,999	40%
	120,000 to 199,999	45%
	200,000+	50%
General Cargo	3,000 to 14,999	0 to 30%
	15,000+	30%
LNG Carriers	10,000+	30%
Gas Carriers	15,000+	30%
Cruise Ships	25,000 to 84,999	0 to 30%
	85,000+	30%

** Relative to a reference line representing the average efficiency of ships built between 2000 and 2010*
Source: American Bureau of Shipping MEPC-74 Brief (https://ww2.eagle.org/content/dam/eagle/regulatory-news/2019/MEPC-74-Brief-r4.pdf)

Beyond newbuild ship design regulation, recently Japan proposed an EEXI ahead of MEPC74 which has received support from Greece, Japan, Norway, Panama, United Arab Emirates, ICS, BIMCO and Intertanko. The EEXI would build upon the EEDI (IMO, n.d.), which applies to new ships, by applying technical efficiency standards to the existing fleet (Chambers, 2019). Their aim being for this to be approved at MEPC 75 with entry into force in 2022. This is somewhat controversial as a mandatory flat rate engine power limit on all ships was initially suggested (i.e. even ships with EEXI equal or lower than the required EEXI would have to comply). However, the latest proposal has moved forward to use the goal-based EEXI proposal as the basis for further consideration in technical approach, without incorporating the prescriptive measure.

EEDI developments such as the third phase of controls being brought forward and the EEXI may improve EEDI effectiveness. However, stakeholders confirmed that EEDI issues such as unequal targeting by sector remain a barrier to EEDI effectiveness. This echoes the literature that indicates it is now widely accepted that ship design efficiency requirements alone will fall short of what is required in order to fully decarbonise the shipping sector by 2050. The European Commission has stated it will propose further measures to tackle GHG emissions from ships, in the absence of adequate progress in the framework of IMO, thereby effectively highlighting that the adoption of EEDI is not sufficient (Psaraftis H. , 2012).

A.4 Appendix 4 – Environmental Ships Index

Table 13-2: Structure of the calculation of the Environmental Ships Index

ESI element	Calculation
Overall ESI Score	ESI = ESI-NOx + ESI-SOx + ESI-CO_2 + OPS; capped at 100
ESI-NOx	ESI-NOx is based on the certified NOx ratings of the engines fitted to the vessel, relative to the regulatory limit, expressed as: $ESI - NOx = 2/3 \times \frac{100}{Total\ rated\ power\ of\ all\ engines} \times \Sigma \frac{(NOx\ limit\ value - NOx\ rating) \times Rated\ power}{NOx\ limit\ value}$ where the sum (Σ) is taken over all main and auxiliary engines
ESI-SOx	ESI-SOx is defined by the relative differences of the sulphur contents of the fuels used, compared to the limit values for those fuels, expressed as: *ESI-SOx = 1/3 x* *30 x relative difference of sulphur content of HIGH S fuel (HFO with sulphur content between 0.5% and 3.5%) +* *35 x relative difference of sulphur content of MID S fuel (MDO with sulphur content between 0.1% and 0.5%) +* *35 x relative difference of sulphur content of LOW S fuel (MDO with sulphur content less than 0.1%)*
ESI-CO_2	= 5 for reporting fuel and distance every half year; additional points are added for each % increase in efficiency (total ESI-CO_2 is capped at 15)
OPS	= 10, if on-shore power supply installation is fitted

Source: https://www.environmentalshipindex.org/Public/Home/ESIFormulas

To May 2020, 9,200 ships have been awarded an ESI score, and it is used in > 50 ports worldwide. The number of ports by region is shown in Table 13-3.

Table 13-3: Numbers of ports using the ESI to rate ships' environmental performance

Region	Number of ports
Europe	43
Asia	4
North America	3
South America	3
Australasia	2
Middle East	1

Source: https://www.environmentalshipindex.org/Public/PortIPs

A.5 Appendix 5 – Fuel descriptions from Phase 1 report

This appendix reproduces the descriptions of the different fuel and their associated production pathways from the Phase 1 report on this study. It should be noted that the work on Phase 2 of the study, leading to the production of this final report, has including updating many of the cost assumptions; therefore, the values presented in the appendix may not match those in the main report.

The presentation of the fuels information in the Phase 1 report included summary information in the main report, together with an extended table in Appendix A.1. The latter table is reproduced at the end of this appendix.

As noted in Section 6.2.1 of the report, the fuel price projections used for the cost modelling in his study were provided by IHS Markit. As these replaced the fuel price data that were developed in Phase 1, and are described in detail in Section 6.2.1 and Appendix A.10, no fuel price data are included here.

LNG

Table 13-4: Production pathway GHG emissions, life cycle emissions (well-to-wake), GHG reduction potential and fuel costs for different LNG pathways.

LNG Production Pathway	Production Pathways GHG emissions (WTT) **g CO_2eq/MJ**	Total life cycle GHG emissions (WTW) **g CO_2eq/MJ**	**GHG reduction potential (%)** [negative values are increases in GHG]
HFO reference	*9.6*	*87.2*	*0*
Global average LNG (A)	18.5	78.1	10.4
LNG onshore Qatar	10.7	80.2	8.3
Regional pathway not specified	19.1	92.7	-6.3
US supply LNG	16	115.54	-32.5
Global average LNG (B)	18.5	127.03	-45.7

Table 13-5: Examples of LNG production pathway emissions.

LNG Production Pathways (WTT)	g CO_2eq/MJ
HFO reference	*9.6*
LNG supplied from Qatar by tanker	10.7
LNG Natural Gas North Sea	8.9
LNG Natural Gas Russia via pipeline	23.1

Source (Verbeek et al, 2011)

Natural gas liquefaction technologies can also impact emission reductions, with industrial gas turbines (IGT) being the most energy intensive (see Table 13-6). Nevertheless, the largest proportion of LNG life-cycle emissions arise from combustion and from methane slip.

Table 13-6: Effect of four natural gas liquefaction technologies on GHG emissions.

LNG Liquefaction technology	g CO_2eq / kg LNG	g CO_2 eq / MJ
Industrial gas turbine (IGT)	360	7.41
Aero-derivative gas turbine (AGT)	220	4.53
AGT and helper motor	150	3.09
Electric-driven compressor	50	1.03

Source: (Sharafian et al, 2019)

BioLNG

Table 13-7: Production pathway GHG emissions, life cycle emissions (well-to-wake), GHG reduction potential and costs of different BioLNG pathways.

BioLNG Production Pathways	Production pathway GHG emissions (WTT*) exc. iLUC**	Production pathway GHG emissions (WTT) inc. iLUC	Tank-to-well GHG emissions (TTW)	Total life cycle GHG emissions (WTW)*	GHG reduction potential
	gCO_2eq				%
HFO reference	*9.6*	*-*	*77.6*	*87.2*	*-*
Municipal waste (closed digestate storage)	24.1	24.1	0	24.1	72.4
Liquid manure (closed digestate storage with methane emission reduction***)	-60.5	-60.5	0	-60.5	169.4
Liquid manure (closed digestate storage)	24.5	27.5	0	27.5	68.5
Whole plant (closed digestate storage)	50.1	53.1	0	53.1	39.1
Wood (Gasification)	15.9	15.9	0	15.9	81.8

**Values do not include possible differences in engine efficiency and engine methane emissions.*
***iLUC=Indirect Land Use Change*
****Pathway includes positive effect of preventing methane emissions by storage and use of biogas instead of releasing to the atmosphere.*

LPG

Table 13-8: Production pathway GHG emissions, life cycle emissions (well-to-wake) and GHG reduction potential and costs of different LPG pathways.

LPG Production Pathway	Production pathway GHG emissions (WTT)	Total life cycle GHG emissions (WTW)	GHG reduction potential
	$g\ CO_2eq/MJ$		%
HFO reference	*9.6*	*86.7*	*-*
Natural gas LPG	8.8	69.9	19.4
Petroleum derived LPG	13.3	77.6	10.5

Ammonia

Table 13-9: Production pathway GHG emissions, life cycle emissions (well-to-wake) and GHG reduction potential from different ammonia production pathways.

Ammonia Production Pathway*	Production pathway GHG emissions (WTT)	Total life cycle GHG emissions (WTW)*	GHG reduction potential
	g CO2eq/MJ		%
HFO reference	*9.6*	*86.7*	*0*
Ammonia (Green) - Municipal waste-based electrolysis	18.1	18.1	79.3
Ammonia (Green) - Hydropower based electrolysis	20.2	20.2	76.8
Ammonia (Nuclear) - Nuclear high temperature electrolysis**	44.7	44.7	48.8
Ammonia (Green)- Biomass based electrolysis	45.2	45.2	48.2
Ammonia (Green) - 100% renewable production (theoretical)***	0	0	100
Ammonia (Green) – renewable 70% Alkaline electrolyser + 30% PEM electrolyser	22.15	22.15	74.6
Ammonia (Grey) - Partial oxidation of heavy oil (POX)	158.9	158.9	-83.2
Ammonia (Grey) - Conventional natural gas feedstock - EU electricity mix	97.3	97.3	-11.6
Ammonia (Blue) – SMR + CCS	12.8	12.8	85.3

Well-to-wake emissions assumed to be the same at Well-to-tank as ammonia combustion is carbon free.
*** Electrolysis is assisted with excess heat from the nuclear power plant.*
**** Assuming future electricity provided by the grid is completely renewably generated.*

Hydrogen

Table 13-10: Production pathway GHG emissions, life cycle emissions (well-to-wake) and GHG reduction potential and costs for different hydrogen pathways.

Hydrogen Production Pathway	Production Pathways GHG emissions (WTT)	Total life cycle GHG emissions (WTW)*	GHG reduction potential*
	g CO_2eq/MJ		%
HFO reference	*9.6*	*87.2*	*0*
Hydrogen (Grey) Conventional - Steam reforming natural gas	87.9	87.9	-0.8
Hydrogen (Blue) – SMR + CCS	N/A	13.9	84.1
Hydrogen (Grey) Electrolysis (UK average grid mix)	122.0	122.0	-39.9
Hydrogen (Green) Electrolysis (UK projected grid mix 2030)	47	47	46.1
Hydrogen (Green) – renewable 70% Alkaline electrolyser + 30% PEM electrolyser	22.19	22.19	74.6

Hydrogen (Green)- theoretical electrolysis (100% renewable electricity)	0	0	100.0
Hydrogen (Green) - Gasification biomass	4.6	4.6	94.7

**Well-to-wake emissions assumed to be the same as Well-to-tank as hydrogen combustion is carbon free.*

Methanol

Table 13-11: Production pathway GHG emissions, life cycle emissions (well-to-wake), GHG reduction potential and costs from different methanol production pathways.

Methanol Production Pathway	Production Pathway GHG emissions (WTT)	Total life cycle GHG emissions (WTW)	GHG reduction potential
	gCO_2eq/MJ		%
HFO reference	*9.6*	*86.7*	*0*
Methanol (Grey) - Natural gas	22.0	98.1	-13.2
Methanol (Grey) - Flared gas	-38.3	37.9	56.3
Methanol (Grey) - Conventional gas	24.4	100.5	-15.9
Methanol (Green) - Biomass - forest residue	5.6	81.7	5.8
Methanol (Green) - Landfill gas	-40.0	36.1	58.6
Methanol (Green) – Synthetic – Power-to-Fuel (PtF) renewable	-68.9	7.2	91.7
Methanol (Grey) - Coal	120.9	197.0	-126

Table 13-12: Approximate additional costs for a newbuild and a retrofit with the methanol fuel system.

New build / retrofit	System component	Cost (Million USD $) *
Newbuild	Engine and equipment costs	5.5
	Storage of methanol	0.1
	Total costs for a newbuild	5.6
Retrofit	Engine costs	3.5
	Other equipment	3.5
	Additional shipyard costs	3.5
	Total costs for a retrofit	10.5

**costs calculated for a ro-ro vessel with 24 000 kW installed main engine power and tank capacity for 3 days sailing.*

Source: (IMO, 2016)

FAME

Table 13-13: Production pathway GHG emissions, life cycle emissions (well-to-wake) and GHG reduction potential from different FAME pathways

FAME Production Pathways	Production pathway GHG	Production pathway GHG	Tank-to-well GHG	Total life cycle GHG	GHG reduction potential

	emissions (WTT) exc. iLUC**	emissions (WTT) inc. iLUC	emissions (TTW)		emissions (WTW)*	
	gCO2eq/MJ					%
HFO reference	*9.6*		-	*77.6*	*87.2*	-
Rapeseed feedstock (glycerine export as chemical or animal feed)	57.0		111.0	0	111.0	-27.3
Rapeseed feedstock (glycerine to internal biogas production)	37.0		91.1	0	91.1	-4.5
Palm oil feedstock (No CH4 recovery, no heat credit from residue)	51.0		94.5	0	94.5	-8.4
Palm oil feedstock (No CH4 recovery, heat credit from residue)	63.0		107.0	0	107.0	-22.7
Palm oil feedstock (CH4 recovery, heat credit from residue)	31.0		74.5	0	74.5	14.6
Waste cooking oil feedstock (purification and transesterification)	13.8		13.8	0	13.8	84.2
Tallow feedstock (purification and transesterification)	26.3		26.3	0	26.3	69.8

**iLUC=Indirect Land Use Change. Note: There is a limit to FAME blending with HFO (up to 20%).*

HVO

Table 13-14: Production pathway GHG emissions, life cycle emissions (well-to-wake) and GHG reduction potential from different HVO pathways

HVO Production Pathways	Production pathway GHG emissions (WTT*) exc. iLUC**	Production pathway GHG emissions (WTT) inc. iLUC	Tank-to-well GHG emissions (TTW)	Total life cycle GHG emissions (WTW)*	GHG reduction potential
	gCO2eq/MJ				%
HFO reference	*9.6*	-	*77.6*	*87.2*	-
Rapeseed feedstock (meal export to animal feed, hydrotreat oil)	57	112	0	112	-28.4
Rapeseed feedstock (meal export to internal biogas production, hydrotreat oil)	37	92	0	92	-5.5
Palm oil feedstock (No CH4 recovery, heat credit from residue)	48.6	104	0	104	-19.3
Waste cooking oil feedstock (purification and transesterification)	8.1	8.1	0	8.1	90.7
Tallow feedstock (purification and transesterification)	24.5	24.5	0	24.5	71.9

Summary of alternative fuels

Table 13-15: Summary of alternative fuels options

Technology	Options/ Applications	Already widely used?	Availability date	Potential fuel consumption/ CO_2 reduction
LNG	LNG-1 (Global average LNG (A)*)	Moderate	Now	10.4%
	LNG-2 (Global average LNG (B)*)	Moderate	Now	-45.7%
	LNG-3 (US supply LNG)	Moderate	Now	-32.5%
	LNG-4 (Regional pathway not specified)	Moderate	Now	-6.3%
	LNG-5 (LNG onshore Qatar)	Moderate	Now	8.3%
BioLNG	BioLNG-1 (Municipal waste (closed digestate storage))	No	Now	72.4%
	BioLNG-2 (Liquid manure (closed digestate storage with methane emission reduction**))	No	Now	169.4%
	BioLNG-3 (Liquid manure (closed digestate storage))	No	Now	68.5%
	BioLNG-4 (Whole plant (closed digestate storage))	No	Now	39.1%
	BioLNG-5 (Wood (Gasification))	No	2025	81.8%
LPG	LPG-1 (Natural gas LPG)	No	Now	19.8%
	LPG-2 (Petroleum derived LPG)	No	Now	11.0%
Ammonia	Ammonia-1 (Municipal waste-based electrolysis)	No	2025	79.3%
	Ammonia-2 (Hydropower based electrolysis)	No	2025	76.8%
	Ammonia-3 (Nuclear high-temperature electrolysis)	No	2030	48.8%
	Ammonia-4 (Biomass-based electrolysis)	No	2025	48.2%
	Ammonia-5 (Electrolysis - 100% renewable production)	No	2025	100.0%
	Ammonia-6 (Partial oxidation of heavy oil (POX))	No	Now	-82.2%
	Ammonia-7 (Conventional natural gas feedstock - EU electricity mix)	No	Now	-11.6%
	Ammonia-8 - renewable 70% Alkaline electrolyser + 30% PEM electrolyser	No	2030	74.6
	Ammonia -9 SMR + CCS	No	2030	85.3
Hydrogen	Hydrogen-1 (Conventional -Steam reforming natural gas)	No	Now	-0.8%
	Hydrogen-2 (Electrolysis (average grid mix))	No	Now	-39.9%
	Hydrogen-3 (Electrolysis (2030))	No	2030	46.1%
	Hydrogen-4 (Electrolysis (renewable energy))	No	N/A	100.0%

Technology	Options/ Applications	Already widely used?	Availability date	Potential fuel consumption/ CO_2 reduction
	Hydrogen-5 (Gasification biomass)	No	2030	94.7%
	Hydrogen -6 (Renewable 70% Alkaline electrolyser + 30% PEM electrolyser	No	2030	74.6
	Hydrogen -7 (Blue SMR + CCS)	No	2030	84.1
Methanol	Methanol-1 (Methanol Natural gas)	No	Now	-12.5%
	Methanol-2 (Methanol Flared gas)	No	2030	56.6%
	Methanol-3 (Methanol Conventional gas)	No	Now	-15.2%
	Methanol-4 (Methanol Biomass - forest residue)	No	2030	6.3%
	Methanol-5 (Methanol Landfill gas)	No	2030	58.6%
	Methanol-6 (Methanol coal)	No	Now	-126.0%
	Methanol-7 (Synthetic Methanol - Power to Fuel (PtF))	No	2030	91.7%
Biofuels (including drop-in fuels)	FAME-1 (Rapeseed feedstock (glycerine export as chemical or animal feed))	No	Now	-27.3%
	FAME-2 (Rapeseed feedstock (glycerine to internal biogas production))	No	Now	-4.5%
	FAME-3 (Palm oil feedstock (No CH4 recovery, no heat credit from residue))	No	Now	-8.4%
	FAME-4 (Palm oil feedstock (No CH4 recovery, heat credit from residue))	No	Now	-22.7%
	FAME-5 (Palm oil feedstock (CH4 recovery, heat credit from residue))	No	Now	14.6%
	FAME-6 (Waste cooking oil feedstock (purification and transesterification))	No	Now	84.2%
	FAME-7 (Tallow feedstock (purification and transesterification))	No	Now	69.8%
	HVO-1 (Rapeseed feedstock (meal export to animal feed, hydrotreat oil))	No	Now	-28.4%
	HVO-2 (Rapeseed feedstock (meal export to internal biogas production, hydrotreat oil))	No	Now	-5.5%
	HVO-3 (Palm oil feedstock (No CH4 recovery, heat credit from residue))	No	Now	-19.3%
	HVO-4 (Waste cooking oil feedstock (purification and transesterification))	No	Now	90.7%

Technology	Options/ Applications	Already widely used?	Availability date	Potential fuel consumption/ CO_2 reduction
	HVO-5 (Tallow feedstock (purification and transesterification))	No	Now	71.9%
Synthetic fuels	DME-1 (Waste wood DME)	No	2030	97.6%
	DME-2 (Farmed wood DME)	No	2030	92.5%
	DME-3 (Coal EU mix DME)	No	Now	-122.5%
	DME-4 (Natural Gas EU production DME)	No	Now	-12.0%
Batteries	Small, short-range vessels	No	2025	65.5%
Nuclear	Nuclear power is considered unsuitable for commercial vessels due to political and public sensitivities	No	Now	N/A

Notes:

* *LNG-1 and LNG-2 differ in the assumptions regarding methane slip*

** *The emissions reduction for BioLNG-2 include the positive effect of preventing methane emissions by storage and use of biogas as fuel instead of releasing to the atmosphere.*

For several of the fuel pathways shown the potential reduction in CO2 emissions is negative, indicating that these pathways produce more emissions than HFO. These pathways are not considered to be valid decarbonisation options and so the cost-effectiveness is given as “N/A”. The use of battery electric vessels is likely to remain a niche application (for relatively small, short-range vessels), so the same cost-effectiveness calculation (based on savings for a significantly larger vessel) is not appropriate.

Table 13-16 is a reproduction of the table presented in Appendix A.1 of the Phase 1 report on this study.

Table 13-16: Production pathway and lifecycle emission values

Fuel	Pathway code	Production Pathway description	Production Pathway GHG emissions (WTT) g CO_2eq/MJ	Total life cycle GHG emissions (WTP) g CO_2eq/MJ	GHG reduction potential calculated (%)	Sources	Comment
HFO	***HFO reference***	***HFO reference***	***9.6***	***87.2***	***0***	(Lindstad and Rialland, 2020)	*WTP converted from g/kwh using assumed engine efficiency of 0.48*
LNG	LNG-1	Global average LNG (A)	18.5	78.1	10.4	(Thinkstep, 2019)	*Differences in global average pathways are due to the way methane slip is calculated in the studies. For price, average gas value of minimum and maximum between May 2017 and May 2020 used. Includes additional assumed liquefaction cost of 4$/mmBT.*
LNG	LNG-2	Global average LNG (B)	18.5	127.0	-45.7	(Lindstad, 2019)	*Differences in global average pathways are due to the way methane slip is calculated in the studies. For price, average gas value of minimum and maximum between May 2017 and May 2020 use. Includes additional assumed liquefaction cost of 4$/mmBT.*
LNG	LNG-3	US supply LNG	16.0	115.5	-32.5	(ICCT, 2020)	*For price the value for US supply LNG in June 2019 was used. Adjusted for inflation.*
LNG	LNG-4	Regional pathway not specified	19.1	92.7	-6.3	(Verbeek, 2015)	-
LNG	LNG-5	LNG onshore Qatar	10.0	80.0	8.3	(DNV GL , 2014) (Reuters, 2020)	*For price, average of minimum and maximum value for LNG between July 2020 and October 2019 used.*

Fuel	Pathway code	Production Pathway description	Production Pathway GHG emissions (WTT) g CO_2eq/MJ	Total life cycle GHG emissions (WTP) g CO_2eq/MJ	GHG reduction potential calculated (%)	Sources	Comment
BioLNG	BioLNG-1	Municipal waste (closed digestate storage)	24.1	24.1	72.4	(Verbeek, 2015) (European Commission, 2017)	*For price, average taken of values of waste biomethane in 2017. Adjusted for inflation and converted to USD. Includes additional assumed liquefaction cost of 4$/mmBT.*
BioLNG	BioLNG-2	Liquid manure (closed digestate storage with methane emission reduction**)	-60.5	-60.5	169.4	(Verbeek, 2015) (IRENA, BIOGAS FOR ROAD VEHICLES TECHNOLOGY BRIEF, 2018)	*For price, 2017 manure-based value used. Adjusted for inflation and converted to USD. Includes additional assumed liquefaction cost of 4$/mmBT. Methane emission reduction comes from avoided emissions from the traditional storage and management of raw manure. It is assumed this does not incur a cost.*
BioLNG	BioLNG-3	Liquid manure (closed digestate storage)	27.5	27.5	68.5	(Verbeek, 2015) (IRENA, BIOGAS FOR ROAD VEHICLES TECHNOLOGY BRIEF, 2018)	*For price, 2017 manure-based value used. Adjusted for inflation and converted to USD. Includes additional assumed liquefaction cost of 4$/mmBT.*
BioLNG	BioLNG-4	Whole plant (closed digestate storage)	53.1	53.1	39.1	(Verbeek, 2015) (IRENA, BIOGAS FOR ROAD VEHICLES TECHNOLOGY BRIEF, 2018)	*For price, 2017 methane from industrial waste-based biogas production value used. Adjusted for inflation and converted to USD. Includes additional assumed liquefaction cost of 4$/mmBT.*
BioLNG	BioLNG-5	Wood (Gasification)	15.9	15.9	81.8	(Verbeek, 2015) (European Commission, 2017)	*For price, average taken of values of from biomethane from wood in 2015. Adjusted for inflation and converted to USD. Includes additional assumed liquefaction cost of 4$/mmBT.*

Fuel	Pathway code	Production Pathway description	Production Pathway GHG emissions (WTT) g CO_2eq/MJ	Total life cycle GHG emissions (WTP) g CO_2eq/MJ	GHG reduction potential calculated (%)	Sources	Comment
LPG	LPG-1	Natural gas LPG	8.8	69.9	19.8	(Unnasch and Waterland, 2011) (GlobalPetrolPrices, 2020)	*Uses WTW methodology adapted for off-road application. Assumed a suitable proxy for shipping. For price, average price of LPG globally as of July 2020 was used.*
LPG	LPG-2	Petroleum derived LPG	13.3	77.6	11.0	(Unnasch and Waterland, 2011) (GlobalPetrolPrices, 2020)	
Ammonia	Ammonia-1	Ammonia - Municipal waste electricity source	18.1	18.1	79.3	(Bicer et al, 2019) (IRENA, 2019) (UK Government, 2019)	*Converted from kg CO2eq per kg of ammonia. Using energy content of ammonia (18.8 MJ/kg). Average production cost taken (2019), adjusted for inflation and converted to USD.*
Ammonia	Ammonia-2	Ammonia - Hydropower electricity source	20.2	20.2	76.8	(Bicer et al, 2019) (IRENA, 2019) (UK Government, 2019)	*Converted from kg CO2eq per kg of ammonia. Using energy content of ammonia (18.8 MJ/kg). Hydropower electricity global average cost identified (Table 1) and used to determine range of values then average calculated. Value adjusted for inflation and converted to USD.*
Ammonia	Ammonia-3	Ammonia - Nuclear power electricity source	44.7	44.7	48.8	(Bicer et al, 2019) (World Nuclear, 2020) (UK Government, 2019)	*Converted from kg CO2eq per kg of ammonia. Using energy content of ammonia (18.8 MJ/kg). Nuclear electricity global average cost identified (and used to determine range of values then average calculated. Value adjusted for inflation and converted to USD.*
Ammonia	Ammonia-4	Ammonia - Biomass electricity source	45.2	45.2	48.2	(Bicer et al, 2019) (IRENA, 2019) (UK Government, 2019)	*Converted from kg CO2eq per kg of ammonia. Using energy content of ammonia (18.8 MJ/kg). Bioenergy electricity global average cost*

Fuel	Pathway code	Production Pathway description	Production Pathway GHG emissions (WTT) g CO_2eq/MJ	Total life cycle GHG emissions (WTP) g CO_2eq/MJ	GHG reduction potential calculated (%)	Sources	Comment
							identified (and used to determine range of values then average calculated. Value adjusted for inflation and converted to USD.
Ammonia	Ammonia-5	Ammonia - 100% renewable production**	0.0	0.0	100.0	-	*Assumes future production from 100% renewable electricity.*
Ammonia	Ammonia-6	Ammonia - Partial oxidation of heavy oil (POX)	158.9	158.9	-82.2	(Lasocki, 2018) (Cox et al, 2015)	*Cost value assumes heavy hydrocarbon feedstock for partial oxidation. Value adjusted for inflation and converted to USD.*
Ammonia	Ammonia-7	Ammonia - Conventional natural gas feedstock - EU electricity mix	97.3	97.3	-11.6	(DECHEMA, 2017) (Cox et al, 2015)	*Cost assumed equivalent to POX process. Value adjusted for inflation and converted to USD.*
Hydrogen	Hydrogen-1	Conventional - Steam reforming natural gas	87.9	87.9	-0.8	(Ricardo, 2019) (Policy Exchange, 2018)	*For price, SMR value in 2018 used. Adjusted for inflation and converted to USD.*
Hydrogen	Hydrogen-2	Electrolysis (average grid mix)	122.0	122.0	-39.9	(Ricardo, 2019) (Policy Exchange, 2018)	*For price, electrolysis average grid value in 2018 used. Adjusted for inflation and converted to USD.*
Hydrogen	Hydrogen-3	Electrolysis (2030)	47.0	47.0	46.1	(Ricardo, 2019) (Policy Exchange, 2018)	*For price, electrolysis value in 2018 used. Calculated from average grid mix but assumes a reduction in price by 30% in 2030. The IEA estimates the price of renewables will fall 30% by 2030. Adjusted for inflation and converted to USD.*
Hydrogen	Hydrogen-4	Electrolysis (renewable energy)	0.0	0.0	100.0	(Ricardo, 2019)	*Assumes future production from 100% renewable electricity.*

Fuel	Pathway code	Production Pathway description	Production Pathway GHG emissions (WTT) g CO_2eq/MJ	Total life cycle GHG emissions (WTP) g CO_2eq/MJ	GHG reduction potential calculated (%)	Sources	Comment
Hydrogen	Hydrogen-5	Gasification biomass	4.6	4.6	94.7	(Ricardo, 2019) (Policy Exchange, 2018)	*For price, gasification value in 2018 used. Adjusted for inflation and converted to USD.*
Methanol	Methanol-1	Methanol Natural gas	22.0	98.1	-12.5	(Winebrake, 2018) (Nyári, 2018)	*CO2e was calculated from CO2 and NOx. GWP of 1 (GHG Protocol) and GWP of 30 used* (Lammel et al, 1995). *For price, average production cost of natural gas based methanol in 2013 was adjusted for inflation and converted to USD.*
Methanol	Methanol-2	Methanol Flared gas	-38.3	37.9	56.6	(Winebrake, 2018) (Lundgren, 2013)	*CO2e was calculated from CO2 and NOx. GWP of 1 (GHG Protocol) and GWP of 30 used. For price, methanol based on furnace gas and excess coke oven gas (Case A) cost in 2013 was adjusted for inflation and converted to USD.*
Methanol	Methanol-3	Methanol Conventional gas	24.4	100.5	-15.2	(Winebrake, 2018) (Nyári, 2018)	*CO2e was calculated from CO2 and NOx. GWP of 1 (GHG Protocol) and GWP of 30 used* (Lammel et al, 1995). *Conventional gas assumed the same as the average production cost of natural gas based methanol (Methanol-1)*
Methanol	Methanol-4	Methanol Biomass - forest residue	5.6	81.7	6.3	(Winebrake, 2018) (European Commission, 2017)	*CO_2e was calculated from CO_2 and NOx. GWP of 1 (GHG Protocol) and GWP of 30 used* (Lammel et al, 1995). *For price, average taken from methanol based on wood cost in 2013. Value was adjusted for inflation and converted to USD.*

Fuel	Pathway code	Production Pathway description	Production Pathway GHG emissions (WTT) g CO_2eq/MJ	Total life cycle GHG emissions (WTP) g CO_2eq/MJ	GHG reduction potential calculated (%)	Sources	Comment
Methanol	Methanol-5	Methanol Landfill gas	-40.0	36.1	58.6	(Winebrake, 2018) (Lee et al, 2020)	*CO2e was calculated from CO2 and NOx. GWP of 1 (GHG Protocol) and GWP of 30 used* (Lammel et al, 1995). *For price average price taken of estimated production cost of methanol production process from landfill gas in 2020.*
Methanol	Methanol-6	Methanol coal	120.9	197.0	-126.0	(Winebrake, 2018) (Quirina et al, 2019)	*CO_2e was calculated from CO_2 and NOx. GWP of 1 (GHG Protocol) and GWP of 30 used* (Lammel et al, 1995) . *For price used value of estimated production cost for coal-based methanol production in 2017. Value was adjusted for inflation and converted to USD.*
Methanol	Methanol-7	Synthetic Methanol – Power-to-Fuel (PtF)	-68.9	7.2	91.7	(Eggemann , 2020) (Bos et al, 2020)	*Combustion emissions of methanol added to WTT value. For price used value of estimated production cost for renewable methanol production (synthetic) from water and CO2 air capture in 2020. Value was adjusted for inflation and converted to USD.*
DME	DME-1	Waste wood DME	2.1 - 2.2	2.1	97.6	(JRC,EUROCAR and CONCAWE, 2014) (European Commission, 2017)	*For price DME from wood average cost in 2015 was taken (assumes lower feedstock price). Value was adjusted for inflation and converted to USD.*
DME	DME-2	Farmed wood DME	5.1 - 18.9	6.5	92.5	(JRC,EUROCAR and CONCAWE, 2014) (European Commission, 2017)	*For price DME from wood average cost in 2015 was taken (assumes higher feedstock price). Value was*

Fuel	Pathway code	Production Pathway description	Production Pathway GHG emissions (WTT) g CO_2eq/MJ	Total life cycle GHG emissions (WTP) g CO_2eq/MJ	GHG reduction potential calculated (%)	Sources	Comment
							adjusted for inflation and converted to USD.
DME	DME-3	Coal EU mix DME	117.3 - 136.1	194.0	-122.5	(JRC,EUROCAR and CONCAWE, 2014) (Williams, 2015)	*Average taken of coal-based DME in 2015. Value was adjusted for inflation and converted to USD.*
DME	DME-4	Natural Gas EU production DME	24.8 – 33.6	97.7	-12.0	(JRC,EUROCAR and CONCAWE, 2014) (Brito Alves, 2005)	*Average taken of DME production costs from natural gas feedstock in 2005. Value was adjusted for inflation and converted to USD.*
FAME	FAME-1	Rapeseed feedstock (glycerine export as chemical or animal feed)	111.0	111.0	-27.3	(Verbeek, 2015) (European Commission, 2013)	*Also includes values excluding and including indirect land use change (iIUC). Average taken of FAME production costs using rapeseed feedstock in 2013. Value was adjusted for inflation and converted to USD.*
FAME	FAME-2	Rapeseed feedstock (glycerine to internal biogas production)	91.1	91.1	-4.5	(Verbeek, 2015) (European Commission, 2013)	*Also includes values excluding and including indirect land use change (iIUC). Average taken of FAME production costs using rapeseed feedstock in 2013. Value was adjusted for inflation and converted to USD.*
FAME	FAME-3	Palm oil feedstock (No CH4 recovery, no heat credit from residue)	94.5	94.5	-8.4	(Verbeek, 2015) (European Commission, 2013)	*Also includes values excluding and including indirect land use change (iIUC). Average taken of FAME production costs using palm oil feedstock in 2013. Value was adjusted for inflation and converted to USD.*

Fuel	Pathway code	Production Pathway description	Production Pathway GHG emissions (WTT) g CO_2eq/MJ	Total life cycle GHG emissions (WTP) g CO_2eq/MJ	GHG reduction potential calculated (%)	Sources	Comment
FAME	FAME-4	Palm oil feedstock (No CH4 recovery, heat credit from residue)	107.0	107.0	-22.7	(Verbeek, 2015) (European Commission, 2013)	*Also includes values excluding and including indirect land use change (iIUC). Average taken of FAME production costs using palm oil feedstock in 2013. Value was adjusted for inflation and converted to USD.*
FAME	FAME-5	Palm oil feedstock (CH4 recovery, heat credit from residue)	74.5	74.5	14.6	(Verbeek, 2015) (European Commission, 2013)	*Also includes values excluding and including indirect land use change (iIUC). Average taken of FAME production costs using palm oil feedstock in 2013. Value was adjusted for inflation and converted to USD.*
FAME	FAME-6	Waste cooking oil feedstock (purification and transesterification)	13.8	13.8	84.2	(Verbeek, 2015) (European Commission, 2013)	*Also includes values excluding and including indirect land use change (iIUC). Also includes values excluding and including indirect land use change (iIUC). Value of FAME production cost from UCO taken from Table 13 (2013). Assumed feedstock based on average market prices for UCO in 2015. Value derived was adjusted for inflation and converted to USD.*
FAME	FAME-7	Tallow feedstock (purification and transesterification)	26.3	26.3	69.8	(Verbeek, 2015) (European Commission, 2013)	*Also includes values excluding and including indirect land use change (iIUC). Also includes values excluding and including indirect land use change (iIUC). Value of FAME production cost from animal fat (tallow) feedstock taken from Table 13 (2013). Assumed feedstock based*

Fuel	Pathway code	Production Pathway description	Production Pathway GHG emissions (WTT) g CO_2eq/MJ	Total life cycle GHG emissions (WTP) g CO_2eq/MJ	GHG reduction potential calculated (%)	Sources	Comment
							on average market prices for animal fat in 2015. Value derived was adjusted for inflation and converted to USD.
HVO	HVO-1	Rapeseed feedstock (meal export to animal feed, hydrotreat oil)	112.0	112.0	-28.4	(Verbeek, 2015) (European Commission, 2017)	*Also includes values excluding and including indirect land use change (iIUC). Average taken of HVO production cost range in 2015. Assumes higher cost for rapeseed oil feedstock. Value was adjusted for inflation and converted to USD.*
HVO	HVO-2	Rapeseed feedstock (meal export to internal biogas production, hydrotreat oil)	92.0	92.0	-5.5	(Verbeek, 2015) (European Commission, 2017)	*Also includes values excluding and including indirect land use change (iIUC). Average taken of HVO production cost range in 2015. Assumes higher cost for rapeseed oil feedstock. Value was adjusted for inflation and converted to USD.*
HVO	HVO-3	Palm oil feedstock (No CH4 recovery, heat credit from residue)	104.0	104.0	-19.3	(Verbeek, 2015) (Festel, 2014)	*Also includes values excluding and including indirect land use change (iIUC). Also includes values excluding and including indirect land use change (iIUC). Average taken of HVO production cost range in 2015. Assumes lower cost for palmoil feedstock. Value was adjusted for inflation and converted to USD.*
HVO	HVO-4	Waste cooking oil feedstock (purification and transesterification)	8.1	8.1	90.7	(Verbeek, 2015) (European Commission, 2017)	*Also includes values excluding and including indirect land use change (iIUC). Also includes values excluding and including indirect land use change (iIUC). Uses HVO production cost in 2015. Assumes for*

Fuel	Pathway code	Production Pathway description	Production Pathway GHG emissions (WTT) g CO_2eq/MJ	Total life cycle GHG emissions (WTP) g CO_2eq/MJ	GHG reduction potential calculated (%)	Sources	Comment
							waste cooking oil there would be a lower feedstock price, lower bound value therefore selected from range. Value was adjusted for inflation and converted to USD.
HVO	HVO-5	Tallow feedstock (purification and transesterification)	24.5	24.5	71.9	(Verbeek, 2015) (European Commission, 2017)	*Also includes values excluding and including indirect land use change (iIUC). Also includes values excluding and including indirect land use change (iIUC). Uses HVO production cost in 2015. Assumes for tallow there would be a lower feedstock price, lower bound value therefore selected from range. Value was adjusted for inflation and converted to USD.*

A.6 Appendix 6 – Assessment of applicability, current implementation, and future ownership of technologies from Phase 1 report

Table 13-17: Summary of applicability of design measures by ship type, as well as their implementation and further uptake.

Vessel Design Measure	Applicable to Vessel type							Already widely implemented	Future ownership / operation (1-5)*
	Gen. cargo	Bulk carrier	Oil tanker	Chem. tanker	Container	Ro-Ro/ Passenger	LNG tanker		
Optimum ship size dimensions	X	X	X	X	X	X	X	Yes	5
Construction weight	X	X	X	X	X	X	X	Yes	5
Hull dimensions (form optimisation)	X	X	X	X	X	X	X	Yes	5
Bulbous bow retrofit	X	X	X	X	X	X	X	Yes	3
Bow thruster tunnel optimisation	X	X	X	X	X	X	X	Yes	3
Hull coatings	X	X	X	X	X	X	X	Yes	3
Interceptors						X		Cruise and Ro-Ro only	3
Ducktail waterline extension	X	X	X	X	X	X	X	Yes	1
Air lubrication	*Not widely applicable (Naval Architect)*							Icebreakers only or pilot projects	1
Trim optimisation and ballast reduction	X	X	X	X	X	X	X	Yes	5
Ballast free vessel design			X		X	X	X	No	NA

* On a scale of 1 to 5, with 1 being never and 5 being definitely, likelihood that operators/ owners will operate/own ships with these measures within the next 10 years.

Table 13-18: Summary of applicability of power assistance measures by ship type, as well as their implementation and further uptake.

Measure	Applicable to Vessel							Already widely implemented	Future ownership / operation (1-5)*
	Gen. cargo	Bulk carrier	Oil tanker	Chem. tanker	Container	Ro-Ro/ Passenger	LNG tanker		
Flettner rotors	X	X	X	X		X	X	No	4
Towing kites		X	X	X	X		X	No	1
Sails	*Not widely applicable – niche applications*							No	1
Solar panels	X				X	X		No	3
Shore power supply	X	X	X	X	X	X	X	No	3

* On a scale of 1 to 5, with 1 being never and 5 being definitely, likelihood that operators/ owners will operate/own ships with these measures within the next 10 years

Table 13-19: Summary of applicability of alternative propulsion technologies and adaptations by ship type, as well as their implementation and further uptake.

Measure	Applicable to Vessel							Already widely implemented	Future ownership/ operation (1-5)*
	Gen. cargo	Bulk carrier	Oil tanker	Chem. tanker	Container	Ro-Ro/ Passenger	LNG tanker		
Large area propellers (LAP)	X	X	X	X	X	X	X	Yes	3
Contra rotating propellers (CRP)	X	X	X	X	X	X	X	Yes	1
Podded thrusters	X	X	X	X	X	X	X	Yes	3
Ducts (PID)	X	X	X	X	X	X	X	Yes	3
Pre-swirl (PID)	X	X	X	X	X	X	X	Yes	3
Post-swirl fins and rudder bulbs	X	X	X	X	X	X	X	Yes	3

*On a scale of 1 to 5, with 1 being never and 5 being definitely, likelihood that operators/ owners will operate/own ships with these measures within the next 10 years.

Table 13-20: Summary of applicability of operational measures by ship type, as well as their implementation and further uptake.

Measure	Applicable to Vessel							Already widely implemented	Future operation (1-5)*
	Gen. cargo	Bulk carrier	Oil tanker	Chem. tanker	Container	Ro-Ro/ Passenger	LNG tanker		
Speed reduction (10%)	X	X	X	X	X	X		Yes	5
Speed reduction (20%)	X	X	X	X	X	X		Yes	5
Speed reduction (30%)	X	X			X	X	X	Yes	5
Advanced port logistics	X	X	X	X	X	X	X	No	3
Optimisation of vessel capacity utilisation	X	X	X	X	X	X	X	Yes	3
Advanced autopilots	X	X	X	X	X	X	X	Yes	3
Weather routing	X	X	X	X	X	X	X	Yes	5
Autonomous shipping	X	X	X	X	X	X	X	No	1-2
Power demand management e.g. lighting	X	X	X	X	X	X	X	Yes	5
Engine efficiency measurements	X	X	X	X	X	X	X	Yes	5
Hull cleaning and propeller cleaning and polishing	X	X	X	X	X	X	X	Yes	5

*On a scale of 1 to 5, with 1 being never and 5 being definitely, likelihood that operators/ owners will operate/own ships with these measures within the next 10 years.

A.7 Appendix 7 – Summary tables of technologies identified

Table 13-21: Summary of power assistance technologies

Technology	Options/ Applications	Already widely used?	Availability date	Likely adoption rate	Potential fuel consumption/ CO_2 reduction	Cost-effectiveness ($/tonne CO_2)
Wind assistance	Flettner rotors; not for container ships	No	Now	Low	3% - 15%	$15.98
	Towing kites; tankers and bulk carriers only	No	Now	Low	1% - 5%	$30.57
	Sails	No	Now	Low	1% - 10%	$1.88
Solar power	Not container ships	No	Now	Medium	0.5% - 2% (of auxiliary engine consumption)	$278.01
Onshore power supply	All vessel types	No	Now	Medium (implementation depends on port infrastructure)	50% - 100% of consumption in port	No cost data available

Table 13-22: Summary of propulsion technology options

Technology	Options/ Applications	Already widely used?	Availability date	Likely adoption rate	Potential fuel consumption/ CO_2 reduction	Cost-effectiveness ($/tonne CO_2)
Large area propellers (LAPs)	All large vessels	Moderate	Now	Medium	2% - 5%	$8.22
Contra-rotating propellers (CRPs)	All large vessels; not compatible with other propulsors	Moderate	Now	Medium	2% - 5%	$8.22
Ducted propellers	All vessel types; not compatible with other propulsors	Moderate	Now	Medium	0.5% - 5%	$12.78
Podded thrusters	All vessel types; not compatible with other propulsors	Moderate (but not on large cargo vessels)	Now	Medium	Up to 15%	$19.97
Pre-swirl	All vessel types; only compatible with LAPs and CRPs	Moderate	Now	Medium	Up to 10%	$3.52

Technology	Options/ Applications	Already widely used?	Availability date	Likely adoption rate	Potential fuel consumption/ CO_2 reduction	Cost-effectiveness ($/tonne CO_2)
Post-swirl	All vessel types; only compatible with LAPs	Moderate	Now	Medium	0.5% - 2%	$14.06

Table 13-23: Summary of engine technology options

Technology	Options/ Applications	Already widely used?	Availability date	Likely adoption rate	Potential fuel consumption/ CO_2 reduction	Cost-effectiveness ($/tonne CO_2)
Fuel injection valve improvements (slide valves)	Diesel-cycle engines	Yes	Now	High	0%	No cost data available
Common rail fuel injection	Diesel-cycle engines	Yes	Now	High	0.40%	No cost data available
Water in Fuel Emulsion/Water Injection	Diesel-cycle engines	No	Now	Low	Small – main benefits are on NOx and particulate matter emissions	No cost data available
Hybrid diesel-electric	Diesel-cycle engines	Yes for cruise ships, not for large cargo vessels	Now	Medium	May cause increase in fuel consumption for large ocean-going vessels	No cost data available
Early Intake Valve Closing (Miller cycle)	Diesel-cycle engines	Yes	Now	High	Unclear, but already widely adopted, so little future benefit	No cost data available
Dual fuel/gas engines	Low pressure (Otto cycle)	No	Now	High (scenario dependent)	None (emissions reduction due to alternative fuel, not engine technology)	No cost data available
	High pressure (diesel cycle)	No	Now	High (scenario dependent)	None (emissions reduction due to alternative fuel, not engine technology) - provides reduced methane slip	No cost data available

Technology	Options/ Applications	Already widely used?	Availability date	Likely adoption rate	Potential fuel consumption/ CO_2 reduction	Cost-effectiveness ($/tonne CO_2)
Ammonia engines (diesel cycle)	Diesel-cycle engines	No	2025	High (scenario dependent)	None (emissions reduction due to alternative fuel, not engine technology)	No cost data available
Carbon capture (CC)	All vessel types (some limitations due to space requirements)	No	2025	Low	Up to 100% emissions reduction; may be accompanied by up to 20% increase in fuel consumption.	$35.37**
Waste heat recovery (WHR)	All vessel types	Moderately	Now	Medium	3% - 8%	No cost data available

*** Only very limited cost data for mobile CC systems are available. The calculation of cost-effectiveness presented here uses an average value estimated for a, 8,000 tonne DWT vessel scaled up to a 60,000 tonne DWT vessel and assumes that the vessel fuel consumption is increased by 20%. It should be noted that other studies (e.g.* (Feenstra, et al., 2019)*) have identified significant higher costs per tonne CO_2, with a strong non-linear dependence on vessel size.*

Table 13-24: Summary of operational improvements options

Technology	Options/ Applications	Already widely used?	Availability date	Likely adoption rate	Potential fuel consumption/ CO_2 reduction	Cost-effectiveness ($/tonne CO_2)
Speed reduction	10% speed reduction	Yes	Now	High	10% - 15% per ship, combined with 5% to 7% increase in fleet size	-$56.03
	20% speed reduction	Yes	Now	Medium	18% - 28% per ship, combined with 12% to 15% increase in fleet size	-$56.36
	30% speed reduction	Yes	Now	Low	24% - 38% per ship, combined with 21% to 26% increase in fleet size	-$56.31
Voyage planning and weather routing	-	Yes	Now	High	0% - 5%	-$56.24
Advanced autopilots	-	No	Now	Medium	0.25% - 1.5%	-$58.10
Autonomous shipping	-	No	2030	Low	Up to 6%	-$55.39
Ship system management	Power demand	Yes	Now	High	0.25% - 5%	-$56.54

Technology	Options/ Applications	Already widely used?	Availability date	Likely adoption rate	Potential fuel consumption/ CO_2 reduction	Cost-effectiveness (\$/tonne CO_2)
Hull and propeller condition management	Energy efficiency measuremen t	Yes	Now	High	Up to 5%	-$56.24
	Hull cleaning	Yes	Now	High	1% - 5%	-$55.39
	Propeller cleaning and polishing	Yes	Now	High	3% - 4%	-$56.61
Vessel capacity utilisation	-	Yes	Now	Medium	0% - 30%	-$56.24
Port logistics	-	No	Now	Medium	Up to 1%	-$51.13

A.8 Appendix 8 – Full decision matrix used to inform fuel and technology package development

Technology/Measure		Criteria score (1-3)				Assessment		
		Readiness level	Likely adoption rate	Cost-effectiveness	Total score	TRL (1-9)	Adoption (1-5)	Cost-effectiveness* ($/tonne CO_2)
Vessel design measures	Optimum ship size dimensions	3	3	0	6	9	5	-
Vessel design measures	Construction weight	3	3	0	6	9	5	-
Vessel design measures	Hull dimensions (form optimisation)	3	3	3	9	9	5	$3.46
Vessel design measures	Bulbous bow retrofit	3	2	3	8	9	3	$9.19
Vessel design measures	Bow thruster tunnel optimisation	3	2	3	8	9	3	$1.44
Vessel design measures	Hull coatings	3	2	3	8	9	3	$6.77
Vessel design measures	Interceptors	3	2	0	5	9	3	-
Vessel design measures	Ducktail waterline extension	3	1	0	4	9	1	-
Vessel design measures	Air lubrication	2	1	2	5	7/8/9	1	$17.27
Vessel design measures	Ballast reduction and trim optimisation	3	3	3	9	9	5	$1.44
Power assistance	Flettner rotors	3	2	2	7	9	4	$15.98
Power assistance	Towing kites	2	1	2	5	7/8/9	1	$30.57
Power assistance	Sails	3	1	3	7	9	1	$6.92
Power assistance	Solar panels	3	2	1	6	9	3	$70.05
Power assistance	Shore power supply	3	2	0	5	8/9	3	-
Propulsion devices	Large area propellers (LAP)	3	2	3	8	9	3	$8.22
Propulsion devices	Contra rotating propellers (CRP)	3	1	2	6	9	1	$30.26
Propulsion devices	Podded thrusters	3	2	2	7	9	3	$19.97
Propulsion devices	Ducts (PID)	3	2	2	7	9	3	$12.78
Propulsion devices	Pre-swirl (PID)	3	2	3	8	9	3	$3.52
Propulsion devices	Post-swirl fins and rudder bulbs (PID)	3	2	3	8	9	3	$14.06
Engine / aftertreatment	Fuel injection valve improvements (slide valves)	3	0	0	3	9	Feedback was to include in baseline.	-
Engine / aftertreatment	Common rail fuel injection	3	0	0	3	9		-
Engine / aftertreatment	Water in Fuel Emulsion (WiFE)/Water Injection	3	0	0	3	9		-
Engine / aftertreatment	Hybrid diesel-electric	3	0	0	3	9		-
Engine / aftertreatment	Early Intake Valve Closing (Miller cycle)	3	0	0	3	9		-
Engine / aftertreatment	Waste heat recovery (WHR)	3	2	1	7	9	3	$81.34
Carbon capture & storage (CCS)		2	1	2	5	4	1	$37.23**

Technology/Measure		Criteria score (1-3)				Assessment		
		Readiness level	Likely adoption rate	Cost-effectiveness	Total score	TRL (1-9)	Adoption (1-5)	Cost-effectiveness* ($/tonne CO_2)
Vessel operational measures	Speed reduction	3	3	3	9	9	5	$0.0
	Advanced port logistics	3	2	3	8	8/9	3	$0.0
	Optimisation of vessel capacity utilisation	3	2	3	8	8/9	5	$0.0
	Advanced autopilots	3	2	3	8	9	3	$0.0
	Voyage planning and weather routing	3	3	3	9	9	5	$0.64
	Autonomous shipping	2	1	3	6	5/6/7	1-2	$0.0
	Power demand management e.g. lighting	3	3	3	9	9	5	$2.46
	Engine efficiency measurements	3	3	3	9	9	5	$0.0
	Hull cleaning	3	3	3	9	9	5	$0.59
	Propeller cleaning and polishing	3	3	3	9	9	5	$0.11

A.9 Appendix 9 – Fuel production infrastructure CAPEX and OPEX data

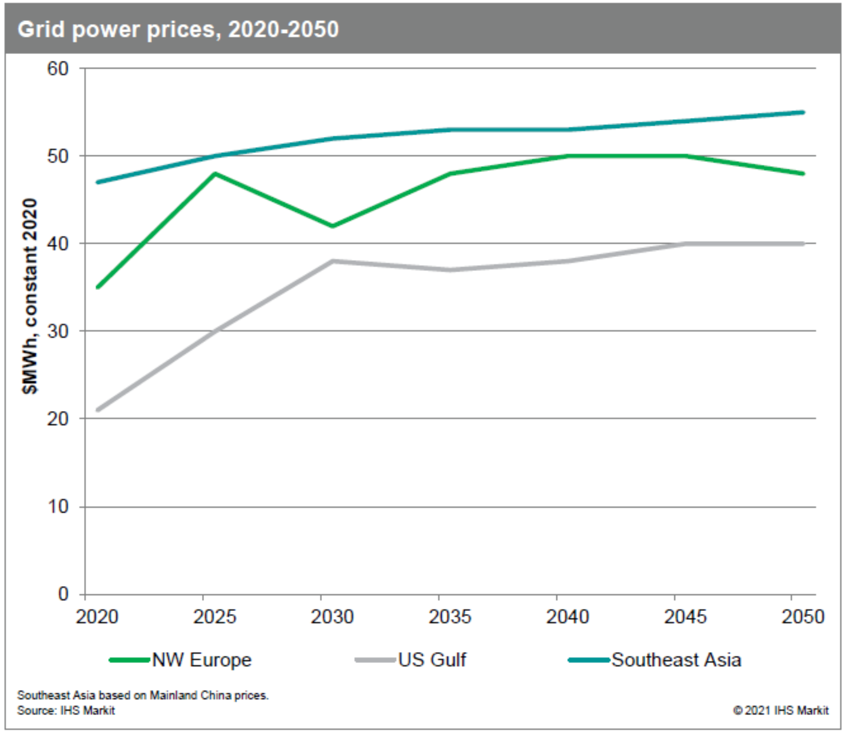
Fuel type	Fuel pathway	Example plant capacity (Mt/yr)	Example plant CAPEX ($m)	Example plant CAPEX/total energy ($/GJ)	Reference(s)	Comment
HFO	Conventional	1.47	1190	$1.01	(FuelsEurope, 2018) (Canadian Fuels Association, 2013) (JWEnergy, 2017) (BP, 2019)	Assumes a split of 0.4% diesel and 0.128% heavy fuel oil production based on FuelsEurope (OECD & IEA) source. Calculations undertaken to convert barrels to tonne for capacity and CAPEX by product type using BP conversion values.
MDO	Conventional	3.91	3720	$1.11	(FuelsEurope, 2018) (Canadian Fuels Association, 2013) (JWEnergy, 2017) (BP, 2019)	Assumes a split of 0.4% diesel and 0.128% heavy fuel oil production based on FuelsEurope source. Calculations undertaken to convert barrels to tonne for capacity and CAPEX by product type using BP conversion values.
LNG	Global average LNG	10.00	10000	$0.52	(CBC, 2020) (OffshoreEnergy, 2015)	Proposed $10B liquefied natural gas project in Guysborough County (Goldboro). Lifetime value taken "for end use in FTA countries for a period of 20 year". Capacity "10 million metric tons per annum" value used. CAPEX of 10 Billion $ value used.
BioLNG	Liquid manure (closed digestate storage)	0.01	14	$2.05	(Navigant, 2019)	Anaerobic digestion plant values (including upgrading unit).
Grey Hydrogen	Steam reforming natural gas	0.79	223	$0.12	(IEAGHG, 2017)	Total capital for base case H2 plant (SMR *without* CCS)
Blue Hydrogen	Natural gas and CCS	0.04	411	$4.69	(IEAGHG, 2017)	Total capital for SMR *with* CCS and liquefaction. SMR plant includes electricity for own consumption from heat recovery.
Green Hydrogen	Hydrogen - Electrolysis (renewable energy)	0.04	719	$8.21	(FCH2 JU, 2017) (Morgan, 2013)	Green hydrogen PEM including liquefaction.

Fuel type	Fuel pathway	Example plant capacity (Mt/yr)	Example plant CAPEX ($m)	Example plant CAPEX/total energy ($/GJ)	Reference(s)	Comment
Grey Ammonia	Conventional natural gas feedstock - EU electricity mix	0.44	705	$4.24	(Brown, 2017)	Natural gas ammonia plant CAPEX.
Blue Ammonia	Natural gas and CCS	0.21	357	$4.56	(Morgan, 2013)	
Green Ammonia	100% renewable production	1.20	5000	$11.02	(Morgan, 2013)	
Grey Methanol	Natural gas	1.50	1166	$1.30	(ADI analytics, 2017)	Based on typical natural gas U.S. methanol plant
Green Methanol	Synthetic methanol - Power to fuel	3.60	1854	$0.86	(Nyári, 2018)	
FAME	Waste cooking oil	0.25	581	$4.15	(ECOFYS, 2013)	Values taken for the Harvest Energy operational plant that produces biodiesel (FAME) from primarily waste oils
HVO	Waste cooking oil (standalone plants)	0.50	321	$0.97	(TOTAL, 2019)	Based on Total's La Mède HVO biorefinery.

A.10 Appendix 10 – Fuel price development narrative

As noted in Section 6.2.1 of the report, the fuel price projections used for the cost modelling in this study were provided by IHS Markit. This Appendix provides the accompanying narratives on the development of those projections.

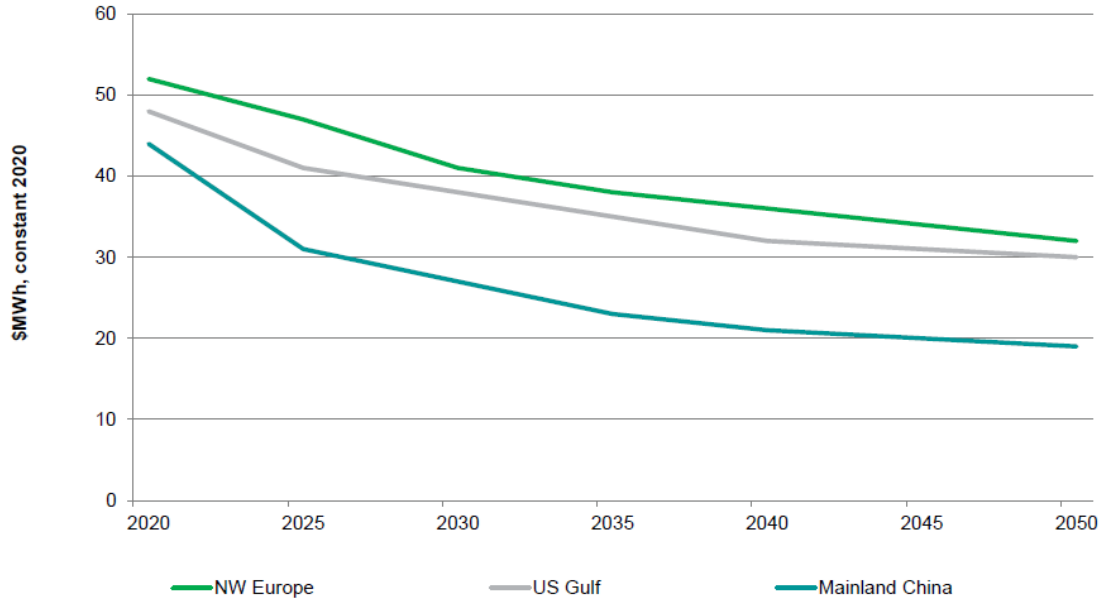
Electrical power prices – sourced via grid



- Grid prices include a mix of energy sources, with the mix evolving through the forecast. This evolution is dependent on the region.
- IHS Markit expects grid prices to increase through the forecast, as a result of increased demand, resulting in greater investment in power generation and transmission. Investments in large-scale renewable projects will be dominating factor.
- Grid prices in Southeast Asia are anticipated to remain stable, compared to other regions. As the prices are based on Mainland China's prices, this will be down to the energy sector being highly reliant on renewable sources.
- In the short-term, the increase of prices in Northwest Europe are a result of gas and oil demand, however these influences on power prices are removed by 2030. IHS Markit expects prices in the region to climb in the first half of the 2030's, as increased investment in renewables, particularly offshore wind-power pushes on-grid prices up. These are expected to tail-off towards the late-2040's, as efficiency gains reduce the demand on the regional grid.
- US Gulf electricity prices are estimated to remain the lowest cost throughout the forecast period. However, IHS Markit expects a steep rise through to 2030, as considerable investment is undertaken in the regional network to meet a surge in demand. Prices are expected to level-off, post-2030, as whilst new and more efficient power generation comes online, it is sufficient to meet demand.

Electrical power prices – via dedicated onshore wind-farm

Onshore wind-farm power prices, 2020-2050



Source: IHS Markit

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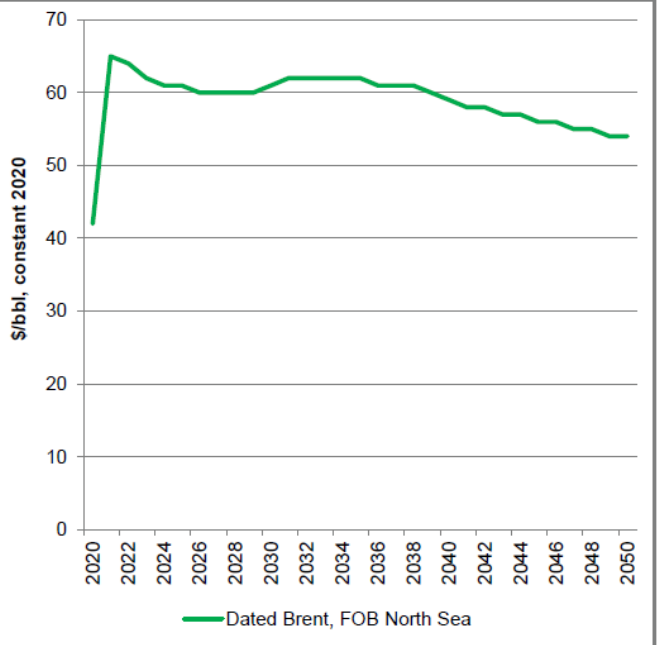
- Onshore wind-farm power is based on a dedicated supply, linked to the plant. This is calculated as the renewable power technology capex of the plant start-up year. Over the course of the forecast, IHS Markit expects costs to reduce. These costs include operation and maintenance costs.
- CAPEX costs are estimated to be lower in Southeast Asia (Mainland China), than in the US or Northwest Europe.
- Production costs are also expected to fall the fastest in the Southeast Asia, -30% in the first five-years, and another -13% between 2025 and 2030, before leveling off to around -5%.
- Production costs in Northwest Europe and US Gulf coast follow a similar reduction, dropping around 10% in the first two five-year periods, ahead of leveling off to around -5% reduction in the final five-year periods.

Dated Brent

Dated Brent, FOB North Sea prices, 2020-2050



Source: IHS Markit

Methodology

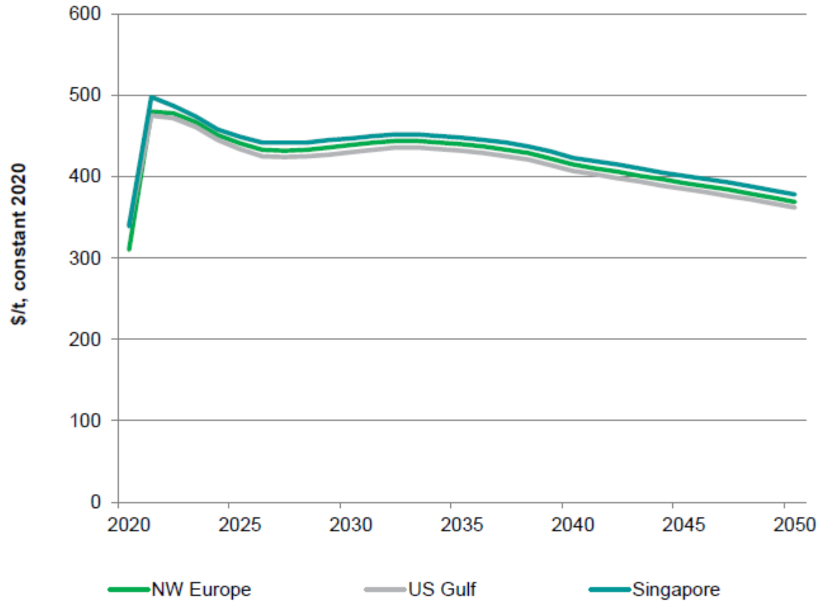
- It is estimated that Brent/Dated Brent is used as the benchmark price for around 65% of crude oil trade.
- IHS Markit uses its Brent outlook as the starting point for forecasting other crude prices and refined product prices.
- Long-term Brent crude prices are projected by IHS Markit on an annual average basis. This long-term price outlooks is based on our fundamental supply and demand models, industry costs, geopolitics, and other factors, including:
  - Full-cycle finding, development, and production costs for volumes required to meet long-term demand and offset base production decline
  - Change in long-term call on OPEC crude
  - Investment and operating climate in key producing countries
  - Market expectations

Pricing

- All oil prices fell in 2020 as a result of the COVID-19 induced demand reduction.
- We expect a price recovery in 2021, following a successful vaccination program which improved market demand.
- In the early 2020s, after 2021, IHS Markit expect a price weakening, as the OPEC+ restricted supply returns to the market, followed by a slight supply tightening in the later 2020s, as a result of the current lack of crude exploration.
- From the mid-2030s onwards we expect crude prices to reduce, in line with falling global oil demand.

HFO

HFO prices, 2020-2050



Note: Based on VLSFO (0.5%S)
Source: IHS Markit

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Methodology

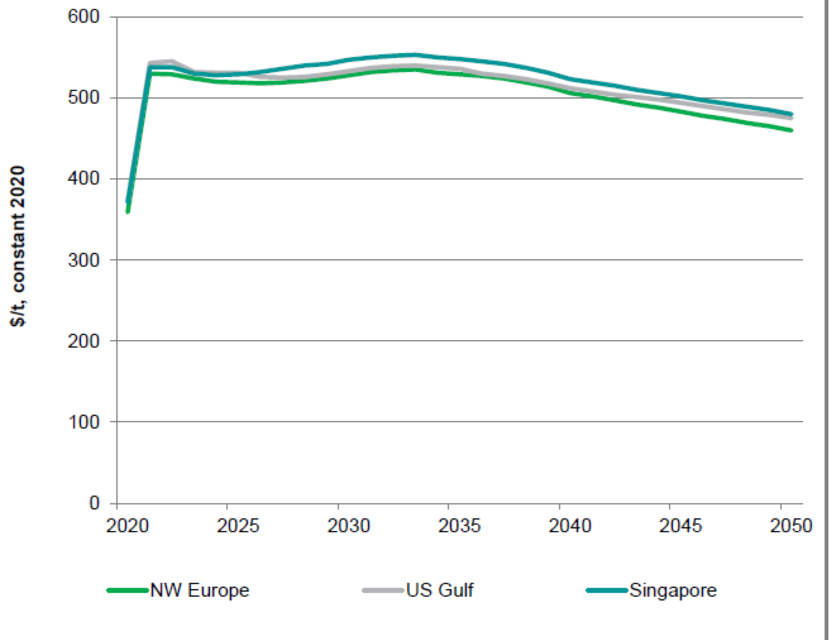
- Heavy fuel oil (HFO) price forecast is directly influenced by crude price. IHS Markit bases these prices on a combination of manufacturing costs (refinery economics) combined with demand and market forces in each regional market.
- Various streams on a refinery are blended to make HFO, the majority comes from the vacuum residue, but a lighter oil "cutter" is also required in order to meet viscosity and density specifications.
- Northwest Europe prices are based on 0.5% sulfur HFO, effectively VLSFO bunker grade.
- US Gulf coast is based on 0.5% sulfur HFO, priced on heavy crude refining in the region.
- Singapore HFO prices are based on Northwest Europe prices (0.5% sulfur HGO), with addition of freight, as this is an important trade flow.

Pricing

- HFO will follow the crude oil price, recovering in 2021 from the 2020 COVID-19 induced low. After peak demand in crude oil in the early 2030's, HFO price will steadily decrease, dropping below $400/t in the mid-2040s.
- The decrease will be exacerbated by the fall in demand for fuel oil, as the fleet begins to transition away from convention bunker fuels.
- Whilst any new ships which enter service consuming HFO will more efficient than their predecessors, to meet EEDI and EEXI targets set out by IMO.

MDO

MDO prices, 2020-2050



Source: IHS Markit

Methodology

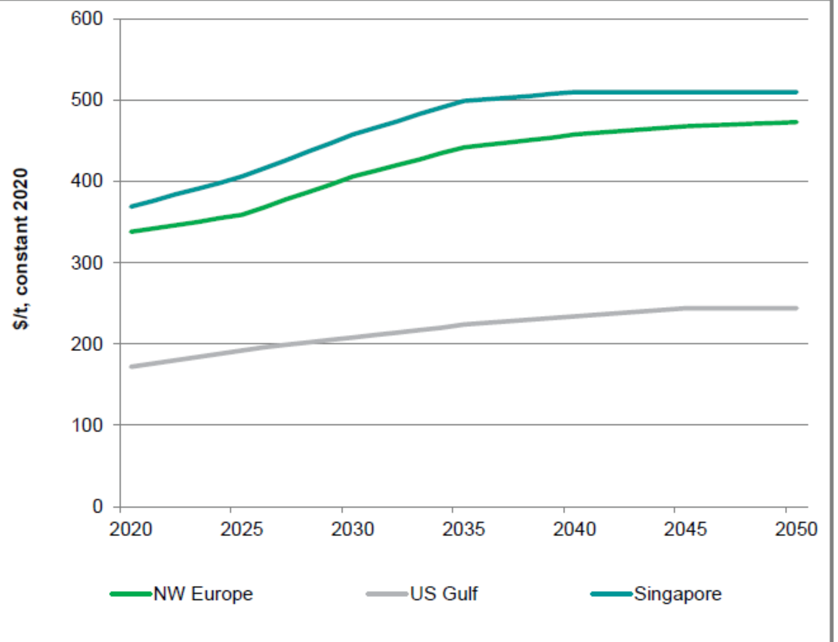
- Marine diesel oil (MDO) is 0.1% sulfur emission control area (ECA) compliant bunker fuel.
- The price forecast is directly influenced by crude price. IHS Markit bases these prices on refining economics, based on each regional market.
- Northwest Europe prices are based on catalytic cracking refinery.
- US prices are based on heavy crude processing through a cracking refinery.
- Singapore MDO prices are based on Northwest Europe prices, with addition of freight.

Pricing

- MDO will follow the crude oil price. Initially recovering in 2021 and then after peak demand in crude oil in the early 2030's, MDO price will steadily decrease, dropping to between $460-$480/t in 2050.
- Like HFO, MDO will see a similar decrease in demand, as the fleet partially transitions away from fossil-fuels.
- MDO price will be further impacted over the forecast period, as it is favoured by smaller vessels. As this fleet is replaced, new vessels are more likely to be fitted with alternative fuels for propulsion, which will create a greater surplus of the product, further pushing the price down across all regions.

LNG

LNG prices, 2020-2050



Source: IHS Markit

Methodology

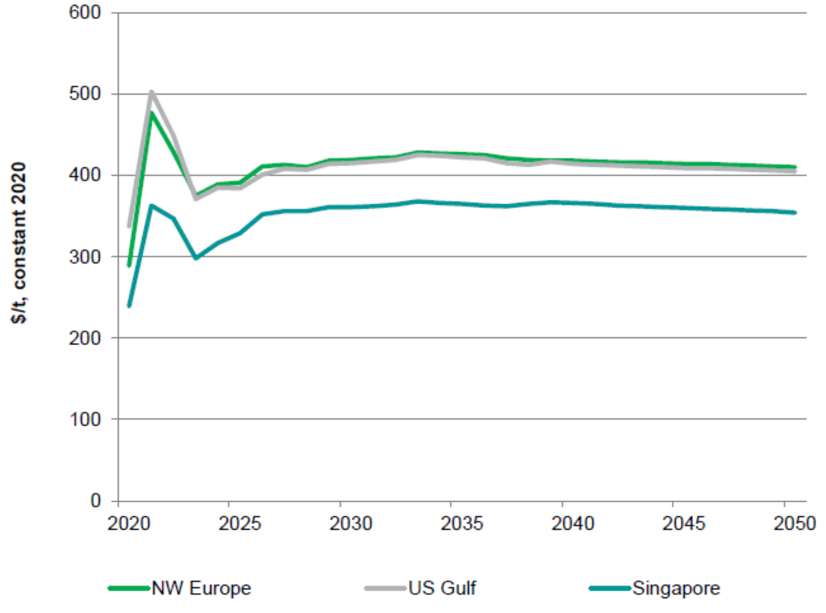
- IHS Markit models the long-term outlooks for contracted liquified natural gas (LNG) deliveries based on the supply demand balance in the relevant market, existing contracted volumes, our expectations for future contracting, the oil price, and the US Henry Hub gas price.
- For US Gulf, prices are based on Henry Hub price.
- Northwest Europe prices include freight, to Zeebrugge.
- Southeast Asia prices include freight, from Middle East.

Pricing

- The LNG market is currently in a substantial period of over-supply. Through the 2020s, IHS Markit expect the LNG market to gradually tighten, as demand increases, but new project sanctions are limited as a result of the low price.
- Over the forecast period, there is expected to be greater demand on LNG for power generation, as coal is phased out. However, an increase in renewables in the power-market will limit this growth.
- Introduction of alternative fuels into the transportation and power generation sectors is anticipated to also ease demand on LNG, slowing down price increases in the mid-2030's.
- Through the forecast, Northwest Europe and Southeast Asians prices are expected to remain higher than US Gulf prices, as there will be a degree of transportation/freight involved to balance supply/demand in the market.

Methanol (grey)

Methanol, Grey prices, 2020-2050



Source: IHS Markit

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Methodology

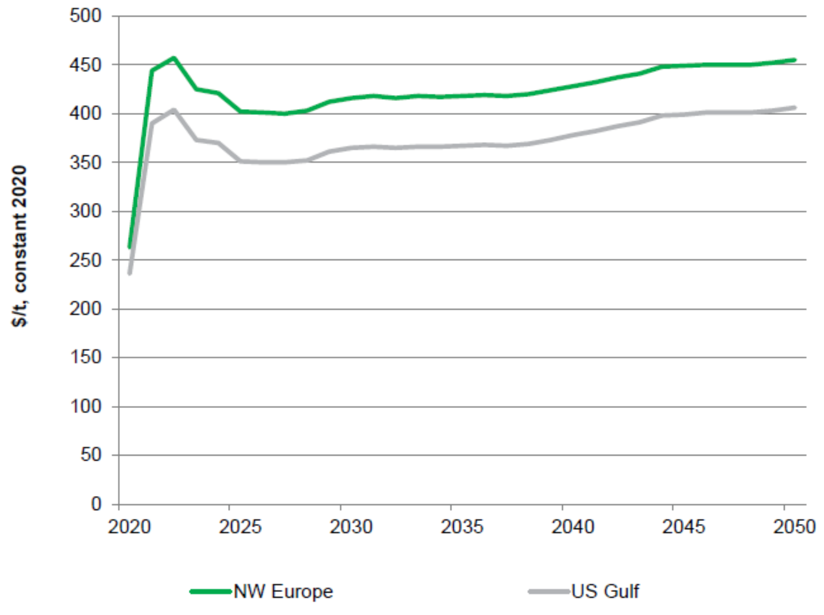
- IHS Markit calculates the forward prices based on the price of the feedstock, as well as the price of methanol's derivatives.
- Methanol feedstocks in Northwest Europe and US Gulf coast are influenced by LNG prices, whilst in Asia, coal is the primary feedstock.
- Methanol is used as a feedstock for a variety of products, including; MTO/MTP (Methanol-to-olefins and methanol-to-propylene), methyl methacrylate (MMA), methylamines, dimethyl terephthalate (DMT), chloromethanes and solvents.

Pricing

- Currently, China has a huge appetite for methanol, which has pushed Northwest Europe and US Gulf prices, to comparable Asian prices, plus freight and taxes. IHS Markit expects this trend to continue through the early part of the forecast, with Asian prices determining prices in other locations.
- Following the post-pandemic demand surge in 2021, prices have temporarily decoupled from LNG, but are expected to settle, as supply re-adjusts between 2021 and 2025.
- Whilst additional domestic methanol production will assist China in meeting the country's rising demand, with an increased demand on methanol as an alternative energy feedstock and in MTO production, the country will still need to rely on imports. This will keep prices in US Gulf and Northwest Europe aligned for the duration of the forecast.

Ammonia (grey)

Ammonia, Grey prices, 2020-2050



Source: IHS Markit

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Methodology

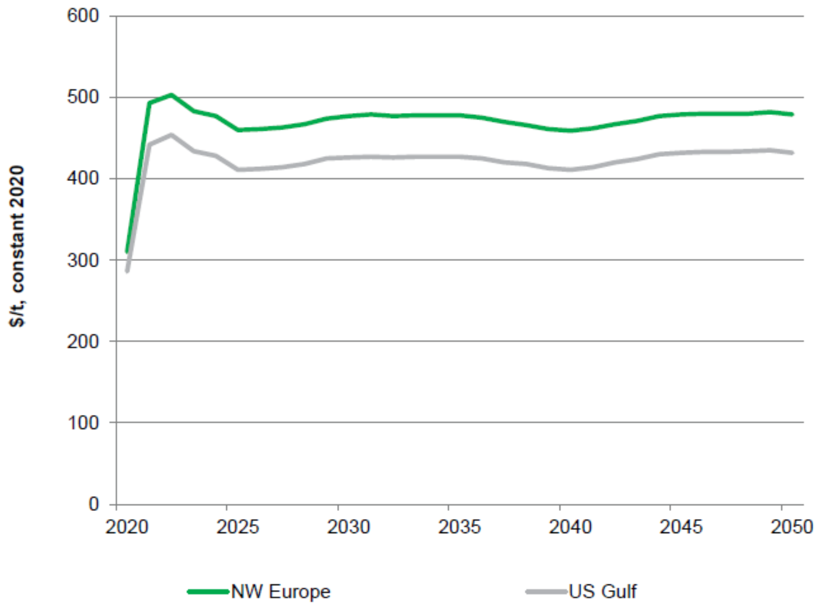
- Grey ammonia is directly influenced by LNG prices in the relative regions. This is because at present LNG is the primary feedstock to make hydrogen, which is required to make ammonia.
- Therefore, ammonia is also closely related to hydrogen prices.
- IHS Markit does not provide a forecast for Singapore.

Pricing

- Following the COVID-19 induced lows of 2020, prices climbed in 2021 as compensation packages and injections into the economy, stimulated consumption. This spike in demand, outweighed the supply, pushing prices up in all regions, and decoupling from feedstock prices. IHS Markit expects this to continue for the short-term, before supply/demand balances, stabilizing prices.
- Through the forecast period, the price of grey ammonia in both Northwest Europe and US Gulf will follow the same trend through the forecast, with the difference in prices being down to freight costs.

Ammonia (blue)

Ammonia, Blue prices, 2020-2050



Source: IHS Markit

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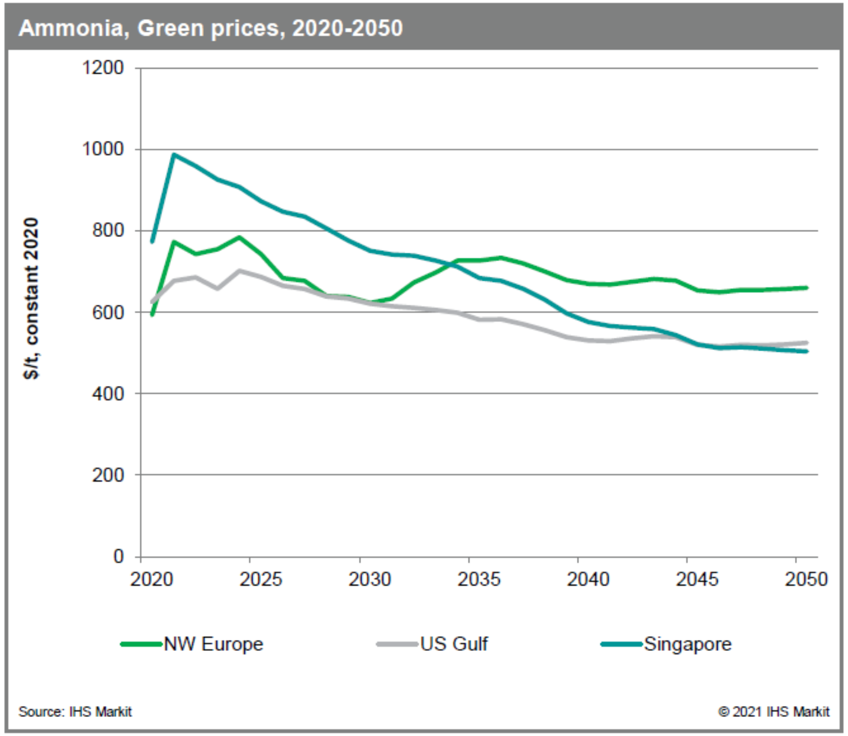
Methodology

- It should be noted there is currently no consensus on pricing for blue ammonia, and therefore IHS Markit has modelled this based on how it is likely to be priced in the market, aligned with hydrogen pricing.
- Blue ammonia prices are priced the same as grey ammonia, influenced by regional LNG prices. However, additional expense of CCS and sequestration is also included.
- Within the forecast, IHS Markit assumes there will be a fall in sequestration costs every decade, as processes become more efficient, transport costs fall, and more sites become available.

Pricing

- Following an abrupt price increase in the short-term, prices will level out. During the mid- and late-2020's, blue ammonia will be priced between $460/t-$477/t in Northwest Europe, roughly around $50/t more than in the US Gulf.
- This price differential between the two locations will remain through the forecast period, with Northwest Europe priced at $479/t by 2050.

Ammonia (green)



Methodology

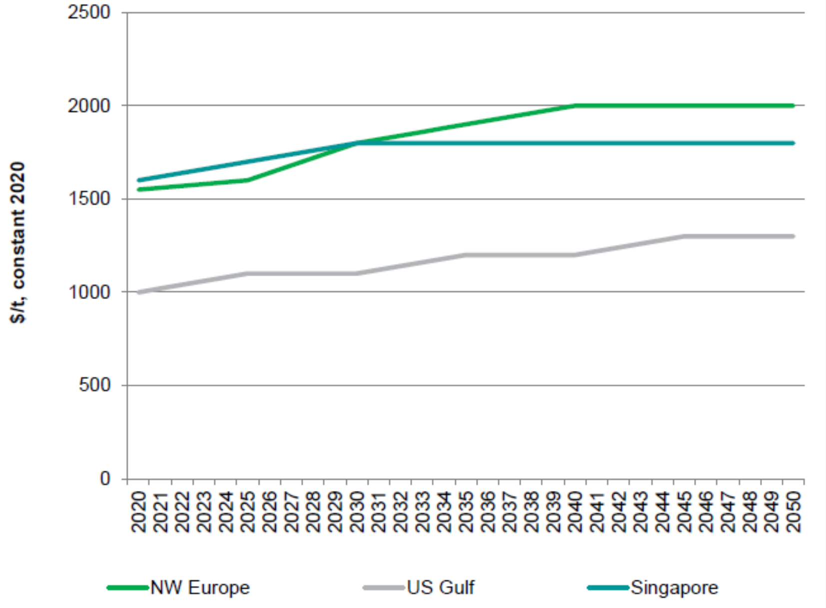
- It should be noted there is currently no consensus on pricing for green ammonia, and therefore IHS Markit has modelled this based on how it is likely to be priced in the market, based on hydrogen pricing (based on grid power supply).
- Whilst guided by blue ammonia prices, the price of green ammonia is modelled around regional LNG prices, as well as electricity prices. For the purposes of this forecast, grid prices are used.
- In order to consider efficiency improvements in the production process, step changes are applied to the forecast every ten years, to reflect the reduced demand for electricity.
- A further reduction is applied every five years, as an incentive discount.

Pricing

- Through the forecast period, green ammonia prices in Southeast Asia are estimated to drop, going from the most expensive to the cheapest, after remaining on par with US Gulf coast through the final decade. Much of this is reduction is likely to be as a result in the reduction in freight costs.
- Within Northwest Europe, prices will fluctuate through the forecast. Increased demand will push prices up, however these increases will be balanced by efficiency improvements in the production process and increased supply, which will push prices back down during periods.
- In contrast to Northwest Europe, prices on the US Gulf coast will steadily drop through the forecast, with ample supply available to meet demand, with efficiently gains in the production process contributing to the cost reduction.

Hydrogen (grey)

Hydrogen, Grey prices, 2020-2050



Source: IHS Markit

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Methodology

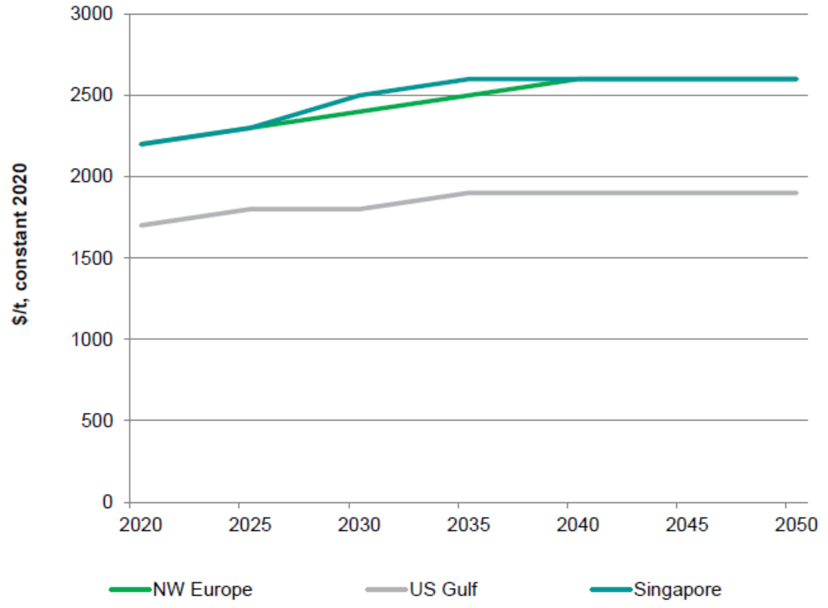
- The forecast is based on grey hydrogen produced from LNG, via a Steam Methane Reforming (SMR) unit. LNG feedstock prices are aligned to regional prices.
- Carbon taxes are omitted from the forecast.

Pricing

- Prices for grey hydrogen are largely driven by the regional price increases of LNG.
- Northwest Europe prices will be the highest of the three regions, due to the requirement to ship the feedstock into the region. Between 2020 and 2040, grey hydrogen prices in the region will rise from $1,600/t to $2,000/t, where they will remain for the remainder of the forecast.
- In US Gulf coast, local availability of the feedstock means the price of grey hydrogen is the lowest of the three locations. During the forecast, we expect grey hydrogen price to rise from $1,000/t to $1,300/t.

Hydrogen (blue)

Hydrogen, Blue prices, 2020-2050



Source: IHS Markit

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Methodology

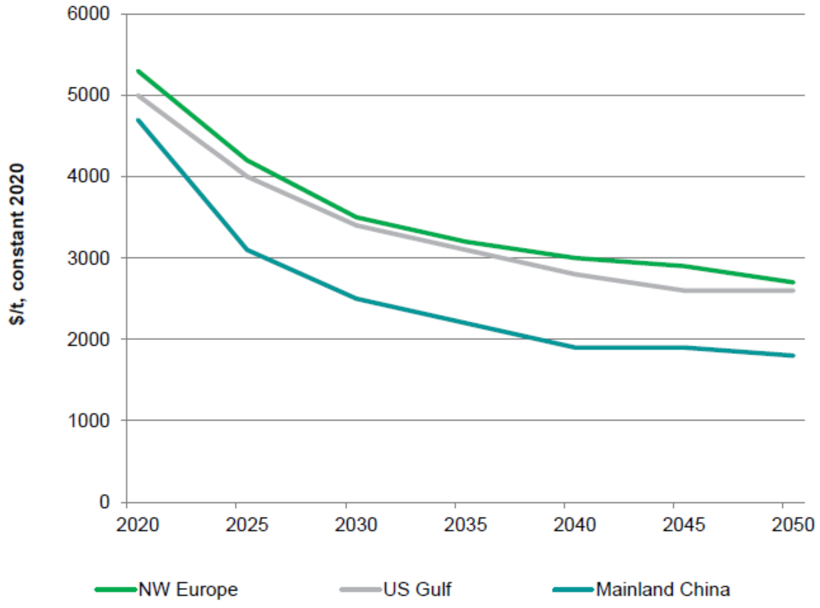
- Forecast is based on blue hydrogen produced from LNG, via an Autothermal Reforming (ATR) unit, with 92% carbon capture.
- Costs associated with CCS and sequestration are included in the forecast.
  - Costs are based on collection of the CO2, transportation by ship (around 500km), then pipeline delivery to offshore storage site (depleted offshore well).
- Any carbon taxes incurred are omitted from the forecast.

Pricing

- Availability of feedstock (LNG) influences prices greatly. Prices on the US Gulf coast will remain the lowest through the forecast period, due to local availability of feedstock and sequestration facilities.
- Northwest Europe and Southeast Asian (Singapore) prices will align through the forecast, with Singaporean costs receiving a premium from the mid-2020's to 2040. This is increase is related to greater transport costs for CO2, which diminish post-2040, as the CO2 supply chain becomes more cost efficient.
- Freight costs, for both blue hydrogen and CO2 waste will widen the delta between US Gulf coast and Northwest Europe & Southeast Asian prices through the forecast, increasing the price of blue hydrogen from $500/t to $700/t between 2020 and 2050.

Hydrogen (green – onshore wind-power)

Hydrogen, Green (onshore wind-power) prices, 2020-2050



Source: IHS Markit

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Methodology

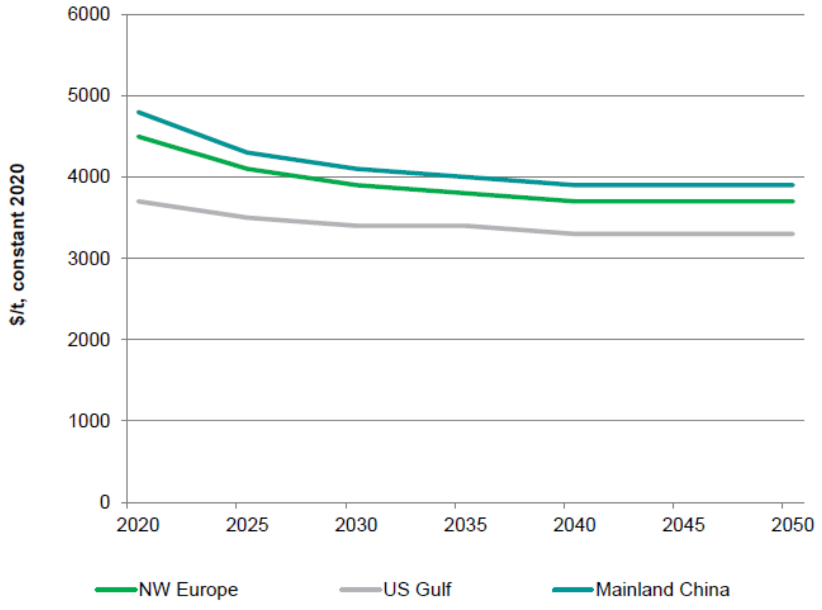
- Green hydrogen is produced via water electrolysis alkaline process, using grid power. Electrical price is the major influence in the pricing of green hydrogen.
- Renewable power, in this scenario is from dedicated onshore-wind power supply.
- IHS Markit's forecast expects there to be an improvement in the efficiency of the electrolysis process, which will reduce demand on electricity during the forecast period.

Pricing

- Whilst LNG feedstock prices will increase, the price of green hydrogen will fall. This is due to the prices being heavily influenced by electricity prices. Mainland China is expected to see the lowest priced green hydrogen, based on the lower priced electricity supply, than compared to the other regions. Over the course of the forecast, the price delta between these regions for green hydrogen will widen, from $600/t in 2020, before peaking at $1080/t, before falling back to $900/t a decade later.
- Prices in Northwest Europe for green hydrogen will fall from $5,300/t to $2,700/t during the forecast period, whilst a similar drop from $5,000/t to $2,600/t will be seen on the US Gulf coast.

Hydrogen (green – grid price)

Hydrogen, Green (grid) prices, 2020-2050



Source: IHS Markit

Methodology

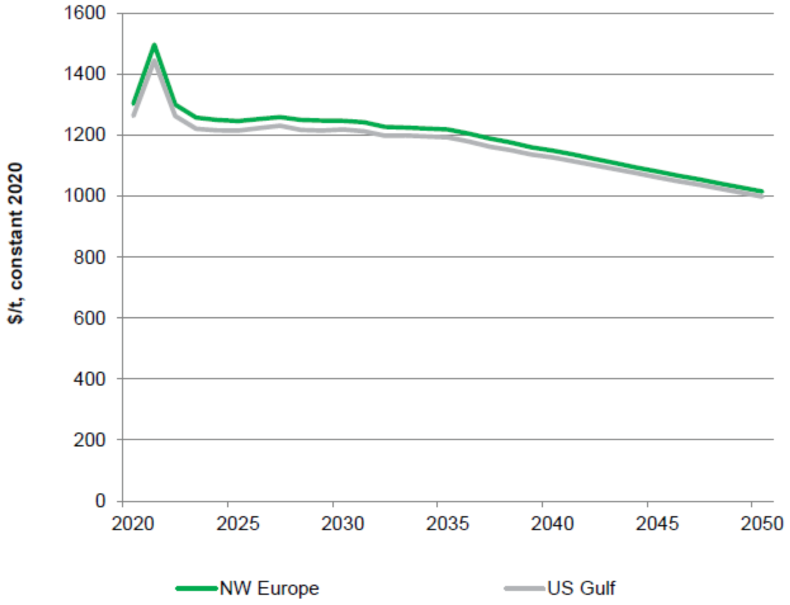
- Green hydrogen is produced via water electrolysis alkaline process, using grid power. Electrical price is the major influence in the pricing of green hydrogen.
- Price for power in this scenario is based on local grid price.
- IHS Markit's forecast expects there to be an improvement in the efficiency of the electrolysis process, which will reduce overall demand on electricity during the forecast period.

Pricing

- With less of an efficiency gain seen in the power generation, electricity prices are more stable throughout the forecast, than seen in the green hydrogen produced from electricity sourced from onshore wind-power. This results in a more stable price for green hydrogen.
- On this basis, green hydrogen on the US Gulf coast will be the lowest priced, of the examples, taking advantage of lower priced electricity. During the forecast, prices will fall from $3,700/t to $3,300/t.
- Mainland China is expected be the most expensive source of green hydrogen. The price differential with US Gulf coast will gradually reduce, as the costs in China fall, starting the forecast $1,100/t more expensive, and dropping to $600/t by 2050. A similar reduction will be seen in the differential between US Gulf coast and Northwest Europe, which will halve from $800/t to $400/t over the forecast period.

FAME

FAME prices, 2020-2050



Note: No price for Singapore
Source: IHS Markit

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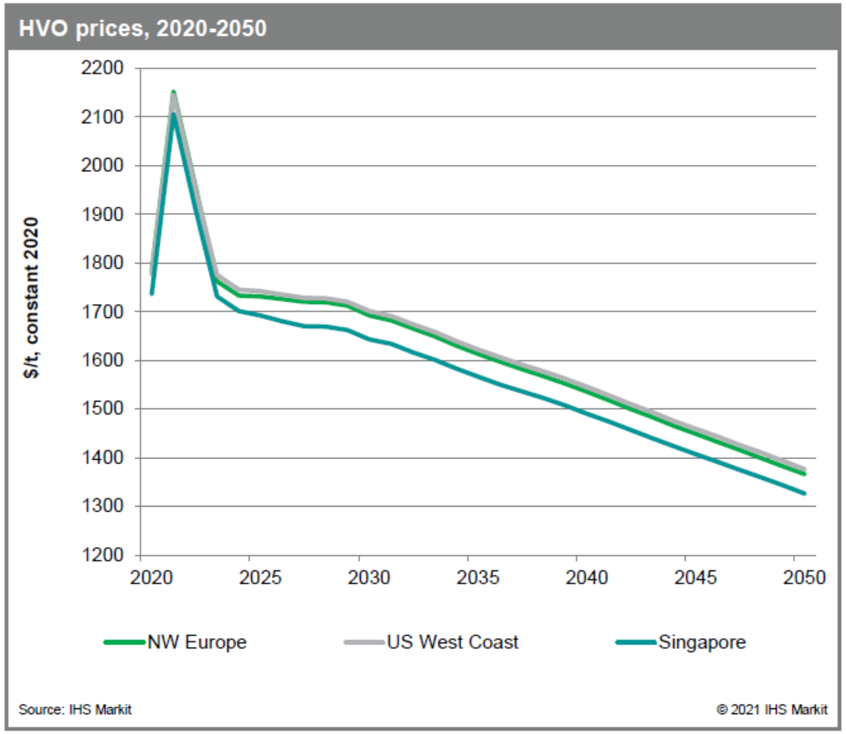
Methodology

- IHS Markit's fatty acid methyl ester (FAME - also often referred to as biodiesel), forecast is based on different product make-ups, depending on the region.
- In Northwest Europe, FAME is based on Used Cooking Oil (UCO). Future prices are guided by historical trends, which are based on F.O. Licht Commodity Analysis.
- On the US Gulf, tallow methyl ester is the basis for FAME, with the price closely aligned to its feedstock in the region.
- IHS Markit expects efficiency gains, and economies of scale to gradually reduce the production costs.

Pricing

- Generally, FAME will fall in value across all regions. This is due to the alignment of the fuel with oil prices, as a substitute for diesel. Whilst demand will increase, at least in the short/medium term so will supply. However, as transportation sectors begin to transition to alternatives, this will weaken demand, further reducing its price.
- In Northwest Europe, a premium has been applied, based on EU's push to increase use of the feedstock from 2021 onwards. Assumption is made, that used cooking oil prices will increase in competition for feedstock with additional HVO capacity being brought online.
- US Gulf – Price of tallow methyl ester is set at a discount to UCO in the region (whilst in Northwest Europe, tallow will be priced at a premium).
- Over the course of the forecast, the price differential between the two locations will narrow, from around $40/t in 2020 to $17/t in 2050.

HVO



Methodology

- Hydrotreated vegetable oil (HVO) prices are calculated by IHS Markit, based on the product make-up in each region.
- In Northwest Europe, HVO production is primarily based on used cooking oil and rapeseed oil. Palm oil and tallow are also considered in the mix. Due to RED2 requirements, palm oil element is gradually phased out.
- On the US Gulf, feedstocks are based on used cooking oil and soybean oil.
- In Southeast Asia (Singapore), feedstocks are based on used cooking oil and palm oil. Tallow is also considered in the mix.
- IHS Markit assumes that through the forecast, improvements in the efficiency of production, and the reduction in cost of feedstocks will reduce overall prices.

Pricing

- Over the course of the forecast, the price of HVO is expected to gradually fall across all regions. This is largely due to a drop in demand for transportation fuels, particularly after 2030, as the transportation sectors begin to move across to alternative fuels, thus, reducing the demand for the fuel.
- Used cooking oil is the dominant price setter across all three regions. Therefore, all three are aligned, and follow the same trend through the forecast.
- Southeast Asia benefits from lower-cost feedstocks, enabling the product to be slightly lower priced than in Northwest Europe, by around $47/t and by $40/t on the US Gulf in 2020.
- Over the course of this forecast, the price delta will reduce to around $40/t between Southeast Asia and Northwest Europe, by which time prices on the US Gulf coast will be $10/t higher than in Northwest Europe.

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