IMO's new Net Zero Framework: Assessing the potential options and costs of compliance

May 2025

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Acknowledgements

Underlying analysis and modelling for this report was commissioned and funded by the Global Maritime Forum (GMF). The report was authored by Deniz Aymer (UMAS) and Dr Tristan Smith (UCL). The views expressed are those of the author, and do not necessarily represent those of GMF.

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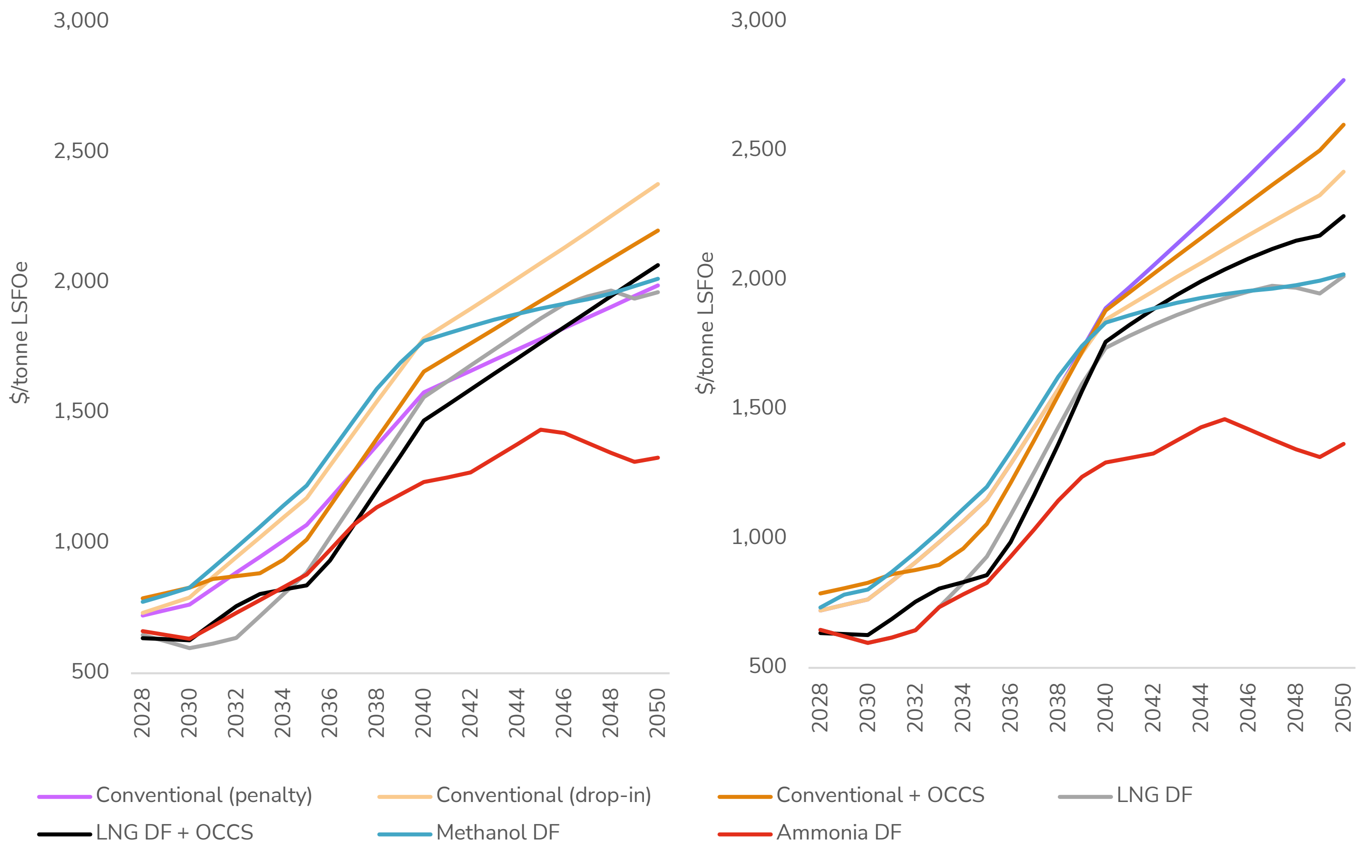
Executive summary

The agreement in principle of IMO's Net Zero Framework (NZF) provides a major step forwards in clarifying the risks and opportunities faced across shipping's value chain during this transition. However, it also leaves key elements uncertain.

This analysis attempts to translate the elements of the framework that have been clarified across different ship specifications and fuel combinations in order to assess the relative competitiveness of those options, and to test for sensitivities against some of the remaining uncertainties—whether related to further policy development, techno-economic fundamentals or commercial decision-making processes. Given the scope of these uncertainties, this assessment only signals at some potential outcomes, but some important inferences can still be made at this stage.

The following charts show the total cost of operation (TCO) calculated for a range of different ship specifications, illustrating the relative competitiveness of these choices under both the NZF as agreed (on the left) and with an indication of how its reward mechanism will be specified and parameters adjusted over time (on the right). For each of the ship specifications, the actual fuel / energy product mix used to minimise the TCO varies over time, from an evolving mix including fossil fuel, pay to pollute, biogenic fuel, blue fuel or e-fuels (fuels made from renewable electricity).

Figure 1: Total cost of operation, assuming no ZNZ reward mechanism and holding RU / SU prices fixed (left); including a ZNZ reward mechanism and increasing RU / SU prices over time (right)



Fuel choice will be dictated by abatement and penalty costs until the mid-2030s, but then increasingly narrowed by emissions intensity

The slate of fuel specifications modelled reflects a low gas price / high biofuel / falling e-fuel price outlook. On this basis, the TCO modelling signals that early in the transition, LNG would have an early competitive advantage relative to other fuel choices.

By the mid-2030s, as the emissions intensity of LNG and conventional / bio fuels shifts the cost of compliance for these ship specifications much higher, the ammonia DF ship specification becomes the cheaper option. Blue ammonia, which also benefits from the low gas price outlook modelled, is initially used, followed by e-ammonia in the 2040s. As the e-fuel with the lowest abatement cost, e-ammonia requires the least amount of support to bridge the cost gap to either LNG or blue ammonia, and applying a reward mechanism setup in that way (Figure 1, right hand plot), shows the potential for e-ammonia to be a competitive compliance pathway even from 2028 onwards.

In the near term, OCCS does not get a compelling endorsement from the TCO analysis, and neither does methanol DF. Over the longer term, the modelled e-methanol does not look likely to be competitive to e-ammonia.

For the large majority of the existing fleet—conventionally fuelled ships—the near-term least cost compliance option under the fuel scenario applied appears to be paying the penalty, enabled by the initial RU2 level being lower than the expected price of bioenergy. In a scenario where the RU2 price is increased (in line with the IMO's commitment to review and revise the RU prices in the future), the relative competitiveness of paying to pollute falls over time as the Base GFI becomes more stringent, indicating that a penalty-based strategy becomes increasingly risky beyond 2031.

The report also explores a scenario which includes a hypothetical 'new' bioenergy oil product priced to make its use competitive could be cheaper than the penalty option. Testing the potential competitiveness of such a fuel indicates that, unless its abatement cost was very competitive and supply was sizeable, it would most likely be blended to enable compliance with the Base GFI, rather than applied in strategies intending to exceed the Direct Compliance GFI in order to generate a large volume of SU revenues (and thus, potentially, reduce the SU price).

From the shipowner's perspective, a near-term outlook which suggests similar levels of competitiveness between different ship specifications (particularly conventional, LNG DF and ammonia DF ships), and significant uncertainties, might encourage shipowners to pursue a range of strategies with multiple ship specifications. However, this study's analysis shows there is also potential to hedge most of the uncertainties using the optionalities embodied in a single ship technology specification: ammonia DF. Over the short term, this choice benefits from exposure to:

1. Natural gas pathway (low gas price and/or strong SU price enabling competitiveness of blue ammonia)
2. E-fuel pathway (if e-ammonia costs reduce faster than expected)
3. Biofuel pathway (if a competitive drop-in biofuel is available)
4. Fossil fuel and pay to pollute (if there is no revision of RU prices)

The ship specification also aligns with the least cost compliance solutions over the medium-to-long term as indicated in the scenarios considered in this study (via blue ammonia and/or e-ammonia).

RUs, SUs and rewards are key drivers of relative competitiveness, but need to be analysed as sensitivity parameters

There is an intrinsic interdependence between the RU-SU-reward parameters. Individually and in combination, they exert pressures that shape the relative competitiveness of different fuel / energy options. Each factor embodies a different type of uncertainty, making assessment currently difficult and potentially leading market participants to ignore or misjudge the effects. This study therefore highlights that current (and, in some case, continuing) uncertainties about RU / SU prices and the reward specification, as well as on the interactions that can occur between them, necessitates that analysis be conducted over a range of potential parameter assumptions, to ensure the robust assessment of any risks and opportunities for different fuel / energy options.

Ports will need to weigh investment in bunkering infrastructure over the timescales dictated by the fuel standard

The advantage that optionality provides to shipowners could also apply to ports. In the near term, ports may focus on infrastructure investment that builds bunkering capacity for the fuel / energy molecules that will continue to be utilised, even as production pathways evolve over time—for example, oil (fuel oil potentially switching to bio), LNG (fossil LNG potentially switching to bio-LNG), and ammonia (blue potentially switching to e-ammonia). However, over the medium-to-long term, the evolving relative competitiveness of these options means demand is likely to become more focused (although not exclusively) on ammonia.

The signals to fuel producers, and particularly ZNZ producers, are less clear over the near term

For fuel producers, the analysis indicates that this group receive the least degree of clarity from the IMO NZF. Signals at this stage include:

Conventional fossil fuel producers: Conventional marine fuels producers are given a clear initial signal of continued demand for their product and may believe the large existing fleet of conventional ships that will continue to need 'oil' will sustain demand out to 2040.

LNG producers: These entities are given a strong positive initial signal, but with future uncertainty over whether there will be a rapid contraction of demand (rising RU price, increasing competition from ammonia), or more stable demand through the 2030s (RU price continuing to support the penalty option, delayed availability and competitiveness of ammonia).

Biogenic fuel producers: This group have perhaps a clearer signal—if they can produce below the current RU2 price thresholds, then there is a strong demand potential, especially for drop-in fuels (conventional oil equivalents).

Blue vs e-ammonia producers: Due to the current lack of specification of the reward mechanism, and the uncertainty related to the scale of e-ammonia that could be rewarded by available IMO funds, blue ammonia producers receive a clearer signal from the NZF than e-ammonia producers. Both, however, should receive a strong long-term signal from NZF, given the 2040 Base GFI stringency and the IMO's 2050 net zero commitment (although this is unlikely to help in the short-term investment case) For both types of producers, there is also short-term uncertainty as to whether shipowners will respond to the NZF by investing in ammonia DF ships, or wait to see signs of investment in fuel production first.

Introduction

In April 2025, the 83rd session of the IMO's Marine Environment Protection Committee (MEPC 83) approved the framework for the IMO's mid-term measures. Several key aspects in the Net Zero Framework (NZF) were quantified over the near-to-medium term, such as the initial trajectories of the fuel standard and the associated pricing for non-compliance. Other sections, such as the guidelines that will dictate the rewards for qualifying zero and near zero fuels and technologies, have yet to be defined.

The amendments from MEPC 83 are due to be adopted in October 2025, and all unresolved elements will need to the clarified before the IMO's mid-term measures come into effect at the start of 2028. However, MEPC 83 has delivered sufficient clarity on the framework for potential outcomes to be modelled and the implications to be evaluated.

In support of an insight brief by the Getting to Zero Coalition on the implications of the IMO's policy measures[1], analysis was undertaken using total cost of operation (TCO) modelling to assess, on a single ship basis, how the IMO's mid-term measures (as defined) could shape the cost of compliance and to highlight where unresolved elements of the framework create uncertainties, and where risks may remain even as these are clarified.

This accompanying technical report expands on the approach and assumptions underpinning the TCO modelling, outlines the scenarios and sensitivities tested in greater detail, and discusses more fully whether the policies defined thus far could already begin to influence the compliance strategies that participants in the industry will undoubtedly need to form.

Lastly, while a single ship TCO model is not representative of the entire fleet, the outputs of the analysis do give some insight into how the IMO's mid-measures are intended to drive shipping's energy transition, and whether they will be effective in doing so, given the levers that are built into the framework.

[1] Getting_to_Zero_Coalition_IMO's_policy_measures:_What's_next_for_shipping's_fuel_transition.pdf

What was clarified at MEPC 83 and what remains uncertain?

Following the landmark agreement in July 2023—which set decisive emissions reduction targets for international shipping—the IMO's process of negotiation and compromise culminated in April 2025 at MEPC 83 with the finalisation of the NZF intended to realise this ambition. If formally adopted in October 2025, the measures will enter into effect from 1st January 2028 for all ships over 5,000 gross tonnes trading internationally.

The NZF defines a structure for the IMO's mid-term measures, but several key aspects remain unresolved. One critical element that has been clarified is the fuel standard. This sets a GHG fuel intensity (GFI) target that obliges a reduction in the well-to-wake emissions intensity of the energy used on ships which can be achieved through the use of lower emission fuels or energy sources, including the use of wind technology, onshore power and, potentially, onboard carbon capture and storage (OCCS).

The IMO has opted for dual trajectories: a 'Base' GFI and a 'Direct' GFI. It has set annual targets for both GFIs until 2035, and also for the 2040 Base GFI. Annual targets for 2036-2040 will be agreed by the start of 2032. All ships must meet the Direct GFI but can reach that target through a range of options. Instead of (or in addition to) lowering the emissions intensity, 'remedial units' (RUs) can be bought from the IMO to meet compliance with either GFI target.

Similarly to the GFI trajectories, there are two forms of RUs:

1. *Tier 1 RU (RU1):* Can used to bridge any portion of the emissions intensity deficit between the Base and Direct GFIs. RU1 is set at \$100/tCO_2e until 2030.

2. *Tier 2 RU (RU2):* Can used to bridge any portion of the emissions intensity deficit between the fuel used and the Base GFI. RU2 is set at \$380/tCO_2e until 2030.

The process for reviewing and defining prices for RUs from 2031 onwards will be agreed by the start of 2028, possibly leading to cycles where RU levels are set for 3-yearly periods. Both types of RUs are effectively 'pay-to-pollute' options, but the higher cost RU2 is intended to nudge a minimum use (down to the Base GFI) of lower emission fuels or other abatement solutions and therefore will need to rise over time to incentivise the industry to choose fuels and technologies that can deliver greater emissions reductions but at a higher abatement cost, over the pay-to-pollute option. Another option for attaining compliance with the Base GFI is to buy 'surplus units' (SUs) which will be generated by ships that exceed the Direct GFI target.

As well as establishing the structure of the fuel standard and associated economic levers, MEPC 83 also made some progress in defining the qualifying criteria for zero or near zero emissions fuels, energy sources and technologies (collectively known as ZNZs). The definition adopted only relates to the GHG emissions intensity of the solution. Until the end of 2034, the GFI threshold for ZNZs is set at 19 gCO_2e/MJ; thereafter it is reduced to 14 gCO_2e/MJ. So far, there has been no further differentiation between solutions, whether relating to sustainability criteria (e.g. land use change for biofuels) or strategic goals (e.g. targeting support to favour long-run solutions). Further definition of ZNZs will be discussed and included in a forthcoming guideline, expected for adoption before 2028. Indeed, the LCA guidelines—which will define the default values for well-to-tank and tank-to-wake emissions intensities for fuels made from different feedstocks and by different production processes—is another key piece of the puzzle that is also missing.

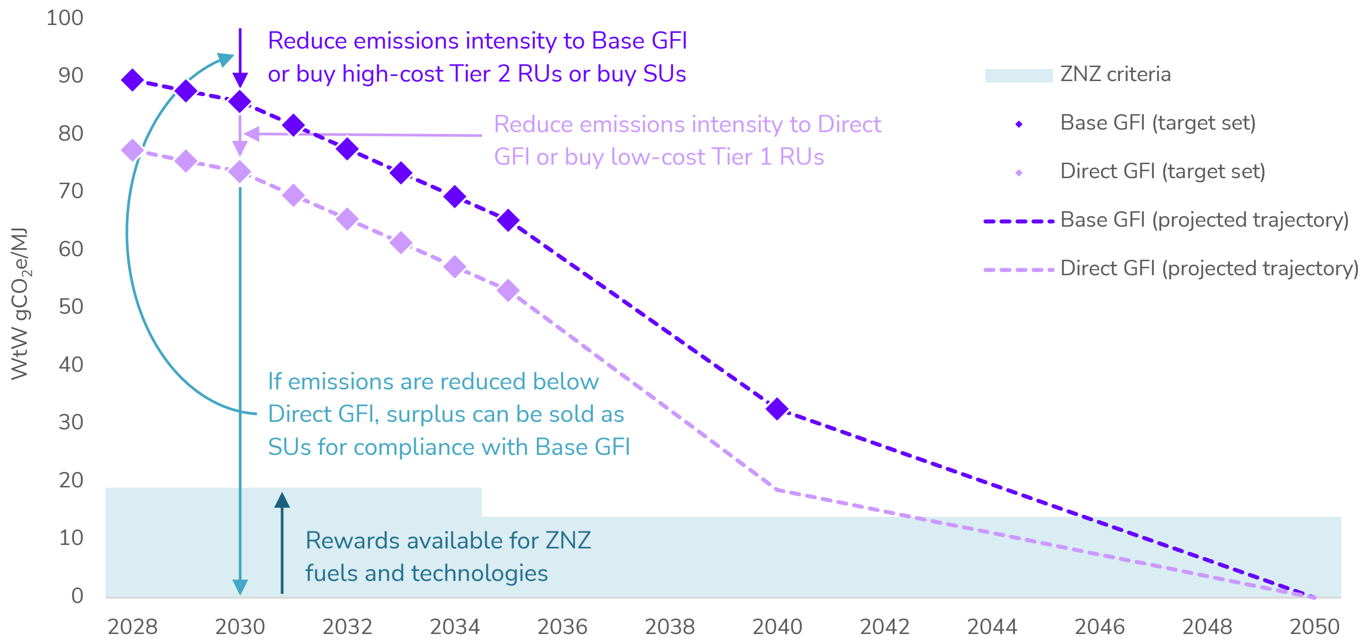
The NZF also affirms that a portion of the revenues raised by the IMO via the sale of remedial units will be directed towards rewarding the use of ZNZs. Guidelines on the structure, qualifying criteria and value of this reward will also need to be in place before the measures enter into effect in 2028. This leaves a crucial factor in the business case for ZNZs uncertain, potentially up until the last MEPC before the mid-term measures come into effect (spring / summer 2027).

The uncertainty regarding how ZNZs will be rewarded, and how this will affect their relative competitiveness, relates both to the specifications of which fuels will be rewarded and the total revenues that will be available for reward. Initial estimates based on the parameters of the IMO's NZF indicate that $11-$12 billion could be raised annually between 2028 and 2030. There is greater uncertainty on how much revenue could be raised after 2030 as this will be influenced by the IMO's adjustments to RU prices and GFI trajectories, and the response to the mid-term measures by the shipping and energy industries—i.e. the types, volume, price and geographical availability of lower emission fuels brought to market, the delivery of ships able to run on alternative fuels, the uptake of abatement technologies, etc.

The IMO's NZF states that the revenues it raises will be used for both ZNZ rewards and wider disbursement purposes (in order to contribute to just and equitable transition). There is no clarity as yet on how the total revenue will be divided between these areas, and what amount might be available for ZNZ rewards. However even at the upper bounds of current estimates, there is only expected to be sufficient revenue to reward initial volumes of ZNZ, and no certainty that the reward revenue will grow to support a scaling-up of ZNZ use beyond those initial volumes. This could penalise the business case for ZNZs which ideally require long-term (e.g. 10-15 years) offtake agreements.

So while MEPC 83 has delivered some clarity that can help entities in the shipping industry begin to chart a path through the transition, the areas where uncertainty still remains will have a greater impact on the risk profile of more ambitious solutions. The purpose of the analysis and modelling presented in this report is to try to provide insights to better understand the risk profiles of different fuel/technology options, and how these are likely to change over time.

Figure 2: IMO Base and Direct GFIs and options for attaining compliance



Approach taken to modelling the IMO’s mid-term measures

Current uncertainties present key challenges to modelling the mid-term measures

Undertaking any modelling and analysis of shipping’s energy transition requires a series of assumptions to be taken, each reflecting how different types of uncertainty are addressed. From the outcomes of MEPC 83 and the elements which have so far been defined in the IMO’s NZF, these uncertainties can be categorised into three broad categories—political, technoeconomic and commercial.

Political uncertainties

At this point in time, there remain key details related to the implementation of the IMO’s NZF that have not yet been agreed, and will only crystallise in guidelines due for adoption over the coming years. These will be negotiated within the IMO process and, as with the NZF, will need to be agreed by finding compromises between the positions taken by different countries. There are 14 individual guidelines that are due for adoption, as well as future revision processes. Some of the key political uncertainties affecting the modelling in this report include:

Adoption of the IMO NZF: For now the NZF has only been agreed in principle, its adoption will be considered in October 2025, and will depend on the position taken by IMO member states (specifically MARPOL Annex VI signatories) at that point in time.

ZNZ definition: At this point in time, the term “ZNZ” has only been defined as a GFI threshold criteria. Its further definition will be finalised in guidelines, along with how the reward for ZNZ is specified.

RU price revision: The process for adjustment of the RU1 and RU2 prices used to incentivise compliance with the GFI thresholds from 2031 onwards will need to be agreed.

NZF revision: The MARPOL amendment that describes the NZF includes a commitment to undertake a 5-yearly review and amendment of the chapter including of its GFI reduction factors, the ZNZ threshold specification, and the limit on the size of ships covered by the regulation.

Interaction with national or regional policy: International shipping already experiences regulation in a number of regimes besides the IMO (for example, in the EU, as well as under national policy elsewhere). Countries or regions may try to use national policy to advance their natural resources or competitive advantage, or accelerate environmental objectives, modifying the incentivisation in local or regional portions of the global markets.

Techno-economic uncertainties

Analysis of the relative competitiveness of different abatement options is broadly characterised by their relative performance (GHG emissions) and relative prices. Whilst there is some data available at this point in time, many of the current options have nascent supply chains, immature markets and are based on unscaled technologies. This makes it hard to estimate production costs, let alone commercial prices. The key parameters with uncertainties include:

Fuel and energy prices: Future pricing of fuels / energy sources and the differences (spreads) in prices between fuels. While production costs can be estimated from the price of key feedstocks (such as oil, gas, hydrogen, biogenic feedstock, renewable energy) plus the costs of supply and delivery, the price at the point of bunkering will be influenced by wider factors.

Fuel and energy emissions intensities: The emissions intensity (WtW gCO_2e/MJ) of different future fuels, whether specified through LCA guideline default values, or those achievable through certification procedures (with those certification procedures also a political uncertainty until the relevant IMO guideline has been adopted).

Abatement technologies: The performance of different component technologies, including onboard and on-land carbon capture and storage technology, as well as more conventional energy storage and conversion machinery.

IMO revenue and rewards: The magnitude of overall revenues that will be raised by the NZF, and the subset of those revenues that will be available for ZNZ rewards.

Commercial uncertainties

The outcome of the regulation will initiate a series of commercial decisions by entities in the shipping industry, which will then shape demand for alternative fuels / energy production and fleet specifications. These decisions will be made at the firm level and, as firms often adopt fundamentally different commercial strategies to manage the range of interacting political and techno-economic uncertainties, and so themselves represent commercial uncertainties:

SU trading: A particular feature of the NZF is that it creates a market for the trading of surplus unit (SU) credits as an alternative form of compliance with the Base GFI. The GHG accountancy of the credits will be tracked in a GHG register, but the pricing will be set by the market, i.e. by the relative supply of and demand for credits. The behaviour of market participants in their commercial strategies therefore directly feeds back to the pricing of SUs, and vice versa.

Producers and fuel / energy value-chain decision making: Investment in fuel and energy production typically involves a ~5 year period between an FID (Final Investment Decision) and the point at which the product can be delivered. Market participants therefore have no choice but to form an outlook on the future prices to assess their relative future competitiveness, and although some risk could be mitigated by securing offtake agreements (e.g. creating a degree of certainty by fixing a price and volume), the exact balance of risk and opportunity is likely variable and uncertain.

Shipowner decision making: The shipowner's decision making is also uncertain. Whilst the 'chicken and egg problem' (i.e. the reluctance to invest without seeing the production and distribution of new fuels mature) is one characterisation, the IMO NZF makes clear that those in the shipping industry will all face the challenge of managing least cost compliance. As with fuel / energy producers, a range of different strategies can be expected, depending on size and age profile of the managed fleet, nature of operations (e.g. liner or tramp shipping), appetite for risk, access to low cost capital, etc.

Approach taken to tackling the key uncertainties within the analysis

Taking all of the aforementioned uncertainties into account, this report has adopted a balanced approach for determining how the elements of the NZF agreed so far could potentially impact the energy transition of international shipping. This process of analysis and basis for the assumptions applied are listed below.

TCO modelling

A simple and transparent analysis technique based on total cost of operation (TCO) modelling has been utilised. This incorporates into the defined policy elements, assumptions about the currently uncertain policy incentives and estimated costs to try to understand the relative competitiveness of different approaches to compliance, across plausible future scenarios. This is not a modelling exercise designed to project expected volumes of demand for future energy commodities, rather it is intended to infer how current and future IMO policies could influence the relative competitiveness of such commodities, and what this implies for the risks and opportunities facing different molecules, production pathways and technologies.

Energy transitions initiate slowly with early adopters, and then accelerate. In this report, the TCO model is used to assess the conditions under which an early adopter business case for operating on new fuels / technologies could be achievable, therefore indicating high-level timings in international shipping's energy transition. A more detailed evolution beyond early adoption would be the subject of future work.

Fuel and technology cost estimates

The estimates that have been applied have built on existing literature for energy/fuel price and technology cost / price assumptions, including previous work analysing IMO policy scenarios, both in IMO's Comprehensive Impact Assessment process[2], and by UMAS and UCL, reviewing the assumptions against emerging evidence[3].

Uncertainties over future regulation

This report assumes that the IMO NZF is adopted in October (based on the degree of political support in April) and adopts conservative assumptions over the undefined portions of the IMO's NZF (e.g. default reward mechanism and revenues) to reflect political uncertainties. Sensitivities to key parameters have been tested, including the potential impact of changes to the key parameters that the IMO can adjust in future (RU prices, GFI trajectories), the specification of the ZNZ reward mechanism and SU price sensitivities.

The analysis initially tests the relative competitiveness of different fuel / energy pathways with SU trading included at a fixed price, with the level of ZNZ reward needed to enable those options to compete commercially derived. The analysis then assesses 1) scenarios reflecting a reduced SU price (representing oversupply of SU's, simulated through the development of a low cost biofuel); 2) the impact of raising RU prices on the level of reward needed to support ZNZs; and 3) the impact of raising RU prices and GFI trajectory adjustments on the potential window for SU trading.

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[2] MEPC 82/INF.8/Add.1 Report of the comprehensive impact assessment of the basket of candidate GHG reduction mid-term measures – full report on Task 2 (Impacts on the fleet); full report can be downloaded from IMODOCS; registration is required

[3] UMAS: How-IMO-mid-term-measures-might-shape-shippings-energy-transition-final.pdf

For TCO modelling to reflect the IMO's NZF, multiple TCOs must be calculated for each fuel

The function of a fuel standard is to gradually limit the GHG emissions intensity of energy used on ships. This has two effects: 1) it dictates when a fuel is no longer compliant—i.e. when its emissions intensity exceeds the GFI; and 2) as a standalone policy, a fuel standard typically stimulates incremental action by incentivising minimum abatement effort. Assuming a viable fuel (i.e. with emissions intensity below the GFI) has an abatement cost above zero (which may not always be the case), the least cost solution would be to use just enough of that fuel to comply with the GFI target.

The IMO's dual GFIs add a layer of complexity to how the fuel standard functions, and this is compounded by the ability to purchase remedial units rather than physically reduce the emissions intensity of the ship. To reach the Base GFI, a fuel or technology will need a (reward-adjusted) abatement cost below RU2 (set at \$380/tCO_2e until 2030) to be cheaper than the pay-to-pollute option. Along similar lines, if the abatement cost of the fuel or technology is below the RU1 price (set at \$100/tCO_2e until 2030), then it will also be more cost effective than the pay-to-pollute option to attain compliance with the Direct GFI. However, if a fuel or technology has such a low abatement cost, the optimal solution would instead be to maximise usage, generate surplus units (if emissions can be reduced below the Direct GFI) and thus benefit from SU revenues.

Therefore, IMO's fuel standard, with its dual GFI and tiered RU pricing, may lead to a 'pick-and-mix' approach to compliance, at least initially, wherein multiple options are utilised depending on the strategy adopted and the prevalent circumstances. To outline the most likely compliance approaches, and how these might evolve over time, the least cost compliance solution has been estimated under a range of assumptions. This solution is primarily influenced by the GFI targets, the costs of RUs and SUs, and of course, the characteristics of each viable fuel and technology option. The relative competitiveness of different fuels and technologies are linked to their emissions intensity (or abatement potential) with respect to the GFI, and how the cost of abatement (net of any ZNZ reward) of these fuels or technologies stack up against RU / SU prices.

To determine which fuels and technologies offer the least cost route to compliance, each solution needs to be assessed in conjunction with the pay-to-pollute and SU trading options. In addition, the ZNZ rewards and any incremental CAPEX and OPEX (whether for dual fuel (DF) capability, OCSS, etc.) need to be incorporated into the assessment. This can be accomplished through TCO modelling across four scenarios (Table 1), with the last three replicated for each fuel / technology combination.

Table 1: Four TCO scenarios modelled

TCO scenario	Assumptions applied to TCO modelling
Penalty TCO	• Base GFI: RU2 (or SU if lower cost) • Direct GFI: RU1
Base TCO	• Base GFI: Minimum low emission fuel / technology use • Direct GFI: RU1
Direct TCO	• Base GFI: Minimum low emission fuel / technology use • Direct GFI: Minimum low emission fuel / technology use
Max TCO	• Maximum low emission fuel / technology use • Generation and sale of SUs if below Direct GFI

The TCO modelling overlays the policy-driven constraints—from both an emissions intensity and abatement cost perspective—onto the price and specification of the fuels and technologies being assessed. While MEPC 83 provides some of the key policy inputs, particularly over the near term, assumptions need to be made about the GFI trajectory post-2035 and RU prices post-2030, and estimates for SU prices formed over the whole period.

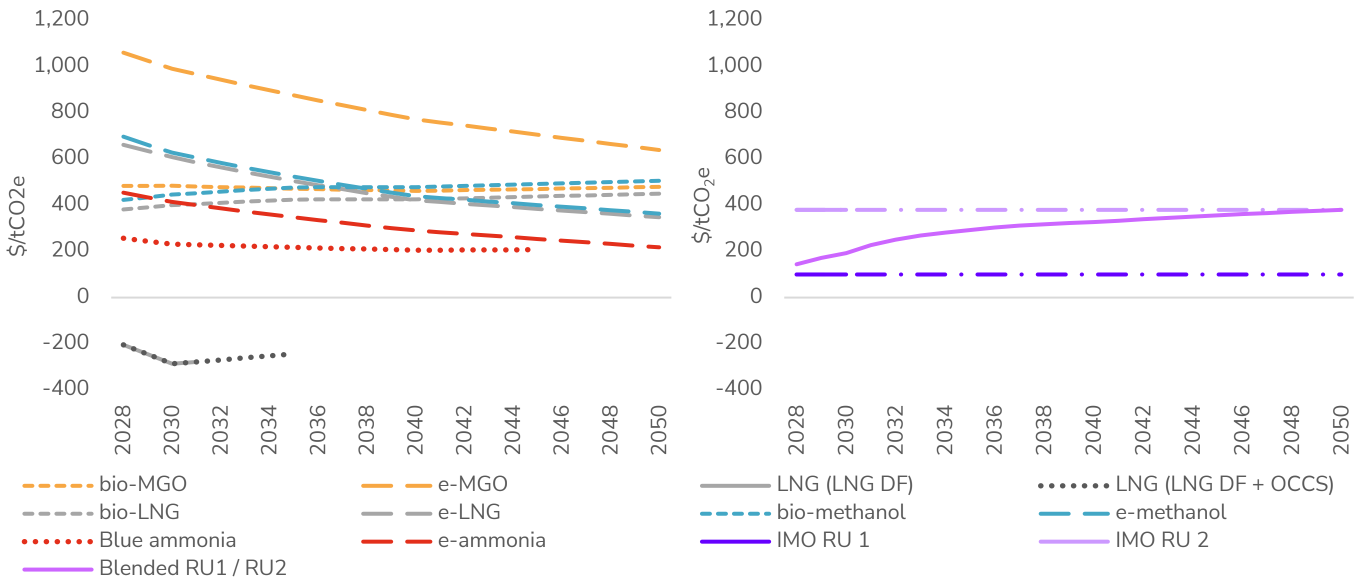
Initial fuel assumptions used in TCO modelling reflect low gas / high biofuel price outlook

Projecting future fuel prices and emissions intensities is subjective and outlooks naturally differ. However, there is consensus on some aspects. It is widely expected that availability of biofuels will be limited (although the sustainability criteria for biofuels may flex the degree of constraint) and demand from other sectors (particularly aviation) will likely drive up prices. On the other hand, fuels produced from renewable energy (e-fuels) are expected to fall in cost if production grows, allowing supply chains to firm and economies of scale to compound.

The TCO analysis presented here applies fuel assumptions (price and emissions intensity) generated as part of the Comprehensive Impact Assessment on the mid-term measures undertaken by the IMO in 2024, but with higher biofuel prices substituted to reflect stringent sustainability criteria, constrained supply and out-of-sector demand. All assumptions (including associated CAPEX and OPEX) and ship / voyage inputs are detailed in the Appendix. The assessment includes OCCS (for conventional and LNG DF ships), but not wind power technologies or the potential contribution to emissions abatement delivered by shore power.

The relative competitiveness of fuels is best viewed through their comparative abatement costs framed within the constraints of the Base GFI (Figure 3). The fuel price and emissions intensity projections used in this TCO assessment reflect a low gas price outlook, and this feeds into the price of both LNG and blue ammonia (for which natural gas is a feedstock with CCS applied during production). While the spreads in abatement cost do not directly translate into the actual competitiveness of the fuels (as marginal CAPEX / OPEX, ZNZ rewards, and SU revenues also need to be accounted for), they do indicate which fuels are likely to be more competitive over which periods and where RU2 prices will likely need to rise to in order to incentivise the industry to adopt low emission fuels rather than simply pay to pollute.

Figure 3: Abatement costs (versus LSFO) of fuels (left) and static RU1 / RU2 costs (right)



Assessment of TCOs under static RU and SU price conditions

While there are aspects of IMO policy which are not yet defined, and there is inherent uncertainty in projecting the future availability, price and specification of alternative fuels, TCO modelling can be used as a tool to help clarify the implicit implications of the fuel standard. Our initial assessment applies the projected GFI trajectories shown in Figure 2, assumes that RU pricing remains constant (RU2 = \$380/tCO_2e; RU1 = \$100/tCO_2e) and SU prices remain at their natural ceiling (i.e. the RU2 price) until 2050. A Base TCO, Direct TCO and Max TCO value is calculated for each combination of ship specification and viable fuel (without any reward yet applied for fuels that fall within the ZNZ criteria) or RU / SU option shown in Table 2.

Table 2: Ship specifications and mix of compliance solutions assessed in TCO scenarios

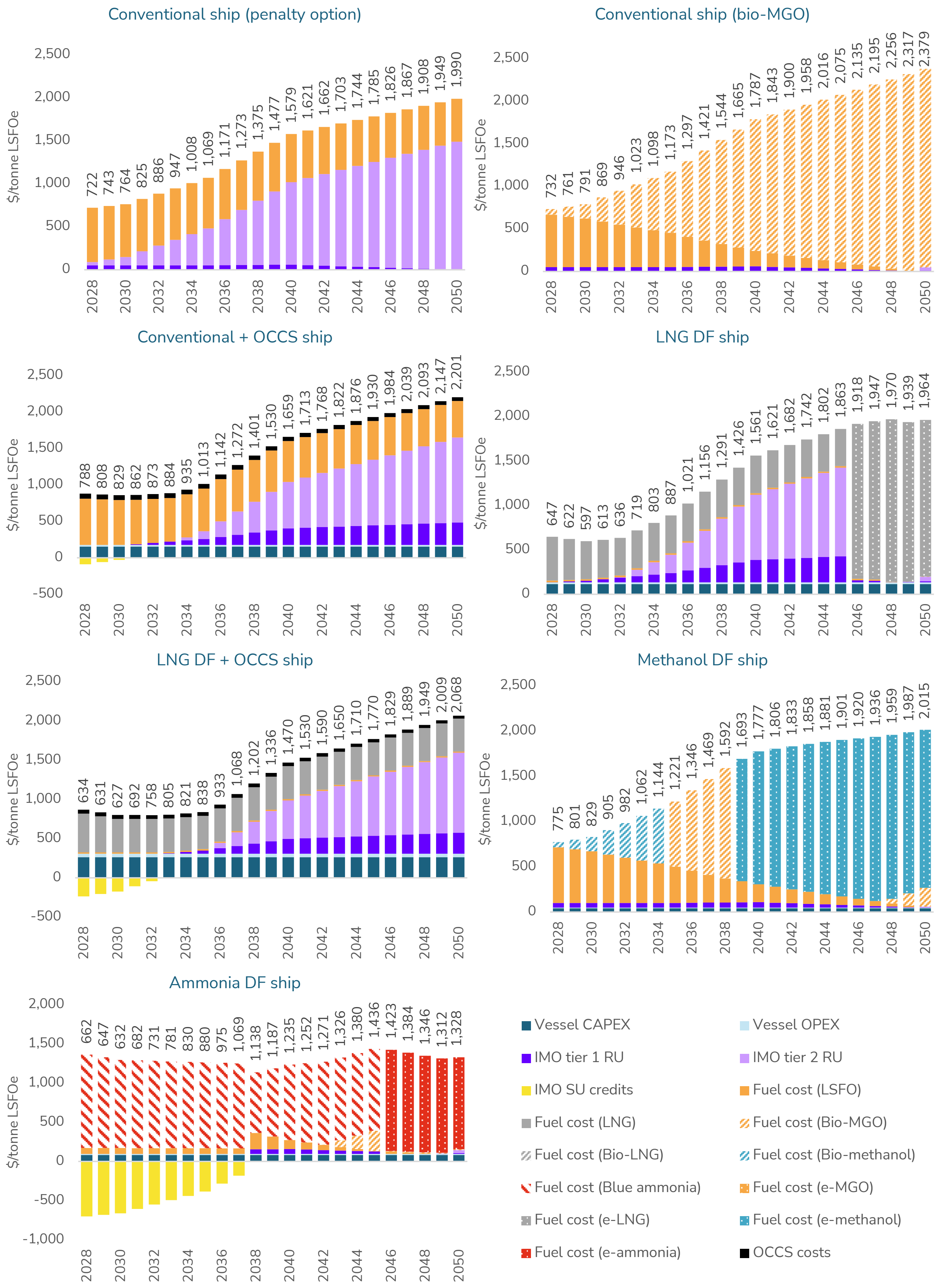
Ship specification	Combinations of compliance solutions applied	TCO scenarios assessed
Conventional	Bio-MGO; e-MGO; RU1; RU2	Penalty; Base; Direct; Max
Conventional + OCCS	Bio-MGO; e-MGO; RU1; RU2	Base; Direct; Max
LNG DF	LNG, bio-LNG, e-LNG; Bio-MGO; e-MGO; RU1; RU2	Base; Direct; Max
LNG DF + OCCS	LNG, bio-LNG, e-LNG; Bio-MGO; e-MGO; RU1; RU2	Base; Direct; Max
Methanol DF	Biomethanol, e-methanol; Bio-MGO; e-MGO; RU1; RU2	Base; Direct; Max
Ammonia DF	Blue ammonia, e- ammonia; Bio-MGO; e-MGO; RU1; RU2	Base; Direct; Max

From the large range of TCOs generated, the least cost solution in each year is extracted for each ship specification (Figure 4). These TCOs are shown in \$/tonne LSFOe, with non-fuel elements (marginal CAPEX / OPEX related to DF capability) converted to this metric by apportioning annualised costs across total annual fuel demand. Therefore, the TCOs represent absolute fuel and penalty costs plus marginal CAPEX / OPEX costs.

For each ship specification, the TCOs reflect the signals indicated in the abatement costs of the viable fuels. Under the fuel assumptions applied, for a conventional ship, it is cheaper to comply via RU1 and RU2 rather than use the bio-MGO (which has an average abatement cost of ~\$475/tCO_2e from 2028–2050). The addition of OCCS allows for a very limited amount of SU generation in the first three years until the Direct GFI can no longer be attained; by 2034, the emissions intensity is above the Base GFI and RU2 is utilised (as the cheaper option compared with bio-MGO).

As the abatement cost of LNG is negative, the least cost solution is to use maximum volumes of LNG for as long as possible (Max TCO). However, the emissions intensity of LNG is too high to exceed (or even meet) the Direct GFI, and so no SUs are generated and RU1s are required from 2028 onwards. By 2032, 100% pure fossil LNG no longer complies with the Base GFI and, as the assumed abatement cost of bio-LNG (averaging ~\$425/tCO_2e from 2028–2050) is higher than the projected RU2 price, 100% LNG + RU1 + RU2 is the lowest cost option until the mid-2040s when e-LNG becomes the cheaper solution. The addition of OCCS extends the runway of LNG with respect to the GFIs, allows for SU generation until 2032 and, over the long term, abates fossil LNG emissions sufficiently for RU1 / RU2 to be lower cost than e-LNG.

Figure 4: Breakdown and cumulative value of lowest cost TCOs for each ship specification

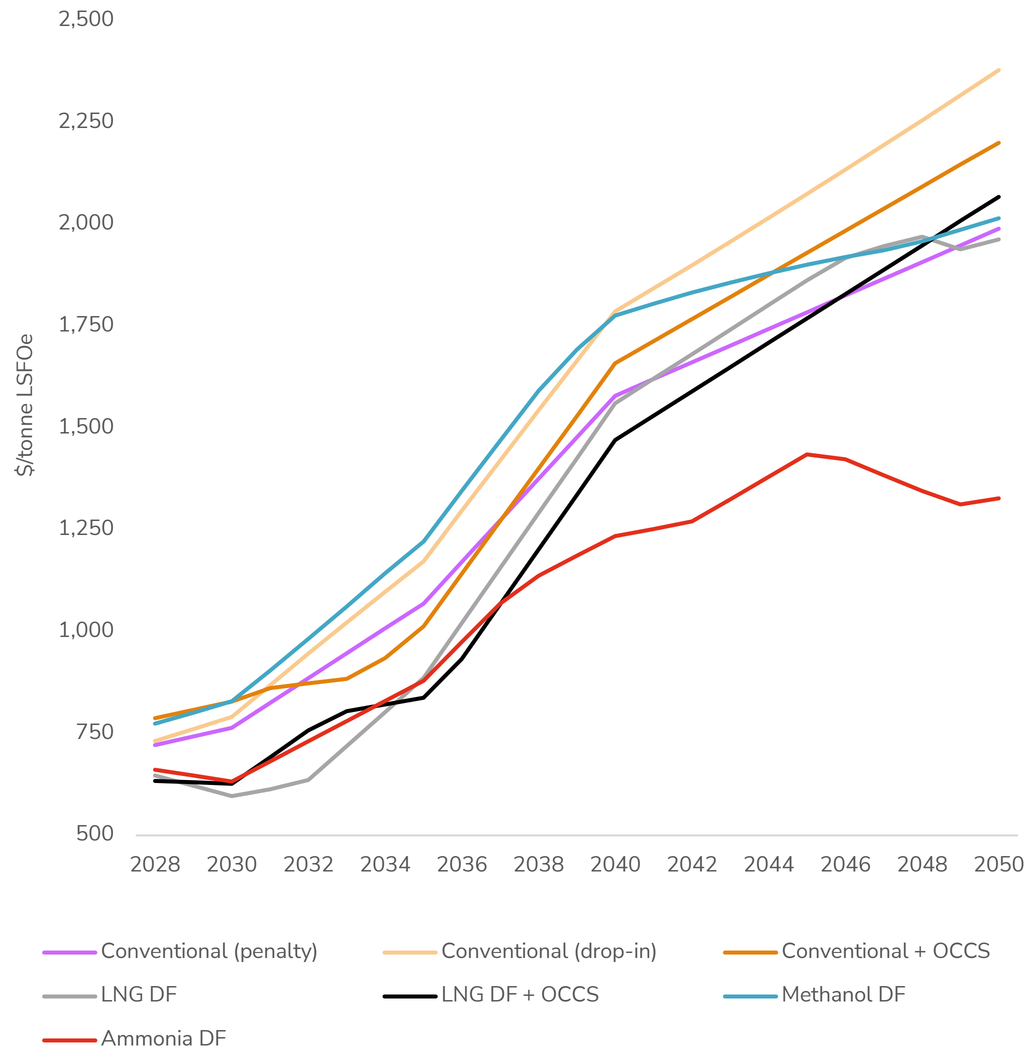


For the methanol DF ship, the least cost solution through to 2050 is the use of minimum volumes (i.e. Base TCO scenario) of low emission fuels: biomethanol until 2034, biodiesel until 2038, and e-methanol thereafter. For the e-ammonia DF ship, blue ammonia has a strong ability to generate SUs (i.e. Max TCO scenario) until the late 2030s before switching to minimum volumes of blue ammonia plus RU1 until the mid-2040s, when the relatively high emissions intensity of blue ammonia means that its needs to be replaced by e-ammonia.

Comparing the least cost TCOs for each ship specification (Figure 5) indicates that LNG offers the overall lowest cost solution until the mid-2030s, before being (briefly) undertaken by LNG DF + OCCS and then ammonia DF (with blue ammonia) in the late 2030s. For LNG DF (with and without OCCS), the negative abatement cost of LNG is sufficient to outweigh the additional CAPEX / OPEX associated with the DF capability. For the ammonia DF ship, the SU revenues over the near term offset the DF CAPEX / OPEX; from the late 2030s, the low abatement cost of blue ammonia (~\$210/tCO_2e) undercuts the cost of compliance for LNG (with and without OCCS) which is using RU1 / RU2 to comply.

In comparison, the conventional and methanol DF ships are initially less competitive than the natural gas-based options as the abatement costs of RU2 and biofuels are higher. Naturally, this outlook will change if different fuel assumptions are applied, rewards for ZNZs are added, RU costs are adjusted post-2030 and/or SU prices fall below the RU2 ceiling. All these scenarios are explored in the following chapters.

Figure 5: Least cost TCOs for each ship specification



Considerations around how ZNZ rewards could be structured

What options exist for the structure and criteria of ZNZ rewards?

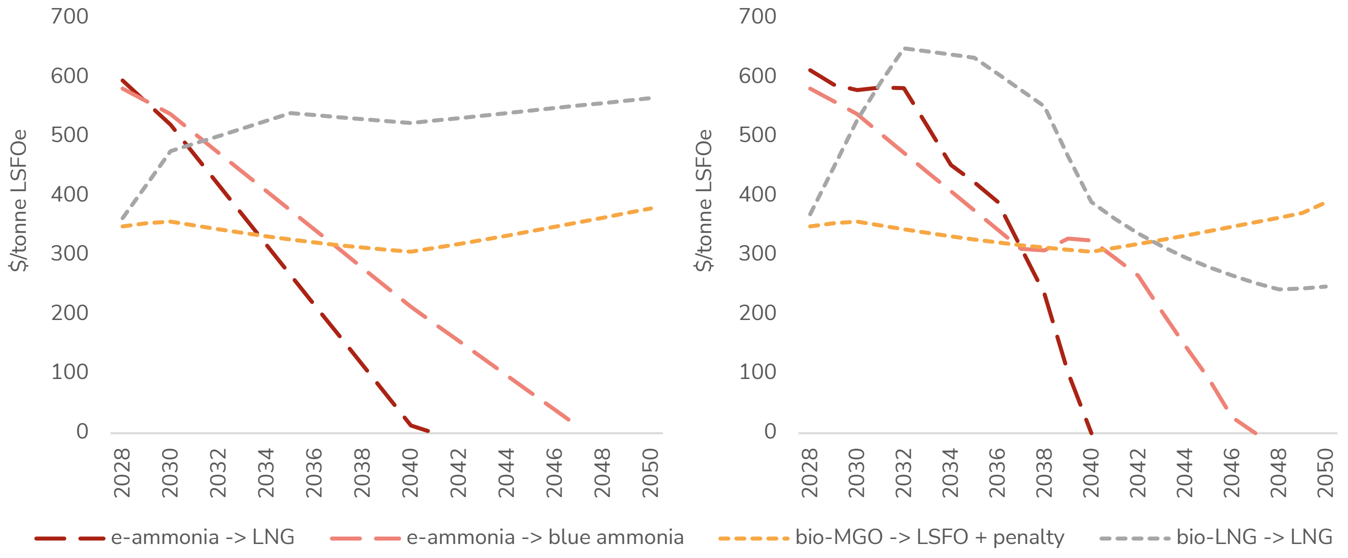
MEPC 83 has set out the emissions intensity limits used as a minimum categorisation of ZNZs, but the guidelines that 1) may differentiate between what subset of qualifying fuels / energy will be defined as ZNZs based on factors such as the sustainability of feedstock and/or the production pathway and 2) will outline the structure for ZNZ rewards, have not yet been drafted. There is a range of options for how ZNZ's may ultimately be defined and how these rewards could be structured. Both the definition and specification of the reward could influence the extent to which ZNZs are incentivised over the near term—including the knock-on effect on the level of overall demand for rewards, and thus the call on the IMO's revenues.

Two different structures for ZNZ rewards have been modelled across a subset of the fuels assessed in the TCO modelling:

1. Reward based on spreads in abatement cost: This reward is based on reducing the difference in abatement costs between the ZNZ and a reference fuel down to the RU2 price (assumed constant at $380/tCO_2e$). This has been applied to e-ammonia (using LNG and blue ammonia as the reference fuel), bio-MGO (using LSFO as the reference fuel), and bio-LNG (using LNG as the reference fuel).

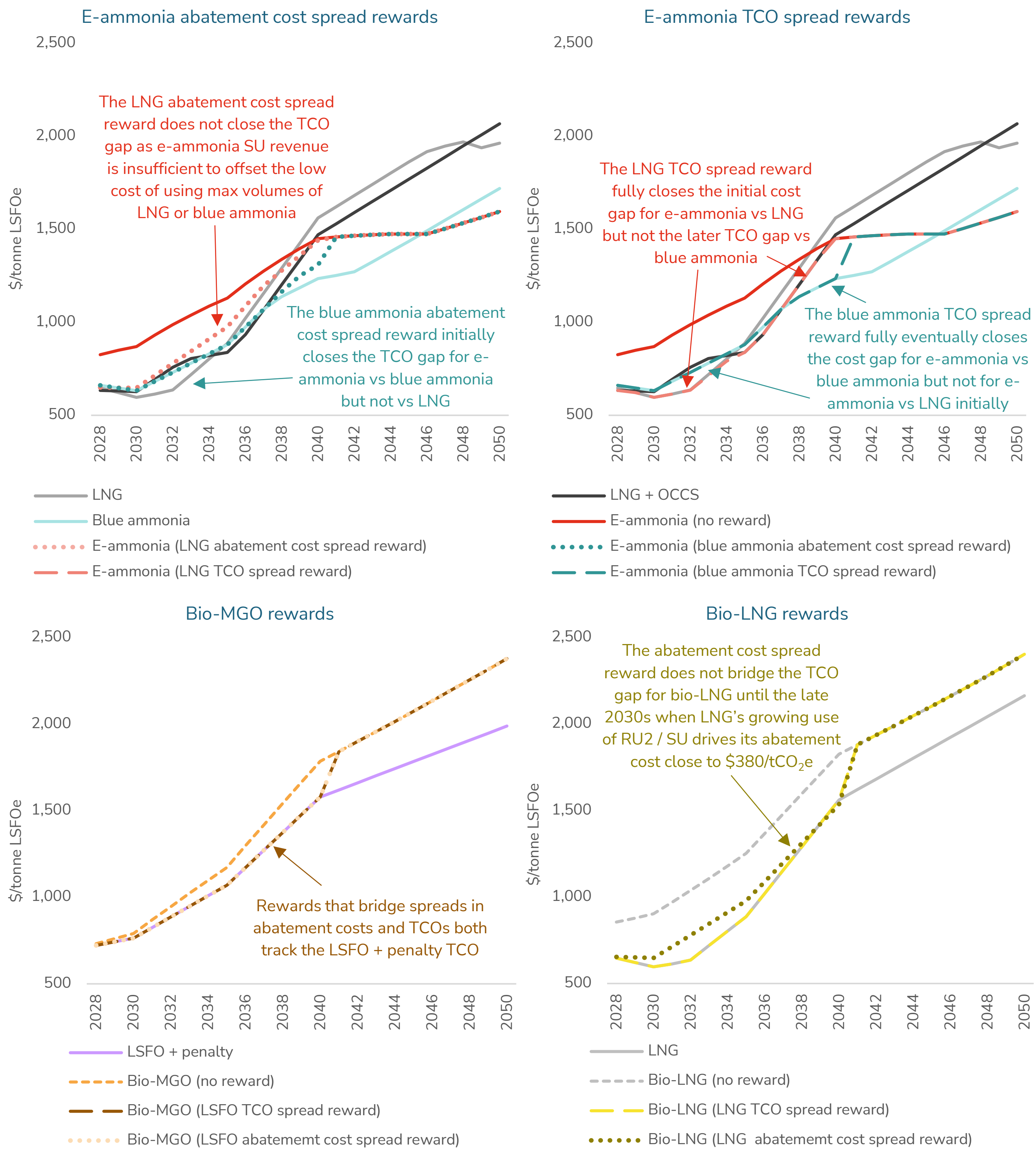
2. Reward based on spreads in TCOs: This reward is derived from the TCO model as the value which bridges the gap between the least cost TCO of the ZNZ and the least cost TCO of the reference fuel. This has been applied to e-ammonia (using LNG and blue ammonia as the reference fuel), bio-MGO (using LSFO as the reference fuel), and bio-LNG (using LNG as the reference fuel, but from the least cost TCO between LNG DF and LNG DF + OCCS).

Figure 6: Derived rewards from abatement cost spreads (left) and TCO spreads (right)



Assuming that ZNZ rewards are only made available until 2040, the effect of the two different types of ZNZ rewards on the three fuels assessed versus the reference fuels is shown in Figure 7. Unlike rewards based on TCO spreads, those based on abatement cost spreads do not bridge differences in CAPEX / OPEX between different fuel types which is why both rewards result in the same outcome for bio-MGO on the conventional ship. The advantage of setting ZNZ rewards based on abatement cost spreads is that only the ZNZ and reference fuel specifications (price and emissions intensity) are needed, and the reward can be aligned current with RU2 pricing. However, ZNZ fuels and abatement technologies which rely on CAPEX investment will be disadvantaged, unlike rewards based on the TCO spread.

Figure 7: TCOs with ZNZ rewards applied until 2040 for e-ammonia, bio-MGO and bio-LNG



Further considerations that may be reflected in the finalised guidelines on ZNZ reward specifications

The IMO has a wider set of approaches to consider than the two assessed in this study when defining the criteria, structure and levels for ZNZ rewards. Ultimately, however, for the rewards to effectively drive early investment in long-run, scalable and sustainable fuel production, there will need to be significant bridging of the cost gap versus 1) the pay-to-pollute option and 2) less sustainable alternative fuels with higher emissions intensity but much lower abatement costs.

This study considers the scenarios in which the IMO rewards fuel / energy from biogenic feedstock (e.g. bio-MGO or bio-LNG) as this is a potential outcome from further IMO process. However, given wider evidence on the constraints of sustainable supply of these feedstocks, relative to international shipping's energy demand, these fuel options may not be deemed to qualify as 'scalable' (i.e. able to scale up to meet shipping's energy demand), and so may be excluded from the reward mechanism to allow for a focus on fuel / energy derived solely from renewable energy (i.e. e-fuels), which are widely believed to be scalable.

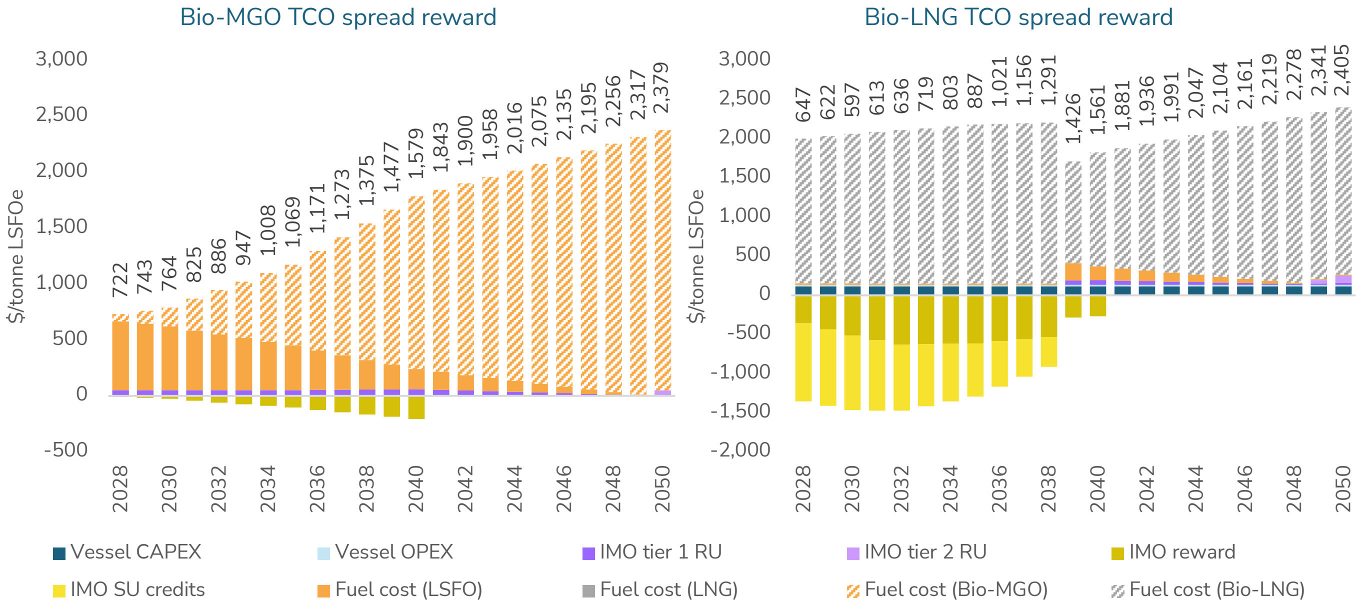
As well as assessing how to appropriately and sufficiently structure ZNZ rewards, the IMO will benefit from considering how demand could vary between different ZNZs. If the reference fuel has a low enough abatement cost for the Max TCO scenario to be the least cost option, the ZNZ will only be appropriately incentivised if the reward is set at a level that triggers a similar Max TCO scenario in the ZNZ fuel. This is because a large enough reward cannot be delivered through minimum ZNZ fuel use in a Base TCO scenario to bridge a cost gap generated by the maximum use of the reference fuel. However, rewards that stimulate this response could also help the business case for ZNZ fuels that can only be (initially) acquired through long-term, fixed volume offtake agreements.

A reward which incentivises the maximum use of a ZNZ could also be lower than a reward which only incentivises minimum volumes. This is because SU revenues would then become an integral part of the ZNZ business case and, in effect, subsidise the level of reward needed to bridge the cost gap. However, while the least cost TCO of both the ZNZ and reference fuel may be rely on SU revenues (e.g. e-ammonia and blue ammonia), the reference fuel may have no exposure to SUs (e.g. bio-LNG and LNG), which then means the risk profile for ZNZs does not mirror that of the reference fuel.

A further factor for the IMO to consider is the potential impact on revenues given the differing levels of demand for rewards between a Base TCO scenario (e.g. bio-MGO) versus a Max TCO scenario (e.g. bio-LNG). Although the reward on a $ per tonnes LSFOe basis for bio-LNG is, on average, approximately twice that of bio-MGO (based on a reward between 2028 and 2040 that bridges the TCO spread to LNG and the Penalty TCO respectively), the absolute amount of reward demanded by a single ship using maximum volumes of bio-LNG (to displace maximum volumes of LNG) would be far higher than a ship using minimum volumes of bio-MGO to meet compliance with the Base GFI.

This is illustrated in Figure 8, where rewards that bridge the TCO gap between bio-LNG and LNG, and bio-MGO and LSFO plus the blended RU cost (as shown in the chart on the right in Figure 6) have been applied until 2040. The breakdown of the TCOs show 1) how the amount of reward needed by the bio-MGO ship scales over time as increasing amounts of bio-MGO are used; 2) how bio-LNG draws much greater amounts of reward from the beginning; and 3) how SU revenues effectively subsidise the level of reward required by bio-LNG to reach parity with LNG.

Figure 8: Breakdown of bio-MGO and bio-LNG TCO under rewards based on TCO spread



So, in setting the criteria for ZNZ rewards and determining the structure by which it can most effectively direct its revenues towards supporting long-run solutions in the 2030s (so as to benefit the wider industry in the 2040s), the IMO will hopefully consider how rewards may be utilised in practice. This includes consideration over how rewards that trigger Max TCO scenarios can be boosted by the revenues generated by SU trading and how rewards that reinforce an incrementalist approach to the transition will need ever greater amounts of reward (compared with the initially high but potentially falling level of rewards for early and ambitious projects focused on scaling long-run solutions).

Potential role of SU trading in shipping's energy transition

The initial results presented in Figures 4 and 8 indicate that SU revenues are an important contributor to the least cost route to compliance over the near term for fuel options with low abatement cost (most notably blue ammonia) and, potentially, for ZNZs in conjunction with rewards. To evaluate the degree to which SU trading could play a role in shipping's energy transition, it is important to understand under what conditions it is a viable strategy, and where it could prove a source of risk.

Any business case relying on SU revenues must contend with an inherent disadvantage

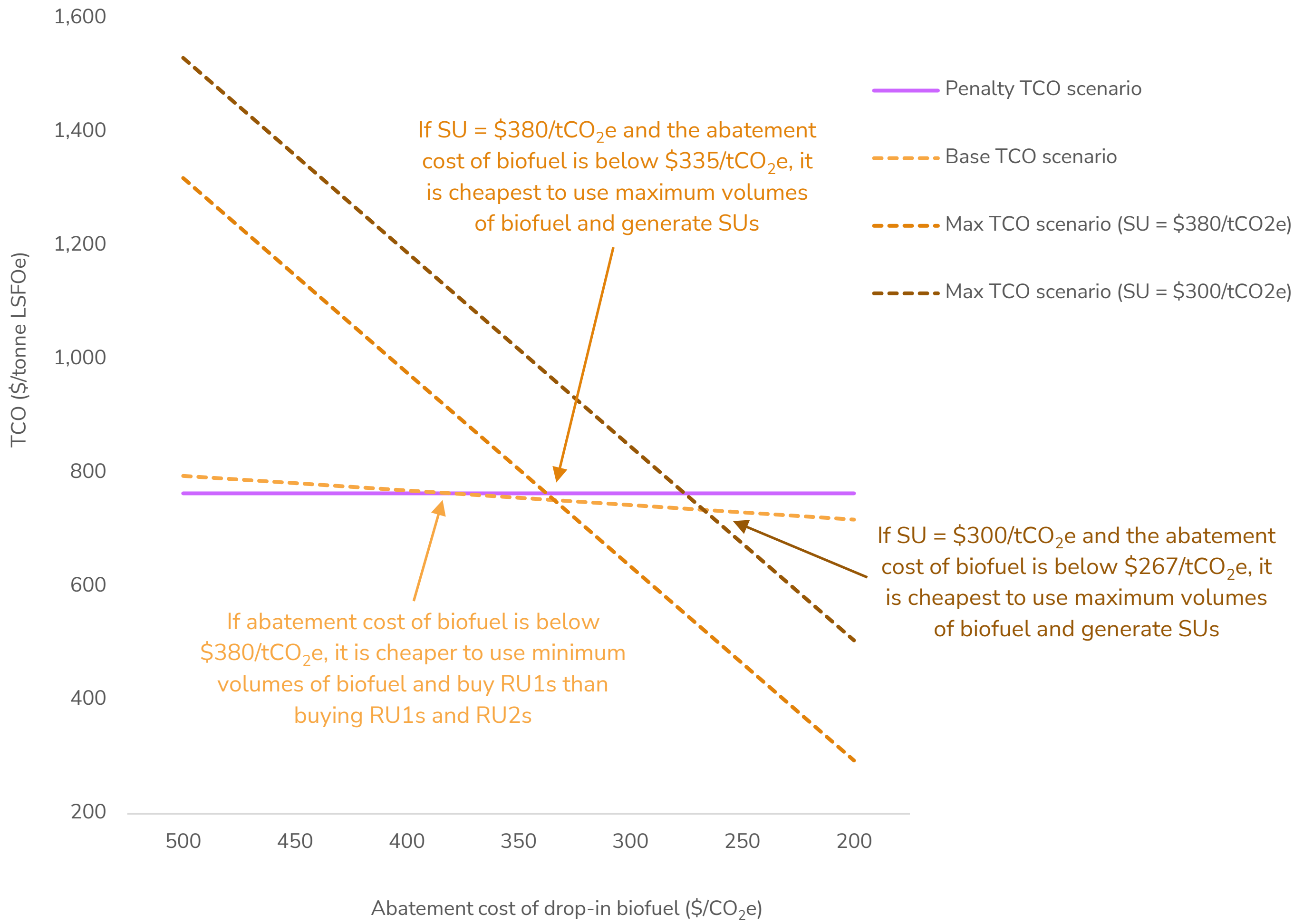
The tiered fuel standard and penalty structure adopted by the IMO has two advantages. Firstly, it reduces the cost of compliance for the portion of the global fleet unable to access lower emission fuels or abatement technologies over the near term. Secondly, it provides the IMO with two levers (the GFI targets and RU levels) by which to balance revenue generation and the stimulation of fuel / technology switching throughout the transition.

The benefit of an option to share overcompliance (i.e. trade SUs) is that it can transform the incrementalism of a fuel standard into incentivisation of more ambitious action early in the energy transition. However, under the tiered GFI and RU structure, overcompliance is disadvantaged. As SUs will only be generated by those operating below the Direct GFI and will only be sought by those operating above the Base GFI, there is an inherent asymmetry in how the cost of overcompliance is shared between both sides of the SU trade equation. For an overcompliance strategy (i.e. Max TCO) to outcompete a minimum compliance approach (i.e. Base TCO), the abatement cost of the low emission fuel will need to be sufficiently below RU2 and/or the SU price high enough to offset the low RU1 cost between the Base and Direct GFIs. The cost of getting from the Base GFI to the Direct GFI then becomes a hurdle that must be overcome in any business case designed to leverage overcompliance and SU trading.

For example, in the first three years of the mid-term measures when RU1 is set to \$100/tCO_2e and RU2 at \$380/tCO_2e, for a drop-in biofuel to outcompete the pay-to-pollute option on a conventional ship, the abatement cost of that fuel would need to be below \$380/tCO_2e. At this abatement cost, the Base TCO scenario is equivalent to the Penalty TCO scenario and minimum volumes of biofuel can feasibly be used to attain compliance with the Base GFI. However, for the Max TCO scenario to outcompete both the Base TCO and Penalty TCO scenarios, the abatement cost of the biofuel would need to be much lower at \$335/tCO_2e (this is assuming that SU prices remain at the RU2 ceiling and the LSFO price and emissions intensity and biofuel emissions intensity are as noted in the Appendix).

The relationship between the biofuel abatement cost and the TCO for the Penalty, Base, and Max TCO scenarios under these conditions in 2030 is shown in Figure 9. As can be seen, there is little sensitivity of the Base TCO to changes in the abatement cost. This is because, in 2030, the emissions intensity reduction required to reach the Base GFI is relatively small, meaning that only a low proportion of biofuel needs to be added to the fuel mix. On the other hand, the Max TCO scenario is highly sensitive to the abatement cost of the biofuel as it completely displaces LSFO, but it is also exposed to risk if SU pricing falls below the RU2 ceiling.

Figure 9: Penalty, Base and Max TCOs across range of biofuel abatement costs in 2030



What would be needed to instigate a supply-driven fall in the SU price?

At face value, there seems to be a potential opportunity to greatly reduce compliance costs by maximising low emission fuel use (if the abatement cost is low enough) and leveraging SU revenues. Could there be a risk that a fuel able to generate significant volumes of SU credits would be available in sufficient quantities to then depress the price of those SUs? This would then have consequences for both the fuels relying on SU revenues (i.e. penalising fuels qualifying for ZNZ rewards) and those utilising RU2s / SUs to achieve compliance (i.e. benefitting those relying on the pay-to-pollute option).

To test this potential risk, a new biofuel was added to the TCO modelling with a low enough abatement cost to displace the use of RU2s—either through direct use by conventional ships to reach Base TCO (i.e. assuming wide availability) or through maximum use and SU generation on a smaller cohort of ships (i.e. assuming a higher barrier to access, such as an offtake agreement or engine modification). The characteristics of the new biofuel are intended to mimic a drop-in biofuel which evolves over time to meet ever more stringent GFI targets and so, as a consequence, has an increasing abatement cost (Figure 10). It is assumed that this new biofuel does not benefit from ZNZ rewards.

Figure 10: Price, emissions intensity and abatement cost (vs LSFO) of new drop-in biofuel

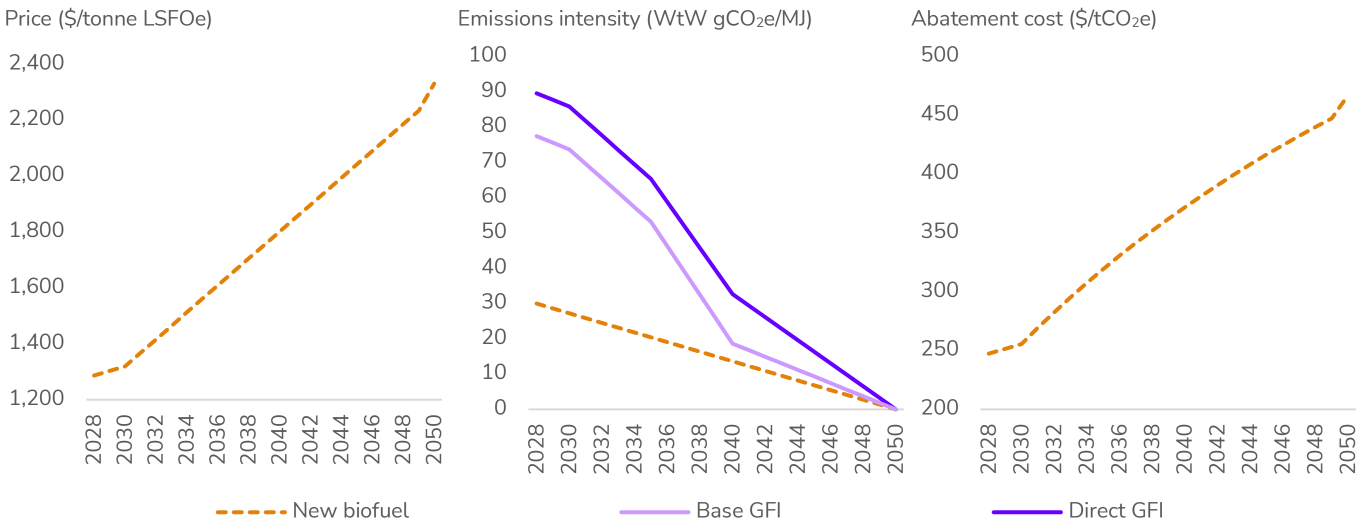
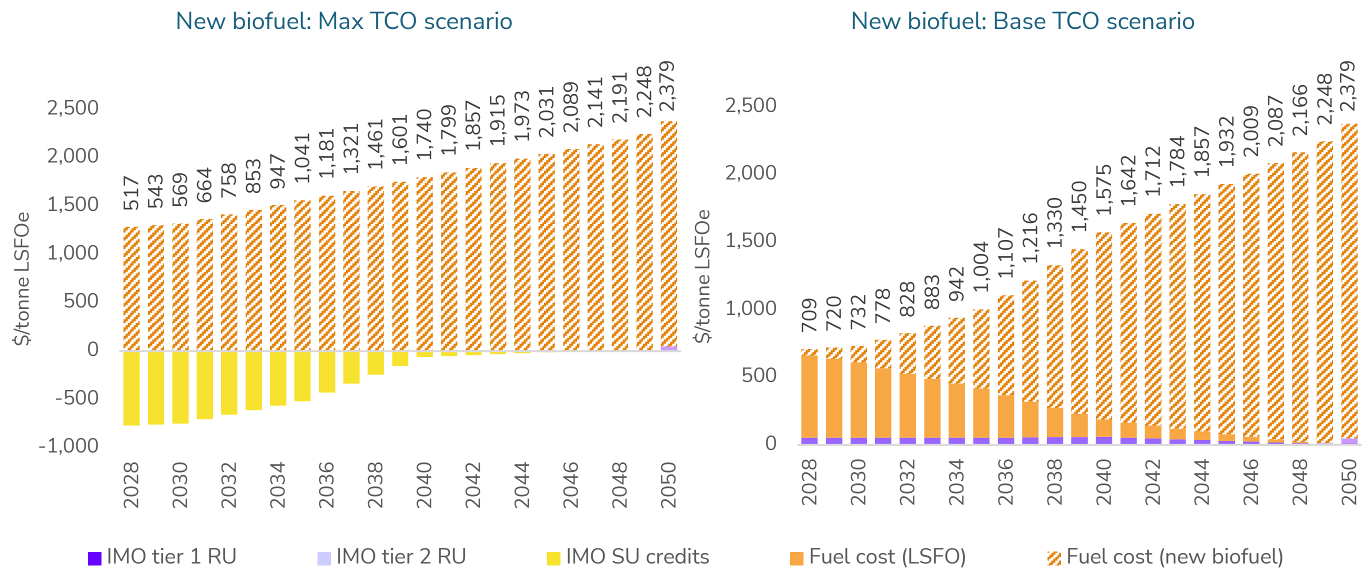


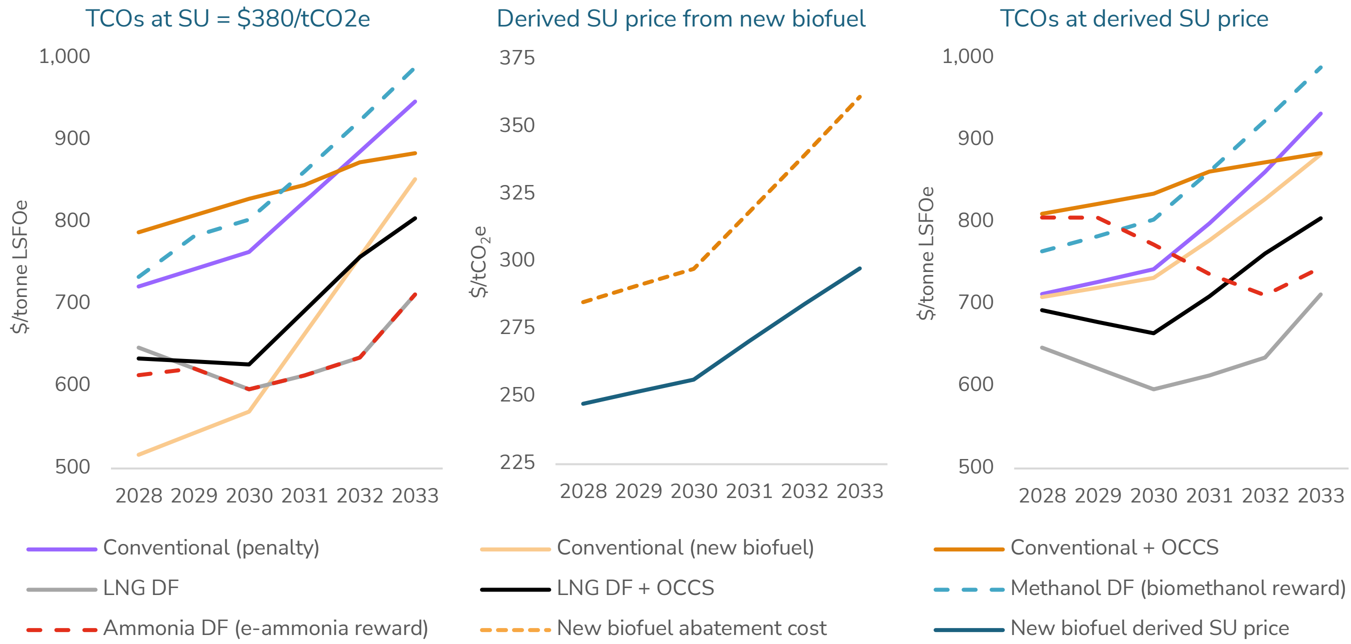
Figure 11 illustrates the breakdown of the Base and Max TCO scenarios for this new biofuel under static RU1 ($100/tCO$_2$e), RU2 ($380/tCO$_2$e), and SU ($380/tCO$_2$e) price conditions. The Max TCO scenario chart (left) reflects that the emissions intensity trajectory of the biofuel means it is physically capable of generating SUs until the mid-2040s (although in incredibly small volumes post-2040). However, the Base TCO scenario (right) becomes the least cost option from 2034 onwards, indicating that SU trading is economically constrained by the falling volume of SUs (and thus revenues) far earlier than the technical limits.

Figure 11: Breakdown of Base and Max TCO scenarios for new drop-in biofuel



Looking at the window for viable SU trading (2028 to 2033), the chart on the left in Figure 12 indicates that the SU revenues help make this new biofuel specification competitive against LNG over the near term (particularly over the period where RU1 / RU2 prices have been fixed). If there was sufficient availability of this new biofuel to oversupply the demand for RU2s / SUs, the floor for the SU price is the value at which the Max TCO equals the Base TCO (i.e. the point at which the marginal cost of using any more of the new biofuel outweighs the marginal SU revenue that could be raised). The derived SU price where this occurs is shown in the middle chart and the impact of applying this SU price across all ship specification TCOs is illustrated in the chart on the right.

Figure 12: Least cost TCOs for each ship specification with new biofuel (left); SU price derived when no constraints on new biofuel availability (centre); least cost TCOs for each ship specification based on derived SU price (right)



***Note:** TCOs assume that ZNZ rewards applied to e-fuels bridge the TCO spread between e-ammonia and LNG and ZNZ rewards applied to biofuels bridge the TCO spread between bio-MGO and Penalty TCO*

The lower SU price decreases the TCO of the pay-to-pollute option (assuming RU2 are supplanted by cheaper SUs) and leaves the LNG DF and LNG DF + OCCS options essentially unchanged over this timeframe (although LNG DF will require increasing volumes of RU2 / SUs in the mid-to-late 2030s). On the other hand, the low SU price penalises the ammonia DF and methanol DF ships (which were running on e-ammonia and biomethanol with the support of ZNZ rewards) in the years where the reward triggered the Max TCO scenario and thus SU creation (2028 to 2033 for e-ammonia and 2028 for biomethanol). The TCO of the very ship / fuel generating sufficient volumes of SUs also rises to what is effectively the ceiling on its TCO.

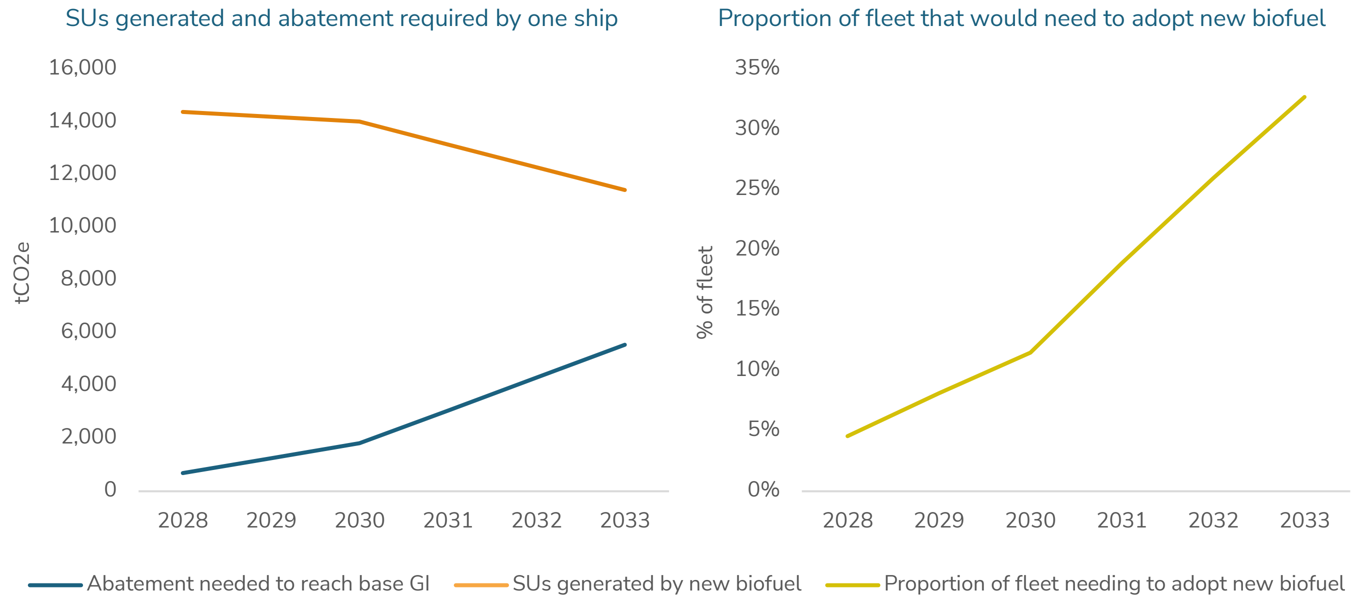
This analysis and worked example also reveal an important interaction between the SU price and the reward mechanism. If the reward mechanism specifies a reward price assuming that the SU price is equal to the RU2 price, but then subsequent SU market dynamics reduces the SU price relative, then the relative competitiveness of different fuel / energy options can easily be materially affected. As long as the reward mechanism remains undefined, this outcome remains a risk for those producing or expecting to operate on ZNZ's.

Is there a risk that the SU price could fall below RU2 prices considering fleet-wide energy use?

Extrapolating from a single ship model to the global fleet scale is a tenuous proposition. However, the relative proportions of 1) the emissions abatement required by a single ship to reach the Base GFI and 2) the volume of SUs that could be generated, give a rough indication of what the maximum take up of this new biofuel would need to be (Figure 13). Over the initial 3-year period, when the Base and Direct GFI trajectories require only small reductions in the GHG intensity of fuel / energy, and the RU2 and RU1 prices are fixed, the take-up of such a fuel needed to outstrip the upper bound on RU2 / SU demand rises from about 5% to 10%.

This estimate is entirely dependent on the projected emissions intensity of any new drop-in biofuel (e.g. such as the specification considered in this example), but these values (5-10%) are a conservative projection given there will be other low emission fuels (e.g. LNG) and abatement technologies (e.g. wind power, shore power, OCCS) that will eat into the total potential demand for RU2s / SUs, as well as additional sources of SU creation (e.g. triggered by ZNZ rewards) that will contribute to the pool of surplus credits.

Figure 13: Emissions abatement required to reach Base GFI and SUs generated by a single ship (left) and illustration of proportion of fleet that would need to adopt new biofuel to SUs in excess of the ceiling for RU2 / SU demand (right)



However, the oversupply of SUs may not be the only reason for the SU price to fall below RU2 levels. It seems likely that the trading of SUs will be through peer-to-peer agreements, with the IMO only fulfilling an administrative function in maintaining the GFI registry (e.g. GHG accountancy only). Without public information on the balance of supply and demand for SUs and/or the terms that have been agreed for the purchase of surplus credits, SUs may tend to trade at a discount to RU2 prices, particularly if associated bureaucratic transaction costs are high or the timing of the trades do not align with the cycle of compliance through RU2 acquisitions. The burden of bureaucracy may also discourage shipowners that only generate small amounts of surplus from trading, given SUs can be banked for two years. In the run up to the period when RU prices can be altered, larger volumes of SUs may be stockpiled in the hope that the ceiling on SU prices will rise.

However, these speculations on how the SU market may function presupposes that an active market will form in the first place. Some of the headwinds that may inhibit this include:

1. In the short term, although the volume of fuels capable of creating an oversupply of SUs is low, there are few existing options that look likely to be competitively SU-generating (given the initial GFI targets and RU prices), and the margins for competitiveness particularly when potential reduction in SU price (relative to an SU price that has a ceiling fixed by the RU2 price) is taken into account, look small.

2. In the mid-to-long term, over which more new fuel supply options at increasingly competitive prices may develop (including in response to ZNZ reward mechanisms), there is a rapidly diminishing revenue potential available from SUs. The volumes that can be produced reduce to negligible levels by the late 2030s, driven by the increasing stringency of the Direct GFI (and thus reducing margin for overcompliance).

Whilst any stakeholder will need to continue to test for a range of sensitivities and scenarios to ensure the robustness of their business case against both high and low SU prices, the apparent unlikelihood of the SU market being flooded by a surplus of SU credits means that the in this analysis, assumption that the future SU price will stay at the RU2 price ceiling (including when there is a rising RU2 price over time), has been retained.

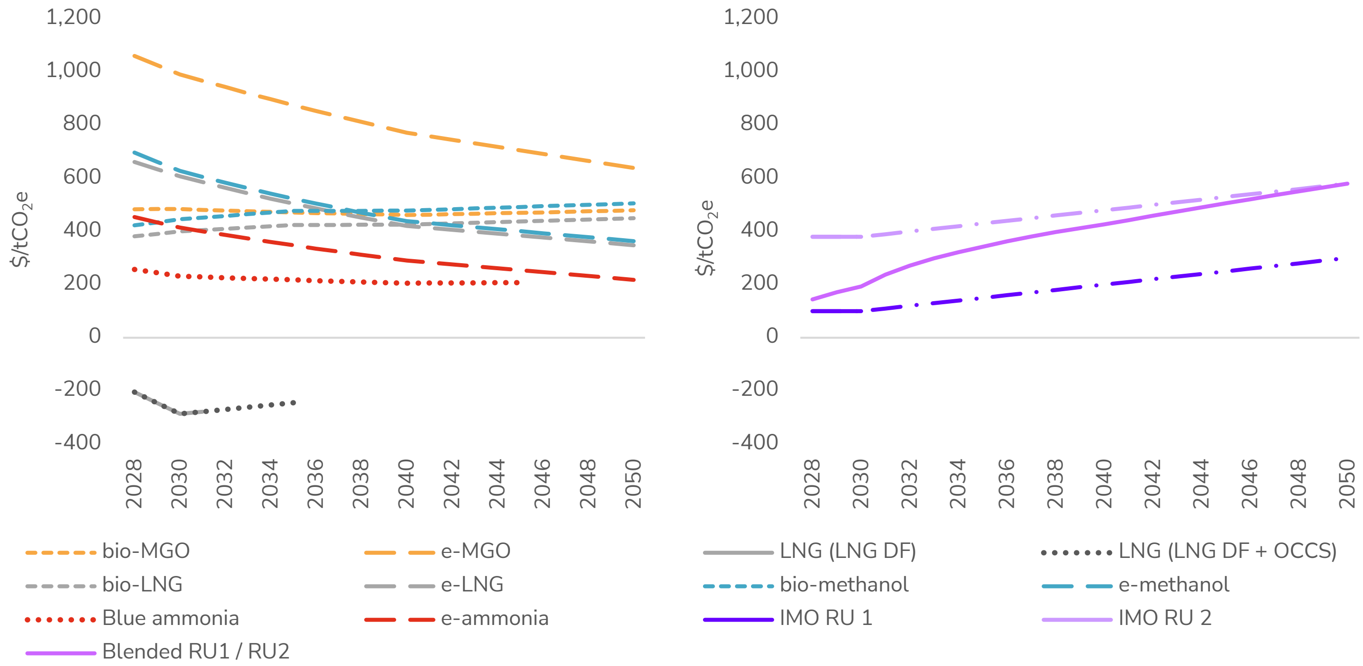
However, as can be seen in the example in Figure 11, while the specification of a fuel can theoretically enable SU generation into the mid-2040s, the economic constraints on SU trading apply far earlier. In the next section, the potential for changes in the parameters of the NZF to widen this SU trading window are considered.

What effects could future adjustment to the NZF parameters have?

Rising RU prices post-2030 can reduce the level of ZNZ rewards required to bridge the TCO gap

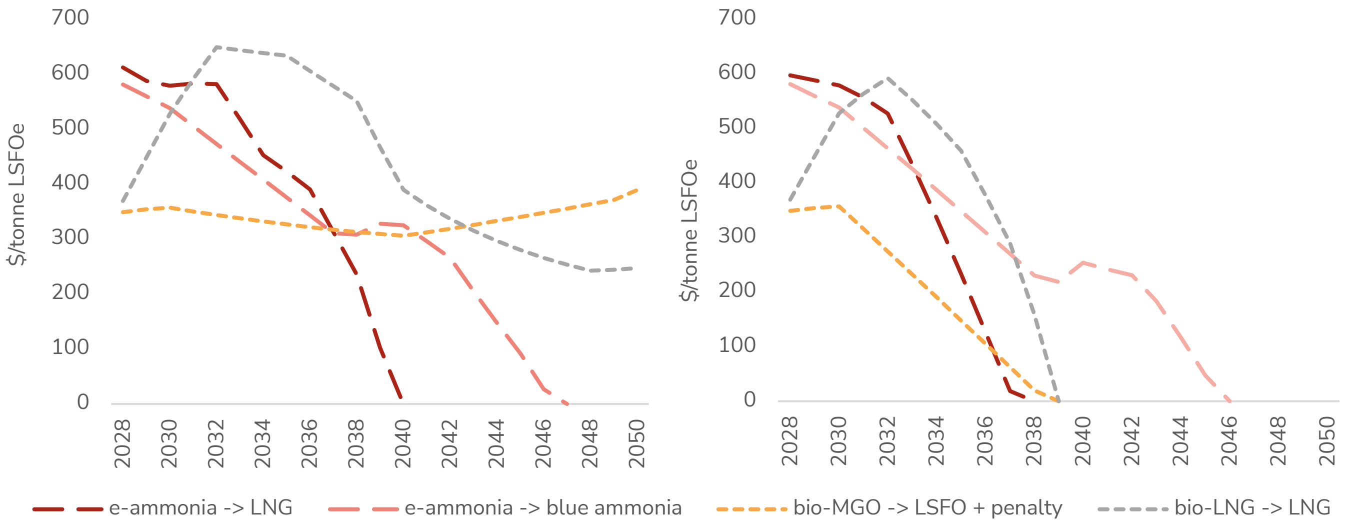
In addition to the ZNZ rewards, the IMO has two levers at its disposal to nudge the industry's response to the mid-term measures towards ZNZs, namely the options to change RU1 and RU2 pricing post-2030 and to alter the GFI trajectories. To illustrate the potential impact of the former, a scenario in which RU1 and RU2 prices rise by \$10/tCO_2e each year from 2031 onwards has been modelled. Figure 14 shows how RU prices and the blended cost of the pay-to-pollute option scale relative to the fuel abatement costs initially modelled (excluding the effects of the reward mechanism). By 2050, the RU2 price rises to \$580/tCO_2e, which is higher than the projected abatement cost of all fuels other than e-MGO.

Figure 14: Fuel abatement cost projects (left) and projected RU1 and RU2 prices (right)



As well as accelerating the timescales over which lower emission fuels with higher abatement costs can compete with the pay-to-pollute option, raising RU prices reduces the amount and duration of rewards required by ZNZs to bridge the TCO gap relative to a reference fuel which relies on the pay-to-pollute option as a means for competitive compliance. Figure 15 illustrates how the long-term demand for rewards by different fuel / energy options under a constant RU and SU assumption, wherein the reward needed (particularly for biofuels) is sharply curtailed by rising RU prices (and assuming that the SU price increases in line with RU2) as the cost gap for both bio-MGO and bio-LNG are being assessed against options relying on RUs. While the same is true for rewards that close the TCO gap for e-ammonia (versus LNG), the impact of higher SU prices is also a key driver in reducing the level of ZNZ rewards needed.

Figure 15: Derived rewards from TCO spreads with constant (left) and rising (right) RU / SU (assuming SU price rises in line with the RU2 ceiling)



Rising RU prices can lead to an earlier switch to ZNZs by ships that previously paid to pollute

The least cost TCOs have been recalculated assuming rising RU and SU prices, and applying ZNZ rewards for e-fuels that bridge the TCO gap between e-ammonia and LNG, as well as also rewards for biofuels that bridge the TCO gap between bio-MGO and the pay-to-pollute option until 2040. Compared to the original calculations (Figure 5), the rising cost of RUs drives up the cost of paying to pollute, thus increasing the TCOs of fuels previously relying on RUs (LNG until the mid-2040s and OCCS until 2050). The former now pivots to e-LNG by 2040 (raising costs in the first half of the 2040s) and the latter switches to bio-MGO (Figure 17).

Figure 16: Original calculation of least cost TCO, no reward, RU and SU prices assumed constant (left) vs least cost TCOs with ZNZ rewards applied and rising RU / SU prices

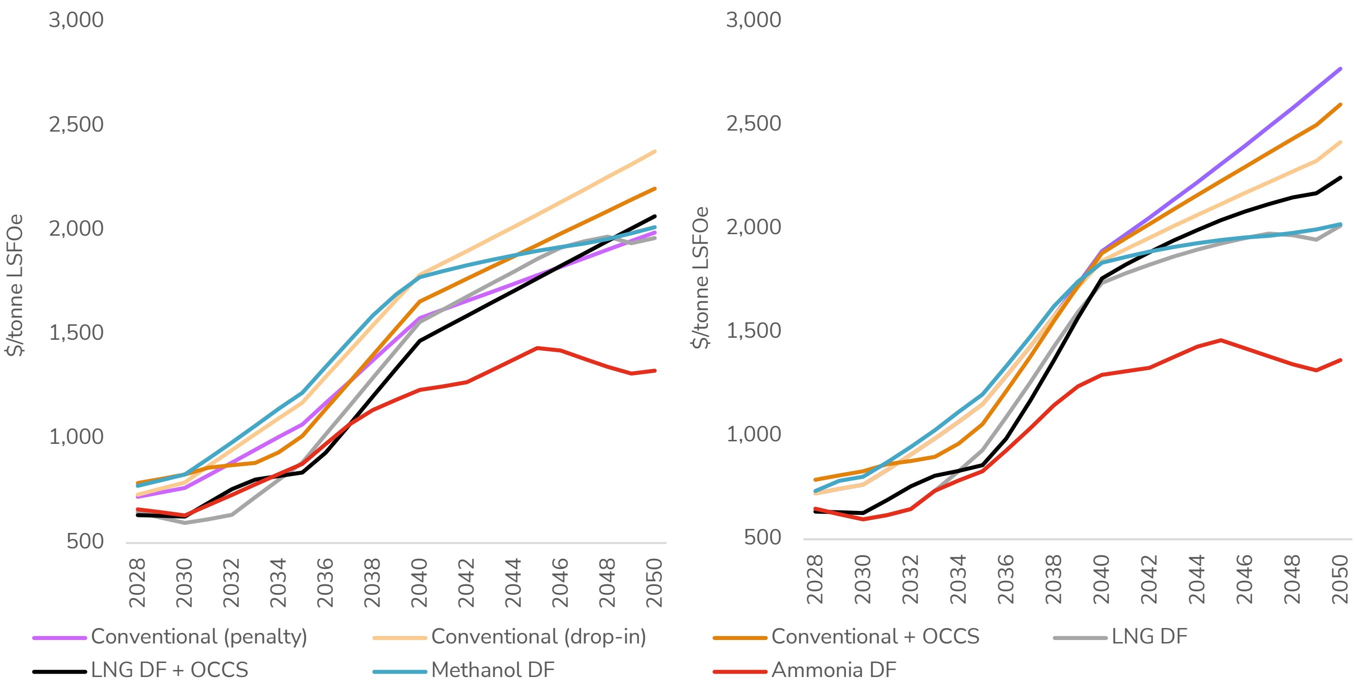
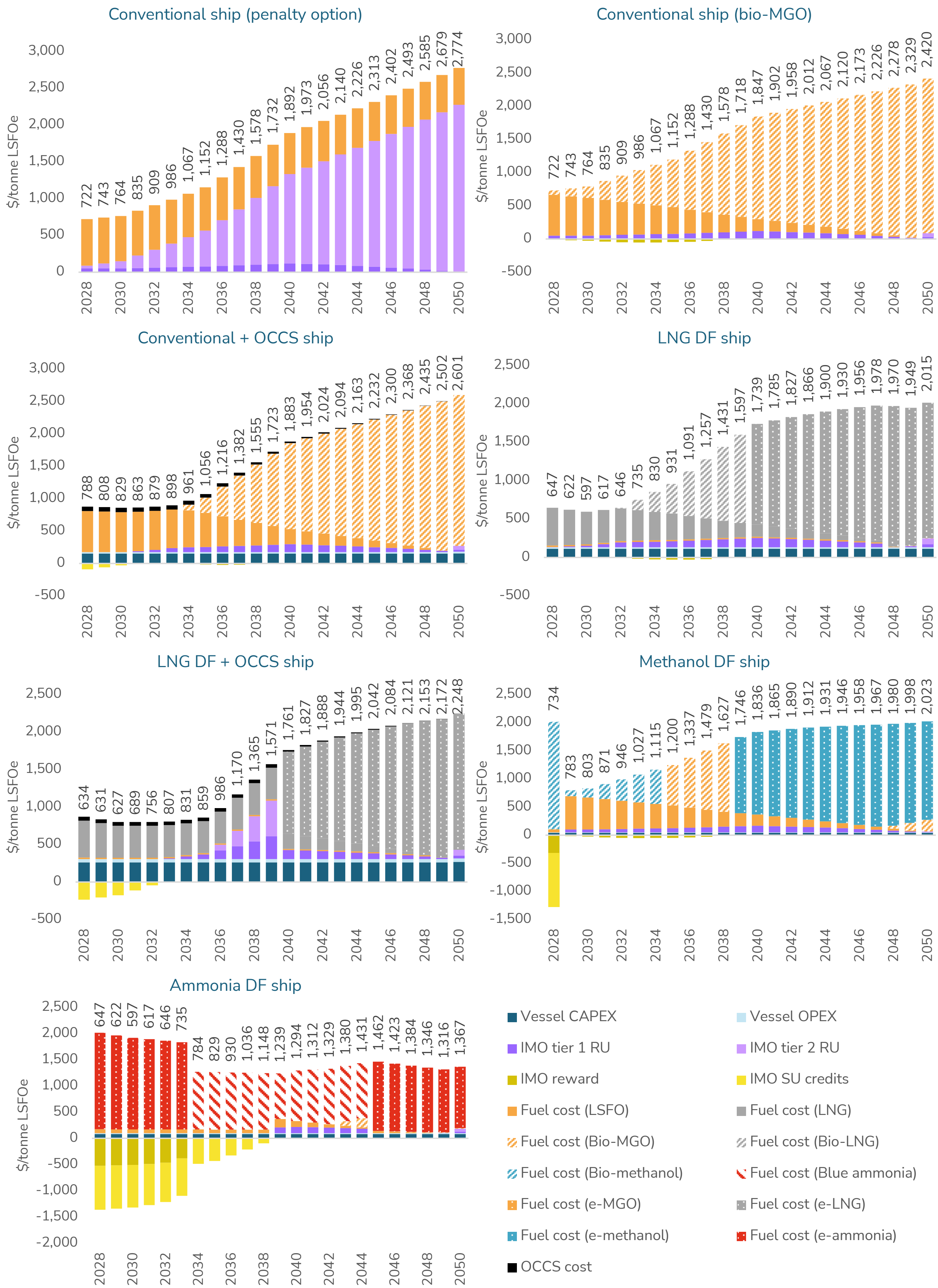


Figure 17: Breakdown of TCOs by ship specification with ZNZ rewards applied and rising RU / SU



Although it is again tenuous to extrapolate from a single ship model to the outcomes across the entire global fleet, compared to the initial TCO calculation shown in Figure 4 where RU and SU prices were held constant and ZNZ rewards had not yet been applied, Figure 17 indicates that with ZNZ rewards and rising RU prices, there could be a clearer (earlier and stronger) signal to shift from a pay-to-pollute strategy to actual abatement options.

With lower demand for RUs / SUs, this could lead to two key sources of tension:

1. At the point where production and availability of competitively priced ZNZ's respond to this signal (e.g. early-mid 2030's), will there be sufficient revenue to fund rewards for the volume demanded? How in turn does this interact with the price of SUs and generation of further revenues, and could this then feed back into the relative competitiveness of different options?

2. How might increasing pressure to use revenues for rewards to sustain growth in ZNZs be responded to politically, given the other demands on the revenues—including for Just and Equitable Transition (JET)?

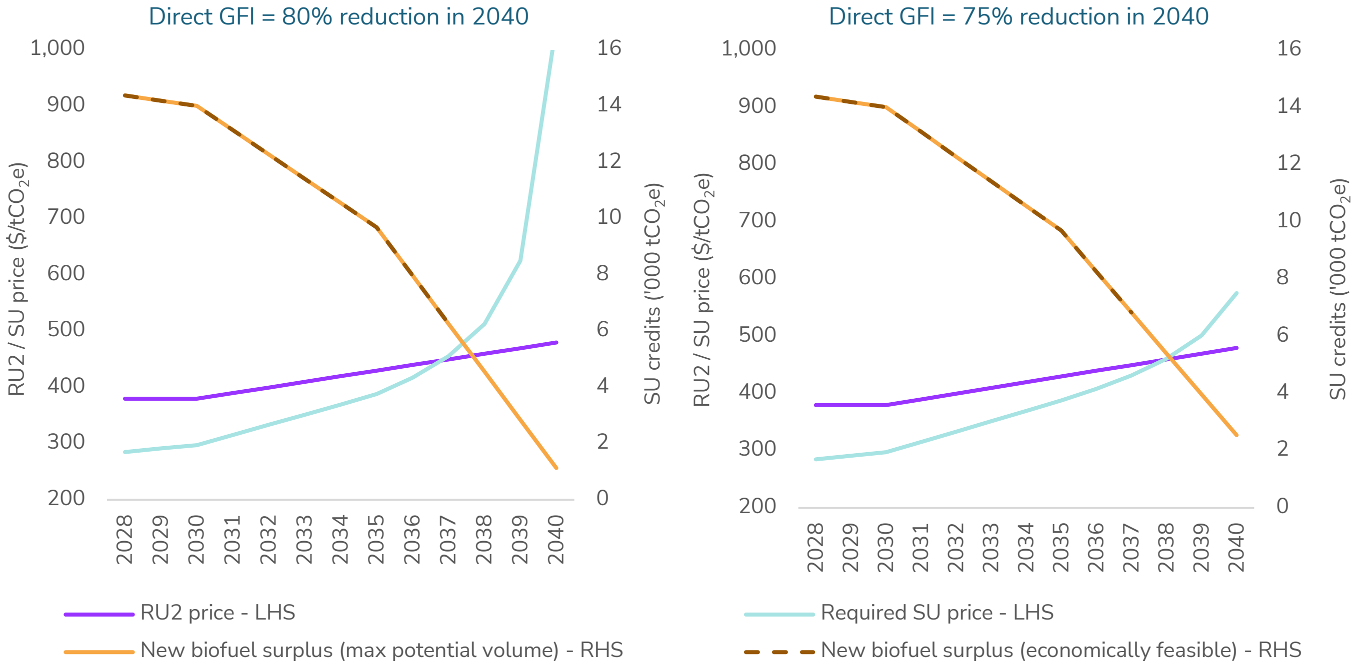
The implications for the uncertainty over the revenue / reward stream present a significant risk to the e-fuel ZNZ business case (production and use) in the later 2030s and early 2040s. Although ammonia as a fuel (and therefore ammonia DF ship specification) looks likely to be a competitive choice, Figure 15 indicates that a sustained reward is needed into the 2040s to ensure e-ammonia remains competitive relative to blue ammonia. If there were a rapid scaling of ammonia use across the sector from the mid-2030s, given challenges to scaling up revenues through RUs during this period, it seems unlikely that there would be sufficient total revenues available to support e-ammonia production and use into the late 2030s / early 2040s (even if considering scenarios of low revenue use for JET).

Can adjustments in the RU2 price and/or the GFIs extend the window for SU trading?

Due to the trajectories of the Base and Direct GFIs, the volume of SUs that can be generated through overcompliance with a low emission fuel is greatly eroded during towards the end of the 2030s but, as could be seen in the new drop-in biofuel example (Figure 11), under constant RU pricing, SU trading could be curtailed far earlier (in 2033) due to economic constraints. The capacity to extend the economic window for SU trading was tested for the scenario of a new biofuel entering the market by 1) raising RU2 prices (at \$10/tCO_2e pa) and 2) reducing the projected Direct GFI in 2040 from 80% to 75% (which has a knock on effect on the linear trajectory of the Direct GFI from 2035–2040 and 2040–2050).

Figure 18 indicates that higher RU2 prices can have an impact on increasing the time-window for SU trading. While adjusting the Direct GFI did allow for greater volumes of SUs to be created in the latter half of the 2030s, it did not accentuate the ability of the higher RU2 price to enable SU trading to be economically feasible until 2037 (after which the SU price required to trigger the Max TCO scenario over the Base TCO scenario rises above the RU2 level). The modelling also indicates that the economic window for SU trading closes rapidly at the end of the 2030s, with the required SU price scaling rapidly as the volume of surplus credits generated falls.

Figure 18: Effect of raising RU2 price and adjusting Direct GFI on extending economic window for SU trading



Conclusion

The agreement in principle of the IMO's NZF provides a major step forwards in clarifying the risks and opportunities faced across shipping's value chain during this transition. However, it also leaves key elements uncertain.

This analysis attempts to translate the elements of the framework that have been clarified across different ship specifications and fuel combinations in order to assess the relative competitiveness of those options, and to test for sensitivities against some of the remaining uncertainties—whether related to further policy development, techno-economic fundamentals or commercial decision-making processes. Given the scope of these uncertainties, this assessment only signals at some potential outcomes, but some important inferences can still be made at this stage.

Fuel choice will be dictated by abatement and penalty costs until the mid-2030s, but then increasingly narrowed by emissions intensity

The slate of fuel specifications modelled reflects a low gas price / high biofuel / falling e-fuel price outlook. On this basis, the TCO modelling signals that early in the transition, LNG would have an early competitive advantage relative to other fuel choices. Whether or not LNG turns out to be more competitive than other fuels by the early 2030s, its relatively high emissions intensity (it cannot generate SUs without OCCS) means that LNF DF ships are reliant on either lower emission drop-in fuels (whether bio-LNG, bio-MGO, e-LNG, etc.) or the penalty option (paying to pollute). This, coupled with the uncertainty in future gas price and abatement cost spreads versus other alternatives, mean that the incentivising signal for LNG could be relatively weak.

Any early competitive advantage for LNG also depends on the specifications of the ZNZ reward. Depending on how this mechanism is calibrated (i.e. which fuels receive rewards, what method is used to derive its value, and what is used as the basis for a reference or target price), ammonia DF could prove equally competitive over the near term.

By the mid-2030s, as the emissions intensity of LNG and conventional / bio fuels shifts the cost of compliance for these ship specifications much higher, the ammonia DF ship specification becomes the cheaper option. Blue ammonia, which also benefits from the low gas price outlook modelled, is the only fuel with an abatement cost lower than the initial RU2 price and the only fuel capable of generating significant volumes of SU into the mid-2030s without ZNZ rewards. At the emissions intensity projection used in the modelling, blue ammonia can be used into the mid-2040s, after which there is a switch to e-ammonia. As the e-fuel with the lowest abatement cost, e-ammonia requires the least amount of support to bridge the cost gap to either LNG or blue ammonia, and applying a reward mechanism setup in that, shows the potential for e-ammonia to be a competitive compliance pathway even from 2028 onwards.

In the near term, OCCS does not get a compelling endorsement from the TCO analysis. There are short periods where the LNG DF + OCCS solution is fractionally the least cost solution, but the CAPEX burden typically makes it less competitive than a ship using the same fuels without OCCS. In the absence of a clear long-term benefit, there may be limited incentive to invest, in both the fleet and associated landside infrastructure, particularly as it is a technology that is still highly uncertain (in terms of real-world performance) and reliant on a wide availability of infrastructure (to ensure regular disposal of captured carbon and therefore high utilisation of the technology).

There is also no compelling endorsement of methanol in the TCO results in the short term. Under these fuel assumptions, biomethanol does not appear competitive relative to LNG or a conventionally fuelled ship paying to pollute, and biomethanol's cost competitiveness does not look likely to generate significant SU revenue. In the longer term, the potential ZNZ e-methanol does not look likely to be competitive to e-ammonia, depending on how rewards are structured there may be some support for its use in the mid-term (e.g. during the 2030's).

For the large majority of the existing fleet—conventionally fuelled ships—the near-term least cost compliance option under the fuel scenario applied appears to be paying the penalty, enabled by the initial RU2 level being lower than the expected price of bioenergy. In a scenario where the RU2 price is increased (in line with the IMO's commitment to review and revise the RU prices in the future), the relative competitiveness of paying to pollute falls over time as the Base GFI becomes more stringent, indicating that a penalty-based strategy becomes increasingly risky beyond 2031.

A hypothetical 'new' bioenergy oil product priced to make its use competitive could be cheaper than the penalty option. Testing the potential dynamics of such a fuel indicates that, unless its abatement cost was very low and supply was high, it would most likely be blended to enable compliance with the Base GFI, rather than applied in strategies intending to exceed the Direct GFI in order to generate a large volume of SU revenues (and thus, potentially, reduce the SU price).

From the shipowner's perspective, a near-term outlook which suggests similar levels of competitiveness between different ship specifications (particularly conventional, LNG DF and ammonia DF ships), and significant uncertainties, might encourage shipowners to pursue a range of strategies with multiple ship specifications. This could also create a challenging environment for fuel / energy producers, potentially resulting in large swings in volume demand and price of their products.

However, even with initial parameters fixed (e.g. for RU prices), and ignoring the reward mechanism, a clear advantage for ammonia DF is evidenced in the mid-2030s. By this point, the competitiveness of ammonia as a technology choice stems from its ability to access blue ammonia—a fuel of low emissions intensity and low abatement cost relative to other fuels. This is not a business case that is dependent on SUs or rewards, which improves its stability and predictability and lowers the risk. As the GFIs begin to aggressively limit the permissible emissions intensities of fuel used, access to e-ammonia (the cheapest e-fuel option), underpins long-term investment decisions on this ship specification and technology choice.

RUs, SUs and rewards are key drivers of relative competitiveness, but need to be analysed as sensitivity parameters

There is an intrinsic interdependence between the RU-SU-reward parameters. Individually and in combination, they exert pressures that shape the relative competitiveness of different fuel / energy options. Each factor embodies a different type of uncertainty, making assessment currently difficult and potentially leading market participants to ignore or misjudge the effects.

There is a risk that assumptions used for decision making will anchor at the initial RU price levels and not recognise that RU pricing will need to increase to ensure GHG emission reductions are achieved in practice, and increasingly ensure scaling up of use of a wider range of potential fuels with higher abatement costs. In a similar vein, as the reward mechanism has yet to be specified, it may be discounted entirely until it has been specified. There is a risk of ignoring these potential developments, as evidenced by the comparison between TCOs calculated with constant RU / SU prices and without a reward factored in versus TCOs with increasing RU / SU prices and ZNZ rewards (Figure 16).

Many stakeholders may be tempted to make initial decisions based on a similar assessment, particularly as the process for reviewing RU2 prices and the specification of the reward mechanism will remain uncertain (potentially up to mid-2027), and future revenue availability may remain uncertain over the longer term.

Some stakeholders may prefer to make decisions using an assumed SU price, given the SU mechanism is currently more clearly defined in the MARPOL amendment and less obviously affected by revenue, reward and political uncertainties. However, this analysis shows that there is also uncertainty around the SU price, driven by the supply of SUs and the reduction in demand for SUs that can arise from technological developments in fuel / energy production processes.

By considering the potential effects of a drop-in bioenergy product at lower abatement cost than initially assumed in this analysis, this report shows that it would simultaneously reduce demand for SUs and increase supply of SUs. Either, or both of these effects in combination, could create significant swings in the SU price, affecting the relative competitiveness of different technology and fuel choices.

This study therefore highlights that current (and, in some case, continuing) uncertainties about RU / SU prices and the reward specification, as well as on the interactions that can occur between them, necessitates that analysis be conducted over a range of potential parameter assumptions, to ensure the robust assessment of any risks and opportunities for different fuel / energy options.

For shipowners, short-term optionality as well as mid-term optimality can both be addressed by ordering ammonia dual fuel ships

The TCO analysis indicates that the strategy to only own and operate conventionally fuelled tonnage will be uncompetitive in the short term (and increasingly so into the medium term). Combining insights from the relative competitiveness of fuels over the short and medium term with uncertainties around the impact of RU, SU and rewards on the relative competitiveness of alternative solutions, there is a clear advantage of retaining optionality across different feedstock and production processes throughout the transition. This type of strategy could also benefit from uncertain but entirely plausible upsides in SU and reward revenues.

For some shipowners with large fleets and the capacity to negotiate with a range of energy suppliers, this may lead to a strategy to operate a fleet of ships with a range of different fuel technology specifications (e.g. a mix of LNG DF, ammonia DF and conventionally fuelled ships), thereby physically hedging across the different options and pathways—at least for an initial period.

However, this study's analysis shows there is also potential to hedge most of the uncertainties using the optionalities embodied in a single ship technology specification: ammonia DF. Over the short term, this choice benefits from exposure to:

1. Natural gas pathway (low gas price and/or strong SU price enabling competitiveness of blue ammonia)
2. E-fuel pathway (if e-ammonia costs reduce faster than expected)
3. Biofuel pathway (if a competitive drop-in biofuel is available)
4. Fossil fuel and pay to pollute (if there is no revision of RU prices)

The ship specification also aligns with the least cost compliance solutions over the medium-to-long term as indicated in the scenarios considered in this study (via blue ammonia and/or e-ammonia). Compared with other ship specifications, ammonia DF covers a wider span of potential solutions (Table 3)

Table 3: Assessing the optionality across different ship specifications and conditions

Ship specification	Least cost choice to 2035	Potential if sufficient reward revenue?	Other optionalities	CCS?
Conventional	Fossil + pay to pollute	Advanced biofuels if eligible in reward specifications	Bio-MGO	Similar or worse competitiveness to other options
LNG	Fossil + pay to pollute	Bio or e-methane depending on reward specifications	Bio-MGO	Similar competitiveness to other options
Methanol	Fossil + biomethanol	Bio or e-methanol depending on reward specifications	Bio-MGO	Not relevant
Ammonia	Blue ammonia (using SUs)	E-ammonia	Fossil + pay to pollute, Bio MGO	Not relevant

Ports will need to weigh investment in bunkering infrastructure over the timescales dictated by the fuel standard

The advantage that optionality provides to shipowners could also apply to ports. In the near term, ports may focus on infrastructure investment that builds bunkering capacity for the fuel / energy molecules that will continue to be utilised, even as production pathways evolve over time—for example, oil (fuel oil potentially switching to bio), LNG (fossil LNG potentially switching to bio-LNG), and ammonia (blue potentially switching to e-ammonia). However, over the medium-to-long term, the evolving relative competitiveness of these options means demand is likely to become more focused (although not exclusively) on ammonia.

The particular challenge for ports is then managing the constrained window over which LNG is competitive, as the TCO results imply that there could be strong demand from LNG DF ships initially, which then reduces. If RU prices do not increase in the 2030s, then a certain volume of demand for LNG may be sustained through shipowners opting to use a pay to pollute strategy. However, if RU price increases, those with LNG DF tonnage may decide to either opt for a biofuel (which could be bio-MGO or bio-LNG, so does not guarantee use of LNG bunkering infrastructure) or retrofit their ships to operate on ammonia. In either scenario, then demand for LNG bunkering services could contract rapidly, leading to a short window in which to earn a return on any LNG bunkering investment.

The IMO's NZF indicates the benefit of a strategy for ports to incrementally develop capacity and bunkering services related to ammonia, whilst also being ready to rapidly scale up those services depending on any revisions to key NZF parameters during reviews (e.g. increasing RU prices, or adjusting GFI limits, which based on this analysis are expected to accelerate the ammonia transition).

The signals to fuel producers, and particularly ZNZ producers, are less clear over the near term

For fuel producers, the analysis indicates that this group receive the least degree of clarity from the IMO NZF. Signals at this stage include:

Conventional fossil fuel producers: Conventional marine fuels producers are given a clear initial signal of continued demand for their product and may believe the large existing fleet of conventional ships that will continue to need 'oil' will sustain demand out to 2040. Under current RU pricing, the relative competitiveness of pay to pollute for this fleet, would lead expectations of significant demand for oil at least out to the mid-2030's.

However, such demand projections will depend on several uncertainties that may make it difficult for these producers to manage their risks:

1. Will the IMO revise up the RU price during the 2030s, more strongly disincentivising pay to pollute as a strategy for the conventional fleet, and thus lead to a more rapid contraction of demand for oil?
2. Will a drop-in biofuel product at sufficiently high volume and low enough price, become available during this period, enabling substitution of oil in conventionally fuelled ships?
3. Will blue ammonia, or rewarded ZNZs, create a significant and growing compliance option during the 2030's, leading to a rapid substitution of energy use away from oil that decade?

LNG producers: These entities are given a strong positive initial signal, but with future uncertainty over whether there will be a rapid contraction of demand (rising RU price, increasing competition from ammonia), or more stable demand through the 2030s (RU price continuing to support the penalty option, delayed availability and competitiveness of ammonia). The challenge for LNG producers is therefore similar to the challenge for LNG infrastructure and bunkering providers – judging the longevity of demand, and the rate of contracting demand during the 2030's.

Biogenic fuel producers: This group have perhaps a clearer signal—if they can produce below the current RU2 price thresholds, then there is a strong demand potential, especially for drop-in fuels (conventional oil equivalents). And this demand should only strengthen and improve if there is subsequent increase in the RU2 price. Depending on the specifications of the ZNZ reward mechanism, if this includes some reward for a subset of biogenic fuels, this may extend the signal and strengthen demand at least for that subset.

Blue vs e-ammonia producers: Due to the current lack of specification of the reward mechanism, and the uncertainty related to the scale of e-ammonia that could be rewarded by available IMO funds, blue ammonia producers receive a clearer signal from the NZF than e-ammonia producers. Both, however, should receive a strong long-term signal from NZF, given the 2040 Base GFI stringency and the IMO's 2050 net zero commitment (although this is unlikely to help in the short-term investment case) For both types of producers, there is also short-term uncertainty as to whether shipowners will respond to the NZF by investing in ammonia DF ships, or wait to see signs of investment in fuel production first.

Appendix

Input data used in TCO modelling

The data used in the TCO modelling is primarily derived from the CIA, but alternative sources are used to adjust assumptions on biofuel prices and the CCS capture rate, and to model the voyage profile of the illustrative ship.

Fuel price, emissions intensity and abatement cost data

Table 4, Table 5 and Table 6 contain the fuel assumptions (yearly price, WtW emissions intensity and abatement cost) used in the TCO modelling. All data is drawn from the IMO CIA other than the cost curves for bio-MGO, bio-LNG and biomethanol (which is based on analysis undertaken for MPEC 79), and the price and emissions intensity of the 'new' biofuel which has been derived from abatement costs to be used as a sensitivity parameter.

Table 4: Fuel price projections 2028-2050 in $/tonne LSFOe; CCS storage costs in $/t$CO_2$e

Year	LSFO	bio-MGO	e-MGO	LNG	bio-LNG	e-LNG	bio-methanol	e-methanol	Blue ammonia	e-ammonia	'New' biofuel	CCS storage
2028	633	1,286	3,580	508	1,909	2,563	2,098	2,750	1,351	2,089	1,286	80
2029	624	1,303	3,513	474	1,941	2,520	2,139	2,682	1,314	2,037	1,303	79
2030	615	1,319	3,446	440	1,972	2,477	2,179	2,613	1,277	1,986	1,319	78
2031	609	1,368	3,403	439	1,997	2,445	2,211	2,580	1,270	1,954	1,368	77
2032	604	1,416	3,360	439	2,021	2,413	2,243	2,546	1,264	1,922	1,416	77
2033	598	1,464	3,317	439	2,045	2,381	2,275	2,512	1,258	1,891	1,464	76
2034	593	1,512	3,273	438	2,070	2,349	2,306	2,478	1,251	1,859	1,512	75
2035	587	1,560	3,230	438	2,094	2,316	2,338	2,445	1,245	1,828	1,560	74
2036	582	1,608	3,187	437	2,103	2,284	2,349	2,411	1,238	1,796	1,608	73
2037	576	1,657	3,144	437	2,111	2,252	2,359	2,377	1,232	1,764	1,657	72
2038	570	1,705	3,101	436	2,119	2,220	2,369	2,343	1,225	1,733	1,705	71
2039	565	1,753	3,058	436	2,127	2,188	2,379	2,310	1,219	1,701	1,753	70
2040	559	1,801	3,015	436	2,135	2,156	2,390	2,276	1,213	1,670	1,801	70
2041	553	1,849	2,966	435	2,143	2,123	2,399	2,240	1,208	1,636	1,849	69
2042	547	1,897	2,918	435	2,150	2,089	2,408	2,205	1,203	1,602	1,897	68
2043	541	1,946	2,870	434	2,157	2,055	2,416	2,170	1,199	1,568	1,946	67
2044	535	1,994	2,822	434	2,164	2,021	2,425	2,134	1,194	1,535	1,994	66
2045	529	2,042	2,773	433	2,171	1,988	2,434	2,099	1,189	1,501	2,042	65
2046	524	2,090	2,725	433	2,178	1,954	2,443	2,063	1,184	1,467	2,090	64
2047	518	2,138	2,677	433	2,185	1,920	2,452	2,028	1,180	1,433	2,138	63
2048	512	2,186	2,629	432	2,192	1,886	2,461	1,992	1,175	1,400	2,186	63
2049	506	2,235	2,580	432	2,199	1,853	2,469	1,957	1,170	1,366	2,235	62
2050	500	2,331	2,532	431	2,206	1,819	2,478	1,922	1,166	1,332	2,331	60

Source: *Non-highlighted fuel prices from DNV CIA (Full report can be downloaded from IMODOCS (documents MEPC 76/7/13 and MEPC 76/INF.68 and addenda); registration is required); highlighted fuel costs (biofuels) from analysis undertaken for MEPC 79 (submitted data can be downloaded from IMODOCS (documents MEPC 79.INF29); registration is required)*

Table 5: Fuel GHG emissions intensity projections 2028-2050 in WtW gCO_2e per MJ

Year	LSFO	bio-MGO	e-MGO	LNG	bio-LNG	e-LNG	bio-methanol	e-methanol	Blue ammonia	e-ammonia	'New' biofuel
2028	91.8	30.0	26.8	77.5	13.5	23.5	10.7	20.7	26.4	16.8	30.0
2029	91.8	28.7	25.9	77.5	13.0	21.8	10.2	19.0	25.7	15.6	28.6
2030	91.8	27.5	25.0	77.5	12.4	20.1	9.6	17.3	24.9	14.4	27.3
2031	91.8	26.2	24.2	77.5	11.7	18.4	8.9	15.6	24.1	13.2	25.9
2032	91.8	25.0	23.4	77.5	10.9	16.7	8.1	13.9	23.4	12.0	24.5
2033	91.8	23.7	22.7	77.5	10.2	15.0	7.4	12.2	22.6	10.8	23.2
2034	91.8	22.5	21.9	77.5	9.5	13.3	6.7	10.5	21.8	9.5	21.8
2035	91.8	21.2	21.2	77.5	8.7	11.6	5.9	8.8	21.1	8.3	20.5
2036	91.8	19.9	20.4	77.5	8.0	9.9	5.2	7.1	20.3	7.1	19.1
2037	91.8	18.7	19.6	77.5	7.2	8.2	4.4	5.4	19.6	5.9	17.7
2038	91.8	17.4	18.9	77.5	6.5	6.4	3.7	3.6	18.8	4.7	16.4
2039	91.8	16.2	18.1	77.5	5.8	4.7	3.0	1.9	18.0	3.5	15.0
2040	91.8	14.9	17.4	77.5	5.0	3.0	2.2	0.2	17.3	2.3	13.6
2041	91.8	13.7	17.4	77.5	4.8	3.0	2.0	0.2	17.3	2.3	12.3
2042	91.8	12.4	17.4	77.5	4.6	3.0	1.8	0.2	17.3	2.3	10.9
2043	91.8	11.2	17.4	77.5	4.4	3.0	1.6	0.2	17.3	2.3	9.5
2044	91.8	9.9	17.4	77.5	4.2	3.0	1.4	0.2	17.3	2.3	8.2
2045	91.8	8.6	17.4	77.5	4.0	3.0	1.2	0.2	17.3	2.3	6.8
2046	91.8	7.4	17.4	77.5	3.8	3.0	1.0	0.2	17.3	2.3	5.5
2047	91.8	6.1	17.4	77.5	3.6	3.0	0.8	0.2	17.3	2.3	4.1
2048	91.8	4.9	17.4	77.5	3.4	3.0	0.6	0.2	17.3	2.3	2.7
2049	91.8	3.6	17.4	77.5	3.2	3.0	0.4	0.2	17.3	2.3	1.4
2050	91.8	2.4	17.4	77.5	3.0	3.0	0.2	0.2	17.3	2.3	0.0

Source: *DNV CIA (Full report can be downloaded from IMODOCS (documents MEPC 76/7/13 and MEPC 76/INF.68 and addenda); registration is required)*

Table 6: Resulting fuel abatement costs (vs LSFO) over period of viability (with respect to Base GFI) 2028-2050 in $/tCO$_2$e

Year	bio-MGO	e-MGO	LNG	LNG + CCS	bio-LNG	e-LNG	bio-methanol	e-methanol	Blue ammonia	e-ammonia	'New' biofuel
2028	484	1,061	-205	-205	382	662	423	697	257	454	454
2029	484	1,026	-246	-246	391	634	434	662	244	434	434
2030	484	991	-287	-287	400	608	446	628	231	414	414
2031	482	967	-278	-278	405	585	452	605	229	400	400
2032	479	944		-270	410	564	459	584	226	387	387
2033	476	920		-261	415	543	465	563	223	373	373
2034	474	898		-253	420	523	471	543	220	360	360
2035	471	876		-245	425	505	477	524	218	348	348
2036	469	854			425	486	478	505	215	336	336
2037	467	833			425	469	478	488	213	324	324
2038	465	812			425	452	478	471	210	312	312
2039	464	792			425	436	478	454	208	301	301
2040	462	772			425	421	478	439	205	290	290
2041	463	759			428	414	481	431	206	283	283
2042	465	745			430	406	484	424	206	276	276
2043	467	732			433	399	487	416	206	269	269
2044	468	719			435	392	489	409	207	261	261
2045	470	706			438	385	492	401	207	254	254
2046	472	692			440	377	495	394		247	247
2047	474	679			443	370	498	386		240	240
2048	476	666			445	363	500	379		232	232
2049	477	652			448	355	503	371		225	225
2050	479	639			450	348	506	363		218	218

Ship, voyage and fuel consumption data

Table 7 contains the remaining data used to model the TCO of an illustrative 213,000 dwt bulkcarrier sailing between Australia and East Asia. Data on the voyage profile is obtained from the UMAS Fuse model, other ship assumptions are from the CIA, and assumptions regarding the capture rate of CCS come from a recent study.

Table 7: Ship and voyage inputs to TCO model

Variable	Unit	Value	Source
Vessel size	dwt	213,000	
Sailing distance pa	nautical miles	65,000	UMAS Fuse model
Average speed	knots	11.5	UMAS Fuse model
Avg. days at sea pa	days	235	UMAS Fuse model
Avg. days at port pa	days	130	UMAS Fuse model
Energy demand at sea pa	GJ pa	280,000	UMAS Fuse model
Energy demand at port pa	GJ pa	20,000	UMAS Fuse model
Total energy demand pa	GJ pa	300,000	UMAS Fuse model
Discount rate	%	4%	DNV CIA
Economic life	years	20	DNV CIA
Scrap value	% of CAPEX	0%	DNV CIA
Pilot fuel (LNG)	%	3%	DNV CIA
Pilot fuel (methanol)	%	9%	DNV CIA
Pilot fuel (ammonia)	%	12%	DNV CIA
LNG DF premium	$m	11	DNV CIA (based on 200,000+ dwt deep sea bulk)
Methanol DF premium	$m	4	DNV CIA (based on 200,000+ dwt deep sea bulk)
Ammonia DF premium	$m	8	DNV CIA (based on 200,000+ dwt deep sea bulk)
CCS system premium	$m	15	DNV CIA (based on 200,000+ dwt deep sea bulk)
CCS capture rate	%	27%	OGCI / Stena report
CCS fuel penalty	%	10%	OGCI / Stena report
DF / CCS / EET OPEX premium	% of CAPEX	1.25%	DNV CIA (OPEX as % of EET CAPEX; assumed to apply to DF CAPEX and CCS CAPEX)

Source: *UMAS; UNCTAD; DNV CIA (Full report can be downloaded from IMODOCS (documents MEPC 76/7/13 and MEPC 76/INF.68 and addenda); registration is required); OGCI / Stena*

Input data on IMO policies

Table 8 shows the values that have so far been stated (highlighted) and projected figures for the IMO's Base and Direct GFIs, RU1 / RU2 prices, and ZNZ criteria.

Table 8: Base and Direct GFI trajectories and RU1 / RU2 assumptions

Year	Base GFI (WtW gCO_2e/MJ)	Direct GFI (WtW gCO_2e/MJ)	RU1 constant ($/$tCO_2e$)	RU2 constant ($/$tCO_2e$)	RU1 increasing ($/$tCO_2e$)	RU2 increasing ($/$tCO_2e$)	ZNZ criteria (WtW gCO_2e/MJ)
2028	89.6	77.4	100	380	100	380	19
2029	87.7	75.6	100	380	100	380	19
2030	85.8	73.7	100	380	100	380	19
2031	81.7	69.6	100	380	110	390	19
2032	77.6	65.5	100	380	120	400	19
2033	73.5	61.4	100	380	130	410	19
2034	69.4	57.3	100	380	140	420	19
2035	65.3	53.2	100	380	150	430	14
2036	58.8	46.3	100	380	160	440	14
2037	52.2	39.4	100	380	170	450	14
2038	45.7	32.5	100	380	180	460	14
2039	39.2	25.6	100	380	190	470	14
2040	32.7	18.7	100	380	200	480	14
2041	29.4	16.8	100	380	210	490	14
2042	26.1	14.9	100	380	220	500	14
2043	22.9	13.1	100	380	230	510	14
2044	19.6	11.2	100	380	240	520	14
2045	16.3	9.3	100	380	250	530	14
2046	13.1	7.5	100	380	260	540	14
2047	9.8	5.6	100	380	270	550	14
2048	6.5	3.7	100	380	280	560	14
2049	3.3	1.9	100	380	290	570	14
2050	0.0	0.0	100	380	300	580	14

Source: *Report of the nineteenth meeting of the Intersessional Working Group on Reduction of GHG Emissions from Ships (ISWG-GHG 19) and the Working Group on Reduction of GHG Emissions from Ships (Full report can be downloaded from IMODOCS; registration is required)*