Zero-Emission Vessels: Transition Pathways.

We’re considering how to turn ambition into reality.
Part of the Low Carbon Pathways 2050 series.

Lloyd’s Register | UMAS

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Contents

How do we turn ambition into reality?

Ships are highly capital-intensive assets with typical operating lives of 20-30 years, longer for some ship types.

At the maximum, therefore, we have just one-and-a-half generations of ships to develop zero-carbon fuels and associated technologies that can fuel our ships safely and efficiently in the future. Zero-emission vessels need to be entering the world's fleet in 2030.

Now, it is our collective responsibility to collaborate with other stakeholders to make sure that the decarbonisation of our industry is achieved and the IMO goal of at least 50% reduction in GHG emissions by 2050 becomes becomes an immediate focus and a realistic target, rather than just a far-away ambition.

In collaboration with University Maritime Advisory Services (UMAS), we set out to understand the milestones and enablers over the required timeframe to create the necessary conditions for the evolution of different pathways towards decarbonisation. We have considered how cost, operating profile and policy measures could influence this and identified milestones over time with regards to the safety, technical, social, economic and environmental aspects of the potential zero-emission vessels (ZEVs) and the associated supply of the zero-carbon fuel options.

We start with a desirable future in which the fuel mix in shipping will be dominated by zero-carbon fuels in 2050 and assess the conditions that need to be created now to achieve this desired future.

At this point in time, there is too much uncertainty to decide on one route, one fuel and one technology for the future transition of the shipping industry. So we need to consider all key primary energy sources that would allow zero-carbon fuels to enter the shipping fuel market: renewable energy, bio-energy and fossil fuels with carbon capture and storage (CCS). Although one of these may look more probable than another, we need to include all potential transition pathways and compare the different conditions to better understand what action may be taken now.

These pathways assume that fuels derived from one energy source will become the dominant fuels in 2050. Although this implies that there are several differences among the pathways, this also means that there are a number of similarities.

With significant investment in research and development in the short-term, technologically all the pathways provide solutions to reach the zero-carbon future as the technology readiness increases and ultimately the costs reduce throughout the transition. Yet action taken in the form of policy, regulations, financial incentives and from shipping's end users is required to incentivise this.

The decade of the 2020s – 2030s is the most significant in terms of action to transition to zero-carbon by 2050. To develop, prove, scale and commercialise the uptake of zero-emission vessels, we must now establish collaborative joint ventures involving not only our own industry participants, but also fuel technology companies, equipment manufacturers and energy developers from other industrial sectors outside of shipping.

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.

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For more details, info.lr.org/ZEV-transition-pathways

About University Maritime Advisory Services (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

The decade of the 2020s – 2030s is the most significant in terms of action.

Katharine Palmer
Global Sustainability Manager, LR

"The decade of the 2020s – 2030s is the most significant in terms of action to set the shipping industry on course to transition to zero-carbon by 2050. We have a collective responsibility to collaborate with all stakeholders to make sure that the decarbonisation of our industry is achieved and the IMO goal of at least 50% emission reduction by 2050 becomes an immediate focus and a realistic target, rather than just a far-away ambition."

Carlo Raucci
Principal Consultant, UMAS

"It doesn't happen very often to experience such moments as a global transition towards a new paradigm. This study has given us the opportunity to reflect on the actions needed to achieve a desirable future with zero-emissions vessels dominating the shipping industry. There are different paths to reach this goal and every turn of a path has its seduction and promises attached. A path may hold so many possibilities for shipping stakeholders, but what is clear is that the era of emitting fossil fuels must be left behind."

The International Maritime Organization's (IMO) Initial Greenhouse Gas (GHG) Strategy represents a significant ambition for the shipping sector. It sets a GHG reduction pathway of at least 50% by 2050 based on a 2008 baseline, with a strong emphasis on reducing to 100% by 2050 if this can be shown to be possible, as shown in Figure 1. **This provides a clear signal of the industry's commitment to reduce GHG emissions from international shipping by ending the use of fossil fuels by mid-century.**

This puts the shipping sector on course for a 2°C pathway, as shown in Low Carbon Pathways 2050[1] and will require a substitute for fossil fuel because energy efficiency improvements alone will not be sufficient. To achieve this, zero-emission vessels (ZEVs) need to be entering service by 2030 and anyone planning to finance, design or build a ship in the 2020s will need to consider how it can switch to a non-fossil fuel later in its operational life.

The need for technological changes and mechanisms that, in various combinations, achieve this level of ambition is becoming more urgent and in Zero-Emission Vessels 2030: How do we get there?[2], we identified the drivers for the viability of ZEVs to be a competitive solution compared to existing fossil-fuelled ships. The next piece of this current puzzle is to help the industry answer the questions in this complex challenge: what needs to happen for ship deployment? And what needs to happen to develop the supply infrastructure?

This report develops potential transition pathways for the decarbonisation of shipping, looking at the milestones and enablers, over the required timeframe and considering cost implications, operating profile and how policy measures could influence this, this report aims to show what is required to enable the transition on both a ship and supply infrastructure. We intend showing what is needed to support the development of an action plan to achieve the IMO's 2050 goal and to demonstrate to all industry stakeholders that action can be taken now.

[1] Low carbon pathways 2050, LR and Shipping in Changing Climates (September 2016)
[2] Zero-emission vessels 2030: How do we get there? LR and UMAS (December 2017)

Pathways for international shipping's Carbon dioxide (CO_2) emissions

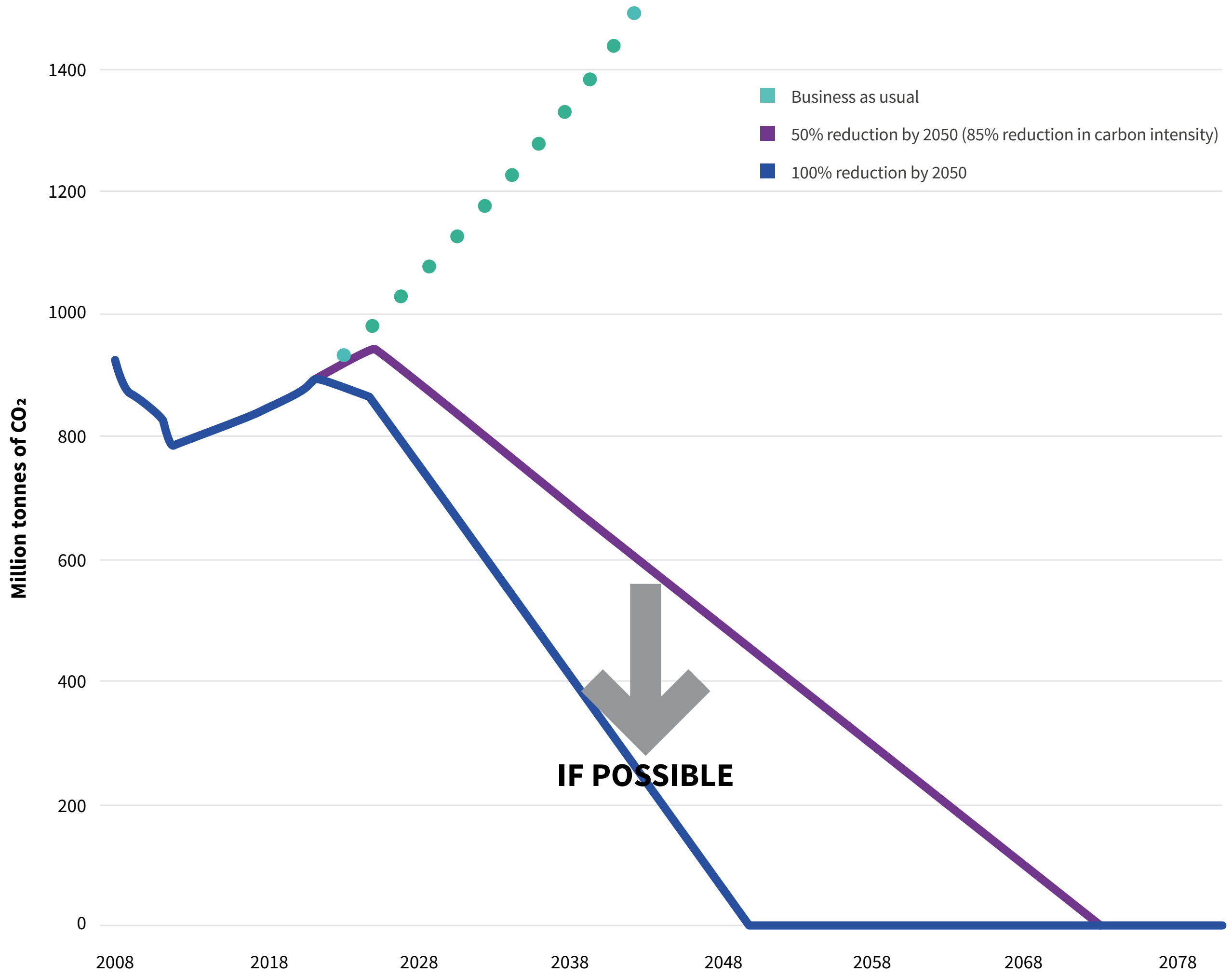

Figure 1: Carbon dioxide (CO_2) reduction trajectory for international shipping in line with the IMO Initial GHG strategy

OUR APPROACH

Our approach aims to identify the conditions that will need to happen to achieve a transition towards a decarbonised shipping industry.

We assume that ZEVs will be characterised by zero-carbon fuels; solar and wind by themselves as ship propulsion are assumed to be insufficient to provide the power needs of international shipping and play a role in hybrid configurations. Therefore, we start with a desirable future in which the fuel mix in shipping will be dominated by zero-carbon fuels in 2050 and **backcasting**[3] to identify milestones and enablers that connect the specified future to the present. Our approach is shown in Figure 2.

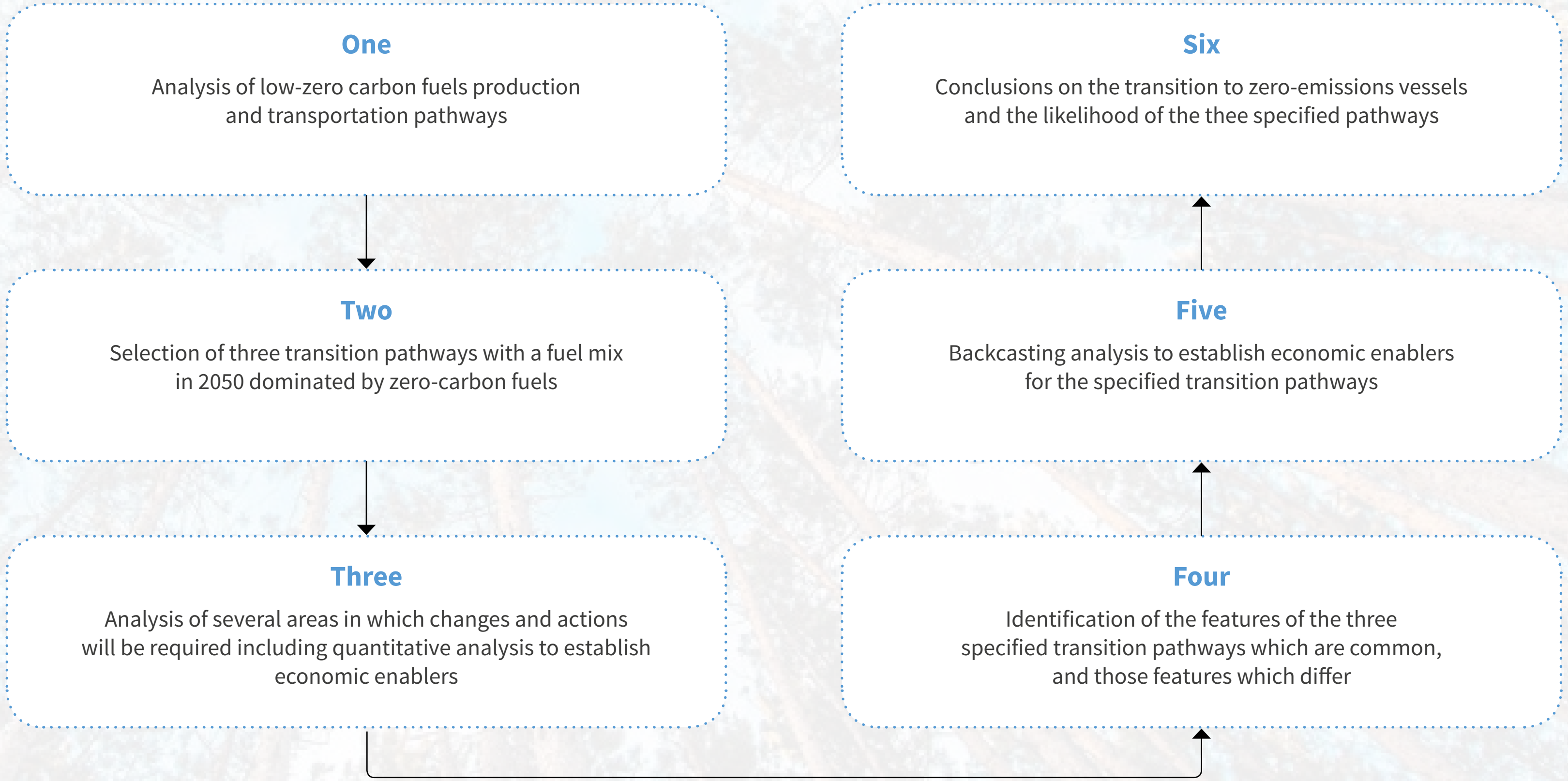

Figure 2: Our approach

[3] Dreborg, K. H. (1996) 'Essence of backcasting', Futures, 28(9), pp. 813–828.

Transition pathways.

To achieve the level of ambition of at least 50% reduction in GHG emissions by 2050, zero-emission vessels need to be entering the world's fleet in 2030. **At this point in time, there is too much uncertainty to decide on one route for the future transition of the shipping industry.** So, to reduce uncertainty, one way is to look at future projections and explore the potential of a combination of different technologies and fuels.

We have included three key primary energy sources that would allow zero-carbon fuels to enter the shipping fuel market; renewable energy, bio-energy and fossil fuels with carbon capture and storage (CCS). Although one of these may look more probable than the others, we have included all potential outcomes in which fuels derived from one of these energy sources will dominate the future fuel mix. Only by including all potential transition pathways are we able to compare the different conditions and better understand what action may be taken now.

These pathways assume that fuels derived from one energy source will become the dominant fuels. Although this implies that there are a number of differences amongst the pathways, there are also several similarities.

We describe the common features to all the three pathways, then provide details on the features that are different for each pathway.

Common features in all pathways

Gradually phasing out fossil fuel-based marine fuels.

In all pathways a transition to zero-carbon fuels will be achieved by 2050. This means that fossil fuel-based marine fuels (such as Heavy Fuel Oil (HFO), Low Sulphur Heavy Fuel Oil (LSHFO), Marine Diesel Oil (MDO) and Liquefied Natural Gas (LNG)) will completely phase out or will take a small share (~10%) of the total **fuel mix** in 2050, as shown in Figure 3. Starting with this assumption ensures that the IMO level of ambition of at least 50% reduction in GHGs by 2050 (compared to a baseline of 2008) will be achieved and that reducing to 100% by 2050 is possible.

In all pathways it is assumed that a mix of fuels will be used in shipping in 2050. However, there will be a family of fuels which will dominate the mix.

The evolution of the fuel mix for shipping over time is linked to the evolution of the global energy system and, in all pathways, the global energy system will need to evolve accordingly to scenarios in line with the 1.5°C Paris Agreement target. The **energy capacity** of the associated primary energy sources (renewable energy, bio-energy, fossil fuels with CCS) will need to grow sufficiently to cover the shipping energy demand in each pathway.

Consequently, zero-carbon fuels will need to be available and produced mainly from renewable electricity, biomass, and natural gas with CCS as represented in Table 1. Our analysis on fuel pathways indicates that all candidate fuels considered in this study have some emissions associated with them because of the ways they would be produced and transported. However, all these fuels have very low CO_2 emissions, and they may have the potential to become zero CO_2 emissions. Therefore, we refer to these fuels as zero-carbon fuels.

Other zero-carbon fuels may exist; however, it is assumed that these will be the main primary energy source for fuels in the future for the shipping sector.

Shipping fuel mix

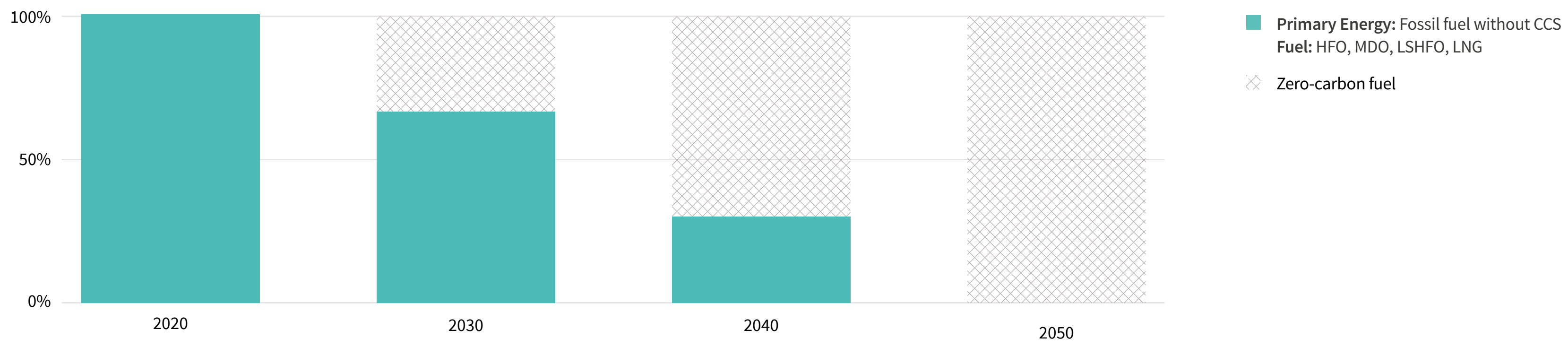

Figure 3 - Illustrative desired shipping fuel mix in 2050

Table 1 - Energy source/zero-carbon fuels considered in this study

	Zero-carbon fuels				
Energy source	Methanol	Gas oil	Hydrogen	Ammonia	Electricity
Natural gas with CCS			NG-H_2	NG-NH_3	
Biomass	bio-methanol	bio-gas oil			
Renewable electricity	e-methanol	e-gas oil	e-H_2	e-NH_3	batteries

Note: Many types of biofuels exist depending on processes and feedstock (first, second and third-generation biofuels). In this study we considered only two cases that are regarded as representative for bio-methanol and bio-gas oil both as second and third-generation. Fuels produced from renewable electricity are referred to as electro-fuels.

The dedicated maritime **supply infrastructure** will need to evolve to satisfy the increasing demand of zero-carbon fuels whilst taking into account the associated upstream emissions. Although LNG is expected to be used as a fuel during the 2020s, there will be a gradual switch over time towards bio-LNG, e-methane, hydrogen/methane blends, which allows the reuse of the LNG infrastructure, although these options cannot be considered as zero-carbon fuels.

However, it is expected that these fuels (bio-LNG, e-methane, hydrogen/methane blends) will find greater market opportunities in other sectors (e.g. heating and power generation) as liquid biofuels and liquid electro-fuels are expected to be more suitable for shipping as this allows the continued use of existing oil infrastructure. Therefore, a key milestone will be a shift from LNG as a fuel for shipping to natural gas as a source with CCS for producing Ammonia (NH_3) and Hydrogen (H_2) for marine applications.

By 2030, **zero-carbon fuels** will need to reach a competitive price that, in combination with a carbon price, will make ZEVs as competitive as vessels using conventional fossil-based fuels. The required carbon price may vary by ship type and size. Zero-carbon fuels also mean potential new technologies on board for power conversion such as fuel cells and batteries, which will need to develop further to provide sufficient power. Moreover, as zero-carbon fuels have a lower energy density than conventional fossil-based fuels, it is expected that in all pathways, gradually ships would be designed to store less energy on board and refuel more often; cruise and RoPax, for example, would reduce their capacity by at least 50%, with the other ship types by at least 30%.

The expected role of energy efficiency technologies and batteries

Energy efficiency technologies have the potential to reduce fuel consumption and therefore emissions. In the short-term (next 10 years) they will contribute to the absolute emissions reduction and will be used in hybrid solutions whilst global coverage of zero-carbon fuels in terms of availability at bunkering ports evolves. It is expected that during the transition period (2020 - 2030) zero-carbon fuels are on average more expensive than conventional fossil-based fuels, and therefore the use of energy efficiency technologies is an important element to stimulate the take-up of ZEVs.

In all pathways, we see that **batteries** play a minor role as a primary energy store/source on board ships because of their limitations in regards to the high cost and relatively low energy volumetric density. In most of the cases, the cost of batteries (cost of storage system) appears to be prohibitive relative to other zero-carbon options. For example, in a small container ship ~1300 TEU, the battery cost can be over 1.5 times that of an equivalent hydrogen storage system and the revenue loss due to the space requirements could be three times more than that of hydrogen storage. Even considering a significant evolution in the development of batteries and a dramatic CCS cost reduction combined with an increase in frequency of recharging to reduce the amount of energy stored on board, and therefore the associated revenue loss, the competitiveness of fully electric ships with batteries appears to be very low, especially for mid-large sized ships.

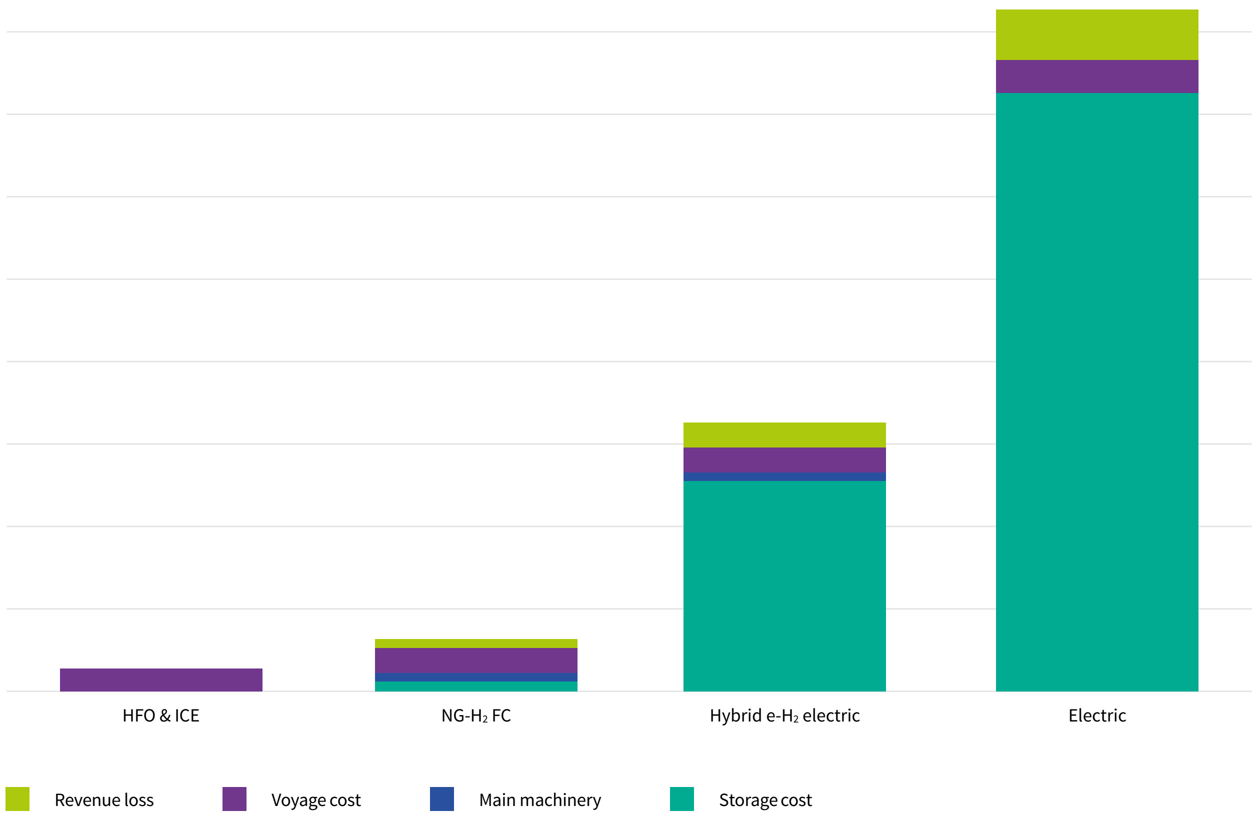

Figure 4 - Additional costs relative to the reference ships for hydrogen-hybrid and full electric with batteries ZEVs[4]

[4]Zero-Emission Vessels: 2030 How do we get there? (December 2017)

In Figure 4 we have assumed a battery cost of 177 $/kWh; in comparison to a range between 100-300 $/kWh[5], and an assumed energy volumetric density of 260 kWh/m^3; in comparison to a range for lithium-ion battery between 200 - 500 kwh/m^3[6]. We can see that the storage costs for batteries outweigh the potential benefits even when factoring in a reduction of bunker capacity by 30%. A significant reduction of these parameters would be required in the future for a fully electric-batteries ZEV to be as competitive as other ZEV options.

There are conditions, however, in which batteries will play a role during the transition period. For example, batteries will result in being competitive for very small passenger cruise and RoPax vessels as part of the energy load/demand management on board in hybrid solutions with conventional fossil-based fuels. They would also continue to be used on shore to manage energy load/demand, allowing onshore power connections for vessels in port. It is expected that this will pick up more rapidly in the first half of the 2020s.

ZEVs that are safely adopted and operated

In the first half of the 2020s, there will be a need to test the **safety aspects** for all potential zero-carbon fuels in marine applications through risk assessment, safer designs and implementation cases. The development of international standards and rules is expected to be technology neutral, so regardless of the specifics of the pathway, they will need to be in place for all options by 2025 to allow ZEV newbuilds to enter the market in 2030.

By 2025 rules and global standards for marine applications will need to include risk mitigation and safe bunkering, transport and on board usage of all zero-carbon fuels such as:

- additional crew training programmes
- emergency shutdown
- optimised storage environment design and venting. This is critical for safety with standards in place to ensure that ventilation is maintained to reduce indoor concentrations below Lower Flammability Limit (LFL) by 4% or 8% in the case of H_2
- risk assessment for the potential release of hot, flammable and/or toxic gases, in addition to potential fires and electrical risks for batteries
- risk assessment procedure for fuel cells, uncontrolled reactions, loss of containment and environmental risks

On the other hand, international standards and supporting guidance and best practice will need to consider:

- the application of International Standards Organization (ISO) 8217:2017 specification of marine fuels; which already covers flash point for fatty acid methyl ester (FAME) and biodiesels to be used as drop-ins or blends, but will need to continue to evolve as new generations of biofuels are developed with different feedstocks and to allow for an increased % of blends and drop-ins
- independent fuel testing of biofuels to ensure compatibility and co-mingling as bunkered as any associated risks are mainly dependent on the feedstock
- robust on board fuel management processes and guidance is necessary to manage any associated risks such as carbon deposits from biofuels with high viscosity and boiling point
- international standards will also need to be in place for the provision of zero-carbon fuels for example the expansion of the International code of safety for ship Using Gases or other low-flashpoint fuels (IGF) code to cover the use of hydrogen and ammonia as a fuel
- international standards for bunkering zero-carbon fuels such as H_2 and NH_3 and guidance on the design and use of these fuel options will also need to be in place
- current natural gas distribution and storage standards will also have to be in place and maintained in a wider range of potential new areas where natural gas (NG) would be used as a feedstock for NH_3 and H_2

By 2028, rigorous hazard studies will have been undertaken and all the risks characterised with mitigation and management solutions to allow zero-emission vessels to be designed, constructed and operated to maintain or enhance safety performance. Associated more sophisticated equipment and safeguards will need to have been developed for the prevention and detection of releases from fuels such as hydrogen, as well as competence and capability built through joint industry projects to prove technology. Beyond 2030, as the first ZEVs are entering the world fleet, more automated, sophisticated equipment provides opportunities for digital applications for continuous monitoring and optimisation of the performance, safety and efficiency of the system.

The role of actors involved, policy-makers, financiers and consumers

In the early 2020s, to enable the transition we will need to see in all pathways the number of zero-carbon **fuel producers** grow. A key milestone to enable the transition is the formation of **alliances** between fuel producers together with original equipment manufacturers (OEMs) and associated technology (e.g. fuel cells, CCS) providers with the aim of increasing the uptake of zero-carbon fuels against the use of conventional fossil-based fuels in shipping. This is expected to begin by focusing on select ship type markets (RoPax, cruise and container due to consumer pressure) and geographical regions where they see potential for the different zero-carbon fuels to compete with conventional fossil-based marine fuels. More specialised alliances would evolve for the purpose of promoting the use of electro-, bio- and natural gas with CCS-based fuels. In the late 2020s, these different alliances and networks will need to continue to grow as more actors enter the market. The alliances between actors promoting the same final energy carriers (e.g. hydrogen and ammonia for electro- and natural gas with CCS-based fuels, methanol and gas oil for bio- and electro-fuel actors) could grow particularly strong. In the 2030s, as the acceptance, availability and uptake of zero-carbon fuels in shipping grows and competition among the different zero-carbon fuel options increases, these actor groups would redirect their attention towards promoting their respective solution as the best and most viable one.

[5]https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF-Lithium-ion-battery-costs-and-market.pdf
[6]https://research.hanze.nl/ws/portalfiles/portal/10687815/Pierie.Appendix_English.pdf

TRANSITION PATHWAYS
(CONTINUED)

In the early 2020s, the role of **civil society** actors in enabling the transition in all pathways will increase by advocating zero-carbon shipping and increasing the pressure on **policy-makers** at the national, regional and international level. Expectations will be high for measures already outlined in the IMO Initial GHG Strategy to be implemented such as command and control regulations, (low to zero-carbon fuel standards), market-based measures and establishing a supportive policy environment for guidelines and best practice, e.g. safe handling of zero-carbon fuel options to achieve the milestone of ZEVs to enter the world fleet in 2030.

In Zero-Emission Vessels 2030: How do we get there?, we showed the we showed the importance of policy and regulation as a driver to enable this transition as technical and operational drivers alone would not be sufficient. In the early 2020s, in all pathways the introduction of short-term GHG reduction measures under the IMO's Initial GHG Strategy will be a condition needed to enable the transition, driving operational energy efficiency improvements and the reduction of GHG emissions. In 2023, the IMO will adopt a revised GHG strategy with expectations for more stringent levels of ambition. The revised strategy would also contain timelines for the implementation of mid to long-term measures such as market-based measures linked to the establishment of a fund for research, development and deployment investments into zero-carbon fuels and technologies and low to zero-carbon fuel standards. While the stringency of these two example policy measures at the time may be low, it is expected to become progressively more stringent to incentivise the uptake of ZEVs leading to the desired future in 2050.

In addition to the implementation of the IMO sulphur cap in 2020, proposals for additional emission control areas (ECAs) for sulphur oxides (SOx) and/or nitrogen oxides (NOx) control, leading to the establishment of more ECAs in the late 2020s and early 2030s, could eventually transform most of the world's coastlines into ECAs in the 2040s. This enabler would drive air pollution standards globally, which subsequently drives the uptake of zero-carbon fuels.

In the early 2020s, an increasing number of countries may develop and implement national action plans to address GHG emissions and air pollution, including in ports. At the same time, as part of these national plans or independently from them, a growing number of **ports** could provide incentives to ships that can demonstrate efforts to reduce GHG emissions. In the 2030s, both the port schemes and national action plans will need to become increasingly ambitious and stringent, offering substantive incentives and funding to ZEVs to create the conditions to support transition pathways to zero-carbon fuels. International pressure on countries to act to reduce ship emissions at a national level could increase as previously mentioned, so that by 2040, national maritime GHG reduction strategies are adopted and become the norm. This will lead to increased levels of investment and stakeholder engagement into zero-carbon fuels globally.

In the early 2020s, following on from voluntary commitments for climate-related financial disclosures, for example the Financial Stability Board's recommendations, a number of major shipping **financiers** will need to commit to aligning their new and existing business activities with international climate goals IMO Initial and revised GHG strategy and Paris Agreement), to assess the climate alignment and climate risk exposure of their shipping portfolios and to set climate alignment targets for their shipping portfolio. The number of climate-aligned financiers will need to grow in the late 2020s and sources of funding would need to diversify, utilising a growing market of debt and equity finance, including green/climate bonds and green stocks. In addition to these sources, development banks would also become active players in the financing of ZEVs, especially those that serve in domestic/coastal waters in specific regions. As the commitments should start taking effect, more finance will become available from the above-mentioned sources for ZEV-activities and less for non-ZEV activities. By the 2030s, the majority of the main shipping financiers should be committed to these actions and implement their commitments. The remaining financiers will join over the course of the 2030s with the last ones signing up in the late 2030s. This will make it increasingly difficult to find finance for non-ZEV activities.

We showed in Zero-Emission Vessels 2030: How do we get there? that the competitive gap between zero-emission vessels and conventional fossil-fuelled vessels was already closing for those that had the ability to pass on a voyage cost premium to a supply chain that values zero-emission services. The expected **environmental consumer pressures** would be the main non-market related driver to enable the transition. In the early years of 2020s, cruise, RoPax and container sectors are expected to be the first movers as a result of this expectation. And as research, development and deployment is proven in these sectors, it is expected to evolve and scale to other sectors so that by 2030 ZEVs are proven for all ship types.

Pathway 1: Renewables dominate.

Marine fuel mix and energy sources

This pathway sees a rapid ramp-up of renewable electricity-based marine fuels in the form of hydrogen, ammonia, e-methanol, e-gas oil and electricity for use in batteries. These electro-fuels will be increasingly taken up at the expense of fossil fuels used without CCS technology. Like electro-fuels, although to a lesser extent, bio-based fuels will gradually enter the fuel mix, as well as hydrogen and ammonia produced from natural gas with CCS as they have a share of the overall energy production.

The transition pathway in terms of energy sources and final marine fuels mix for this pathway is represented in Figure 5.

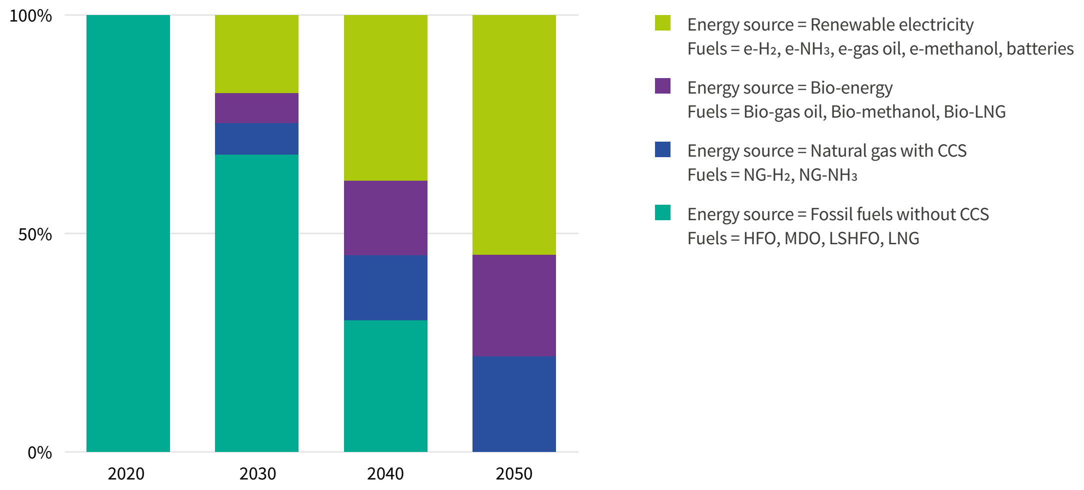

*Figure 5 - Energy source and marine fuels mix assumed in **renewables dominates** pathway*

PATHWAY 1
(CONTINUED)

The first milestone for this pathway is that the **capacity of renewable electricity** globally grows significantly. Renewable electricity will need to reach approximately 50, 150, 200 exajoule (EJ) respectively in 2030, 2040, 2050 similar to the values of one of the Intergovernmental Panel on Climate Change (IPCC's) scenarios in line with a 1.5°C transition shown in Figure 6. It is expected that the majority of the renewable electricity demands will be from buildings, industry and cars, and therefore shipping would need to compete or find synergies with these sectors in order to access the amount of renewable energy required to produce electro-fuels. Therefore, it will be very important to analyse the energy intensity of the production methods, for example, the production of e-methanol is very energy intense and consequently, a greater availability of renewable electricity would be required.

During the 2020s the development of **electro-fuels production** will need to continue and grow exponentially, to provide the initial incentive for further cost decreases through research and development. By 2030, renewable electricity will need to be available at a price of approximately 19 $/megawatt hour in locations such as Latin America and the Middle East[7], where cheap electro-fuels will start to be produced and transported to major bunkering hubs as known today. This price of electricity would make electro-fuels very competitive, for example, e-hydrogen could reach 400 $/HFO equivalent (HFOe) (1.2 $/kg H_2) of which 82% is linked to the renewable electricity price, as shown in Figure 7. The availability of water in these locations could be an issue, which will need to be resolved at a relatively low cost.

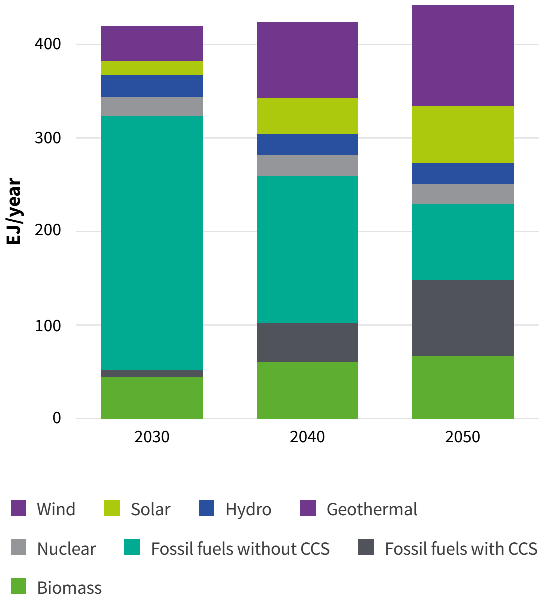

Figure 6 - Assumed energy production transition under the ***renewables dominate*** *pathway*[8]

Hydrogen production from renewable electricity (liquefaction storage) cost breakdown

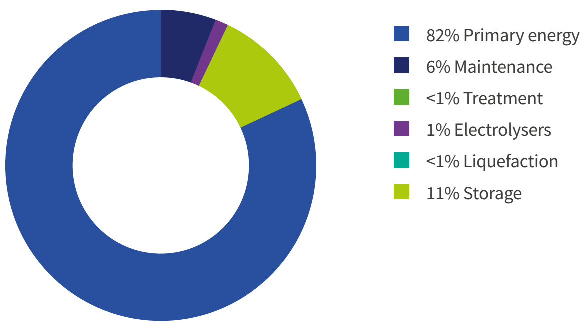

Figure 7 - Hydrogen production from renewable electricity (liquefaction storage) cost breakdown

[7]Zero-carbon fuel production costs and assumptions
[8]Huppmann D. at .al (2018), IAMC 1.5°C Scenario Explorer and Data hosted by IIASA. Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis, 2018

During the first half of the 2030s, cheap renewable electricity will need to spread to more geographical locations. Electrolyser costs will need to be below 500 $/kW in 2030 and gradually decrease over time until reaching 250 $/kW, which will further decrease the final fuel price and be competitive against conventional fossil-based marine fuels marine fuels. Distribution of renewable electricity will need to be ensured worldwide using different energy carriers, including hydrogen and ammonia.

Because of the development of electro-fuels supply infrastructure, in many of the bunkering hubs, **electro-fuels prices** will need to be of the order shown in Figure 8. This means that during the second half of the 2030s NG-based fuels will become considerably more expensive than electro-fuels in the majority of the bunkering ports.

The required development of on board technologies

During the 2020s, research and development for **on board technologies** will be very important to determine which of the electro-fuels will have the potential to become the predominant fuel. The main technologies that would require further development are: fuel cells and storage systems (particularly for hydrogen). If electro-fuels such as e-NH_3 and e-H_2 will be used in an internal combustion engine (ICE) then the latter would need some further development, although there are already examples being shown. This indicates that the required development would be less significant than the research and development required for fuel cells and hydrogen storage.

In the first half of 2020s, ICE technologies may offer a better trade-off in terms of costs and efficiency than fuel cells. The latter will need to scale up with regards to the power requirement and develop accordingly with the maritime specific requirements. It is likely that the type of fuel cells would be different depending on type/size. This analysis suggests that by 2030, the capital cost of fuel cells will become as competitive as the sister ZEVs using ICE. The efficiency of fuel cells may also increase significantly from the assumed initial value of 60% used in this study, which would incentivise the use of fuel cells over ICE.

The potential of hydrogen is particularly linked to the development of storage technologies. E-H_2 would be cheaper than e-NH_3 and e-methanol to produce, however, it is harder to handle on board ship. By 2030, the capital cost of liquid hydrogen storage would need to reduce from 56 $/kg initially assumed to 15 and 30 $/kg (the current investment cost of liquid hydrogen storage found in the literature varies between 27 and 333 $/kg[9]) to become as competitive as the ZEVs using e-NH_3.

Nevertheless, these conditions would make hydrogen the favoured fuels only for small-to-medium sized ships. Figure 9 shows the **relative competitiveness** of a ZEV using e-H_2 for a small-medium sized container ship. For a large ship travelling long distance, the revenue loss due to the storage space requirement may be very high and the reduction of storage and machinery costs would not be sufficient to compete with other options such as e-NH_3 and e-methanol.

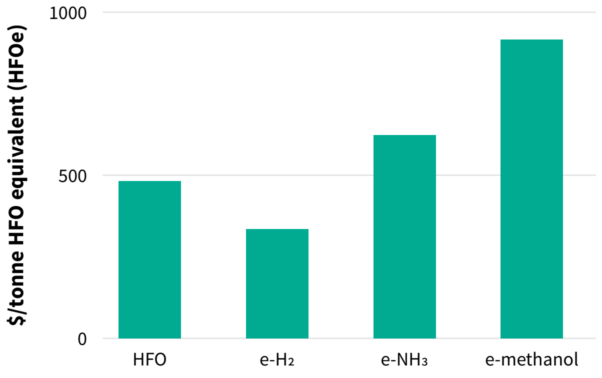

Figure 8 - "Backcasted" electro-fuel prices in 2030 needed to make ZEVs using these fuels competitive

Project annual costs in 2030

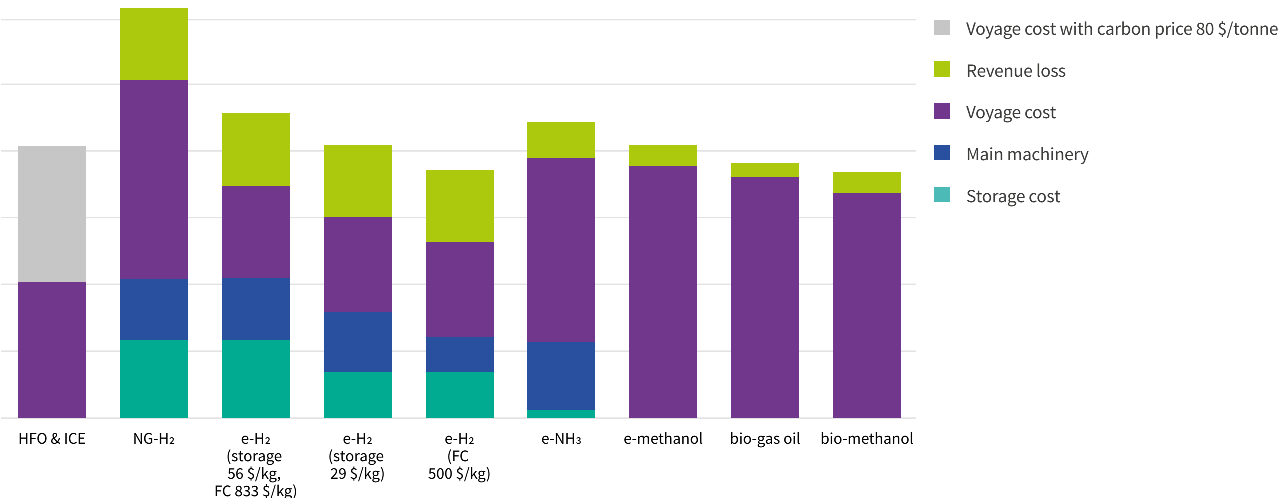

Figure 9 - Relative competitiveness of ZEVs using electro-fuels for a small-medium sized container ship

[9]https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapHydrogenandFuelCells.pdf

If fuel cells develop faster than liquid hydrogen storage systems, then ZEVs using e-NH_3 in combination with fuel cells would become more competitive than the sister ZEVs using ICE, as well as the ZEVs using bio-gas oil and bio-methanol. E-gas oil is unlikely to play a crucial role as its prices may remain very high, affecting negatively the voyage costs.

Actors, policy-makers and financiers for electro-fuels

In this pathway, with global renewable energy production growing, awareness of the maritime industry as a consumer of electro-fuels is expected to grow, enticing a growing number of **electro-fuel providers** to enter the market, trial and demonstrate their fuel options in the early 2020s. Around the mid-2020s, electro-fuel actors could start to organise themselves in alliances and, albeit to a lesser extent, may join forces with biofuel actors to advocate against natural gas in favour of their fuel option and together with the bio fuel actors, against natural gas. As the number of **actors and alliances** grow and electro-fuel networks reach the size and strength of natural gas networks in the late 2020s, the market will need to start to consolidate, resulting in a few large and powerful electro-fuel providers in the 2030s.

In the early 2020s, **civil society** actors actively will need to advocate for electro-fuels as these are seen as the most environmentally-friendly and sustainable option, with efforts intensifying in the late 2020s and persisting throughout the 2030s.

In the early 2020s, **governments** worldwide will need to continue to promote, incentivise and invest in renewable electricity production. In the late 2020s, countries with surplus capacity and low production costs would begin investing in the production of electro-fuels and the development of bunkering infrastructure. This development will need to continue in the 2030s with large marine electro-fuel producing countries emerging.

As a result, **policy-makers**, would see the merits of electro-fuels compared to bio-fuels and to natural gas. In the early 2030s, international policies would emerge on sustainability standards for marine biofuels, regulating the use of natural gas-based fuels as well as of CCS.

In response to this, **financiers** in the 2030s would primarily invest in shipping activities related to electro-fuels.

Addressing emissions and safety concerns

By 2023 air pollution concerns would continue grow, especially in environmentally sensitive coastal areas and closed seas (e.g. South China Sea, Mediterranean, current emission control areas (ECA) etc.) and could likely lead to the introduction of new NOx and SOx ECAs. In this sense zero-carbon fuels that demonstrate a clear reduction for all air pollutants such as H_2 with fuel cells or batteries would be attractive. Nevertheless, technological solutions will need to be readily available at cost competitive prices to ensure that pollutants such as NOx emissions from ammonia and biofuels will be minimised.

By 2030, electro-fuels will need to offer the best GHG and air pollutant abatement benefits compared to conventional fossil-based marine fuels, but also compared to other zero-carbon fuels options. By 2035, further competitiveness of electro-fuels could be guaranteed as NG as feedstock reduces, which is primarily driven by its perceived adverse environmental effects. Concerns around GHGs from NG would mean a shift to the use of CCS, which may still not be fully developed, making NG feedstock fuels less appealing.

By 2028, the **safety concerns** around hydrogen and ammonia will need to be minimised by proven pilot projects and as such fuels are increasingly perceived as safe to handle. For example, the health risks associated with the toxicity of ammonia will need to be minimised with vessels designed with ventilated engine rooms. These pilot projects with such designs could minimise any opposition to ammonia based on safety.

Pathway 2: Bio-energy dominates.

The transition to bio-energy for the marine fuel mix

This pathway assumes bio-energy based fuels to be largely available and gradually taken up in shipping. Electro-fuels also enter the fuel mix but to a lesser extent, as well as hydrogen (H_2) and ammonia (NH_3) produced from natural gas with CCS. Shipping is not a complete zero emissions system in 2050 as conventional marine fuels based on fossil fuels will still be used mainly because they would be blended with biofuels.

The assumed transition pathway in terms of energy sources and final **marine fuels mix** is represented in Figure 10.

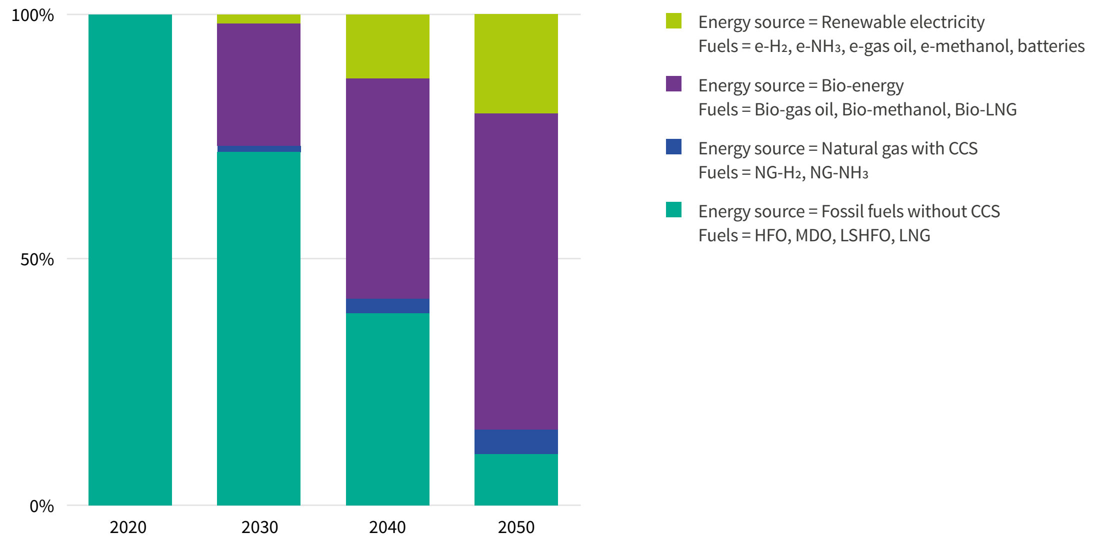

*Figure 10 - Energy source and marine fuels mix assumed in **bio-energy dominates** pathway*

PATHWAY 2

(CONTINUED)

This pathway sees bio-energy being one of the main solutions to climate change. **Bio-energy capacity** will need to grow significantly, reaching approximately 60, 150, above 300 EJ respectively in 2030, 2040, 2050, similar to the values of one of the IPCC's scenarios in line with a 1.5°C transition shown in Figure 11. The capacity of bio-energy will need to extend worldwide, starting from countries with a lot of biomass, for example Brazil. This would require a massive change in global land use with large areas dedicated to biomass cultivation in the order of 2.5 billion hectares and beyond, and strongly dependent on the biomass type used and the yield achieved.

During the 2020s, bio-energy and the associated **supply of biofuels** will be used in other sectors (e.g. aviation), therefore shipping would need to compete or find synergies with these sectors to ensure a priority access (e.g. as being considered as one of harder-to-abate sectors). By 2023, biofuels standards based on lifecycle assessment would need to be in place which will ensure the carbon neutrality for this type of fuels. By 2025, the existing fleet will need to perceive bio-based fuels as the best option while infrastructure and main machinery development are taking place for the other zero-carbon fuels. At the same time, ICE using bio-gas oil and bio-methanol will need to be available with the specific standards and additional global requirements needed to meet the safety standards. A lack of significant development in H_2 and/or NH_3 infrastructure over the second half of the 2020s (including expansion of a global grid for renewable electricity) will reduce competition with bio-based fuels.

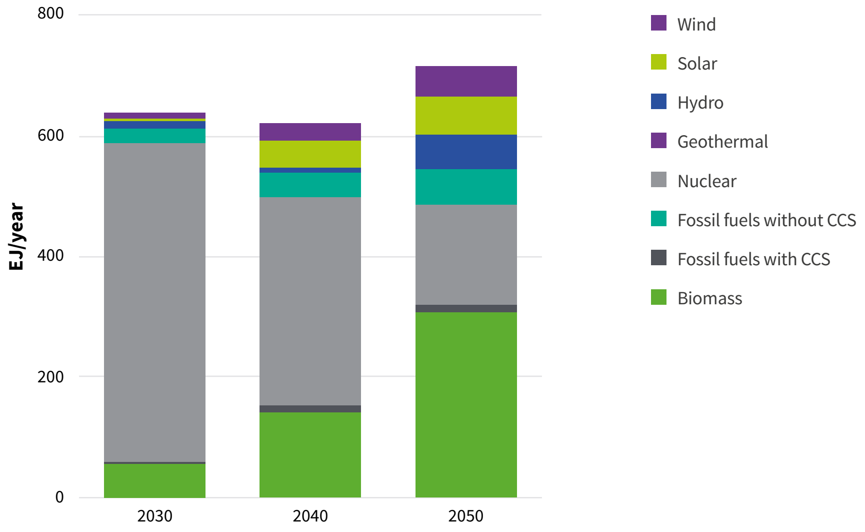

Figure 11 - Assumed energy production transition under the ***bio-energy dominates*** *pathway*[10]

[10]Huppmann D. at .al (2018), IAMC 1.5°C Scenario Explorer and Data hosted by IIASA. Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis, 2018

The need for competitive prices of biofuels

A key milestone for this pathway is the reduction in **price** for bio-based fuels by 2030.

Assuming a price of HFO of 416 $/tonne, ZEVs using bio-based fuels would be as competitive as a vessel using HFO with an average fuel price of approximately 670 $/HFOe with a carbon price of 50 $/tonne and 510 $/HFOe without a carbon price . Figure 12 shows the breakeven points for bio-gas oil and bio-methanol. Each box shows the variance across ship type/size, considered in this study, with and without a carbon price.

Future biofuels prices are very uncertain, in 2030 our analysis indicates a range between 846 and 902 $/HFOe (depending on assumed biofuel type and energy content). This means that the milestone for this pathway is that biofuels would need to reduce their projected price in 2030 by 21%-26%, under a scenario with a carbon price of 50 $/tonne and by 40%-43% assuming no carbon price in place

By 2040, the price of biofuels will need to continue to gradually reduce as a result of the learning curve and economies of scale without being affected by issues related to their sustainability (e.g. land usage and competition with food production).

Figure 12 - Breakeven points (BEP) of bio-gas oil and bio-methanol prices for the ZEVs using those fuels across ship type/sizes relative to the reference ship using HFO

PATHWAY 2
(CONTINUED)

Actors, policy-makers and financiers for biofuels

Similar in the way that the production of electro-fuels grows as shown in the renewables dominate pathway, global and in particular regional bio-energy production will need to grow. The awareness of the maritime industry as a consumer of biofuels will entice **biofuel providers** to enter the market, trial and demonstrate their fuel options in the early 2020s as is already starting to be shown. Around the mid-2020s, biofuel **actors** may form alliances with electro-fuel actors, with the aim of promoting their fuel option over fossil-based options. If biofuel networks reach the size and strength of natural gas networks in the late 2020s, the market will need to start to consolidate, resulting in a few large and powerful biofuel providers in the 2030s.

In the early 2020s, biofuels will need to be seen as the most environmentally-friendly and sustainable option for this pathway to evolve. From the mid-2020s onwards, and in response to sustainability concerns related to biofuels, biofuel actors will need to actively promote the environmental benefits and sustainability credentials of biofuels to all stakeholders, including civil society and policy-makers.

In the early 2020s, **governments** worldwide will need to continue to promote, incentivise and invest in biomass production and biofuel generation. In the late 2020s, countries with large availability of biomass would need to invest in the production of marine biofuels and the development of bunkering infrastructure. This development will need to continue in the 2030s with large marine biofuel producing countries emerging.

In connection with the development of any international regulations on low to zero-carbon fuel standards which could emerge in the mid-2020s, **blend standards** would need to be developed and implemented to increase the uptake of biofuels over time to reduce GHG emissions. The blending standard could be implemented sooner, allowing a more manageable transition to bio-energy for shipping.

Similar to the previous renewables dominate pathway, **policy-makers** would become convinced of the merits of bio- and electro-fuels compared to fossil-based fuels and in the 2030s **financiers** will need to commit themselves to primarily invest in shipping activities related to bio - and electro-fuels.

Addressing environmental concerns for biofuels

For a bio-energy transition to evolve over the required time period, **environmental concerns** around biofuels will need to be addressed. By 2025, other species emissions (e.g. NOx, particulate matter (PM)) from bio-based fuels will need to be resolved with further development of emissions-reduction technologies. Bio-methanol initially may be most appealing in RoPax and cruise industry segments. By 2030, the sustainability of bio-based fuel production and distribution will need to be politically and socially accepted. This acceptance of biofuels will be supported through sustainable and efficient land-use policies put in place by the countries where the biofuels are being produced. For example, it will be possible to track sustainable and non-sustainable biofuels with technologies and there will be clear standards for blending and mixing along the fuel supply chain. By 2035, further discussions around environmental footprints of new bunkering infrastructure for hydrogen and ammonia may also increase favourability of biofuels, which have less requirements for additional safety concerns and can use established HFO/MDO bunkering infrastructure.

Pathway 3: Equal mix.

A transition with a no-dominating energy source

This pathway assumes both a ramp-up of renewable electricity-based marine fuels and bio-based fuels. However, alongside these fuels, also hydrogen and ammonia produced from natural gas with CCS gradually enter the **fuel mix**. The transition pathway in terms of energy sources and final marine fuels mix is represented in Figure 13. Shipping is not a complete zero-emissions system in 2050 as conventional fossil-based marine fuels will still be used mainly because they would be blended with biofuels.

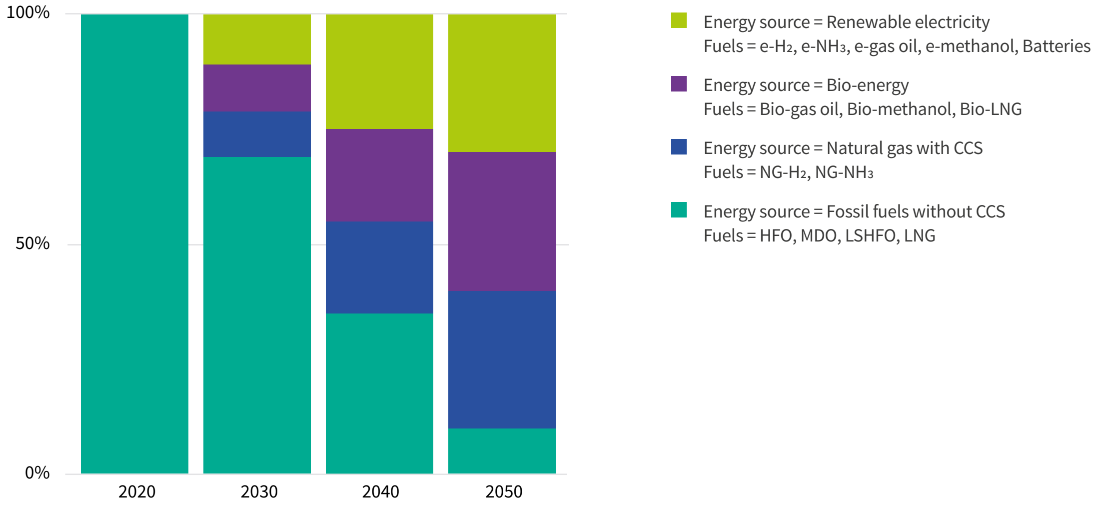

Figure 13 - Energy source and marine fuels mix assumed in ***equal mix*** *pathway*

PATHWAY 3
(CONTINUED)

The cornerstone of this pathway is a consistent growth in the **capacity of all energy sources**, which will need to see the three main energy sources (renewable electricity, bio-energy and natural gas with CCS) increase significantly. In particular, fossil fuels with CCS energy capacity will need to reach approximately 20, 70, 100 EJ respectively in 2030, 2040, 2050, similar to the values of one of the IPCC's scenarios in line with a 1.5°C transition shown in Figure 14. This means that over the transition period a significant share of this energy source will need to be dedicated for the shipping energy demand.

During the first half of the 2020s, the **supply infrastructure** will need to evolve in a differentiated way depending on specific locations. The availability of very cheap natural gas in a few areas will lead by 2025 to it being used in steam methane reforming (SMR) to produce hydrogen and/or ammonia for shipping.

Figure 14 - Assumed energy production transition under the ***renewables dominate*** *pathway*[11]

[11]Huppmann D. at .al (2018), IAMC 1.5°C Scenario Explorer and Data hosted by IIASA. Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis, 2018

The role of CCS technology

In addition to the conditions outlined in the previous two pathways for electro-fuels and bio-based fuel, ZEVs using natural gas-based fuels will also have a growing role. In this context, by 2030, the **price** of natural gas will need to reach approximately 4 $/MMBTU which will make ZEVs using NG-NH_3 with ICE as competitive as the ZEVs using electro-fuels and biofuels. However, in some locations the price of natural gas will need to be below 2 $/MMBTU to make these ZEVs more attractive relative to the conventional fossil-fuelled ship. The associated prices of NG-H_2 and NG-NH_3 produced without CCS will need to be below 480 $/HFOe and 640 $/HFOe.

CCS technology will need to be perceived as crucial to address climate change (natural gas will continue to play a longer role in society but CCS needs to develop and be proven). Therefore, by 2025 more research and development on CCS will be needed to decrease the associated capital expenditure (capex). During the first half of the 2030s, a further development in CCS would bring the price of natural gas to a lower level. The CCS technologies are expected to reduce by 50% (from the assumed 331 $/tonne to 133 $/tonne), at the same time, the capex of fuel cells technology will also experience a reduction of more than 80% (from 833 $/kW to 100 $/kW). As a consequence, the competitiveness of these ZEVs improves. The associated prices of NG-H_2 and NG-NH_3 produced with CCS will need to be about 420 $/HFOe and 550 $/HFOe.

By 2035, CCS will need to be proven and a widely used technology and combined with environmental regulations on fuel standards using NG as feedstock. By 2040, ZEVs using NG-based fuels will be established in some niche areas.

A further reduction in natural gas price of about 1 $/MMBTU and capital investment of hydrogen storage system by 50% (from 56 to 33 $/kg) would make those ZEVs as competitive as the conventional fossil-fuelled ships.

An illustrative example of how costs and associated **competitiveness** may change over time is provided in Figure 15 for a medium size bulk carrier.

Actors in the equal mix pathway

With renewable and bio-energy growing at a roughly equal pace, some **actors** will need to enter the maritime sector in the early 2020s to promote marine bio- or electro-fuels and prove the fuels' viability. **Alliances** across zero-carbon fuel options will need to form to a certain extent in the early 2020s, but remain limited in strength and size, with actor groups focusing on promoting their respective fuel options as the best and creating competition between the different options. While electro and biofuel promoting networks would grow in the late 2020s, they may not reach the same size and strength of the already established natural gas network and hence struggle to compete with it.

In the early 2020s, the shift from promoting LNG as an end-fuel to natural gas as a source for alternative zero-carbon fuel options will need to be supported by a growing number of **CCS providers** entering the market and successfully testing their technologies. In the late 2020s and early 2030s, natural gas networks will need to promote natural gas-based fuels as proven ZEV options and highlight the supply and price insecurities of renewable and bio-energy. This will need to be in parallel to biofuel actors being unable to overcome the perceived sustainability concerns related to their fuels.

When a global shift to renewable and bio-energy occurs in the 2040s, fossil fuel actors will need to see maritime as one of the last remaining markets and push for natural gas-based fuels, including through price incentive and **government** support.

Over the transition period, **financiers** have no preference regarding their investments into activities related to ZEV shipping and ZEV fuels, as long as these are aligned with international climate goals.

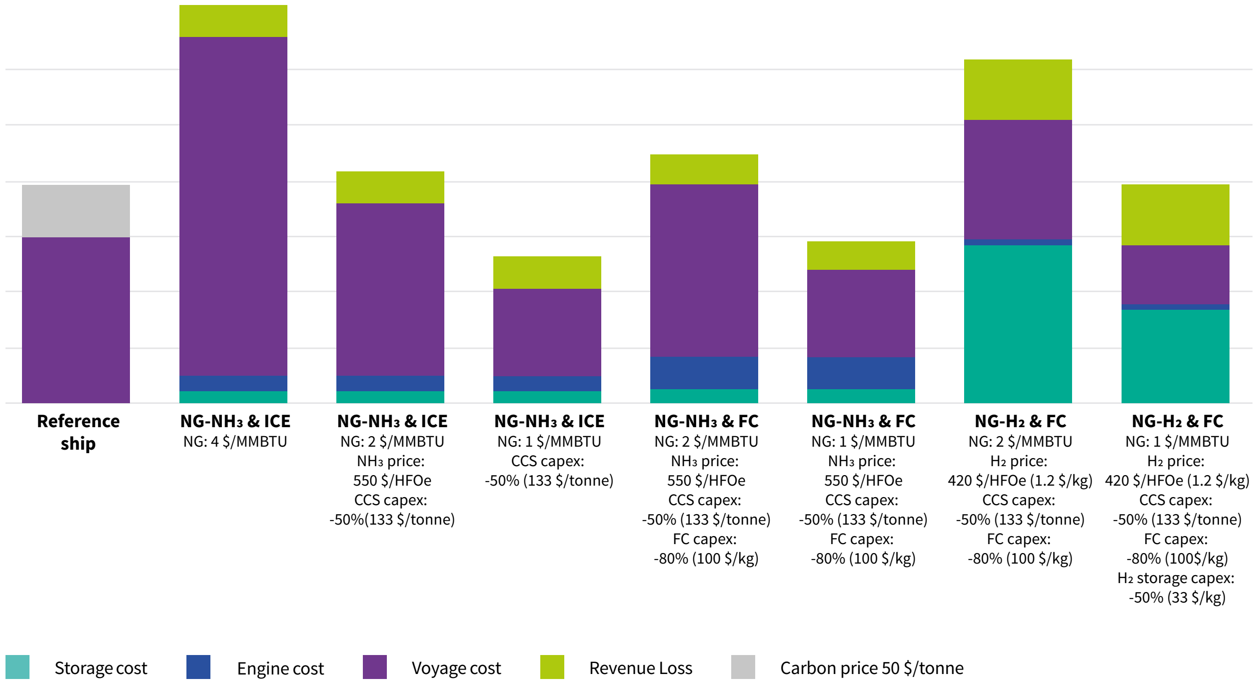

Figure 15 - Relative competitiveness of ZEV using NG-based fuels for a medium-size bulk carrier

Conclusions.

All pathways will achieve the IMO's level of ambition of at least 50% reduction in GHGs by 2050 and go beyond to show that zero is possible. They all lead to a mix of fuels but with different dominant fuels. Although it is difficult at this stage to decide on one route, fuel or technology, there is a need to better understand what the interactions are over time between the applications on board ships and the production and supply in order to take early action.

Shipping's decarbonisation is now a reality."

Nishatabbas Rehmatulla
Principal Consultant, UMAS

"Shipping's decarbonisation is now a reality. In April 2018, the shipping industry became the first international sector to have committed a sector wide GHG target of reducing emissions by 'at least' 50% by 2050 on 2008 levels. Shipping is now faced with a rapidly evolving landscape to which firms need to adapt. This rapid evolution is only likely to continue as we witness more fundamental threats of climate change, political alignment on decarbonisation and increasing awareness amongst shipping's stakeholders, final consumers, charterers and financiers. This work provides important evidence of the commercial viability of technological solutions to achieve decarbonisation in light of these external influences, which often act as enablers but also as barriers to this aim."

Shane Balani
Surveyor on Development, LR

"Identifying the fuel of the future that will power ships sustainably is a difficult task fraught with risk and no easy answers. This work embodies a crucial step in this process, whereby we explore the complex and numerous routes to producing, supplying and using different fuels to ships, and the associated costs and emissions of doing so. It highlights the fact that a detailed and holistic approach is required to be certain that we are pursuing a reality with the best possible solution."

The next decade up to 2030

Zero-carbon fuel production and supply needs to clarify rapidly and suppliers must demonstrate emissions and sustainability credentials. Uncertainty around which fuel might be available, in what quantities, at what price and their sustainability credentials, risks delaying important critical path decisions and investments in the world's fleet and infrastructure.

All pathways show a strong link between how the fuel production and supply evolves and which fuel shipping will use. Zero-carbon fuel producers need to start entering the marine market in the early 2020s and grow in scale throughout the decade. By 2030 technology readiness and costs (e.g. electrolysis and CCS), which ultimately affects the price of the end-fuel, will need to lead to zero-carbon fuels being competitive against the conventional marine fossil fuels as the price of fuels is a major driver for the economic case of a ZEV.

Zero-carbon fuel producers will need to prove that zero-carbon fuels have close-to-zero operational and upstream GHG emissions. This may have several implications:

- LNG suppliers would shift from promoting LNG as an end fuel to natural gas as a source for producing ammonia and hydrogen with CCS
- Biofuels producers will need to prove that the ways these fuels are produced and supplied to the ships have the potential to bring real benefits in terms of emissions reduction, whilst simultaneously ensuring all the sustainability issues and risks have been addressed
- Electro-fuels producers, will need to prove that the electricity required to produce these fuels is rapidly approaching zero-carbon

This decade would likely be characterised by a significant change within the energy supply markets with many zero-carbon fuels producers demonstrating the potential superiority of one fuel over the other. Besides the upstream emissions and sustainability credentials, a fuel's potential availability will be another fundamental driver. This is associated with the limits on the capacity of the energy feedstock source. This is currently an uncertainty, and fuel producers would need to demonstrate both the feasibility of the infrastructure development required up to 2030 and the potential for growth up to 2050 in line with an increasing shipping energy demand. For example, the **bio-energy dominates** pathway relies on access to cheap sustainable biofuels and on the assumption that to meet just the shipping energy demand, an area as large as the size of India is dedicated to biomass cultivation by 2030 and that this has the potential for growth up to 2050 to an area as large as twice the size of Australia, for 1st and 2nd generation biofuels.

In the next decade, the shipping sector has an important role to play in working collaboratively with the energy suppliers to clarify their requirements and send clear signals from the different segments within shipping for these zero-carbon for which shipping will need to secure supply.

Zero-emission vessels development needs full-scale prototypes and pilot studies now, exploiting any available opportunities that can enable early adoption

This decade will be characterised by prototypes of ZEVs and deployment in niche areas. **The decade 2020 – 2030 is the most significant decade** in terms of research and development with the following decades based on scaling and commercialisation. Therefore this **stresses the urgency for action now.**

There are a number of aspects to consider such as the safety, the storage and associated space requirements, and the specific fuel consumption (which takes into account the energy content of the fuel and the efficiency of the main machinery) in transitioning to ZEVs. Zero-carbon fuels may have new technologies associated with their use and, depending on the level of readiness and how future development evolves, these will have a certain cost attached. Prototypes and pilot projects are essential for enabling a better understanding of what these costs are, so commercial competitiveness of the different options can be more accurately calculated and help identify ways in which these costs could be further reduced.

In this decade, easy to store zero-carbon fuels may be more attractive whilst waiting for further technology development on the more complex to store zero-carbon fuels. In this respect, ammonia and methanol have an advantage when compared to hydrogen, especially when the revenue lost

Continued on next page...

Colin Robertshaw
Consultant and Doctoral Researcher, UMAS

"Through consideration of the respective production processes there exists the potential to expand the range of alternative fuels that may be considered as compatible with decarbonisation of the maritime industry. In this way a number of alternatives that would otherwise be discounted, due to their emission characteristics as fossil-fuels, may be reconsidered in the form of biomass and renewable energy derived variants (i.e. bio- and electro-fuels)."

Domagoj Baresic
Consultant and Doctoral Researcher, UMAS

"Through history, shipping faced countless challenges and solved many of them with technology, whether this meant gradual improvements, breakthroughs or at times a radical break with the past. The great challenge of our time is climate change and it is inevitable that technology will play a defining role in addressing it. This study aims to explore the possibilities of how technological solutions can be used to create a foundation for a zero-emission shipping industry. The future will likely include a complex set of gradual and radical solutions, with some still in development and this study has highlighted several paths towards a sustainable future."

due to the storage space requirements are significantly high and the voyage costs are relatively low. In other words, if the cargo space is of high value it may be more cost effective to pay for a more expensive fuel and bunker more frequently to reduce the overall cost. On the other hand, fuels that can be used in an internal combustion engine with minor modifications, may offer a better trade-off, to begin with, in terms of costs and efficiency than fuels used with fuel cells.

Biofuel use in the short-term must not hinder efforts on electro-fuels.

Biofuels offer the opportunity for the shipping sector to re-use existing infrastructure and main machinery and can enable a gradual transition through increasing blends, allowing a less disruptive route for shipping over the decades. However, reliance on them in the short-term could undermine the further development of the likely more long-term resilient solutions such as electro-fuels. If biofuels play a short-term role, this must not hinder investment into research, development and deployment (RD&D), prototypes and pilots of electro-fuels.

Batteries may not be the energy storage solution for deep-sea shipping, but they still have an important role.

In all pathways, batteries play a minor role as they are deemed only suitable for small ships and short distances due to limitations with regards to the high cost and relatively low energy volumetric densities when compared to other zero-carbon options. The role that batteries plays in the shorter term (2020s) to enable a transition and gradually phase out the use of fossil fuels should not be under-estimated, whilst other technologies for zero-emission vessels are developing. In fact, batteries will be very important during this decade in hybrid solutions and for onshore power connections whilst in port.

It's not just about technology and fuels development, a lot of work is needed on the development of policy, the public sphere, standards and rules.

Other important developments are expected to happen in this decade. This includes the policy development, the public sphere influence and the development of international standards and rules.

The progress with GHG policy is very important because shipping policies entering this decade, in order to help enable cost-effective decarbonisation of shipping, are likely to have a very significant impact on the sector. The role of enabling policy in all potential transition pathways is strong, including policy to stimulate RD&D, prototypes and pilots in the early 2020s, followed by command and control regulations in various combinations with economic instruments. These may become more stringent over time to help provide a level-playing field and close the competitiveness gap with conventional fossil fuels and technology and increase the uptake of ZEVs.

The public sphere is also very important because first adopters are likely to be driven by an expected increase in consumer pressure in the sectors to which they are most directly linked, e.g. cruise, RoPax and container shipping sectors. Some of these ship types are associated with liner routes, shorter distances and scheduled itineraries, which will enable technology to be proven and tested in the 2020s before scaling to deep-sea international sectors such as dry and wet bulk sectors. The importance of the role of ports and national administrations in providing incentives in the short-term, and as the priority to reduce GHG emissions increases over time, the development of infrastructure for zero-carbon fuels will be scaled based on the learnings from the first adopters' joint industry projects.

All the potential transition pathways rely on the quick development, by the 2020s, of the international standards and rules that address the safety aspects of all zero-carbon fuels and their associated technologies as a major milestone to enable shipping's decarbonisation transition.

The 2030s

Scaling up the zero-carbon fuels production relies on clarity on the direction taken in the wider energy system.

Estimating what will happen in this decade is critical for evaluations of the likelihood of the three pathways. A clear signal from the evolution of the energy system (going towards a massive electrification or pointing towards bio-energy) would influence the marine fuel producers' strategies. By meeting the expected fuel prices threshold and the expectations on upstream emissions reduction and energy capacity set in the previous decade, a family of fuels would gradually dominate the fuel mix.

For example, the **renewables dominate** pathway relies on the access to very cheap renewable electricity and a significant reduction in capex for technologies to facilitate the fuel production and the deployment of ZEVs using electro-fuels. If bio-based fuels fail to prove their availability and sustainability and natural gas with CCS demonstrates limited competitiveness or viability, as other sectors decarbonise then electro-fuels may dominate the shipping fuel mix. In this context, hydrogen could play a crucial role for the decarbonisation of the shipping sector either as final fuel or as input source for other zero-carbon fuels. Finding overlaps with other sectors' needs of supply chains, storage and demand management requirements will be increasingly important to ensure the cost-effective scaling of the supply and infrastructure for shipping.

Fuels derived from fossil-fuels with CCS may not dominate the marine fuel mix due to their limited expected competitiveness and availability, as other sectors decarbonise in line with the Paris Agreement and therefore could have a smaller role to play in shipping's transition and gradually be phased out in time. However, an alternative to this scenario would be the equal mix pathway, in which the uncertainty on energy source and zero-carbon fuels production persist and fuel produced from fossil-fuels with CCS will have the same share of other zero-carbon fuels.

Zero-emission vessels deployment sees a consolidated set of technologies, fuel cells hold great promise as part of that consolidation.

The 2030s will be characterised by the consolidation of dominant technologies on board. To enable this consolidation, research and development undertaken in the previous decade becomes very important.

The interactions between the various ZEV options in terms of price, revenue loss and machinery costs will by now have been better understood and determined. For example, the scaling up of fuel cells in terms of their power requirement and any specific maritime requirements could lead to full-scale deployment of this technology. Fuel cell technologies and hydrogen storage systems may experience dramatic capex reduction improving the competitiveness of the ZEVs using fuel cells and in combination with hydrogen. If these technologies meet the expected thresholds of price and performance, it is likely that ZEVs using them would have a clear advantage.

Technology development especially in terms of storage can make direct use of hydrogen as a fuel more competitive relative to other options. But in some cases, the revenue loss is so high that it doesn't matter how much storage space can be reduced and what the machinery costs are, because hydrogen is always less competitive when compared to e-NH_3 and e-methanol.

Electro-fuels such as hydrogen, ammonia and methanol are less dense energy fuels, requiring ships using them to hold greater quantities on board. Therefore, ships running on these fuels may require a fundamental change to their operating profile and gradually through this decade ships would be designed to store less energy on board and bunker more frequently accordingly with the growing availability of these fuels.

LNG assets will need to find ways to be competitive in the emerging landscape.

Ships using LNG as fuel will need to consider a transition towards bio-LNG, e-methane or blending LNG with electro-fuels like hydrogen to help continuously reduce the fuel's carbon content. These pathways for decarbonising LNG will likely put shipping users of LNG in competition with other market sectors such as heating for these fuel options, which will be particularly important for fuels with expected constraints on supply such as bio-LNG. The shipping transition to zero-carbon may be more suited to liquid biofuels and liquid electro-fuels as existing oil infrastructure can be re-used.

The end game up to 2050, which pathway are we likely to be on?

The likelihood of the three transition pathways out to 2050 is very difficult to assess, and there could be a possibility that over the decades until 2050 we may experience more than one dramatic fuel switch; for example, a growing share for biofuels during the 2020s and major shift towards electro-fuels later in the 2030s and 2040s. In any of the cases, during the decade from 2040 to 2050, there would be a consolidation of the markets whether it will be a fuel mix dominated by electro-fuels, biofuels, or whether it will be an equal mix, with different dominant fuels along different routes.

Jean-Marc Bonello
Consultant and Doctoral Researcher, UMAS

"The future of shipping and prosperity of global trade is inextricably linked to a departure from a fossil fuel-based status quo. The insight provided by this study elucidates possible options for leaders in the industry to take back to their boardrooms and be empowered to act in the short term to achieve long-term decarbonisation."

Isabelle Rojon
Consultant, UMAS

"The recent IPCC Special Report on 1.5°C tells us that in order to limit global warming to 1.5°C, global CO_2 emissions need to be reduced to net zero by 2050, which will require rapid, far-reaching and unprecedented transitions in all aspects of society – including in the shipping industry. This study has allowed us to examine in a holistic manner the zero-emissions solutions available, as well as the changes that we need to make happen for the shipping industry to transition to a low- or zero-carbon system."

2020s (present to 2029)

COMMON TO ALL
RENEWABLES
BIO-ENERGY
EQUAL MIX

2030s (2030 to 2039)

COMMON TO ALL
RENEWABLES
BIO-ENERGY
EQUAL MIX

2040s (2040 to 2050)

COMMON TO ALL
RENEWABLES
BIO-ENERGY
EQUAL MIX

ACTORS

- Actors continue pushing for their respective ZEV fuel options in isolation, creating competition between them
- Due to global shift to renewable and bio-energy, fossil fuel actors see maritime as one of the last remaining markets and promote natural gas-based fuels

MARKET FACTORS

- NG-NH_3 becomes completely replaced with NG & CCS NH_3 due to the growth in GHG concerns
- Assuming no major change in production methods, e-methanol and bio-methanol co-exist and do not compete, but more with bio and e-gasoils
- Blends of NH_3 and H_2 in different configurations with fossil fuels persist in certain segments of industry

NON-MARKET AND ENVIRONMENTAL FACTORS

- E-NH_3 and NG-NH_3 co-exist due to separate yet complementary environmental benefits
- E-NH_3 is an environmental niche for cruise and RoPax industries; only applicable for larger RoPax vessels (cargo capacity losses)
- Growing environmental concerns limit benefits of e-methanol and e-gasoil due to relatively high GHG emissions and NOx emission

LANDSCAPE AND EXTERNAL FACTORS

- Electro and NG-NH_3 both co-exist due to separate yet complementary environmental benefits
- In 2049/2050, fossil fuels with CCS energy reaches approximately 100 EJ

SUPPLY AND BUNKERING INFRASTRUCTURE

- Bio and electro-fuels supplement NH_3 in certain segments (regional, and vessel types) and co-exist side by side
- Growth and spread of CCS technologies
- NG & CCS remains profitable due to limited spread and development of RE capacities

PROPULSION

- Growth in e-gasoil is counteracted by the relatively high voyage costs associated with the fuel compared to NH_3/H_2 and additional costs from additional technological measures to reduce higher NOx emissions
- As crude oil segments continue decreasing, and with growing spread of NH_3/H_2 bunkering in combination with increasing environmental standards, biofuels are losing ground
- Only where biofuels are large part of blend (particularly bio-methanol) can biofuels compete, with limited supply due to maximum potential production
- Biofuel is used in certain RoPax and cruise segments where capacity losses from NH_3 and H_2 would be expected (not able to increase bunkering frequency)
- Crude oil tankers take up more NH_3, but the industry by this point is a small niche segment of the shipping industry
- Cruise and RoPax more diversified due to cargo capacity losses if long voyages without bunkering for NH_3
- Biofuels/electro-fuel blends (electro-fuels minor part of blends become specialised fuels for certain segments of cruise and RoPax industry, with limited usage outside)
- Spread globally due to well-developed expert network from biofuel producers

DEFINITIONS

Actors
Includes all principal stakeholders involved in the development of ZEV options and feedstocks (shipowners, operators, energy companies, policy-makers, politicians, NGOs, IGOs, national and sub-national institutions).

Policies and institutions
Includes regulations, standards, international agreements and associated organisations with jurisdiction over ZEV and feedstock development (national, regional, multinational, EU, UN and IMO).

Market factors
Includes all commodity developments related to feedstocks (prices, supply/demand, trends), ZEV internal market developments (prices, supply/demand) and any associated market trends.

Non-market and environmental factors
Includes all environmental concerns/benefits (SOx, NOx, GHG, PM emissions, etc.) associated with various ZEV options in the context of their likely transition pathway development.

Landscape and external factors
Includes any additional macro-economic, political, socio-cultural or other developments outside of the maritime industry or principal energy feedstocks that could affect the future transition/development of ZEV options and respective feedstocks.

Supply and bunkering infrastructure
Includes any technical and cost-developments associated with the construction, upkeep and evolution of supply and bunkering infrastructure for the ZEV options. This includes costs of infrastructure, with reference to market factors, policies, etc. but not discussing these in detail (as they are covered in their respective categories).

Propulsion
Includes any technical, storage-size and cost-developments associated with the construction, upkeep and evolution of ZEV vessels, with a specific focus on on board infrastructure. Any reference to other developments (which are not on board) is done only in order to support the narrative of on board infrastructure development.

Acronyms.

BEP - Break-Even Point

Capex - Capital Expenditure

CCS - Carbon Capture and Storage

CO_2 - Carbon Dioxide

ECA - Emissions Control Area

EJ - Exajoule

FAME - Fatty Acid Methyl Ester

FC - Fuel Cell

GHG - Greenhouse Gases

H_2 - Hydrogen

HFO - Heavy Fuel Oil

HFOe - Heavy Fuel Oil Equivalent

ICE - Internal Combustion Engine

IGF - International Code of Safety for Ship Using Gases or Other Low-Flashpoint Fuels

IGO - Inter-Governmental Organisation

IMO - International Maritime Organization

IPCC - Intergovernmental Panel on Climate Change

ISO - International Standards Organization

Kg - Kilogram

kW - Kilowatt

LFL - Lower Flammability Limit

LNG - Liquefied Natural Gas

LSHFO - Low Sulphur Heavy Fuel Oil

MDO - Marine Diesel Oil

MMBTU - Million British Thermal Unit

MWh - Mega Watt Hour

NECA - NOx Emission Control Area

NG - Natural Gas

NGO - Non-Governmental Organisation

NH_3 - Ammonia

NOx - Nitrogen Oxides

PM - Particulate Matter

OEM - Original Equipment Manufacturers

RD&D - Research, Development & Deployment

RE - Renewable Electricity

SECA - SOx Emission Control Area

SOx - Sulphur Oxides

SMR - Steam Methane Reformation

TEU - Twenty-Foot Equivalent Unit

UN - United Nations

ZEV - Zero-Emission Vessels

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info.lr.org

www.u-mas.co.uk

info.lr.org/ZEV-transition-pathways

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