Zero-Emission Vessels 2030. How do we get there?

We're considering the drivers that will make Zero-Emission Vessels viable.
Part of the Low Carbon Pathways 2050 series.

Contents

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Cover photo supplied by Chuttersnap

Keeping pace with a changing world.

Fossil fuels provide society in general, as well as shipping, with a high-density and low-cost energy source that is comparatively easy to store, handle and transport. We have had decades to optimise the design, maintenance and operation of the shipping system to suit the fossil 'paradigm'. But the world is changing. It is, therefore, unsurprising that when looking for a non-fossil, zero-emission and sustainable energy source, as we must urgently now do, it's difficult to see an obvious 'silver bullet'.

The first milestone in the IMO Greenhouse Gas (GHG) Roadmap is approaching: MEPC 72, which is in April 2018. The world is watching to see if an ambitious reduction strategy in line with the Paris Agreement can be delivered. To achieve this ambition, Zero-Emission Vessels (ZEVs) will need to be entering the fleet in 2030 and form a significant proportion of newbuilds from then on.

This transition to a new mix of fuels now has broad government and industry buy-in. It is inevitable that a policy process starts with the definition of the objective, but the question we are increasingly asked is: How are we going to achieve this in practice?

In order to answer this, in collaboration with University Maritime Advisory Services (UMAS), we started by asking shipowners what they were looking for. We found that a number of considerations were important. In particular, they wanted the options to be viable at a moderate carbon price (e.g. \$50/tonne CO_2) and without too great an increase to the capital cost of the ship. They were also keen to ensure that we don't just move the impact of the CO_2 emissions upstream, to the electricity generation or fuel production process.

To test these requirements, we examined seven technology options applied to five different case study ship types. These options consist of various combinations of battery, synthetic fuels and biofuel for the onboard storage of energy, coupled with either a fuel cell and motor, internal combustion engine (ICE); or a motor for the conversion of that energy store into the mechanical and electrical energy required for propulsion and auxiliary services.

Decarbonisation is a huge challenge."

Katharine Palmer
Global Sustainability Manager, LR

"There is no doubt that decarbonisation is a huge challenge for our sector and that we all have a clear responsibility to ensure actions are taken to drive our operational emissions to zero at a pace matching actions taken across the rest of the world and other industry sectors. By assessing different decarbonisation options for different ship types, we identify the drivers that need to be in place to make them a competitive solution and we aim to show the opportunity for a successful and low-cost decarbonisation pathway for shipping."

Tristan Smith
Reader, UCL

"This report demonstrates the potential solutions for shipping's zero-emission transition. By sharing the findings, we hope it can provide inspiration and focus for shipping's collective efforts to ensure we reach a zero-emission scenario swiftly and with minimal cost and disruption to trade."

Many of these options are evolving rapidly and it is reasonable to anticipate that the costs of fuel cells, batteries and hydrogen storage could all reduce significantly, especially if they become important components of another sector's decarbonisation, or if action taken during shipping's transition assists with the technology's development.

Ultimately, none of the zero-emission options in their current specifications completely satisfied the shipowner requirements, with the most significant gap identified being voyage costs. This leaves regulatory intervention, such as a high carbon price, necessary in the near future if we are to ensure take-up.

Nevertheless, there is certainly potential for a significant portion of the competitiveness gap to be closed as the enabling technologies and infrastructures are further developed. And for those in shipping with niche access to a low-cost supply of zero-emission fuel or energy sources, or an ability to pass on a voyage cost premium to a supply chain that values zero-emission services, the gap may already be closed.

About Lloyd's Register (LR)

We started out in 1760 as a marine classification society. Today, we're one of the world's leading providers of professional services for engineering and technology – improving safety and increasing the performance of critical infrastructures for clients in over 75 countries worldwide. The profits we generate fund the Lloyd's Register Foundation, a charity which supports science and engineering-related research, education and public engagement around everything we do. All of this helps us stand by the purpose that drives us every single day: Working together for a safer world.

In a world of increasing complexity – overloaded with data and opinion - we know that our clients need more than technology to succeed. They need an experienced hand. A partner to listen, cut through the noise and focus on what really matters to them and their customers. Our engineers and technical experts take pride in the craft of assurance. That means a commitment to embracing new technology, and a deep rooted desire to drive better performance. So we consider our customers' needs with diligence and empathy, then use our expertise and over 250 years' experience to deliver the smart solution for everyone.

After all, there are some things technology can't replace.

Lloyd's Register

For more details, visit **info.lr.org/zev2030**

About UMAS

UMAS is a sector-focused commercial advisory service that draws upon the world-leading shipping expertise of the UCL Energy Institute, combined with the advisory and management system expertise of MATRANS. In combination, UCL Consultants, the UCL Energy Institute and MATRANS operate under the UMAS branding.

UMAS undertakes research using models of the shipping system, shipping big data (including satellite Automatic Identification System data), and qualitative and social science analysis of the policy and commercial structure of the shipping system. Research and consultancy is centred on understanding patterns of energy demand in shipping and how this knowledge can be applied to help shipping transition to a low-carbon future. UMAS is world-leading in two key areas: first, using big data to understand the trends and drivers of shipping energy demand and emissions; and, second, using models to explore 'what ifs' for future markets and policies.

Our mission is to accelerate the transition to an equitable, globally sustainable energy system through world-class shipping research, education and policy support.

UMAS

For more details, visit **www.u-mas.co.uk**

ZEVs – Where are we now, and where do we need to be?

The world is watching. The first milestone in the IMO GHG Roadmap is approaching: MEPC 72, which is in April 2018. Can we deliver an ambitious GHG reduction strategy in line with the Paris Agreement?

In its Third GHG Study[1], published in 2014, the IMO estimated that shipping accounted for 2.33% of global CO_2 emissions between 2007 and 2012, and they forecast that this will grow between 50% and 250% under a business-as-usual scenario.

Under the Paris Agreement, nations have committed to keeping the global mean temperature increase to well below 2°C of pre-industrial levels by 2100, while aiming for 1.5°C. Extending shipping's current emissions' contribution into a future 2°C scenario gives us an initial estimate of a shipping CO_2 budget of 33Gt over the time period from 2011 to 2050. This is significantly reduced to 18Gt under the 1.5°C ambition.

As demand for shipping continues to grow, another way of looking at this is the reduction in carbon intensity – the carbon emissions relative to the transport demand. Under the 2°C scenario, this is a reduction of between 60% and 90%, depending on ship type, as shown in Figure 1.

In our previous report, Low Carbon Pathways 2050, we showed that, as a sector, to achieve an absolute reduction in CO_2 emissions of 50% by 2050 consistent with a 2°C pathway, ZEVs need to be entering service by 2030. These vessels, with operational emissions containing zero or negligible GHGs, would need to represent a significant proportion of newbuilds from this point onwards.

This represents a paradigm shift for our industry, similar to one already occurring in the automotive and energy sectors. This shift is away from technologies that aim to increase efficiency and optimise conditions for conventional engines, because they are deemed to no longer be the focus of progress. Instead, the overarching global aim of ending all use of fossil fuels needs to be targeted through the adoption of ZEVs – those that can truly emulate the logistics provided by current fleets, but with no operational emissions.

That we're accountable for reducing our emissions is beyond doubt. What's less clear is how we can decarbonise without causing increased CO_2 emissions in fuel production, simply moving the GHG problem upstream. The challenge facing global energy production networks is therefore one that permeates decision making for decarbonisation within the shipping sector.

On the plus side, as the uptake of renewable energy sources gathers momentum in upstream production, we are strongly placed to capitalise upon the opportunities that this can bring, as well as to influence, invest in, and accelerate the process.

There is no doubt that decarbonisation is a huge challenge for our sector and that we all have a clear responsibility to ensure actions are taken to drive our operational emissions to zero at a pace matching actions taken across the rest of the world and other industry sectors. Crucially, this can only happen when commercial pressures, technical developments and the wider regulatory policy landscape coincide. This transition to a new mix of fuels now has broad government and industry buy-in. It is inevitable that a policy process starts with the definition of the objective, but the question we are increasingly asked is: How are we going to achieve this in practice?

This report aims to demonstrate the viability of ZEVs, identifying the drivers that need to be in place to make them a competitive solution for decarbonisation.

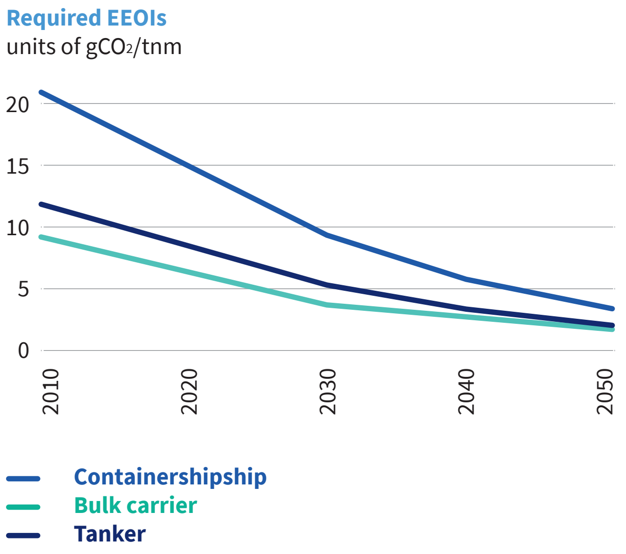


Figure 1 Demand and required aggregate Energy Efficiency Operation Indicator (EEOI) consistent with shipping's 2.33% share of total CO_2 and a 2°C stabilisation pathway taken from our Low Carbon Pathways 2050 report.

[1] Third IMO GHG Study 2014

Our approach.

In order to understand the viable potential decarbonisation options for 2030, we are continuing along the path to decarbonisation shown in Figure 2.

The path to decarbonisation:

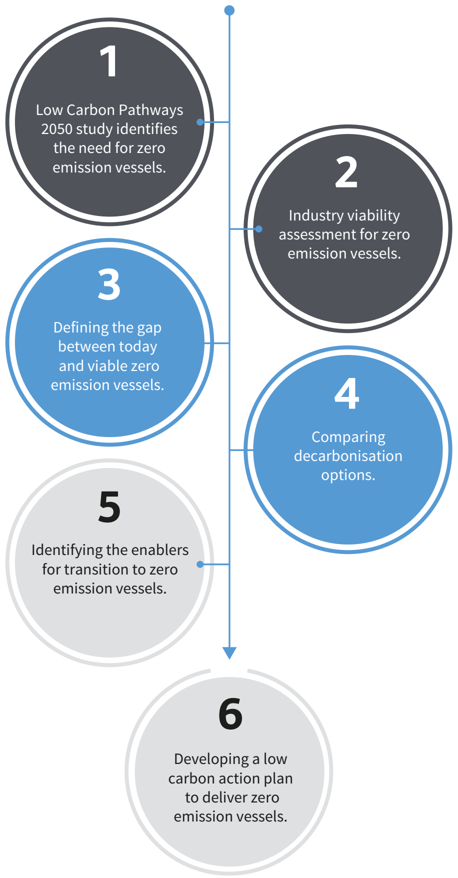


Figure 2 Approach to pathway for decarbonisation

Following stage 1, the Low Carbon Pathways 2050 study, we conducted a survey of shipowners, forming stage 2. We started by understanding what is needed to make ZEVs a reality, which we did by listening to the thresholds that shipowners believe will need to be passed for various zero-emission fuels and technological options. We discussed a range of factors involved in implementing zero-emission fuels and technologies, including relative costs, the global supply chain, carbon pricing and upstream emissions, in order to identify what is most important in influencing a decision. We also considered the likelihood of costs being passed on in the supply chain, and whether shipping customers would be willing to pay more for zero-carbon shipping. We used the results, shown in Figure 3, to define the threshold levels that need to be met to make ZEVs viable.

The survey revealed a broad consensus on the need for decarbonisation, with an overwhelming majority of shipowners regarding ZEVs as central to this process. It also underlined that shipping as a business will adopt ZEVs if they're commercially viable and technically feasible. Therefore, we have chosen to focus our analysis on the economic analysis, including the costs/impacts associated with capital expenditure, the operational costs associated with storage, handling and cargo-carrying capacity, and how carbon pricing can influence this. This report presents our findings and sets out to answer specific questions raised by the shipowners in our survey:

- How do ZEV options compete with one another?
- Are certain ZEV options better for certain ship types?
- What are the cost implications of building and operating ZEVs?
- Does changing the range of a ship affect the suitability of a particular ZEV technology?
- How do ZEVs compare to a heavy fuel oil (HFO) reference ship at different levels of carbon pricing?
- What are the implications of upstream emissions?

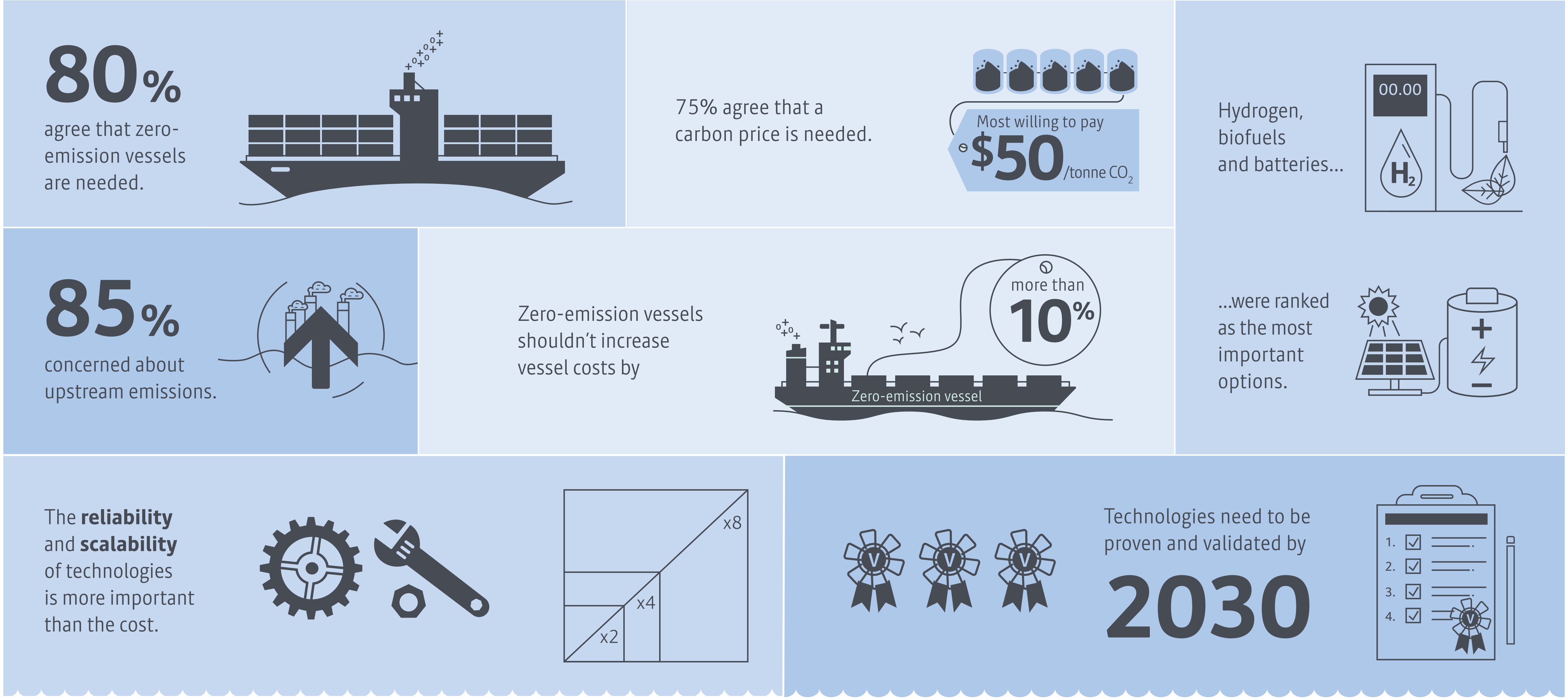


Figure 3 Shipping stakeholder survey responses[2]

[2]Research conducted jointly by LR Group Ltd and UMAS.

We start by asking the question: Which ZEV technologies are most viable to deliver vessels that can match the capabilities of today's conventional ships? We have answered this by calculating the lifetime profitability and cost implications for all possible combinations of seven ZEV technologies across five ship types and under three different regulatory and economic scenarios. Explanations of these variables are provided in the following sections of the report.

We've assessed each technology to determine the implications for storage, handling and cargo-carrying capacity and have performed an in-depth economic analysis to identify whether any of the seven candidates show clear benefits over the others. We have not included a detailed description of the design implications and installation of ZEV-related technologies on board vessels. This allows us to identify where a more detailed evaluation of the non-economic criteria is needed, where and how threshold gaps can be reduced or closed, and what enablers may be required.

All analyses are performed against an HFO reference ship. This is assumed to run on HFO with a two-stroke engine and a scrubber on board to ensure compliance with sulphur emissions regulations.

To answer the next questions regarding the effects of vessel range and carbon pricing, we've further refined these results by conducting sensitivity studies on the ZEV technologies.

Finally, we have considered sources and production methods for the different fuels in order to understand the implications of upstream emissions.

To answer the questions:

- How do ZEV options compete with one another?
- Are certain ZEV options better for certain ship types?
- What are the cost implications building and operating of ZEVs?

INPUTS

7 ZEV technologies

Electric
Hybrid hydrogen
Hydrogen fuel cell
Hydrogen + ICE
Ammonia fuel cell
Ammonia + ICE
Biofuel

5 ship types

Bulk carrier
Containership
Tanker
Cruise
RoPax

3 regulatory and economic scenarios

Green Electricity
Green Ammonia
Green Hydrogen

ANALYSIS

Modelling and analysis approach

1. Define any assumptions for alternative fuels and ZEV related technology developments.
2. Using the assumptions in step 1 and of the technical and operational specification of a HFO reference ship, define the technical and operational specifications for all seven ZEV technologies including any resulting modifications to the main machinery, deadweight, power and range.
3. Estimate the extra capital cost of the main machinery in comparison with the HFO reference ship.
4. Estimate the difference in cargo capacity due to the ZEV fuel storage technology onboard.
5. Estimate the annual fuel consumption and CO_2 emissions over the in-service life of the vessel.
6. Estimate the the cash flow (revenue, costs) and the net present value (NPV) for all ZEVs compared to the HFO reference vessel.

OUTPUTS

Lifetime profitability

The overall annual profit and the profitability index used to indicate how the ZEVs compete with one another.

Cost implications

Any lost revenue, additional capital costs and any extra voyage cost for ZEV implementation.

To answer the questions:

- Does the range of a ship effect the ranking of ZEVs?
- How do ZEVs compare to a reference ship – what level of carbon pricing is needed in 2030?

ANALYSIS

Sensitivity analysis

Adjustment of ship range, imposed carbon price and interest rate on capital costs to determine how significant these factors are to ZEV feasibility.

OUTPUTS

Effect of ship range

The impact of altering the ship's range, through reducing bunkering capacity, on the costs associated with cargo carrying capacity and main machinery costs.

Effect of carbon price

The impact of changing the assumed carbon price to explore which ZEVs become more profitable than the HFO reference ship, and at what point they do.

Effect of interest rate

The impact of different interest rates on capital expenditure costs.

To answer the question:

- What are the implications of upstream emissions?

Upstream emissions

Upstream emissions associated with each technology group were calculated, to assess whether ZEVs produced whole life cycle emission reductions.

Based on this approach to defining profitability, we can identify the different drivers for these costs.

To understand why this happens, it can be helpful to consider some of the relationships and interactions that occur between the various drivers of profitability, as represented in Figure 4.

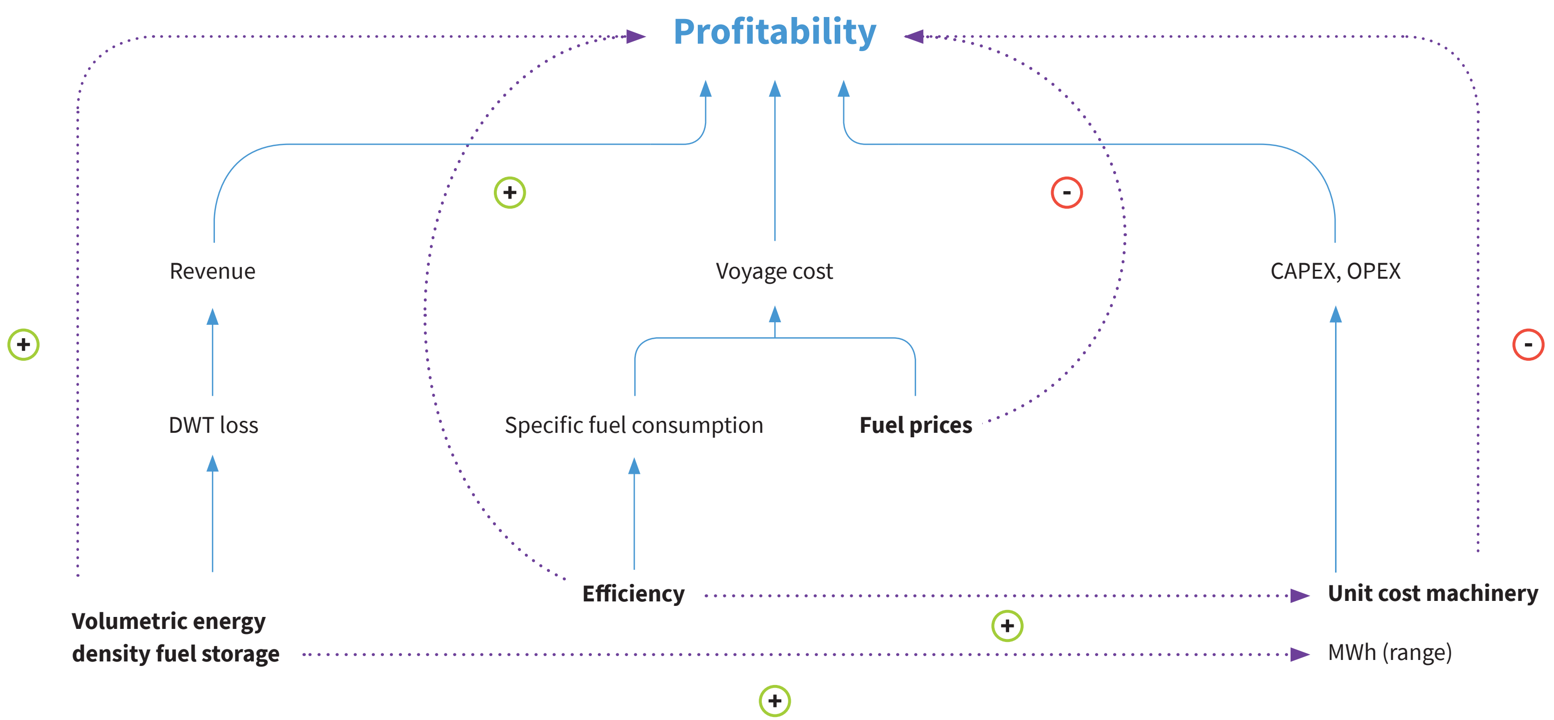


Figure 4 Key relationships between profitability drivers

Seven technology options for ZEVs

The logistical challenges faced by shipping, as well as the wide range of operational requirements, mandates the need to consider an equally wide range of potential technologies, particularly given the present lack of a clear dominant solution suitable for all types of ship. We've considered seven technology groups as identifiable candidates to enable ZEVs; these are not exhaustive, and other candidates may exist. These are set out in Table 1.

We've selected these seven candidates on the basis that they can feasibly replace a conventional ship's propulsion requirements without major alterations to voyage times, routes or cargo-carrying arrangements. Crucially, they can also be considered as genuine ZEVs, since they all produce zero or negligible GHG emissions under continuous operation. The exception to this is sustainable biofuel, which does produce GHG emissions in combustion, but is included here under the assumption that these are net-zero over a lifecycle.

Well-developed technologies that have been under the consideration of the industry for many years have not been included in the scope of this study. Nuclear-powered ships, for example, still face significant barriers to global acceptability and therefore operability, and so remain outside the scope of this study until such barriers have been addressed and threshold levels have been implicitly identified by the industry. Wind power and other technology groups that contribute to increased efficiency are also not included, having been deemed unsuitable as the primary means of powering a ZEV.

Key enablers to the uptake of ZEVs are explored in this study. While upstream emissions are not under the ownership of the shipping industry, it is crucially important to consider their impact at this stage to prevent investment in technologies that may ultimately not be any more 'green' than those of a conventional ship. Different future scenarios, assuming different fuel mixtures and generation methods, have been used in order to identify threshold levels that represent environmental feasibility for the ZEV combinations. Economic feasibility is also considered over the lifetime of the vessel, offsetting potential savings in operational expenditure with the initial investment in the new technology and the effect of a carbon price as an additional means of accelerating the uptake of ZEVs.

Electric	**Hybrid hydrogen**	**Hydrogen fuel cell**	**Hydrogen + ICE**
Batteries	Hydrogen storage	Hydrogen storage	Hydrogen storage
Electric motor	Batteries	Fuel cell	'Emergency' HFO tank
	Fuel cell	Electric motor	Dual fuel internal combustion engine (ICE)
	Electric motor		

Ammonia fuel cell	**Ammonia + ICE**	**Biofuel**
Ammonia storage	Ammonia storage	Biofuel tank
Reformer	'Emergency' HFO tank	Internal combustion engine
Fuel cell	Dual fuel internal combustion engine (ICE)	
Electric motor		

Table 1 ZEV technology and machinery combinations

Three regulatory and economic scenarios

There is uncertainty in how these technologies will evolve over the next 10 years – in terms of both performance and cost – and in the prices and availability of the different fuels. To allow for this uncertainty and to test whether the conclusions drawn from the analysis are robust to different futures, we have defined three different current foreseeable futures. Table 2 provides a summary of the scenarios for this study, with descriptions of the key parameters for each technology. The scenario names have been chosen based upon the input assumptions, considering the main 'green' fuel available in each scenario; they do not, however, indicate that the particular fuel is the most preferable. An explanation of the different assumptions used and the justifications for the variations chosen can be found in the Assumptions section.

Further to these three scenarios, three types of sensitivity analysis have been undertaken. The first is by changing the assumed carbon price, the second by changing the bunker capacity (and therefore the assumed range), and the third by changing the interest rate used to calculate the net present value.

Green Electricity

- Electricity is produced from mainly renewable sources, with carbon sequestration commonplace, resulting in high prices but with very low, or even negative, emissions. This encourages development in battery technology, although prices remain high here.
- Hydrogen is produced cheaply from fossil fuels, typically stored as a compressed gas, while ammonia is produced from a combination of 'green' electricity and cheap hydrogen.
- Third-generation biofuels are available to the industry, with no emissions in the direct production lifecycle.

Green Ammonia

- Ammonia produced with near-zero emissions is widely available to the shipping industry.
- Electricity is produced cheaply, mainly from fossil fuels; batteries can be mass-produced and prices fall.
- Hydrogen is produced from a mix of renewable and fossil-fuel sources. Both fuel cell efficiency and storage technology improve, but at a high cost.
- Third-generation biofuels are available to the industry, with no emissions in the direct production lifecycle.

Green Hydrogen

- Hydrogen is produced exclusively from renewable sources with no emissions, but comes at a high price.
- Fuel cell technology becomes highly efficient, while a focus on improved hydrogen storage tanks lowers their capital costs.
- Electricity is produced cheaply from a mix of fossil fuels and renewable sources, leading to battery technology development and a moderate fall in price.
- Ammonia is produced from a mix of expensive 'green' hydrogen and cheap electricity, resulting in mid-range emissions at a high cost.

		Green Electricity	Green Ammonia	Green Hydrogen
Biofuel	Cost	Central	Central	Central
	Emissions	Low	Low	Low
Electricity	Cost	High	Low	Low
	Emissions	Low	High	High
Hydrogen	Cost	Low	Central	High
	Emissions	High	Central	Low
Ammonia	Cost	Central	High	High
	Emissions	Central	Low	Central

Table 2 Cost and emission comparisons between alternative fuels and conventional HFO (Further information available in the Assumptions)

Five different ship types

We have applied this approach to five different ship types and sizes for seven different combinations of zero-emission technology, as shown in Table 3.

Ship type	Bulk carrier	Containership	Tanker	Cruise	RoPax
Representative ship size category	53,000 dwt	9,000 TEU	110,000 dwt	3,000 dwt	2,250 dwt
	Electric				
	Hybrid hydrogen				
	Hydrogen fuel cell				
	Hydrogen + ICE				
	Ammonia fuel cell				
	Ammonia + ICE				
	Biofuel				

Table 3 Combinations of five selected ship types and sizes and seven ZEV technologies

Viability of ZEVs – Comparing the decarbonisation options.

When comparing the results of the analysis, the different scenarios present different relative levels of viability for ZEVs, depending on the sensitivities of the parameters to different ship types and operating profiles. It is implied that there are different optimal choices of fuel, machinery, design and operation. The analysis is considered for each ship type and size category (e.g. 35,000–59,999 dwt bulk carriers) in turn, and, when appropriate, the results are aggregated for presentation.

How do ZEV options compete with one another?

Figure 5 shows the comparative profitability of the seven different options, with the results aggregated for all ship types considered and shown for each scenario on a scale of 0–1 of relative profitability (with 1 being the most profitable and 0 being the least profitable).

Overall, biofuel is the most profitable zero-emission solution, followed by ammonia and hydrogen (synthetic fuels) with internal combustion machinery. Hybrid and electric solutions, which require large quantities of batteries at high capital cost, are the least competitive. However, the relative profitability of hydrogen and ammonia changes under different scenarios, since the prices for these fuels vary. The order in which ZEVs appear based on their profitability (from the highest to the lowest) is the same in all scenarios.

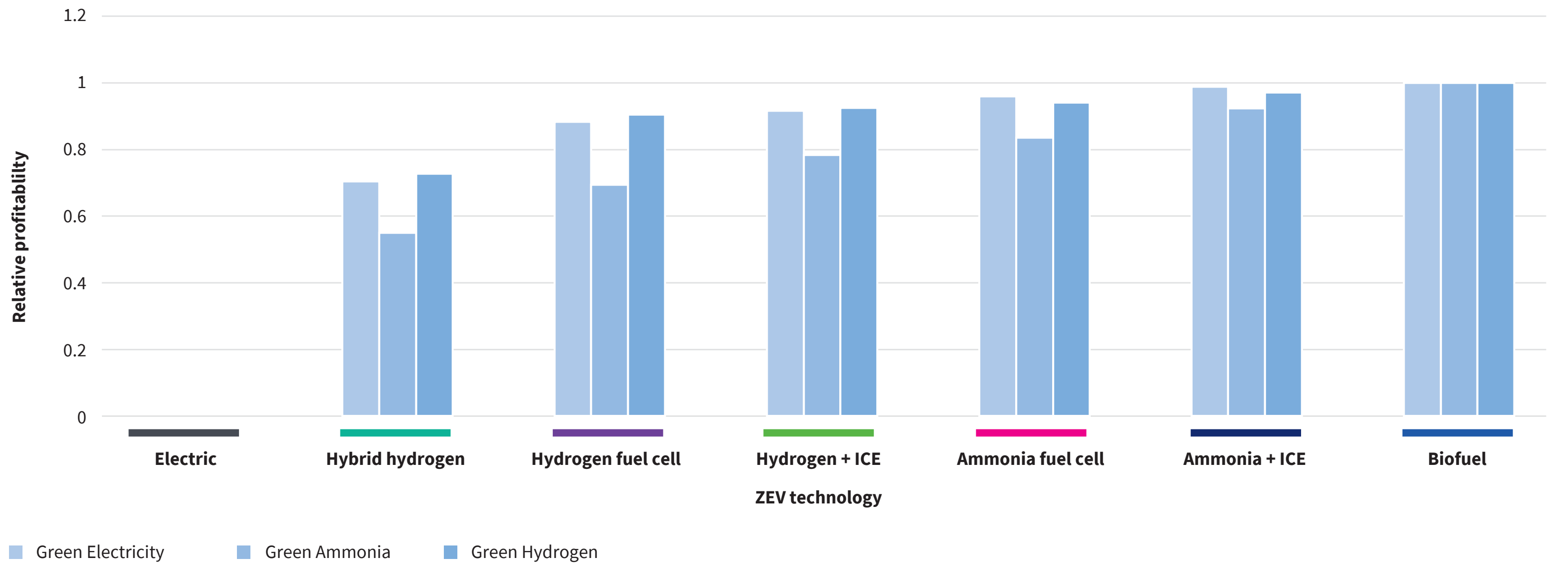


Figure 5 The relative profitability of ZEV technologies aggregated for all ship types and scenarios

Figure 6 shows how the profitability of these options varies relative to the baseline HFO reference ship, and how this can vary significantly depending on the scenario. Only the top two most profitable ZEV options are displayed – biofuel and ammonia internal combustion. There is no scenario under which the ZEV options are likely to be more profitable than the HFO reference ship. This underlines the importance of policy and regulation as drivers for change, since market forces alone appear unlikely to prove sufficient.

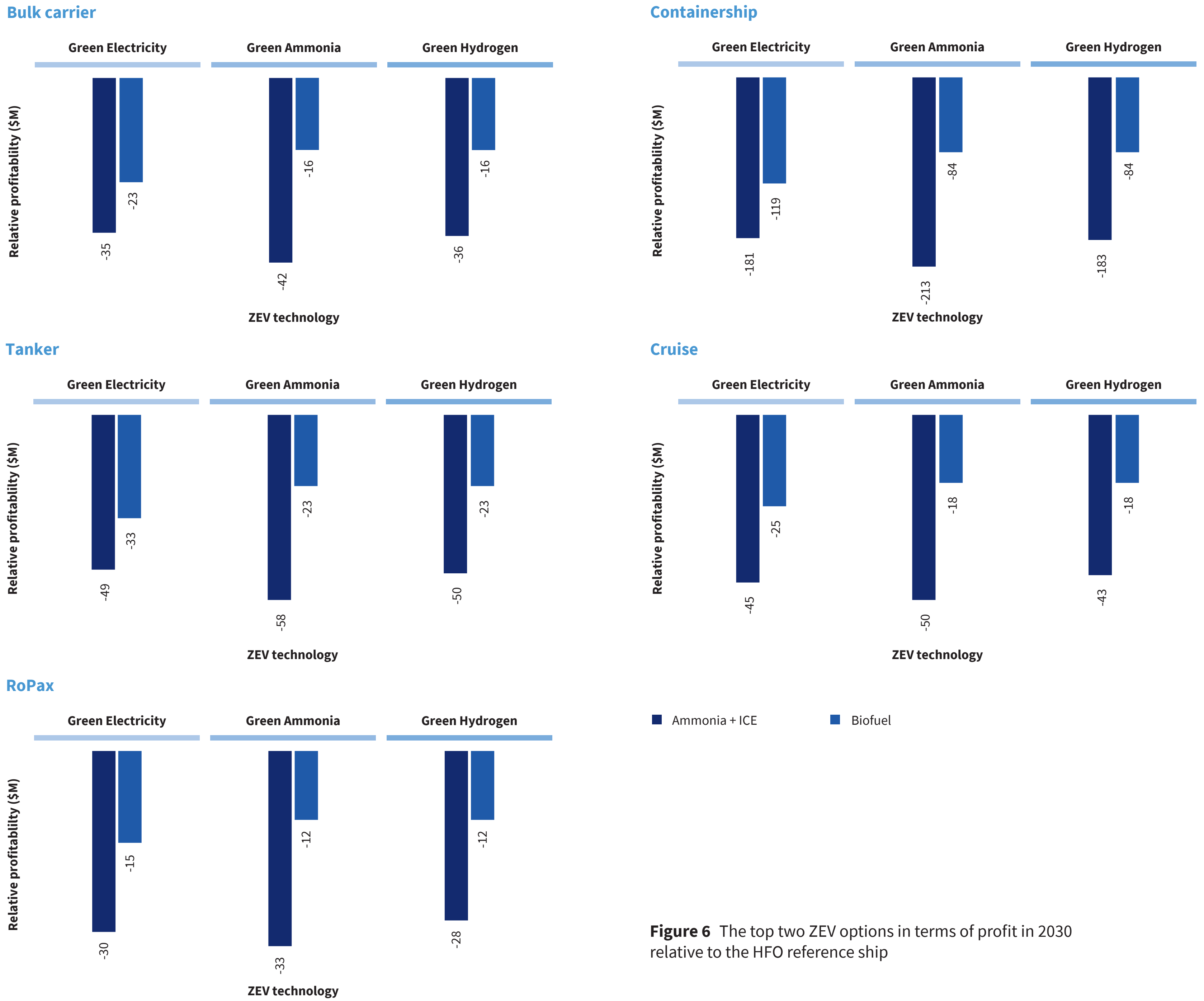


Figure 6 The top two ZEV options in terms of profit in 2030 relative to the HFO reference ship

Figure 7 details the relative profitability for the different ship types. Again, this is shown on a scale of 0–1; and, again, biofuel is always the most profitable option in all scenarios, closely followed by ammonia internal combustion machinery. The most significant gap is between Green Ammonia and the other two scenarios – Green Electricity and Green Hydrogen. This is because biofuel generally requires no significant extra capital cost when using conventional ship machinery and storage; and the capital costs of the other six options are not sufficiently balanced by higher through-life efficiencies or lower fuel/carbon costs.

The ammonia internal combustion vessel is the second-best option in all cases. The ammonia fuel cell and hydrogen fuel cell vessels are very close to each other, regardless of the scenario. Ammonia fuel cell vessels can sometimes be very competitive; hydrogen fuel cell vessels are generally less so.

Hybrid hydrogen vessels are almost always the second-least-profitable option. The electric vessel is the least profitable in all scenarios, and for all the ship types and sizes considered here.

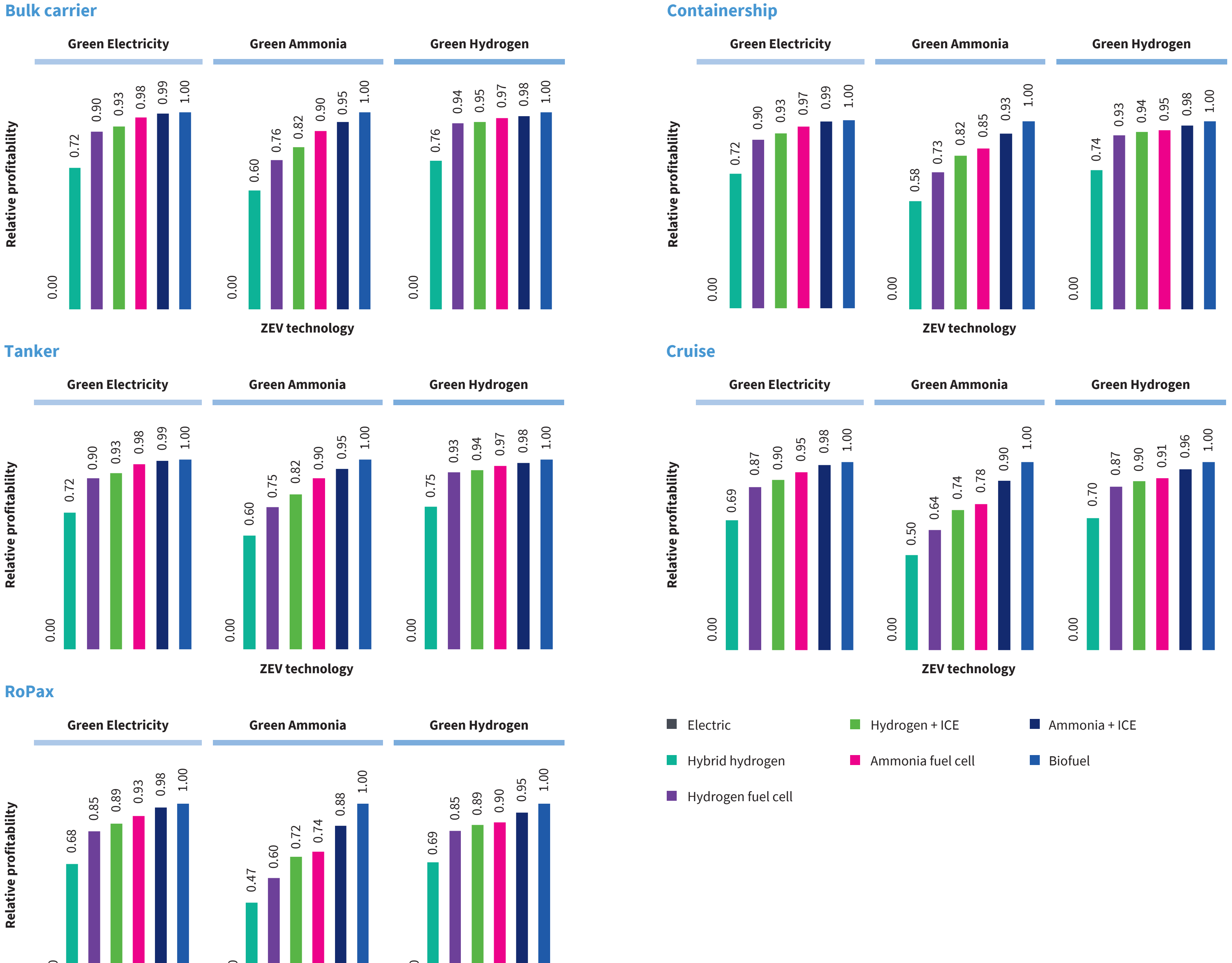


Figure 7 The relative profitability of ZEV technologies for all ship types and scenarios

What are the cost implications of building and operating ZEVs?

Cost contributions

Further explanation of the different rankings of profitability can be obtained from the relative contribution of different cost drivers for each of the technologies. Figure 8 shows the contribution to overall costs for each of the options. To demonstrate these relationships clearly, we present only the Green Ammonia scenario in Figure 8.

The overall cost comprises extra capital costs on main machinery and storage; new technologies may require higher capital cost than the reference ICE or fuel storage systems, or may even be cheaper. Extra voyage costs may arise from fuel price projections or technological developments, such as improved efficiency. Finally, as a result of revenue being lost due to the different volumetric energy density of the alternative fuel stored on board, extra space may be required, resulting in a loss of cargo capacity, and therefore a loss in revenue for the operators.

Electric
In this scenario, electricity is comparatively cheap and actually delivers a lower voyage cost than the HFO reference ship. This benefit is most significant for cruise and RoPax vessels. Revenue loss arising from reductions in cargo space to accommodate batteries appears largely insignificant for most ship types. The major exceptions are in cruise and RoPax vessels, owing to the amount of energy storage required.

The electric motor is assumed to be cheaper than a conventional engine – producing capital cost savings and improved profitability in all ship types. However, even assuming the cost of batteries per unit of energy falls substantially (to $25/kWh) their additional capital outlay remains much more significant than the associated positives, always making the electric vessel the least profitable option.

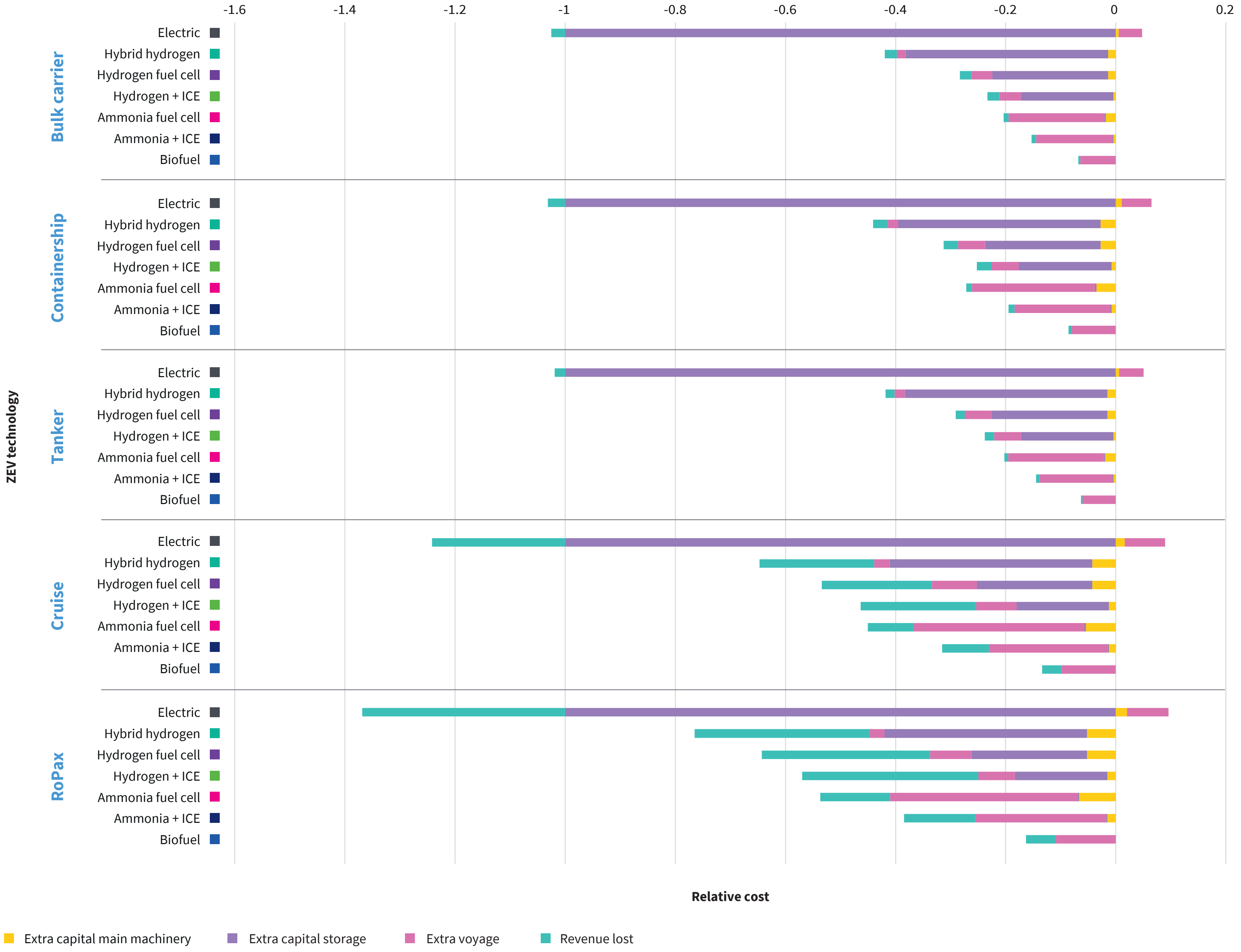


Figure 8 Relative cost implications of ZEV technologies for all ship types under the Green Ammonia scenario against the HFO reference ship

Ammonia and hydrogen
These component costs illustrate the trade-off between these two fuels. In this scenario, hydrogen has a smaller increase on voyage cost than ammonia, because it is cheaper per unit of energy. However, hydrogen's lower density means it requires more onboard storage, increasing the capital cost and reducing both cargo space and revenue. Consequently, the pros of hydrogen are approximately counterbalanced by its cons in many of the ship types.

In this scenario, the extra capital cost of the fuel cells, whether for use with ammonia or hydrogen, outweighs any reduction in fuel consumption relative to the internal combustion options, making these options less competitive in all ship types.

Biofuel
Under the projected biofuel and oil prices in this scenario, biofuel vessels incur only the extra voyage cost. As we discuss later, however, these price projections need to be considered in the context of the availability and sustainability of biofuel.

Capital costs

Our market survey results (see Figure 3) show a desire for no more than a 10% increase in ship capital costs for ZEVs. Figure 9 shows how the additional capital cost varies for each ship type under each of the scenarios and technology options.

The results show that the biofuel vessels come with near-zero extra capital costs. However, even the next lowest – ammonia internal combustion and ammonia fuel cells – is around the industry's threshold of 10%. The most expensive propulsion option is the electric vessel, where additional capital costs range from $170 million to $8,500 million, depending on ship type and scenario. Overall, containership TEU 8,000–11,999, relative to the other cases examined, shows both the highest additional cost and the greatest percentage increase.

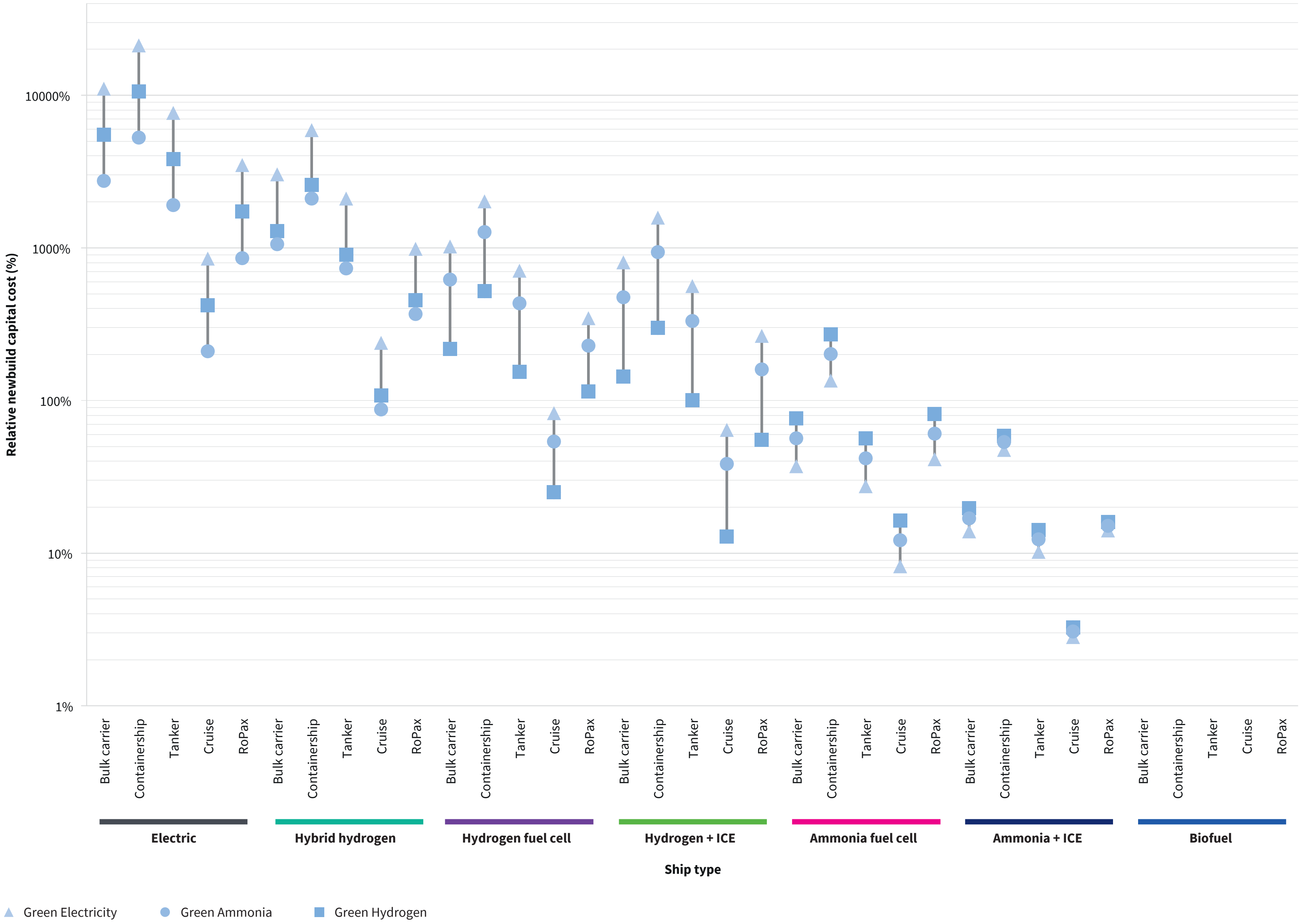


Figure 9 Relative ZEV technology capital costs for all ship types and scenarios

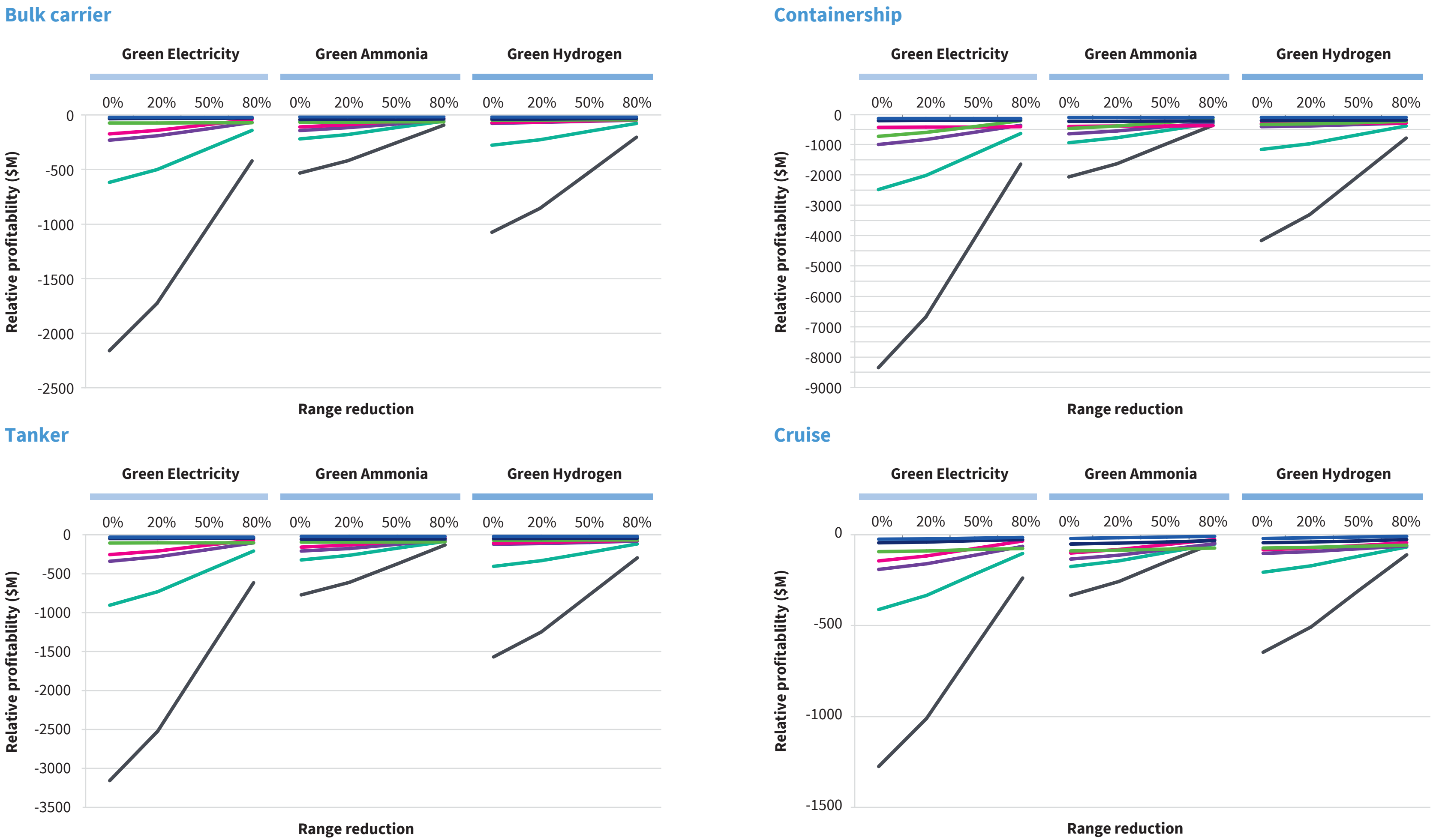
Does the range of a ship effect the ranking of ZEVs?

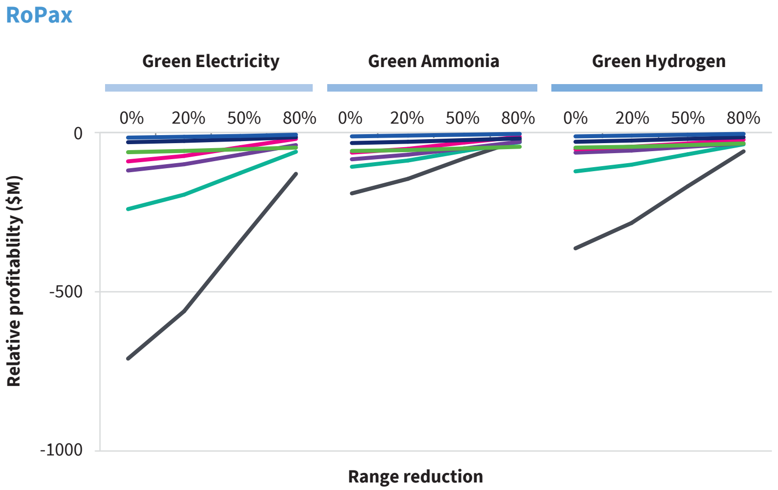
As we saw in Figure 8, the capital costs of storage and the associated revenue loss due to reduced cargo space can be important profitability drivers, particularly for batteries and hydrogen. These costs are a function of the assumed range of the ship needing to match the range of current ship designs. Therefore, reducing range would reduce these costs accordingly; however, the ship would also require more frequent bunkering.

To understand whether such changes in bunkering might be a way to influence the competitiveness of these options, a sensitivity study on range was undertaken, which considers reducing the range by 20%, 50% and 80%.

We can see changes in both the relative profitability of the different options and the absolute profitability relative to HFO reference ship, as shown in Figure 10.

Even with lower range requirements, biofuel is consistently the most profitable. For most ship types, both hydrogen options (ICE and fuel cell) are closer to equivalent ammonia-based systems. With an 80% range reduction, the electric vessel outcompetes synthetic fuel options, and becomes more profitable for cruise and RoPax vessels.





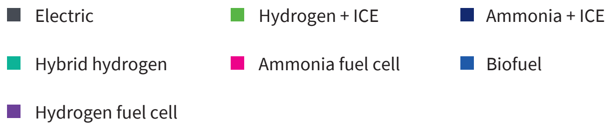


Figure 10 The impact of range reduction on the profitability of ZEV technologies for all ship types and scenarios

Further insights are provided when we look at how overall costs and individual cost components change as a function of the ship's range. Figure 11 shows the capital costs for storage and revenue loss for each sensitivity scenario across the ship types.

As we have already seen, the revenue loss for containerships due to the hydrogen storage system has a reduced impact as the range is reduced, because less fuel storage capacity is required.

In some cases, revenue loss becomes a positive effect, as we are gaining space in comparison to the HFO reference ship (negative values).

For electric vessels, reducing extra capital costs for batteries makes batteries a more interesting option.

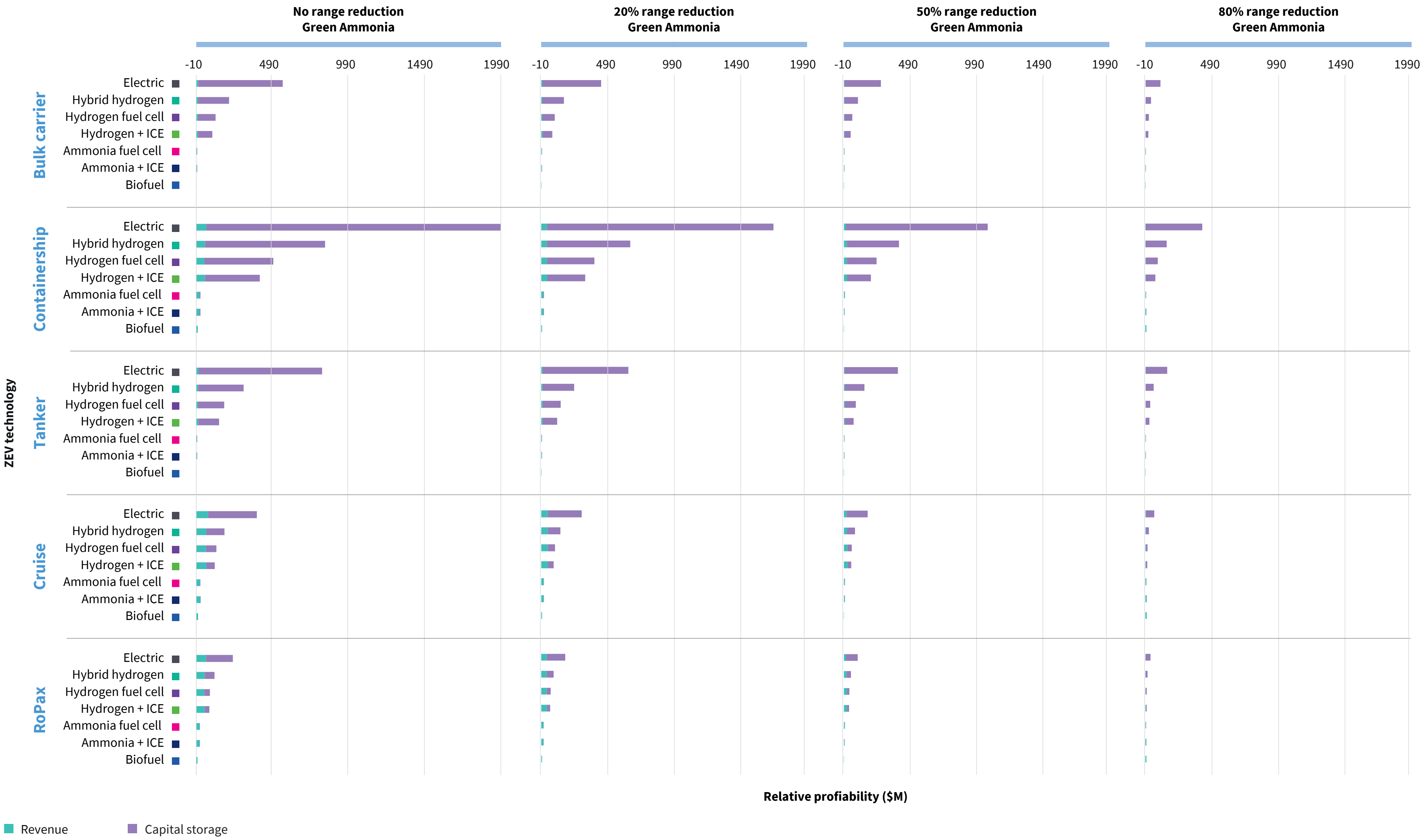


Figure 11 The impact of range reduction on costs of ZEV technologies for all ship types and Green Ammonia

How do ZEVs compare to the HFO reference ship, and what level of carbon pricing is needed by 2030?

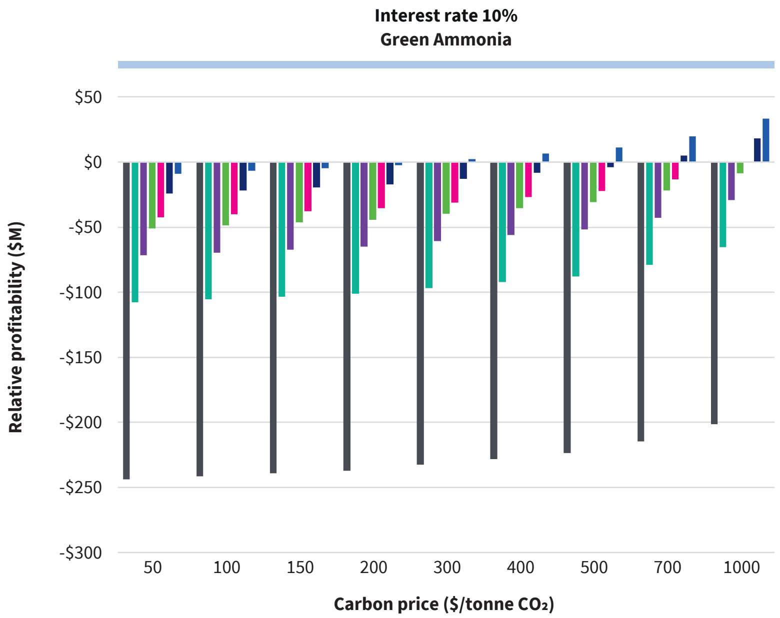
Our industry survey (see Figure 3) shows that, as well as limiting capital cost increases, ZEV technologies should be competitive with conventional propulsion at a carbon price/levy of \$50/tonne CO_2. Accordingly, we have assumed this carbon price in our three scenarios.

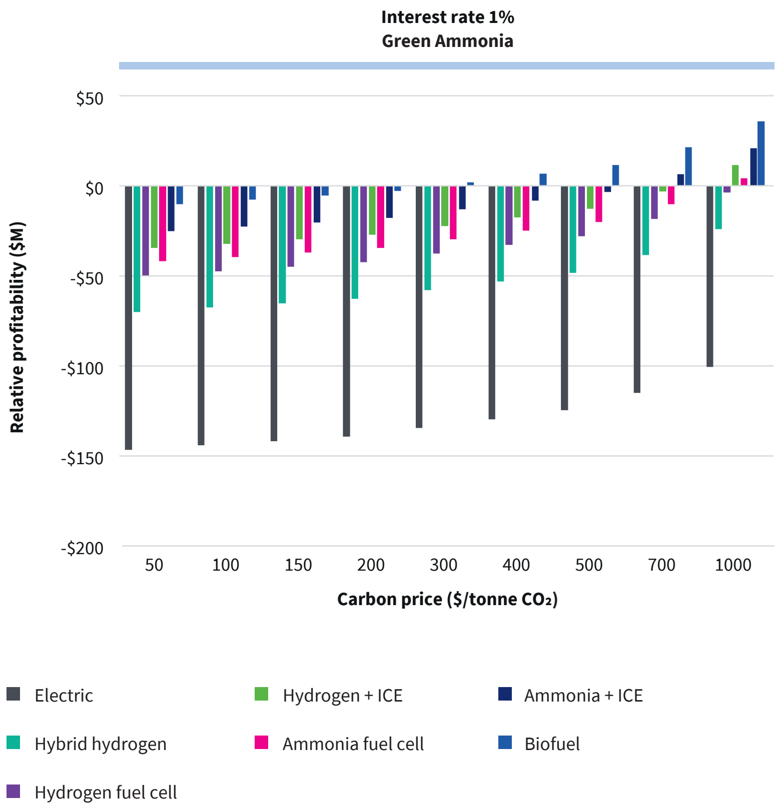
A carbon price increases the voyage cost competitiveness of zero-carbon/emission fuels relative to fossil fuels. Importantly, if the price is high enough, it can also improve the competitiveness of those options that incur additional capital costs.

However, as shown in Figure 6, even at our assumed carbon price of \$50/tonne CO_2, none of the options we have examined are competitive relative to conventional fuel. As such, we have carried out a further sensitivity study, assessing the profitability of ZEVs in comparison with the HFO reference ship at various different levels of carbon price in order to explore at which level the different ZEV options become profitable. Figure 12 presents the results for two ship types – containership and RoPax – under the Green Ammonia scenario.

As well as adjusting the carbon price, we have looked at what happens when we reduce the interest rate on capital from 10% to 1%. This is designed to simulate the effect that low-cost loans might have on stimulating future uptake, and investigate the extent to which cost of capital might be a barrier to their entry.

Containership





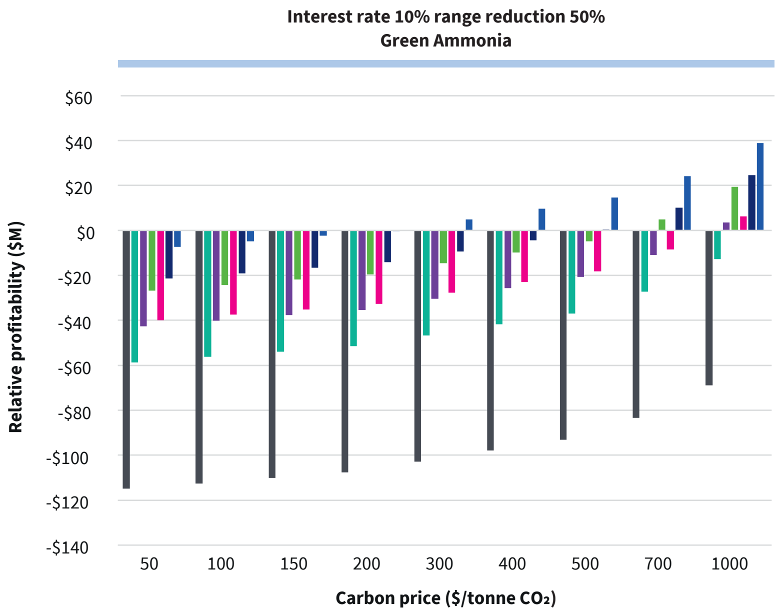


Figure 12 Effect of carbon pricing and interest rates on the relative profitability of ZEV technologies

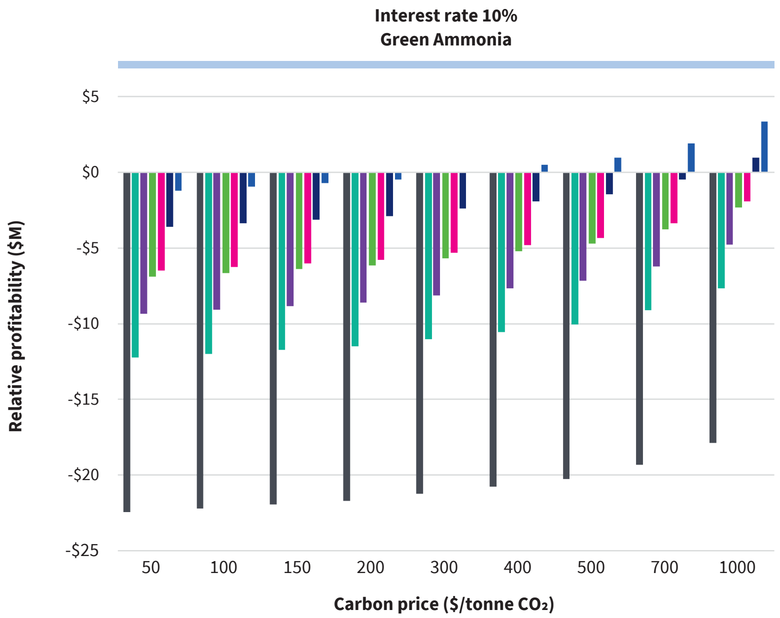
The results show that zero-emission options only become competitive with conventional propulsion for carbon prices in the order of $250/tonne. At this price point, the biofuel vessel would become competitive relative to a conventionally propelled ship. The synthetic fuel options (ammonia/hydrogen) become competitive at approximately $500/tonne in the low cost of capital scenario, and slightly higher for the high cost of capital scenario.

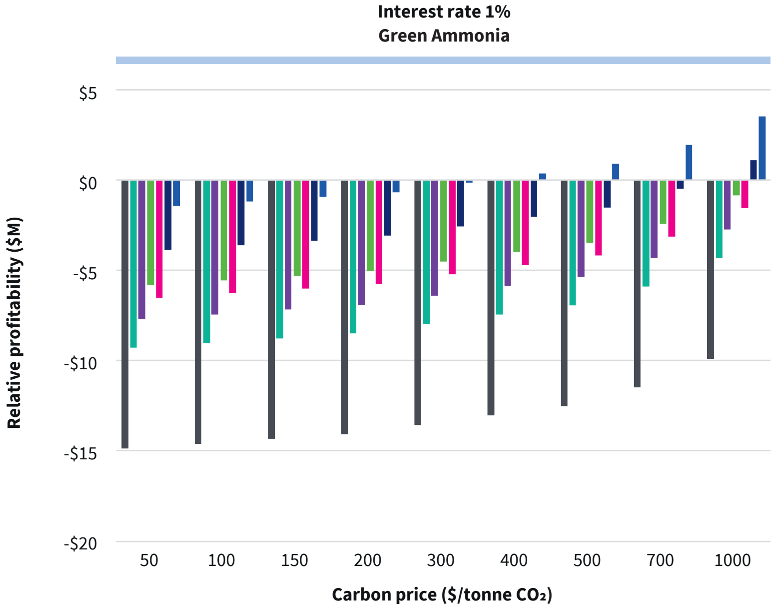
While a lower cost of capital (lower interest rate) does reduce the carbon price at which several of the zero-emission technologies become competitive, it only has a minor impact on the competitiveness of the biofuel and ammonia with ICE options. For these two leading options, the competitiveness with a conventionally propelled ship is dominated by the spread on fuel price – ammonia/biofuel vs fossil fuel.

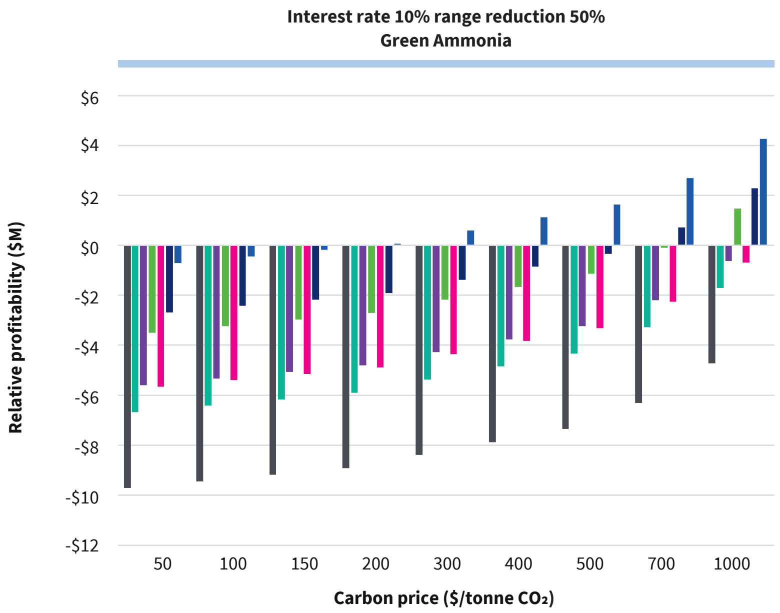
Although we have shown our results for container and RoPax ships only, a similar pattern is observed for all the other ship types and sizes included in this study report. The only difference is in the absolute carbon price at which each technology becomes competitive with conventional propulsion.

The level of the carbon price at which the different ZEV options become profitable should not be generalised for the entire shipping segment because these particular levels are considering only the cases (ship size categories) included in this study.

RoPax







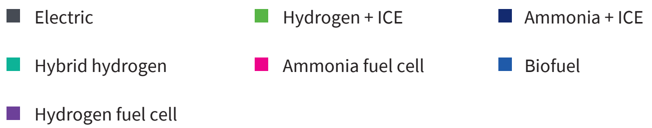


Figure 13 Effect of carbon pricing and interest rates on the relative profitability of ZEV technologies

What are the implications of upstream emissions?

Our consultation with shipowners also showed that, understandably, they do not want to address CO_2 emissions in our industry only for the problem to be shifted upstream. For many of the zero-emission options, the way in which the energy/fuels are currently produced results in high CO_2 emissions. For example, hydrogen, ammonia and electricity are produced from fossil-fuel feedstocks, which release CO_2 as they are reformed or generated.

To assess whether the move by shipping to zero emissions would produce whole lifecycle emission reductions, we calculated the upstream emissions associated with each of the options. As with other inputs to these calculations, we cannot be sure how the actual configuration of the production processes will look in 2030, so we have considered a range of likely scenarios.

The results are presented in Figure 14. Upstream emissions are shown as the sum of the percentage of operational and upstream emissions of ZEVs. If the zero-emission option has an upstream score of 100% or greater, it has produced no net benefit in CO_2 terms over the lifecycle of the fuel's/energy source's production and use.

Although commonly assumed to be net-zero hydrocarbons, the CO_2 emitted in the combustion of biofuels is equal and opposite to the CO_2 absorbed as they grow, therefore they have not been included in Figure 14 because their upstream impacts are more complicated than the manufacturing processes associated with synthetic fuels and electricity. Several of the first-generation biofuels that are produced from food crops like wheat and maize can have significant upstream CO_2 impacts due to changes in land use – for example, if land is deforested to produce them. Furthermore, there are significant impacts due to competition with food that could result in increased food prices.

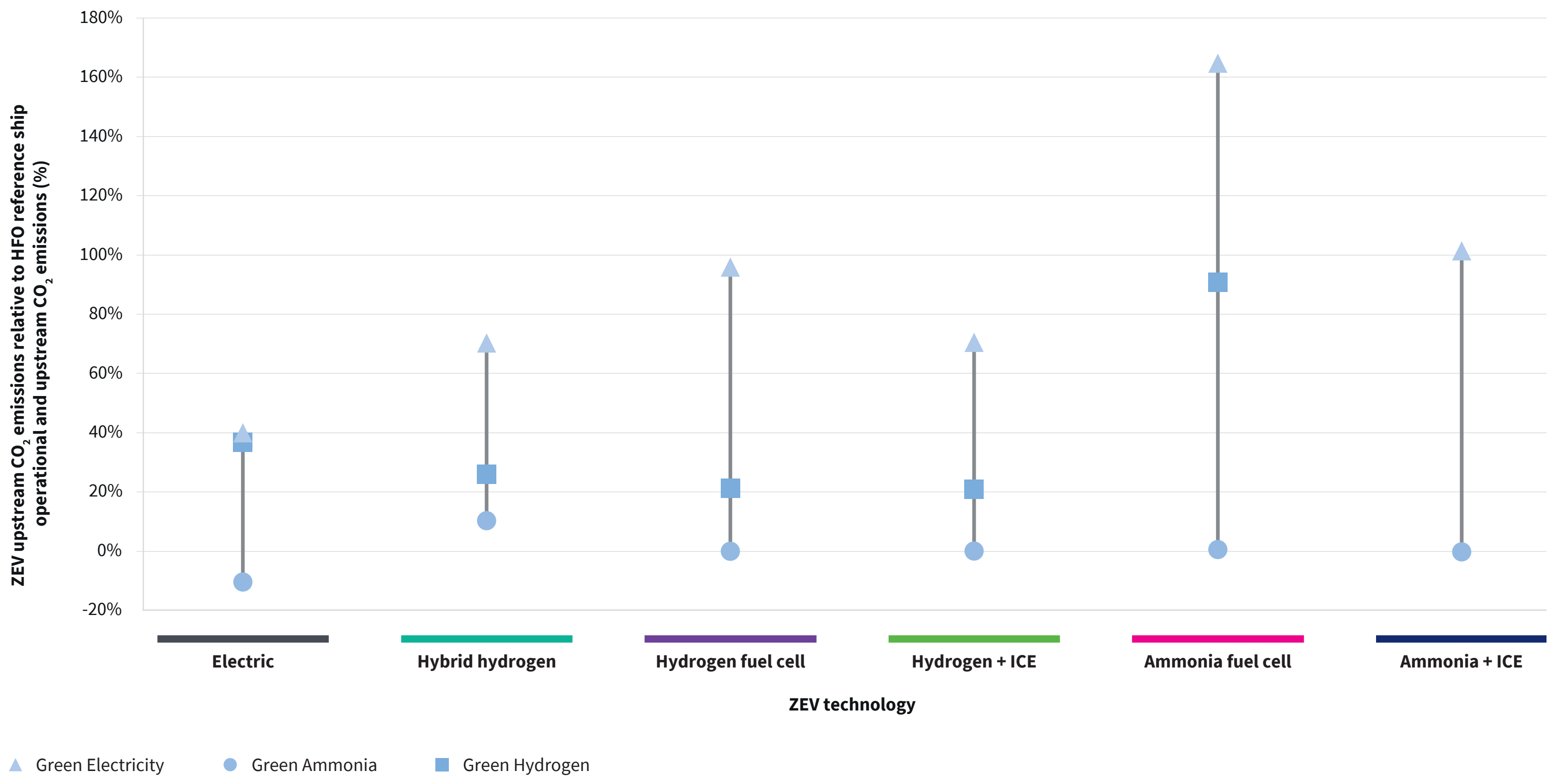


Figure 14 Upstream CO_2 emissions for ZEV technologies relative to the HFO reference ship's operational and upstream CO_2 emissions

Therefore, direct comparison between these options in upstream terms is difficult. For this study, only prices indicative of advanced or third-generation biofuels that can be generated from waste or non-food-competing sources, such as algae, are used. For the production of such advanced biofuels, it is also theoretically possible for the process to produce negligible net emissions.

These results show that several ZEV options in several scenarios can have similar or, in fact, worse lifecycle CO_2 emissions than conventional fossil-fuel propulsion. This is because of the way we currently depend on fossil fuels for chemical processes and electricity generation. Crucially, however, the results also demonstrate that all ZEVs have the technical potential to reduce total CO_2 emissions to almost zero.

In practice, as the global economy decarbonises in line with the Paris Agreement, chemical manufacturing and energy generation will also need to decarbonise – as is clearly already happening with electricity. So this process of upstream decarbonisation will happen 'naturally' over time; however, to have a significant impact on global CO_2, the timing of shipping's move to zero-emission options may need careful management.

We have focused on upstream emissions of CO_2 because it is the dominant GHG in existing processes. However, there are several other GHGs that may be significant (such as methane and nitrous oxide) and these require more investigation to evaluate whether they have significant impacts for any of the specified options.

Conclusions.

How do ZEVs compete with each other?

Biofuels
From the perspective taken in this study, advanced biofuels appear the most attractive ZEV solution currently available. They consistently outperform their zero-emission competitors economically due to their low capital cost implications for machinery and storage, and low fuel and voyage costs. Based on the scenario and price, they meet the thresholds for adoption indicated in our original industry survey. This is perhaps not a surprising finding and is a conclusion already reached by many in the sector. However, unfortunately, the search cannot stop here because biofuels have two key, and coupled, challenges – sustainability and availability. Advanced (e.g. non-food-derived), sustainability-certified biofuels will be required if production in the quantities needed as a full replacement shipping fuel is not to clash with other more basic societal objectives, such as the production of food for a growing population. Whether this results in a finite and partial supply taking a share of overall shipping energy sources, or practical limits on production causing prices to rise to the point where biofuel options become uncompetitive relative to the 'next best' option remains unknown and needs further work. In the meantime, it pays to consider what the 'next best' might be.

Batteries
The ships we selected as case studies are primarily operating over medium to long (i.e. trans-oceanic) voyages. Here, battery technology is simply not competitive and still requires significant further evolution in terms of performance and cost reduction before it could be preferable to synthetic fuel options, unlike for some of the smaller ferries travelling very short distances.

Synthetic fuels – hydrogen and ammonia
In terms of competitiveness, the 'middle ground' is therefore the synthetic fuels – hydrogen and ammonia. Two different machinery options are explored for these fuels, and it is the ICE that generally outcompetes the fuel cell and electric motor combination at current estimates. This is primarily because the internal combustion solution has a lower capital cost for propulsion machinery, in spite of the slightly worse efficiency than the fuel cell, and therefore requires more fuel and higher storage capital costs, meaning greater lost revenue due to payload reduction.

With both fuels, ICEs generally outperform fuel cells and electric motors at current estimates. When used with fuel cells, their relatively low energy density means they require more onboard storage, increasing capital cost and reducing cargo space and revenue. These negative effects on competitiveness can be significantly reduced, however, by shortening the range between bunkering and thus the onboard storage requirement. For many ships, this approach could make the shift to a zero-emission option significantly easier.

A further advantage of internal combustion solutions, particularly from the perspective of a technology transition, is that they could be used as dual (or even tri) fuel, running different fuels depending on availability and pricing.

Of hydrogen and ammonia, it is the latter, in combination with the ICE, that appears the most competitive. This is because of the lower capital costs associated with the onboard storage of ammonia, relative to hydrogen. This is not consistent though, and hydrogen and ammonia are interchangeable as the most competitive energy sources, depending on the scenario and ship type.

A lot will depend on how the technology and feedstocks associated with the production and storage of hydrogen and ammonia mature and how this impacts the balance between their respective prices as fuels and the storage costs on board.

Both hydrogen and ammonia, particularly when used with fuel cells, involve higher capital costs in terms of storage. Also, due to the lower energy density, they reduce payload capacity, contributing to lower competitiveness relative to both biofuel and conventional fuel. These negative impacts on competitiveness can be significantly reduced if the range (the distance covered between bunkering) is reduced. This is not viable if the range is already close to the limit needed (to cross an ocean, for example). However, for many ships, the move to a zero-emission option may be made significantly easier if a lower requirement for onboard storage and more frequent bunkering is used.

Commercially viable ZEV options will be extremely important."

Shane Balani
Marine Graduate Surveyor, LR

"Bringing ZEVs into service by 2030 will not be easy. The industry must collectively work to mould this possibility into a commercial reality in a way that can exploit the benefits of doing so – not least the opportunity of leading the world towards a sustainable future."

Carlo Raucci
Principal Consultant, UMAS

"Having a commercially viable option for a ZEV in the near future will be extremely important. This study is the first step to understanding the drivers, benefits and challenges of the most promising technologies. The shipping industry now has a unique opportunity to contribute to the large potential for improvements of such technologies and aim for a profitable zero-emission service."

What are the cost implications?

Of the technologies considered, it is reasonable to anticipate that the costs of conventional components (e.g. the ICE, ammonia storage and biofuel storage) will not change significantly. However, the cost of fuel cells, batteries and hydrogen storage could all reduce significantly, especially if they become important components of another sector's decarbonisation, or if action taken during shipping's transition assists with the technology's development.

But, ultimately, in terms of the shipowner requirements (no more than a 10% capital cost increase, competitiveness at a \$50/tonne CO_2 carbon price and negligible upstream emissions), none of the zero-emission options conceived, including advanced biofuels, completely satisfy the criteria.

Scenarios were foreseen where both the 10% capital cost increase and negligible upstream emissions requirements could be met by both biofuel and synthetic fuel solutions. But the gap still remained on voyage costs, which, at least for the fuel/energy price scenarios considered, could only be made competitive with conventional propulsion and oil if a large carbon price (greater than \$200/tonne CO_2) was applied. This lack of competitiveness on voyage costs became more acute with the move to low upstream emission sources of synthetic fuels and electricity.

Fortunately, the technology and processes that are contributors to this gap in voyage cost competitiveness are currently low in terms of maturity and have definite potential for improvements and economies of scale. Electrolyser technology for the production of 'green' hydrogen and ammonia, batteries and low-cost renewable energy is experiencing rapid development.

Even in the timescales covered by this study, there is potential for a significant portion of the competitiveness gap to be closed; gauging this will be the focus of further study. For those in shipping with niche access to a low-cost supply of these fuel/energy sources, or an ability to pass on a voyage cost premium to a supply chain that values zero-emission services, the gap may have already closed.

Where do we go from here?

In order to consider how shipping reduces carbon dependency and to move forward from where we are today to where we need to be, we need to consider the wider energy system and energy technology. We need to consider how this is changing and how it will continue to change over the next decade.

By assessing different decarbonisation options for different ship types, our objective is to deliver a roadmap. This is framed in the context of setting objectives and measures to demonstrate that there is a pathway, as well as the opportunity, to ensure the successful and low-cost decarbonisation of the shipping industry.

The key questions to be asked now are: What needs to be done? Who needs to be involved? Where is the investment needed? And how is this going to be driven and incentivised to deliver a low-carbon action plan?

The Lloyd's Register (LR) Group and University Marine Advisory Services (UMAS) remain committed to supporting the industry on this journey and will continue to collaborate with industry stakeholders to gather research and facilitate the sharing of the balanced and independent information associated with the potential solutions to this complex change in the way in which we operate the shipping industry of tomorrow.

ZEVs are central to achieving the aim of decarbonisation."

Nish Rehmatulla
Research Associate, UMAS

"In our quest for decarbonisation, we know the direction of travel but perhaps not the pace. It is becoming increasingly clear that the pace of change is fast. We listened to what the shipping industry had to say; from the owners and operators surveyed, most agreed on the need for decarbonisation and that ZEVs will be central to achieving this aim. Yet, this work shows that this will not happen without regulations – a high price on carbon is required to make ZEVs viable, which is at odds with what the industry is prepared to pay."

Gary Pogson
Innovation Owner, LR

"I'm passionate about driving sustainable practices, and a key element in supporting industry stakeholders to adopt such a philosophy is the availability of balanced and independent information associated with the potential solutions. This report details a range of potential options for decarbonisation and, importantly, identifies that one must consider emissions in a whole asset lifecycle context."

Acronyms and assumptions.

Acronyms

CAPEX	Capital expenditure
CO_2	Carbon dioxide
DWT	deadweight
EEOI	Energy Efficiency Operational Indicator
GHG	Greenhouse gas
H_2	Hydrogen
HFO	Heavy fuel oil
ICE	Internal combustion engine
IMO	International Maritime Organization
MEPC	Marine Environment Protection Committee
MWh	Megawatt hour
NH_3	Ammonia
OPEX	Operating expense
SFC	Specific fuel consumption
TEU	Twenty-foot equivalent unit
ZEV	Zero-emission vessel

Assumptions

The approach used in this study has the following premises:

- It excludes the technical analysis and design issues that ZEV-related technologies may have on board vessels.
- ZEVs are assumed to be compliant with all environmental regulations.

The study focuses on the economic analysis, estimating the cash flow for all ZEVs and a HFO reference ship under different assumptions, in regards to:

- Alternative fuels' availability, economy and production methods.
- Technology developments (costs and performance).

It is a scenario-based analysis; in each scenario, a three-stage process was used to define the input assumptions. Fuel availability was assessed and used to project prices per unit of energy, considering the methods used to produce the fuel, as well as the original energy source. This consideration was then carried forward, alongside appropriate emission factors, to determine the emissions footprint of the fuel. Finally, technological developments were projected under each scenario to determine prices for capital expenditure on each component of the fuel storage, conversion and propulsion system, as well as to model their efficiency.

The reference ship is assumed to run on HFO with a two-stroke engine with a scrubber on board to ensure compliance with sulphur regulation. Scrubbers are assumed to be open loop, and cost assumptions are taken from the IMO assessment of fuel oil availability study.

Detailed assumptions are available on request.

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