MISSION POSSIBLE

REACHING NET-ZERO CARBON EMISSIONS FROM HARDER-TO-ABATE SECTORS BY MID-CENTURY

ENERGY TRANSITIONS COMMISSION

SECTORAL FOCUS

SHIPPING

The **Energy Transitions Commission (ETC)** brings together a diverse group of leaders from across the energy landscape: energy producers, energy users, equipment suppliers, investors, non-profit organizations and academics from the developed and developing world. Our aim is to accelerate change towards low-carbon energy systems that enable robust economic development and limit the rise in global temperature to well below 2˚C and as close as possible to 1.5˚C.

In November 2018, the ETC published ***Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century***. This flagship report is available on our website. This report describes in turn:

- Why reaching net-zero CO_2 emissions across heavy industry and heavy-duty transport sectors is technically and economically feasible;
- How to manage the transition to net-zero CO_2 emissions in those harder-to-abate sectors of the economy;
- What the implications of a full decarbonization of the economy are for the energy system as a whole, in particular in terms of demand for electricity, hydrogen, bioenergy/bio-feedstock, and fossil fuels, as well as carbon storage requirements;
- What policymakers, investors, businesses and consumers must do to accelerate change.

This Sectoral Focus presents in more details the underlying analysis on shipping decarbonization that fed into the ETC's integrated report *Mission Possible*. It constitutes an updated version of the consultation paper with the same title published by the ETC in July 2018.

We warmly thank all experts from companies, industry initiatives, international organizations, non-governmental organizations and academia, who have provided feedback on this consultation paper. Their insights were instrumental in shaping the *Mission Possible* report and this updated Sectoral Focus.

The *Mission Possible* report and the related Sectoral Focuses constitute **a collective view of the Energy Transitions Commission**. Members of the ETC endorse the general thrust of the arguments made in this report but should not be taken as agreeing with every finding or recommendation. The institutions with which the Commissioners are affiliated have not been asked to formally endorse the report. The list of our Commissioners at the time of publication can be found in the *Mission Possible* report.

In 2019, the Energy Transitions Commission will continue to engage actively and work with key policymakers, investors and business leaders around the world, using our analysis and the unique voice of the ETC to inform decision-making and encourage rapid progress on the decarbonization of the harder-to-abate sectors. We are keen to exchange and partner with those organizations who would like to progress this agenda. Please contact us at info@energy-transitions.org.

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REACHING NET-ZERO CARBON EMISSIONS FROM SHIPPING

Emissions from shipping currently amount to circa 0.9Gt CO_2 accounting for almost 3% of total global emissions, but, under a business as usual scenario, they could grow to almost 1.7Gt by 2050[1]. **Demand for shipping is indeed expected to keep increasing with global economic growth**, although some new economic trends, like the return of some industrial activities to developed economies or the expected decrease in international shipping of coal, oil and gas as the economic systems are decarbonized, might alter this upward trend.

Shipping appears to be the most difficult transport mode to decarbonize, because of the high cost of low-carbon technologies – estimated cost per tonne of abated CO_2 between US$150 and US$350 – and of the transition challenges created by long asset replacement cycles and by the fragmented and international nature of the industry.

In the long term, **ammonia** used either in internal combustion engines or in fuel cells is likely to be the most cost-effective zero-carbon fuel option, especially for long distances, while some short-haul segments of the fleet could switch to electric motors (combined with batteries or hydrogen fuel cells). However, these technologies are unlikely to scale up before the 2030s-2040s, which might call for a range of transitional measures enabling some short-term emissions reduction.

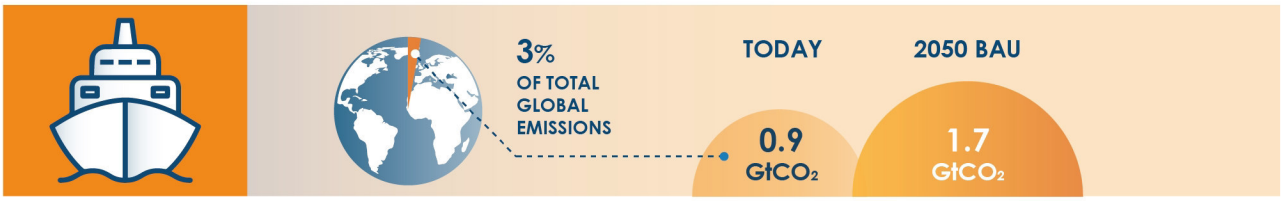
SUPPORTING ANALYSIS

The Energy Transitions Commission work on shipping has drawn extensively on the existing literature (cited throughout this document). Original analysis was developed in partnership with our knowledge partner **University Maritime Advisory Services**, building on their model of technology pathways and cost scenarios for the decarbonization of shipping. This document solely reflects the views of the Energy Transitions Commission.

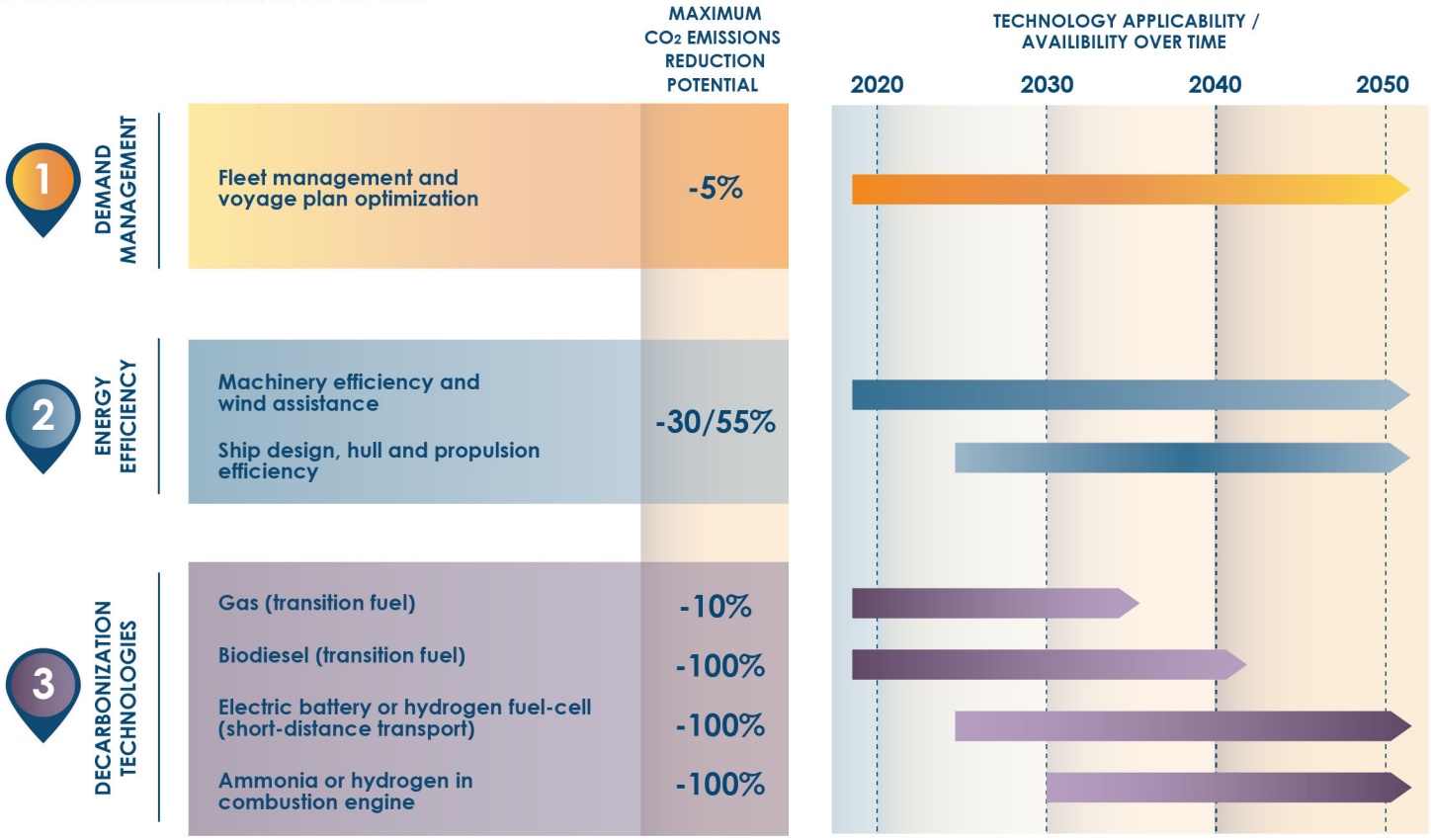
[1] International Energy Agency (2017), *Energy Technology Perspectives*

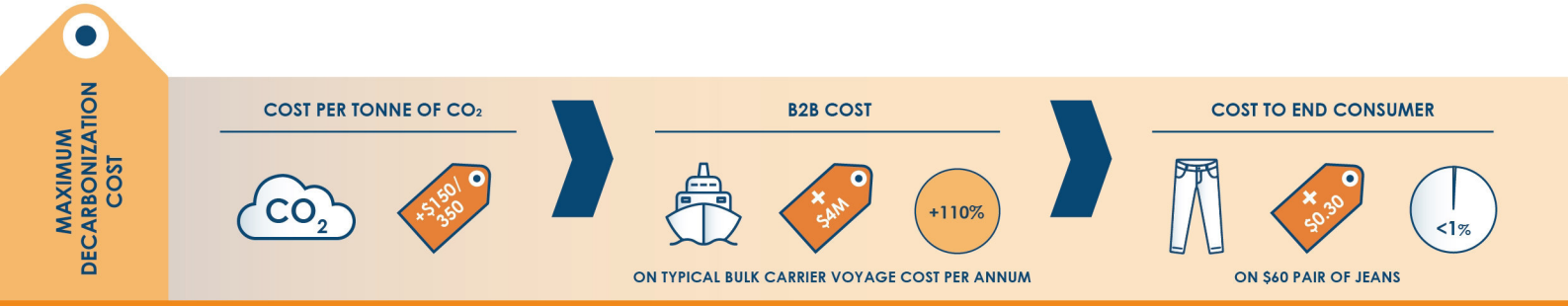
ENERGY TRANSITIONS COMMISSION

HOW TO REACH NET-ZERO CO_2 EMISSIONS FROM SHIPPING



REACHING NET-ZERO CO_2 EMISSIONS FROM SHIPPING IS POSSIBLE BY COMBINING 3 MAJOR DECARBONIZATION ROUTES:





TOP 3 ACTIONS TO ACCELERATE THE TRANSITION FOR...

INNOVATION

- Improve energy efficiency of ship, equipment and design
- Reduce the cost of green ammonia (by reducing the cost of electrolysis)
- Reduce the cost and grow the supply of biofuels produced from truly sustainable biomass

POLICY

- IMO: develop a detailed international roadmap to reach zero CO_2 emissions by mid-century
- IMO: tighten the Energy Efficiency Design standards for new built ships, and set Operational Efficiency standards for the existing fleet
- IMO or coalition of governments: enforce a carbon tax on HFO and/or a "green fuel" mandate

INDUSTRY/BUSINESSES

- Ship owners: invest in available energy efficiency technologies and in R&D and early deployment of decarbonization technologies
- Ports: Develop supply of low-carbon fuels and adapted fuel storage for hydrogen or ammonia
- Global logistics companies: commit to increasingly tight carbon intensity targets for freight transport

1. OVERVIEW OF THE CHALLENGE

A. DEMAND TRENDS BY MID-CENTURY

Shipping traffic has grown continuously over the last several decades and this trend is likely to continue in future, with **international freight strongly correlated with economic growth**. Overall world seaborne trade has grown in volume at a 3% annual growth rate since the 1970s[2], with the majority of that growth coming from international merchandise trade. Projections for total freight volumes, measured in tonne-miles, suggest a possible global growth of +240% by 2050 (which represents a 3.4% average annual growth rate)[3] [Exhibit 1].

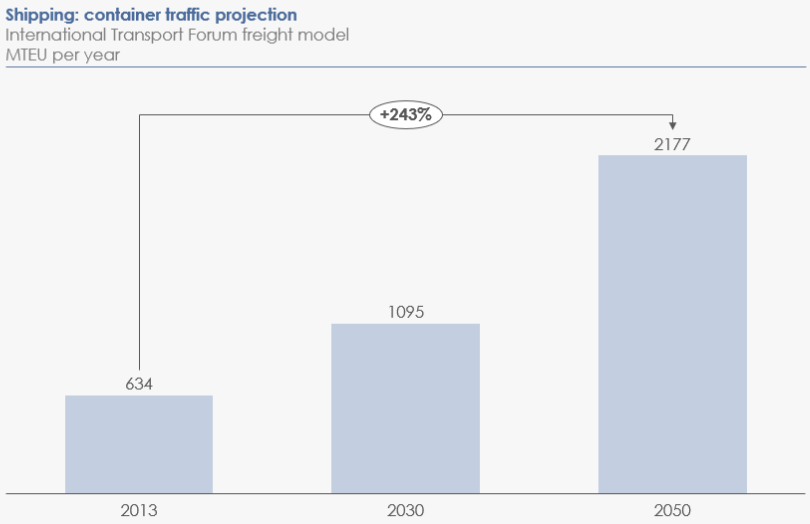
Passenger ship traffic represents less than 10% of emissions today, but the cruise industry is the fastest growing segment of the industry with 6-7% annual growth rates in the 1990-2020 period, driven by larger capacity new builds and ship diversification (e.g. luxury ships, hotel ships, river ships)[4].

We consider in this paper 5 segments of shipping, which together account for 66% of the global merchants ships number and 95% of global tonnage:

- **Bulk carrier**, which transport loose cargo i.e. without any specific packaging to it and generally contains items like food grains, ores and coals or cement. They represent 32% of all ships number and 40% of the global tonnage;
- **Containership**, which carry all of their load in truck-size intermodal containers. They represent 6% of all ships number and 18% of the global tonnage;
- **Tanker**, which are designed to carry bulk liquids (most predominantly chemicals, oil and LNG). They represent 18% of all ships number and 30% of the global tonnage;
- **Cruise ships**, passenger ships designed for pleasure voyages, represent 2% of all merchants ships and 4% of the global tonnage;
- The acronym **RoPax** (roll-on/roll-off passenger) describes a vessel built for freight vehicle transport along with passenger accommodation, e.g. ferries. They represent 8% of all merchants ships and 3% of the global tonnage.

[2] UNCTAD (2017), *Review of maritime transport*
[3] DNV GL (2017), *Maritime forecast to 2050*
[4] Cruise market watch (2017)

Shipping traffic is expected to increase significantly in the next 30 years



Source: IFT (2017), *IFT Transport Outlook 2017*

Exhibit 1

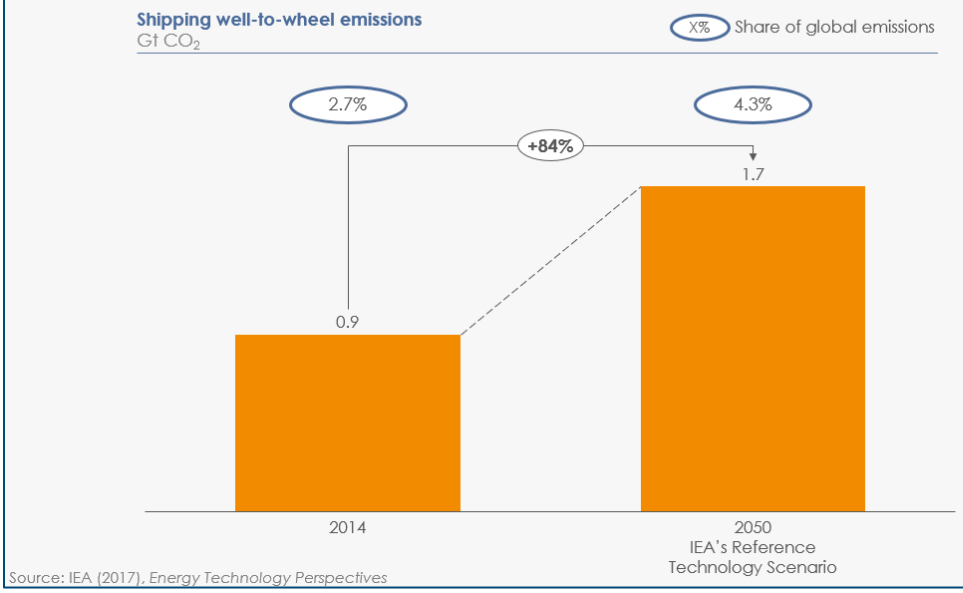
B. CARBON EMISSIONS – AND OTHER ENVIRONMENTAL IMPACTS

Today, **the global shipping sector emits 0.9Gt CO_2**, which is about 11% of total transport sector emissions and 2.8% of total global emissions from the energy and industrial systems. Under a business as usual scenario, these CO_2 emissions could almost double and reach 1.7Gt by 2040[5] [Exhibit 2]. **The vast majority of the emissions derive from international freight traffic** (87%). Containerships, bulk carriers, and oil, gas and chemical tankers account for 85% of total emissions [Exhibit 3].

Non-CO_2 emissions are also a major issue for the shipping industry. Fuel combustion emits SO_2 and NO_X, which, through chemical reactions in the air, are converted into fine particles, sulphate and nitrite aerosols. Along with black carbon (soot), these increase the health impacts of shipping pollution. Estimates suggest that ships are responsible for 15% of global NO_X and 8% of global sulphur gas emissions[6].

[5] IEA (2017), *Energy Technology Perspectives*
[6] IMO (2014), *Third IMO study GHG study 2014*

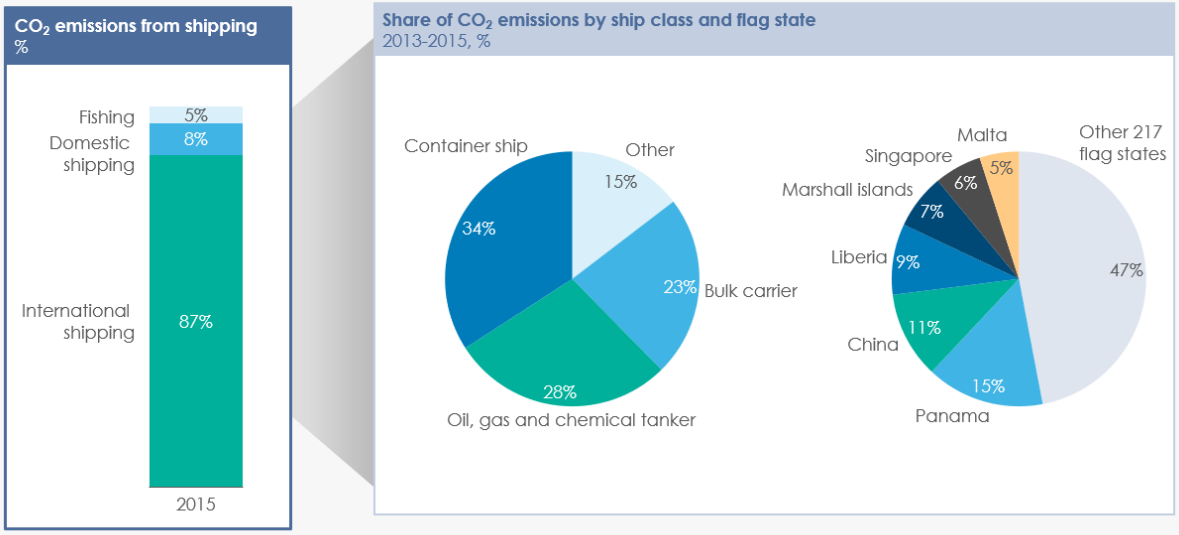
Carbon emissions from shipping could increase by 84% by 2050 in a business-as-usual scenario



Source: IEA (2017), *Energy Technology Perspectives*

Exhibit 2

Container ships, bulk carriers and tankers represent 85% of the emissions from shipping



Source: ICCT (2017), *Greenhouse gas emissions from global shipping, 2013–2015*; IMO (2014), *Third IMO GHG Study 2014*

Exhibit 3

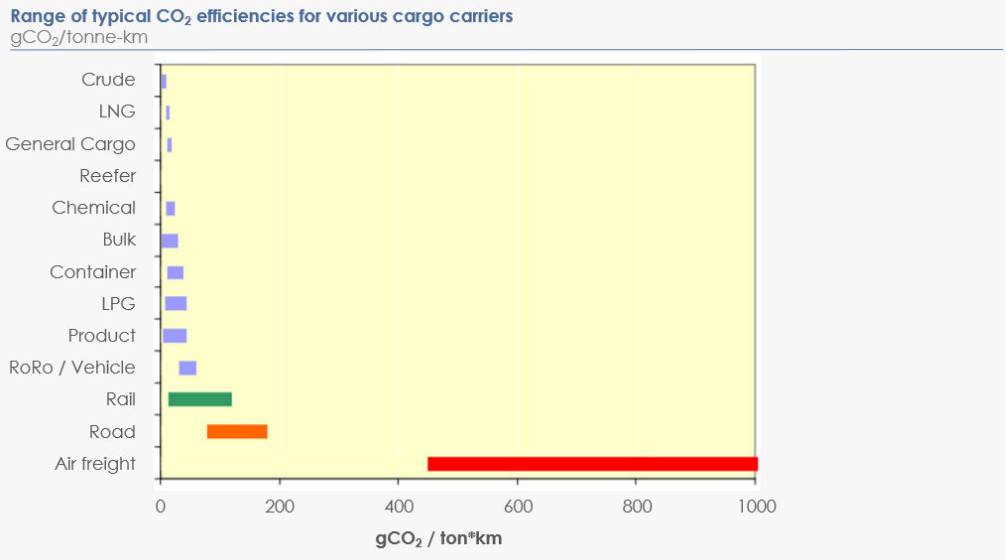
2. REDUCING CO_2 EMISSIONS BY CURBING TRAFFIC VOLUMES

Opportunities to curb demand growth are more limited in the transport sector compared to the industrial sector. Economic development drives higher demand for services which sustain good standards of living: freight transport is driven by global economic growth and passenger transport by higher mobility demand in emerging economies. This is also true in heavy industry, but demand for raw materials can be mitigated by reducing the amount of materials required to offer the same level of services – e.g. reducing the amount of virgin steel required to build a house – whereas it is more difficult to apply that same logic to cut demand for mobility services.

Moreover, as **shipping is already one of the lowest-emitting freight transport mode by tonne-kilometer** [Exhibit 4], opportunities for modal shift to lower-emission modes are more limited than, for instance, in aviation. A significant shift of China-to-Europe trade from ship to rail might be possible, potentially reducing costs, carbon emissions and time to supply. This would, however, require a major rail infrastructure build-up and similar shifts are unlikely to be feasible for other major international trade routes, where there is no land corridor. It is also possible that in some specific circumstances, short-distance shipping might be less energy-efficient than land-based transportation and considerably more polluting in terms of NO_X and SO_X emissions. Our judgement is that, in total, **these opportunities for modal shift cannot have more than a marginal impact on total demand**.

In parallel, **operational efficiency improvement**, in particular improvements in fleet management, better optimization of voyages, and an optimal approach to ship speed, could enable a 5% reduction in carbon emissions within the fleets adopting these different measures. If applied to 75% of the global shipping traffic, it **would only trigger a 4% reduction in carbon emissions for the sector as a whole** [Exhibit 5][7].

Shipping is the freight traffic mode with the lowest emissions per tonne-km

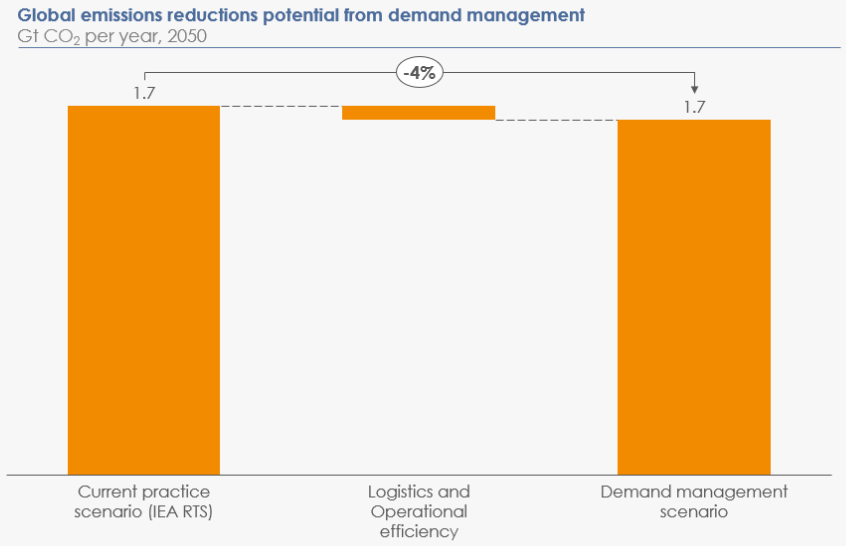


Source: IMO(2009), *Second IMO GHG Study 2009*

Exhibit 4

[7] SYSTEMIQ analysis for the Energy Transitions Commission (2018), based on expert interviews

Demand management can cut emissions from shipping by 4% by 2050



Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 5

Shipping demand is therefore very unlikely to be reduced through climate-related policies and initiatives. However, **it may turn out to be below current forecasts** as a result of some possible economic trends:

- Some manufacturing activity may return to developed economies as the potential for radical automation reduces the importance of low-cost labor, which could reduce international container trade.
- Eventually, falling global demand for coal, oil and gas will cut international trade in those commodities (which currently represent more than a quarter of total carbon emissions from shipping).

These trends may, moreover, be accelerated by the increase in freight cost which will inevitably result from effective measures to achieve supply-side decarbonization as described in Section 4.

By contrast, the required transition to a low-carbon and eventually zero-carbon economy may create **some new demands for shipping capacity**. In particular, it is possible that there will be massively expanded international trade in hydrogen and ammonia, as use of these fuels scales up and production costs in locations with favorable renewable energy resources come down.

Given those different trends, **global shipping volumes are very likely to continue rising**. Shipping decarbonization must therefore be achieved primarily via a reduction in carbon emissions per tonne-mile.

3. IMPROVING ENERGY EFFICIENCY

While shipping compares favorably to other transport modes in terms of energy input per tonne-kilometer, there is still very significant **potential to increase the energy efficiency of existing ships and engines** even while continuing to use existing HFO-based propulsion. Strong policy action and/or coordinated shipping industry initiatives will however be required to achieve a material proportion of these theoretically available improvements.

Research suggest that **new ship design** should focus on improving hull shapes and materials, building larger ships, achieving drag reductions (reducing frictions between ship and water) and hotel-load savings (on non-propulsion energy requirements). Estimates suggest that, together with incremental improvements in the efficiency of existing engines and propulsion systems, these improvements could in principle deliver overall energy efficiency improvements of 30 to 55% for new built ships compared to the existing fleet[8]. In addition, wind-sail assistance technologies could also very significantly reduce fuel use.

Some of these technologies could be **retrofitted on the existing fleet** – widening of container vessels, improving shape to reduce wave resistance or optimizing propellers – which is particularly important given the long lifetime of ships. Overall retrofitting could improve the energy efficiency of the existing fleet by 15%[9].

But while the theoretical potential is clear, it is widely recognized that **the structure of the shipping industry makes it more difficult to drive towards optimal efficiency** than in, for instance, the aviation industry. In particular, the multiple different arrangements for the division of responsibility between ship owners and ship operators, the fragmented nature of regulation through the flagging system, and the significant role for short-term charter contracts, reduces the ability of and incentives for any one party to make efficiency-improving decisions and investments, even in situations where these could in principle deliver major cost reductions. The crucial issue in shipping, to a greater extent than in other sectors, is therefore not just what technical solutions are possible, but how to ensure that barriers to implementation are overcome. We address this issue in the recommendations section of this paper.

4. DECARBONIZING SHIPPING

Although there is very significant potential to improve the energy efficiency of shipping operations, achieving full decarbonization will necessarily require **a shift from heavy fuel oil (HFO) to alternative fuels or engines**. In the long run, ammonia used either in internal combustion engines or in fuel cells, is likely to be the most cost-effective zero-carbon fuel option, especially for long distances, while some short-haul segments of the fleet could switch to electric motors (combined with batteries or hydrogen fuel cells). Achieving full decarbonization is likely to cost US$150-300 per tonne of CO_2 saved, making shipping one of the most expensive sectors to decarbonize and adding significantly to total freight costs. This should, however, only have a limited impact on the cost of products shipped around the world.

[8] Rocky Mountain Institute (2005), *Winning the Oil Endgame*
[9] DNV GL (2015), *Retrofitting: Where the savings are*

A. DECARBONIZATION OPTIONS: TECHNICAL FEASIBILITY COMPARISON

To achieve full decarbonization, shipping will need to go beyond energy efficiency improvements and deploy zero-carbon fuel/engine technologies. The Energy Transitions Commission, in partnership with University Maritime Advisory Services, has investigated the technical feasibility and cost of a range of decarbonization options [Exhibit 6].

Technology options considered in the analysis

Technologies	Description of engine components	Description of storage components
• Electric	• Electric motor	• Battery
• Hybrid hydrogen	• Fuel cell system • Electric motor	• Battery • Hydrogen storage
• Hydrogen fuel cell	• Fuel cell system • Electric motor	• Hydrogen storage
• Hydrogen + ICE	• Dual ICE motor	• Hydrogen storage • "Emergency" HFO tank
• Ammonia fuel cell	• Fuel cell system • Electric motor	• Ammonia storage • Reformer
• Ammonia + ICE	• Dual ICE motor	• Ammonia storage • "Emergency" HFO tank
• Biofuel	• ICE motor	• Fuel tank as per HFO
• Bio-methanol	• ICE motor	• Methanol tank
• LNG	• ICE motor	• LNG storage

SOURCE: UMAS analysis ; Lloyds Register & UMAS (2017), *Zero-emission Vessels 2030*

Exhibit 6

Efficiency and volumetric characteristics of the ships

	Total energy efficiency, %		Energy density gravimetric, kWh/kg	Energy density volumetric, kWh/liter	Weight density, kg/liter
• Fuel ICE	49%	• 50% ICE EE • 98% fuel storage EE	11.25	10.46	0.93
• Electric	90%	• 95% electric motor EE • 95% battery EE	0.30	0.16	0.53
• Hydrogen fuel cell	40%	• 60% fuel cell EE • 70% H2 storage EE • 95% electric motor EE	33.33	2.00	0.06
• Hydrogen + ICE	35%	• 50% ICE EE • 70% H2 storage EE	33.33	2.00	0.06
• Ammonia fuel cell	47%	• 60% fuel cell EE • 98% storage EE • 85% reformer EE • 95% electric motor EE	5.22	3.75	0.72
• Ammonia + ICE	49%	• 50% ICE EE • 98% fuel storage EE	5.22	3.75	0.72
• Biofuel	49%	• 50% ICE EE • 98% fuel storage EE	6.67	5.87	0.88
• Bio-methanol	49%	• 50% ICE EE • 98% fuel storage EE	5.58	4.91	0.88
• LNG	40%	• 50% LNG engine EE • 80% LNG storage EE	15.30	6.43	0.42

SOURCE: UMAS analysis ; Lloyds Register & UMAS (2017), *Zero-emission Vessels 2030*; SYSTEMIQ analysis for the ETC

Exhibit 7

The options considered can be grouped into:

- **Electric engines** driven either by batteries or by hydrogen/ammonia fuel cells;
- The continued use of existing combustion engines, but with **hydrocarbon fuels which have lower lifecycle carbon emissions** – biofuels, bio-methanol or LNG;
- Continued use of existing ship engines, but with **fuels which are truly zero carbon emissions** at the point of use and can also be produced in a zero-carbon fashion – either hydrogen or ammonia.

Each of these options appears to be a technically feasible way to power a ship. Their relative attractiveness depends on (i) three technical factors described below – weight/volume characteristics of the energy source, total energy efficiency, and ability to use existing assets –, (ii) carbon-intensity (see subsection b), and (iii) cost (see subsection c).

Three technical factors are particularly crucial to determine most suitable decarbonization option for different types of ships and different travel ranges [Exhibit 7]:

- **Weight and volume characteristics:** The different energy sources which could be used have very different gravimetric and volumetric energy densities. Compared with HFO, hydrogen has a much higher energy per kilogram, but a much lower energy per liter. Batteries are seriously disadvantaged versus liquid hydrocarbons on both the weight and volume dimensions. Ammonia is less energy dense than fuel oil either per kilogram or per liter, but it is far less disadvantaged than batteries on either dimension, and almost twice as dense as hydrogen on a volume basis.
- **Total energy efficiency of the system:** Battery-driven electric ships would have a major advantage, with the combined efficiency of batteries and electric engines ensuring that 90% of the electricity input to the battery turns into propulsive power/kinetic energy driving the ship[10]. All other options involve much more significant energy losses, either because of the inherent thermodynamic inefficiency of any combustion engine or because of the energy losses involved in (i) pressurizing or liquefying hydrogen or natural gas, (ii) using fuel cells to turn hydrogen into electricity, (iii) using a reformer to turn ammonia into hydrogen.
- **Ability to use existing assets:** This is a particularly important consideration in an industry with very long asset replacement cycles. For instance, for dry bulk ships, depending on the size of the ships, average age of demolition varied between 20 and 30 years in 2016. Options that utilize existing engines therefore have a major advantage over the electric engine options, which require engine replacement and are more difficult to retrofit on the existing fleet.

Exhibits 8 to 10 show the implications of the combination of energy densities, total energy efficiencies, weight and volume characteristics for the **combined weight and volume of fuel storage plus engine systems** – presenting results for different types of ships and different travel ranges. The conclusions we draw from this analysis are that:

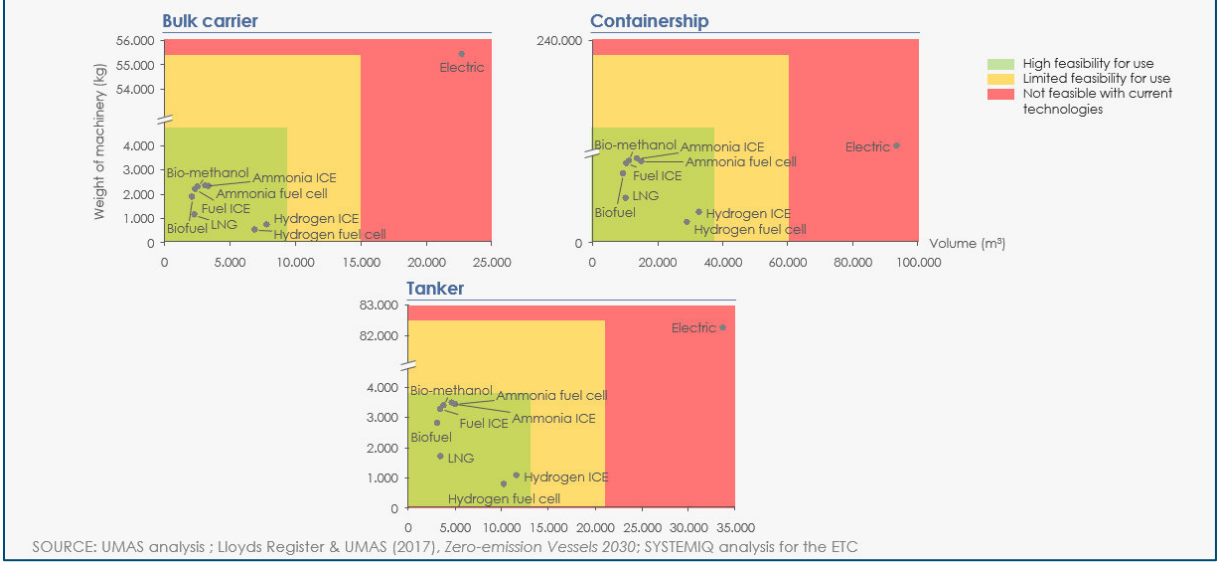
- Despite their potential energy efficiency advantage – and until and unless there is a major breakthrough in battery density on both gravimetric and volumetric basis – **battery electric ships are not feasible for long-distance freight, nor long-distance**

[10] Note: Our calculations on energy efficiency does not include any energy losses upstream in the production of hydrogen (from electrolysis) or of ammonia (from electrolysis plus Haber-Bosch synthesis), or indeed energy losses in the upstream production of fossil fuels.

cruising, but could be technically feasible for short-distance cruising and RoPax services.

- **All the other alternatives lie in a technically feasible range**, though the hydrogen options would involve a potentially significant sacrifice of cargo space which would have a material economic cost. The implications of this for total cost of operation are captured in the cost analysis in subsection C.

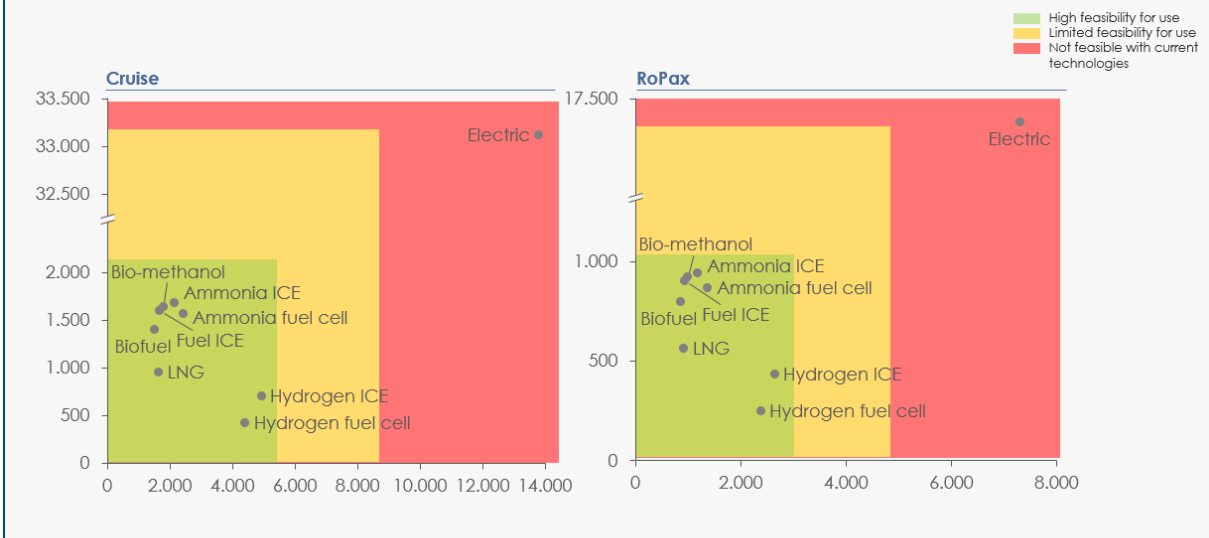
Weight and volume characteristics of freight ships in 2030



SOURCE: UMAS analysis ; Lloyds Register & UMAS (2017), *Zero-emission Vessels 2030*; SYSTEMIQ analysis for the ETC

Exhibit 8

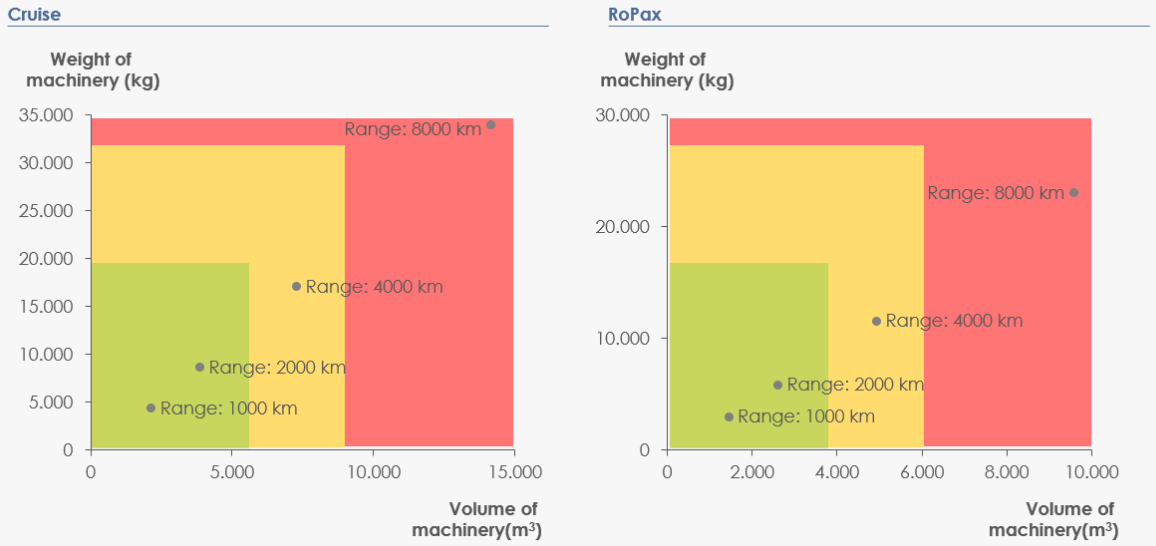
Weight and volume characteristics of Pax ships in 2030



SOURCE: UMAS analysis ; Lloyds Register & UMAS (2017), *Zero-emission Vessels 2030*; SYSTEMIQ analysis for the ETC

Exhibit 9

Weight and volume characteristics of electric Pax ships depending on range



SOURCE: UMAS analysis ; Lloyds Register & UMAS (2017), *Zero-emission Vessels 2030*; SYSTEMIQ analysis for the ETC

Exhibit 10

Box 1 – Testing ammonia in shipping

In January 2018, a new project was announced by a Dutch consortium including Yara, the world's biggest producer of ammonia, C-Job Naval Architects, Proton Ventures and Future Proof Shipping (FPS), a spinoff from Enviu. The initial phase of this two-year project will involve theoretical and laboratory work and will result in a pilot-scale demonstration of "the technical feasibility and cost effectiveness of an ammonia marine tanker fueled by its own cargo". In order to make this project more focused for the shipping industry, there will be an in-depth focus and assessment of the safety of ammonia in bunkering, storage, consumption and leakage/failure. The outcome of this research project will be crucial for the adoption of full-scale ammonia fuels in the shipping industry.

B. DECARBONIZATION OPTIONS: CARBON INTENSITY COMPARISON

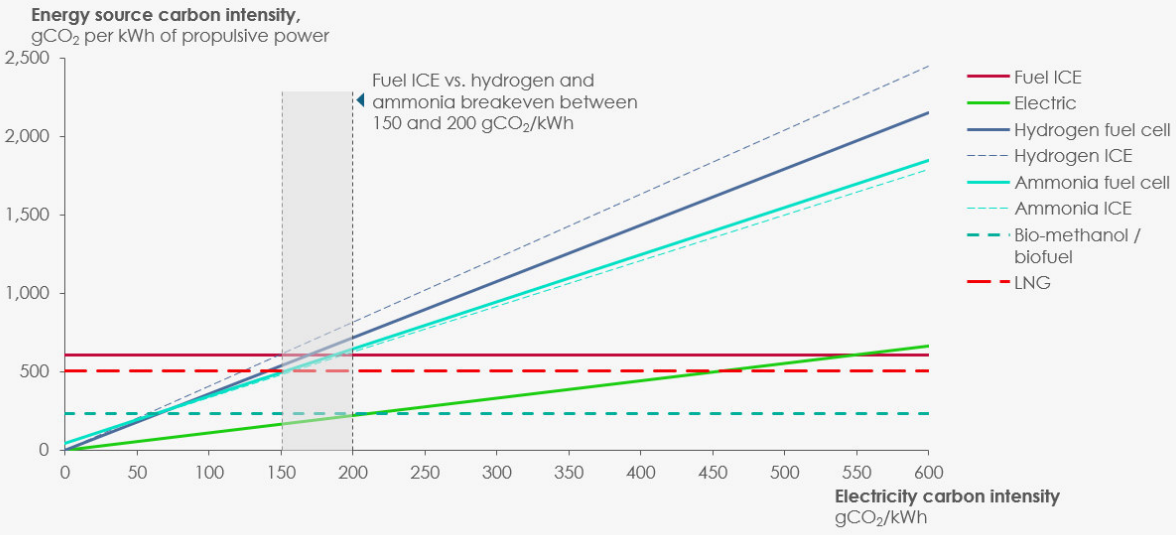
As well as assessing the technical feasibility and comparative cost of the different options, it is important to consider how far they can reduce carbon emissions. Total decarbonization is only possible if (i) using zero-carbon electricity directly in electric engines, (ii) using hydrogen if it is either produced from electrolysis of zero-carbon power or from steam methane reforming combined with carbon capture, (iii) using ammonia produced based on such hydrogen, or (iv) using sustainable biofuels[11].

But other options may potentially achieve greater emission reductions in the short term as long as electricity is still produced from high-carbon power sources. It is therefore important to analyze **how the carbon intensity of electricity impacts the trade-offs between different decarbonization routes**. This analysis, summarized on Exhibit 11, shows that:

[11] The carbon and land use implications of use of biofuels is described in more details in chapter 6 and 7 of the ETC report *Mission Possible* (2018).

- In the few short-haul sub-sectors where electrification is technically possible, **battery-electric ships** would produce less emissions than HFO once the carbon intensity of electricity goes below 550gCO_2/kWh. Almost all major developed economies are already or will soon be below that level, but China is still significantly higher (around 800gCO_2/kWh) and India higher still (around 1,000gCO_2/kWh).
- **Ammonia** requires a carbon intensity of electricity below 200gCO_2/kWh to produce lower carbon emissions than HFO ships. For **hydrogen**, the breakeven value is between 150 and 175gCO_2/kWh, depending on type of engine (fuel cell or ICE). These low levels are already achieved in several EU countries – in particular the Scandinavian nations and France – and UK is approaching this level with a carbon intensity forecast for 2018 of between 200 and 250gCO_2/kWh, and a strategy to reach 100g by 2030[12]. But other major regions of the globe are far from these levels. This implies that hydrogen and ammonia should either be produced in regions with low carbon intensity of electricity, or from dedicated renewable power plants, to be an appropriate decarbonization option in the medium term.
- For both **bio-methanol and biofuel**, the overall impact on emissions depends on the full lifecycle emissions of the fuel. Both could in principle deliver significant emissions reductions (up to 100% eventually, but most probably around 60-70% in the medium term) with the emissions produced at point of use offset by the CO_2 absorbed as biomass grows. Contrarily to electric, hydrogen or ammonia solutions, however, they would still produce emissions at point of use and contribute to local air pollution. As described in subsection e of this document and, at length, in Chapters 6 and 7 of the *Mission Possible* report, the desirability of any bio-based fuel also depends on the sustainability of the biomass from which it is produced and must be assessed within the context of the demands for biomass resources from all other sectors of the economy.
- **LNG ships** can produce 9% to 12% less emissions than HFO ships in principle, but only if upstream methane leakages are under control. LNG cannot deliver eventual complete decarbonization of shipping. As electricity production decarbonizes, electricity-based fuels will therefore eventually become far less carbon-intensive.

Carbon intensity per kWh depending on electricity carbon intensity and technology



SOURCE: UMAS analysis ; Lloyds Register & UMAS (2017), *Zero-emission Vessels 2030*; SYSTEMIQ analysis for the ETC

Exhibit 11

[12] National Grid's Carbon Intensity API (2018), *http://carbonintensity.org.uk/*

C.DECARBONIZATION OPTIONS: COST COMPARISON

In 2017, **Lloyd's Register and University Maritime Advisory Services (UMAS) produced a report on Zero Emission Vessels**[13] which assessed how the total capital and operating costs for a specific journey length for each of the five main categories of ship would change if either of the eight alternative fuel/engine options were adopted in existing ships[14]. The ETC has worked with UMAS to run additional scenarios using the same model.

In our Reference case, **the cost of electricity** available to ships, which also forms the input cost for hydrogen and ammonia production, is assumed to be **US$0.07 per kWh**. This corresponds to the ETC's estimate of the likely maximum cost of electricity in a power system relying at 85-90% on intermittent renewables from 2035 onwards[15]. In our "Low-cost electricity" case, we consider how the economics would change if the cost of electricity were a far lower **US$0.02 per kWh**. This reflects our assessment[16], shared by the International Energy Agency (IEA) in their most their recent report on Renewable Energy for Industry[17], that the price of electricity in locations with the most favorable combinations of wind and solar resources is likely to fall to that level and eventually below.

Exhibit 12 shows estimates of the total annual cost of running different types of ships with HFO (including both annualized capital costs and operational costs), which constitutes the base case, and the **additional costs that would be triggered by a shift to alternative technologies**. Exhibit 13 shows the results for bulk carriers expressed in percentage increases rather than in absolute terms. The figures illustrate that:

- Battery electric vehicles are the only alternative apart from LNG to have lower voyage costs[18], but, in total cost terms, the battery electric option appears to always be the most expensive because of the high costs of batteries and the revenue lost as a result of space requirements for energy storage[19].
- The hydrogen-based options (either hydrogen used in fuel cells or hydrogen burnt in existing engines) are significantly more expensive because of higher fuel costs, storage costs, and lost revenues.
- The ammonia, biofuel and bio-methanol options all face a roughly equal cost penalty. This cost penalty results mostly from higher fuel costs, with other costs (capital costs and revenue lost in particular) not materially different from the HFO base case. Total annual cost would be about 120% higher than with HFO.
- LNG costs are roughly similar to the base case using HFO.

[13] Lloyd's Register & UMAS (2017), *Zero-emission Vessels 2030*
[14] The model therefore compares cost of retrofitting existing HFO ships, rather than comparing costs for new builds.
[15] Energy Transitions Commission (2017), *Better Energy Greater Prosperity*
[16] Energy Transitions Commission (2018), *Mission Possible – Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century*
[17] IEA (2017), *Insight Series: Renewable Energy for Industry*
[18] Variable costs associated with a specific voyage, including items as fuel, port charges and canal dues.
[19] Revenue loss arising from reductions in cargo space to accommodate zero-carbon engines and fuel or power storage.

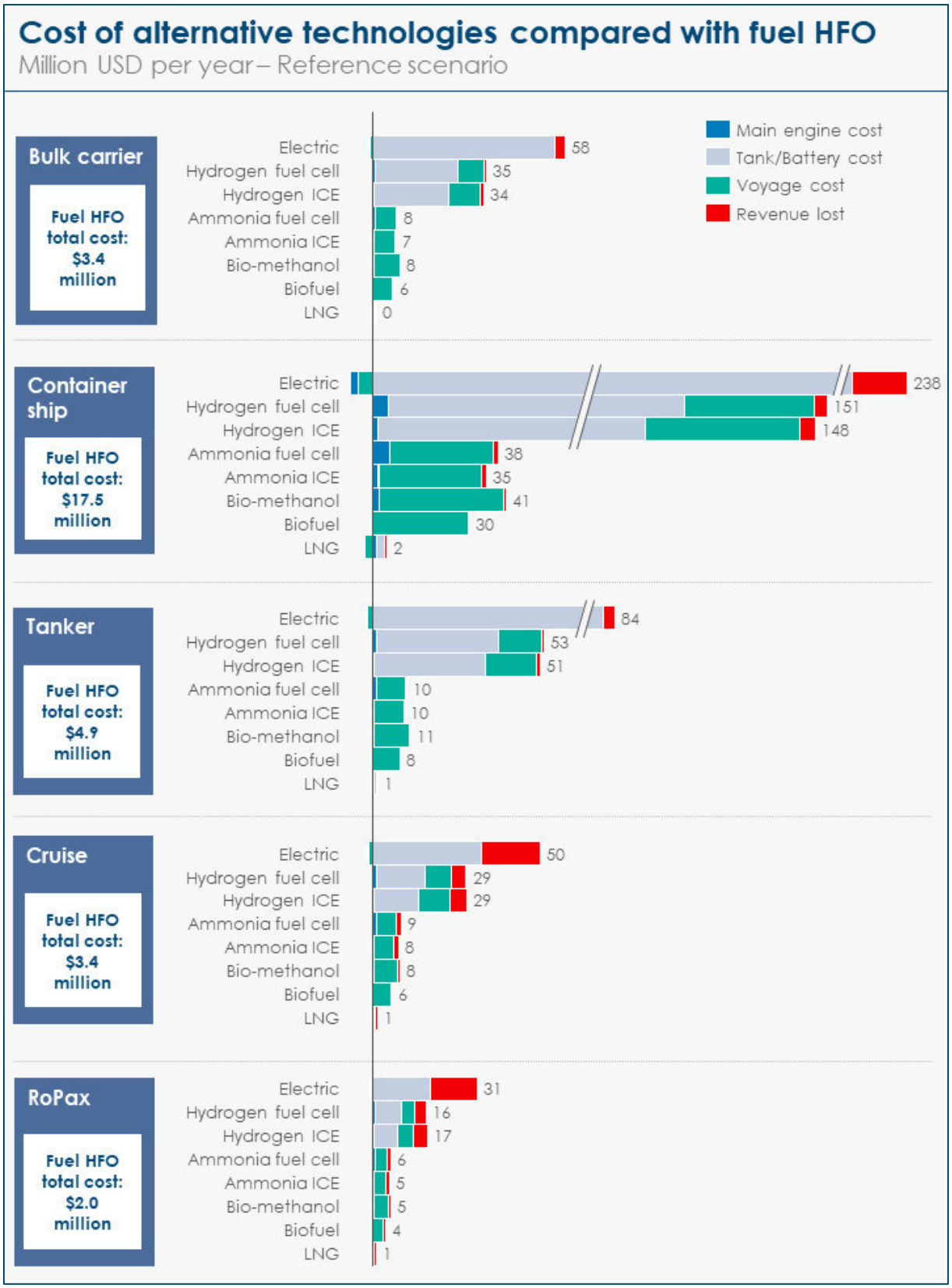

Cost of alternative technologies compared with fuel HFO
Million USD per year – Reference scenario
Main engine cost
Tank/Battery cost
Voyage cost
Revenue lost
Bulk carrier
Fuel HFO total cost: $3.4 million
Electric 58
Hydrogen fuel cell 35
Hydrogen ICE 34
Ammonia fuel cell 8
Ammonia ICE 7
Bio-methanol 8
Biofuel 6
LNG 0
Container ship
Fuel HFO total cost: $17.5 million
Electric 238
Hydrogen fuel cell 151
Hydrogen ICE 148
Ammonia fuel cell 38
Ammonia ICE 35
Bio-methanol 41
Biofuel 30
LNG 2
Tanker
Fuel HFO total cost: $4.9 million
Electric 84
Hydrogen fuel cell 53
Hydrogen ICE 51
Ammonia fuel cell 10
Ammonia ICE 10
Bio-methanol 11
Biofuel 8
LNG 1
Cruise
Fuel HFO total cost: $3.4 million
Electric 50
Hydrogen fuel cell 29
Hydrogen ICE 29
Ammonia fuel cell 9
Ammonia ICE 8
Bio-methanol 8
Biofuel 6
LNG 1
RoPax
Fuel HFO total cost: $2.0 million
Electric 31
Hydrogen fuel cell 16
Hydrogen ICE 17
Ammonia fuel cell 6
Ammonia ICE 5
Bio-methanol 5
Biofuel 4
LNG 1

Exhibit 12

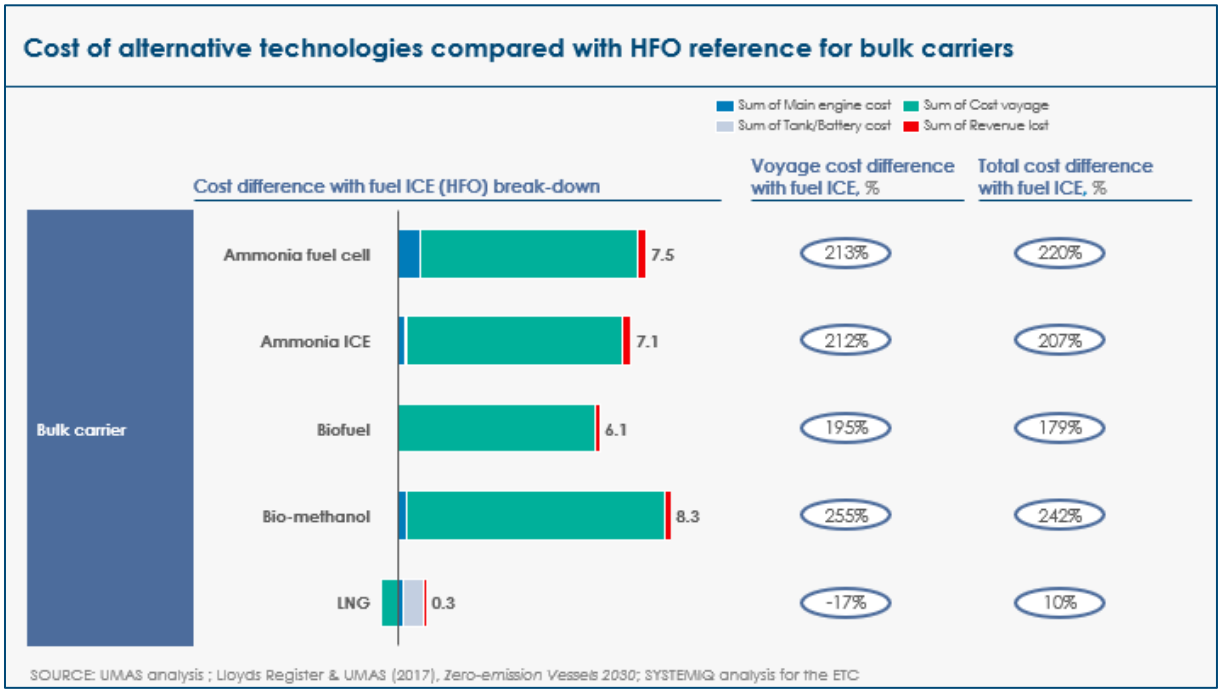


Exhibit 13

In a "Low-cost electricity" case [Exhibits 14 and 15], there would be a change in which low-carbon alternative to HFO would be most cost-competitive:

- The battery electric and hydrogen options, though now fully competitive with or even better than HFO on a voyage cost basis, would still be far more expensive than HFO on a total cost basis.
- The ammonia option would become significantly cheaper than the biofuel or bio-methanol options, whose economics are unchanged by lower electricity prices. Relative to HFO, however, the ammonia option would still be 50-60% more expensive in terms of voyage costs.
- The economics of the LNG option would be unchanged and remain very close to HFO.

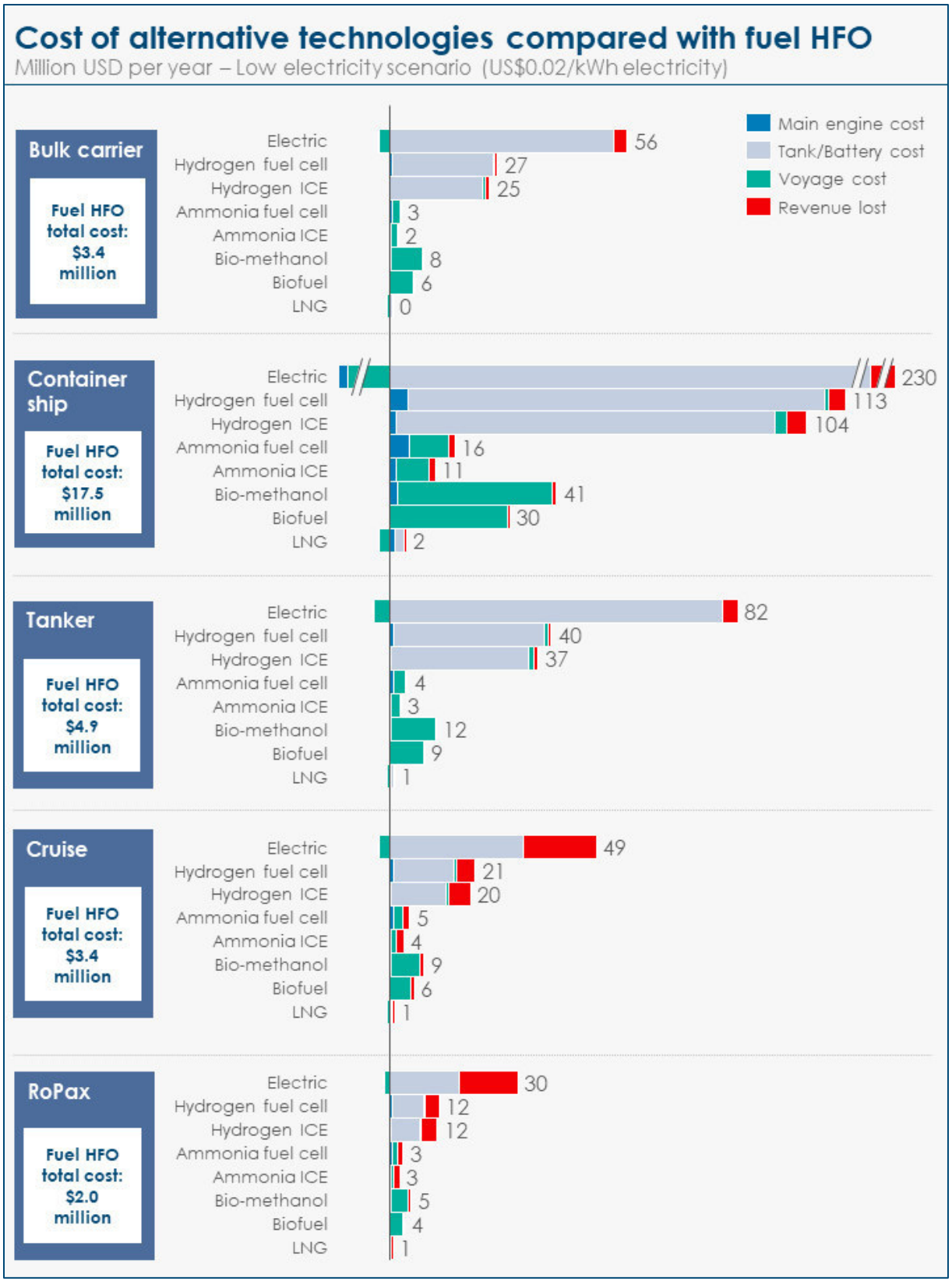

Cost of alternative technologies compared with fuel HFO
Million USD per year – Low electricity scenario (US$0.02/kWh electricity)
Main engine cost
Tank/Battery cost
Voyage cost
Revenue lost
Bulk carrier
Fuel HFO total cost: $3.4 million
Electric 56
Hydrogen fuel cell 27
Hydrogen ICE 25
Ammonia fuel cell 3
Ammonia ICE 2
Bio-methanol 8
Biofuel 6
LNG 0
Container ship
Fuel HFO total cost: $17.5 million
Electric 230
Hydrogen fuel cell 113
Hydrogen ICE 104
Ammonia fuel cell 16
Ammonia ICE 11
Bio-methanol 41
Biofuel 30
LNG 2
Tanker
Fuel HFO total cost: $4.9 million
Electric 82
Hydrogen fuel cell 40
Hydrogen ICE 37
Ammonia fuel cell 4
Ammonia ICE 3
Bio-methanol 12
Biofuel 9
LNG 1
Cruise
Fuel HFO total cost: $3.4 million
Electric 49
Hydrogen fuel cell 21
Hydrogen ICE 20
Ammonia fuel cell 5
Ammonia ICE 4
Bio-methanol 9
Biofuel 6
LNG 1
RoPax
Fuel HFO total cost: $2.0 million
Electric 30
Hydrogen fuel cell 12
Hydrogen ICE 12
Ammonia fuel cell 3
Ammonia ICE 3
Bio-methanol 5
Biofuel 4
LNG 1

Exhibit 14

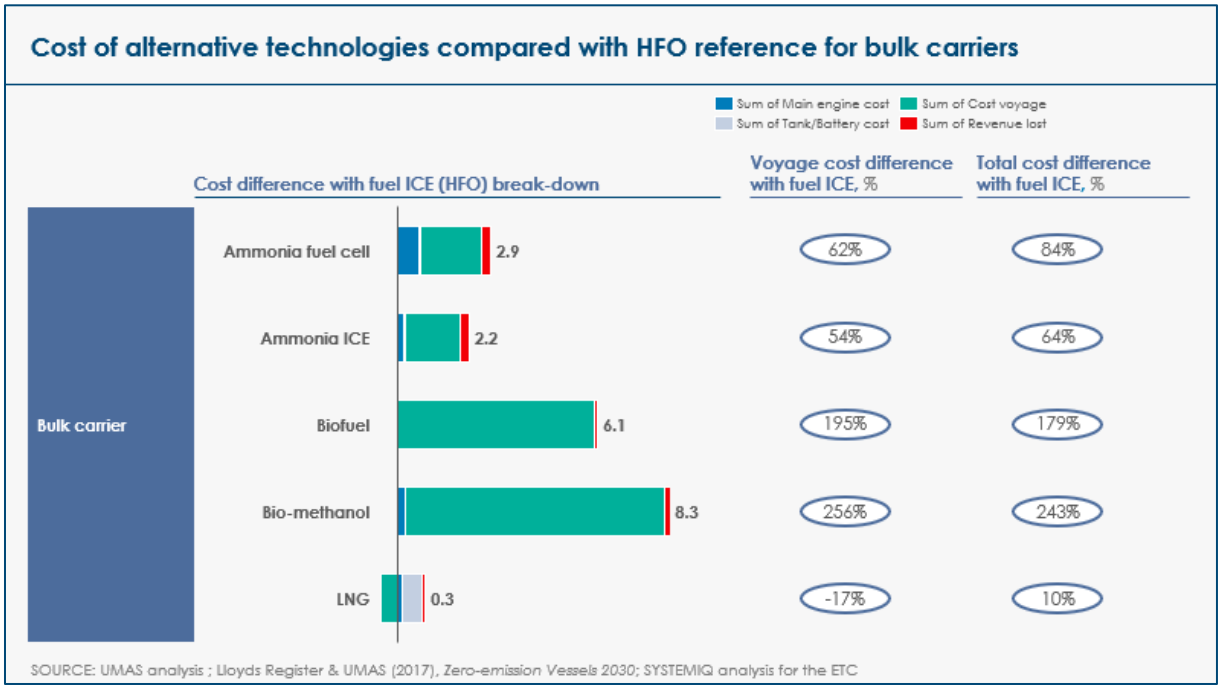


Exhibit 15

Exhibit 16 shows more precisely how the **relative costs of the different technology options change for bulk carriers as the electricity price varies** and Exhibit 17 shows how these trade-offs would be affected by the introduction of a carbon price[20]. This analysis shows that:

- Ammonia would be cheaper than biofuels if electricity prices fell below about $0.05-$0.06 per kWh.
- There is no electricity price at which ammonia is cheaper than HFO without the imposition of a carbon price.
- Ammonia would become cheaper than HFO if electricity costs were less than $0.06 per kWh with a carbon price of $300 per tonne of CO_2, or if electricity costs were less than about $0.02-0.03 per kWh with a carbon price of $150 per tonne of CO_2.

This cost comparison would be somewhat more favorable to the low-to-zero carbon options if, rather than comparing the additional costs incurred to retrofit ammonia storage to existing HFO ships, we compared the cost of alternative new build ships. But it seems almost certain that, even on a new build basis and with very low renewable electricity prices, **decarbonizing shipping will cost at least US$150 per tonne and up to US$300** and will imply a significant increase in freight rates.

The good news, however, is that even significant increases in freight cost would **add only slightly to the final price of delivered products**. If, for instance, freight costs are 5% of the ex-factory price of manufactured products, and the ex-factory price 50% of the final retail price, a 50% rise in freight rates would only imply an increase of 1% or less in prices of end consumer products imported by ship.

[20] The battery electric option is not considered in this analysis since the weight and space penalty makes it uneconomic for long-haul bulk shipping.

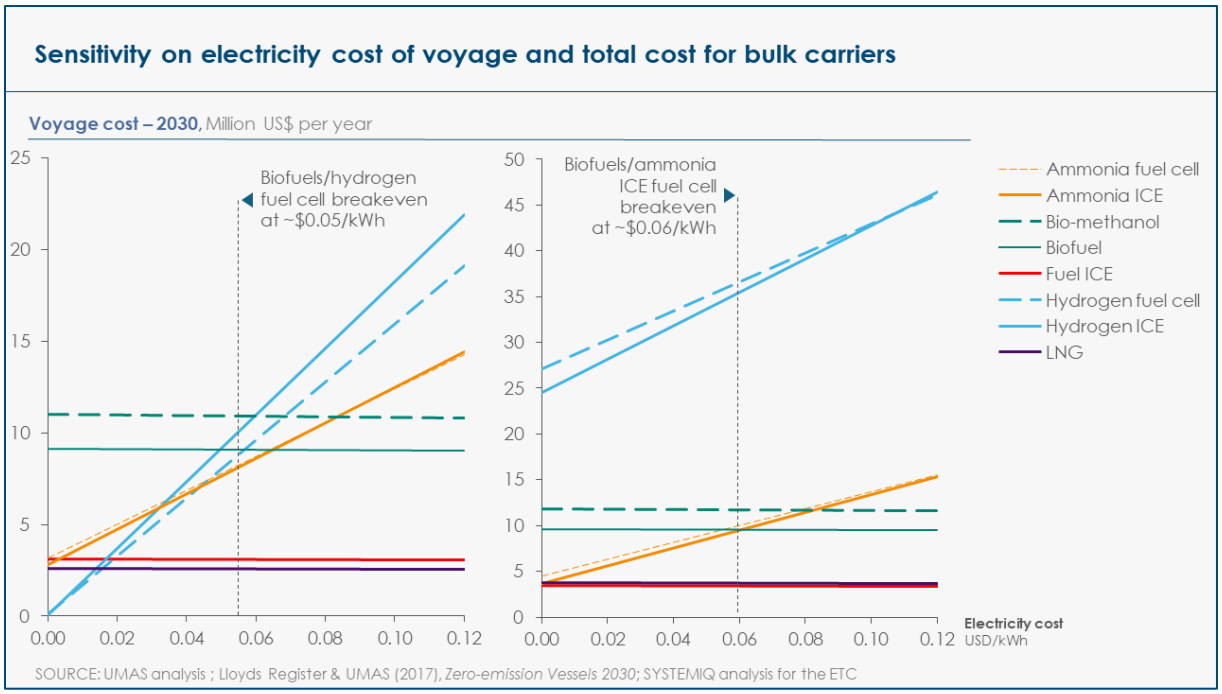


Exhibit 16

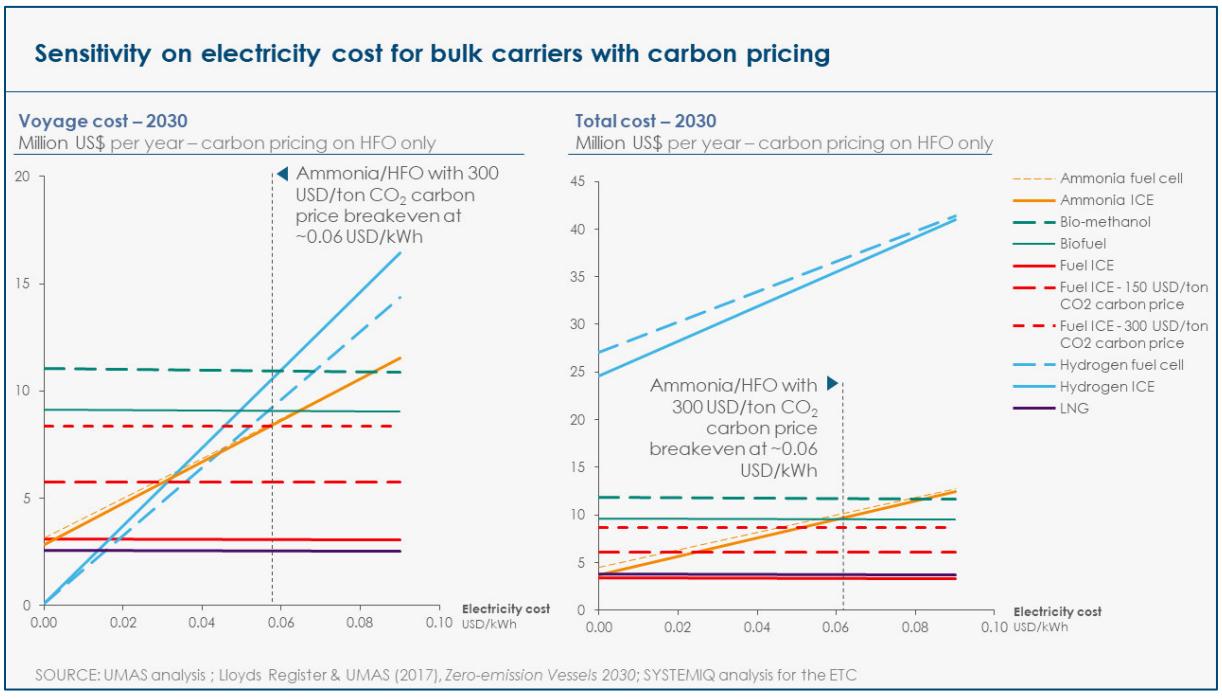


Exhibit 17

D. SUSTAINABILITY ISSUES IN THE USE OF BIOFUELS

Biofuels have the advantage of being a "drop-in fuel", which can be used in all existing engines and distribution assets without the need for retrofitting. On the basis of current UMAS estimates, which assume a biofuel from algae and bio-methanol cost respectively 200% and 250% higher than HFO (per kinetic kWh[21]), biofuels are unlikely to beat the ammonia option on costs. But several factors could actually carve out **a prominent role for biofuels in the shipping industry, at least during a transitional period**:

- Biofuels production and use in ship engines is a proven technology, whereas use of ammonia is still at development stage. They could therefore be deployed faster.
- Sustainable biofuels may have a greater carbon emissions reduction potential than hydrogen and ammonia as long as the carbon intensity of the electricity used for electrolysis remains high or as long as hydrogen remains produced from SMR without carbon capture.
- Biofuels costs may come down significantly. Aviation sector experts suggest that biofuels may already be available at a price 2-3 times above fossil based jet fuel[22], and the price premium is expected to fall significantly within the next decade. The level of carbon pricing at which biofuels could compete with HFO could therefore drop and biofuels could be cost-competitive versus ammonia, even with low electricity prices.

However, it is important to consider (i) the available global supply of truly sustainable biomass for energy use, and (ii) whether there are other sectors which should have a higher priority claim on limited sustainable biomass given the lack of any feasible alternative decarbonization options. These issues are considered in chapters 6 and 7 of the ETC's report *Mission Possible*[23].

Our key conclusions are that:

- Estimates of **sustainable biomass available** for energy use vary greatly, but analysis suggests that 70EJ per annum of sustainable biomass for energy and feedstock would certainly be available by mid-century. This could in principle easily cover total shipping industry energy use, which is currently around 10EJ and might grow to some 13EJ over the next 30 years.
- **Aviation should have the highest priority claim** on limited sustainable biomass resources, given the lack of any feasible alternative to liquid hydrocarbons as the energy source for international flight. **Trucking by contrast is a low-priority sector**, given the feasible alternatives of electricity and hydrogen. **Shipping represents an intermediate case**, with alternative technically feasible routes to decarbonization (e.g. ammonia), but with these likely to be significantly higher cost than HFO, and only delivering carbon emission reductions once electricity is very significantly decarbonized.
- It is essential, however, that **biofuels are sourced in a truly sustainable way**, which should ideally not involve the significant use of plants which compete with food production, but be based primarily or entirely on waste streams (municipal, agricultural or forestry waste) or lignocellulosic sources. This implies that a tight definition of what constitutes a "sustainable biofuel" must be embedded in any policy aiming to increase biofuels uptake in aviation.

[21] Bio-methanol cost per ton of fuel is 80% superior to HFO, and the energy density is twice lower (5.6 kWh/kg vs 11.3 kWh/kg for HFO), whereas energy density of biofuel and HFO are similar.
[22] SYSTEMIQ analysis for the Energy Transitions Commission (2018)
[23] Energy Transitions Commission (2018), *Mission Possible – Reaching net-zero carbon from harder-to-abate sectors by mid-century*

5. COST OF FULL DECARBONIZATION OF SHIPPING

As Sections 2 through 4 argued, it is technically possible to achieve full decarbonization of the shipping sector "within itself" through a mix of solutions including ammonia, hydrogen and biofuels for long-haul shipping, and electric engines for short-haul shipping. However, the cost of these solutions is still prohibitive, making the shipping sector a challenging one in the efforts to bring carbon emissions from the transport sector to zero. This chapter considers in turn:

- The cost to the economy derived from the abatement cost per tonne of CO_2 saved;
- The implications for the cost of fuel and, lower down the value chain, for the imported goods purchased by the end-consumer.

A. COST TO THE ECONOMY

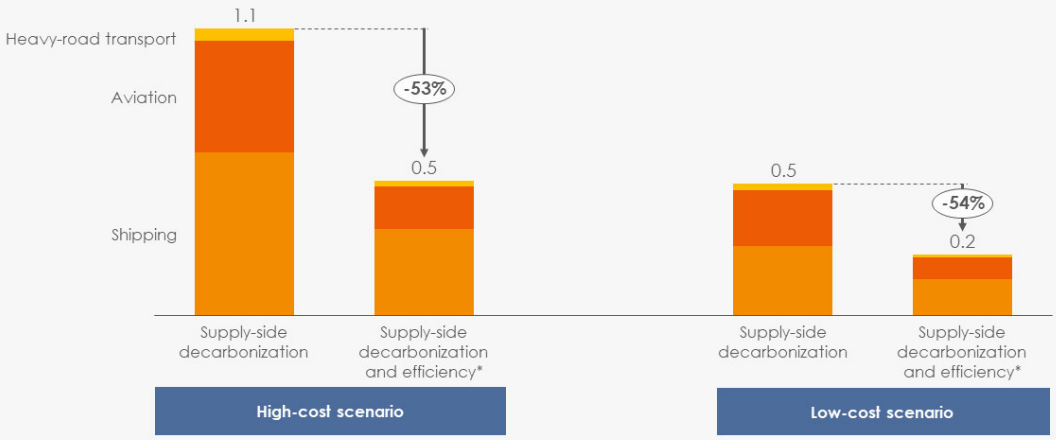
Actual abatement costs – and the least-cost routes to decarbonization – will depend on future technological developments and cost trends. Based on the joint ETC-UMAS analysis, we estimated that the use of an alternative zero-carbon fuels like ammonia used in an Internal Combustion Engine (ICE), summed up with engine and tank capital cost and revenue loss arising from reduction in cargo space, could add a total cost penalty of US$3 million to US$7 million per year for a bulk carrier (US$4 million in an intermediary case), with voyage costs representing 70% to 90% of the total cost penalty. It corresponds to a total cost increase of 100% to 200% (110% in an intermediary case), and an abatement cost of US$150-300/tonne of CO_2. This is based on a scenario where electricity costs are between US$0.03 and US$0.06 per kWh, which makes sense in a globalized ammonia market where ammonia is produced in sunny places favorable to very low-cost electricity generation.

An initial estimate of the maximum annual cost to the global economy of achieving net-zero CO_2 emissions within the shipping sector (with no use of offsets) can be generated by multiplying these abatement costs with the volume of CO_2 emissions projected by mid-century in a business-as-usual scenario. This indicative "cost to the economy" appears to be very low compared with an indicative 2050 global GDP: running a fully decarbonized shipping industry could amount to less than 0.2% of global GDP in 2050, or less than US$600 billion per annum [Exhibits 18 and 19].

This could be significantly reduced by three factors:

- **Lower renewable energy costs**: if zero-carbon electricity was available at US$20/MWh or below, the total cost of the zero-carbon fuel route would be reduced by ~60%.
- **Energy efficiency**: energy efficiency improvements (via ship design, sail assistance, or slower speeds), combined with demand reduction and improved platform management, could reduce the total fuel consumption of the shipping industry by half, in the most aggressive scenarios, and therefore reduce total decarbonization costs for the sector by half too, bringing it to lower than 0.10% of global GDP.
- **Future technological development**: the cost of decarbonization could be dramatically reduced, or even eliminated, by new and unanticipated technologies. For instance, if technological improvements were to increase the efficiency in biomass-to-biofuel transformation and make bioenergy from lignocellulosic sources or algae cost-competitive, or if cost-competitive synfuels were brought to market, it might become possible to decarbonize shipping with drop-in fuels (exact substitutes to HFO which do not require any equipment retrofit, nor result in any revenue loss) at near-zero cost.

Shipping is the costliest transport harder-to-abate sectors to decarbonize



Note: The term "efficiency" covers energy efficiency and demand management in transport.
Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018) based on Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit 18

Decarbonizing harder-to-abate sectors would cost significantly less if pursuing energy efficiency improvement and demand management opportunities

Note: The term "efficiency" covers energy efficiency and demand management in transport.
Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018) based on Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit 19

B. B2B COST AND END-CONSUMER COST OF DECARBONIZATION

In the absence of a technological breakthrough, decarbonizing shipping will have a significant impact on international freight costs. However, this should not translate into major increases in costs faced by end consumers:

- **At the business-to-business level**, total costs for a typical bulk carrier could be increased by US$4 million per year, representing **a +110% increase,** if using zero-carbon fuels instead of conventional fuels.
- The impact on **end consumer prices**, however, is likely to be limited: for instance, a 110% increase in international freight voyage costs would only translate in a price increase of US$0.30 or less than 1% on the cost of a pair of jeans priced US$60 and shipped from a production site in Southeast Asia to the US west coast.

The major cost barrier to the decarbonization of the shipping sector is therefore not the cost to the global economy, but **how to encourage the uptake of technologies that would currently be cost-adding** in a highly competitive and fragmented industry where incentives and responsibilities are split between ship owners and operators. The implications of this for appropriate policy are considered in Sections 6 and 8.

6. CONCLUSIONS AND POLICY IMPLICATIONS

The route to decarbonize shipping appears to be more complex than for the other heavy-duty transport sectors. Trucking can almost certainly be decarbonized at a low or even nil cost by shifting over time to increasingly cost-competitive battery electric or hydrogen powered vehicles. Decarbonizing aviation will likely entail high costs per tonne of CO_2 saved (e.g. $100 or more), but the technological pathway is at least clear, as long-distance international flights will almost certainly continue to require a liquid hydrocarbon fuel, and the sector is split across a relatively limited number of players. In comparison, **decarbonization of shipping is also likely to be costly and will suffer from two additional obstacles: the greater uncertainty about which technology option is likely to dominate and the fragmentation of the industry**. However, this analysis still leads to three sets of conclusions.

First, **energy efficiency is essential.** Improving the energy efficiency of ships and ship engines will be crucially important and could make a far greater contribution to decarbonization in shipping than in trucking and aviation. The potential for emissions reduction is currently greater in shipping precisely because, until now, existing industry structures have created weaker incentives to optimize design and operation. Given that zero-carbon alternatives will likely not be market ready before the 2030s, energy efficiency improvement would provide an essential source of early emissions reductions in the 2020s and would, in turn, significantly reduce the cost of moving to lower-carbon fuels in the following decades.

Second, **we can have a high confidence that zero-carbon shipping can technically be achieved by mid-century**, given that a range of alternative options are currently being developed that would make full decarbonization possible:

- **Battery or hydrogen-based electrification** may play a significant role in the RoPax, river freight and shorter-distance cruising sectors. But, unless and until there is a major breakthrough in battery density, the primary route to shipping decarbonization will be through the use of zero-carbon fuels in combustion engines.
- **Ammonia** seems likely to prove an attractive route to eventual total decarbonization but shifting to ammonia will only make sense in either cost or carbon emissions terms if and when very cheap renewable energy becomes available. Its long-term role should almost certainly be large, but the optimal transition may be initially slow.
- **Hydrogen** use could in theory be an alternative to the use of ammonia but is likely to be penalized by its lower energy density, which would result in a higher revenue loss for ship operators.
- **Biofuels** could technically play a significant role in decarbonization if the cost of truly sustainable biofuels can be significantly reduced. However, its use is constrained by the availability of truly sustainable biofuels.
- Although **LNG** may seem like a cost-effective route to some short-term emissions reductions (if and only if upstream methane leakages are brought down) while truly zero-carbon technologies are brought to market, this option can only be considered as transitional. LNG can indeed not deliver anything like a full decarbonization of the sector. The industry therefore needs to avoid overinvesting in LNG infrastructure which must have a limited lifetime if the net-zero emissions by mid-century target is to be achieved.
- **The optimal long-term balance between ammonia and sustainable biofuels should emerge over time** in the light of evolving relative cost trends.

While it is neither possible nor necessary to predict precisely what will be the balance between the different decarbonization routes described above, it is essential to put in place policy levers that will drive the search for and adoption of the most cost-competitive zero-carbon technology.

Finally, given that zero-carbon technologies are not yet cost-competitive with HFO, this implies the need to use price levers (a carbon price) or green fuel mandates (without specifying one particular technology) to drive progress. The impact of such measures on freight cost should be manageable:

- While very low electricity prices or lower biofuel costs may in future significantly reduce the cost penalty of shifting from HFO to zero-carbon fuels, it seems likely that the cost of decarbonization per tonne of CO_2 will initially be significant (e.g. $100-$150 per tonne) with tangible implications for total freight costs (+65-90%).
- For most commodities and manufactured goods, this implies only modest increases in total product prices (e.g. a 1% increase in retail prices for imported manufactured goods if freight rates rise by 50%) and these incremental costs will have to be accepted as the unavoidable cost of decarbonization.
- But, given the internationally competitive nature of shipping, and the ease with which ships can choose different refueling locations, policy measures which impose significant increases in freight costs – whether via overt carbon prices or via green fuel mandates – will require international coordination, most likely orchestrated through the International Maritime Organization (IMO).

7. EXISTING INDUSTRY INITIATIVES

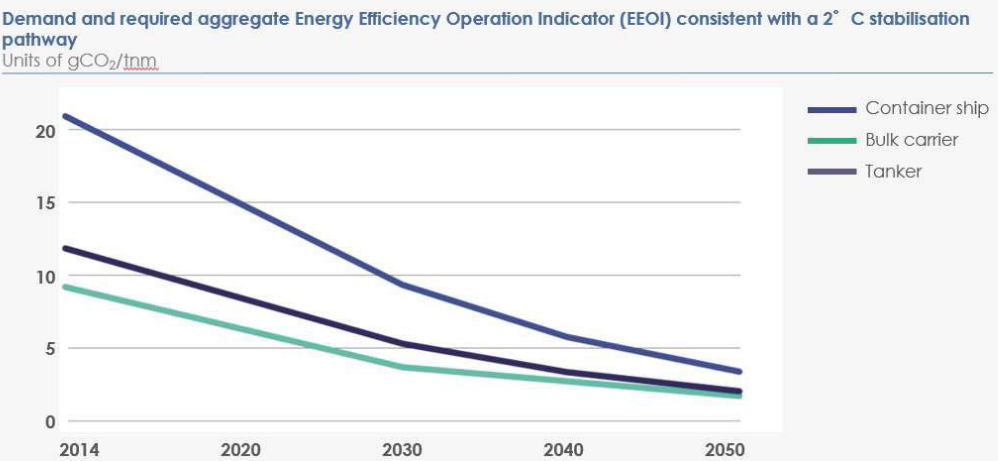
In April 2018, the International Maritime Organization (IMO) published its initial greenhouse gas reduction strategy, establishing **the objective of an absolute GHG reduction of at least 50%** below 2008 levels by 2050 with the intention, if possible, to achieve a 100% cut[24]. The former target is believed to be compatible with the Paris objective of well below 2°C, while the latter would be compatible with the Paris aspiration of limiting global warming to 1.5°C. Given the likely growth in shipping traffic volumes, the first target would already require a reduction of 70% in the carbon intensity of shipping (i.e. emissions per tonne-kilometer) over the next 30 years [Exhibit 20].

Meeting this objective will clearly **require not just significant improvements in the energy efficiency of ships and engines, but a switch to low- and eventually zero-carbon energy sources**. Following on from the IMO publication, the International Chamber of Shipping (ICS) published a short response report, which supported and further reiterated the fact that eventually reaching the goal of zero emissions from shipping can only be derived from zero-carbon fuels.

Setting the objective has, in itself, a powerful effect on industry participants, since **it implies that all new ocean-going vessels entering service from the late 2020s must be able to use zero-carbon solutions**, either immediately or later in life through light retrofitting. If further detailed agreements make all industry participants convinced that the objective is irreversible, multiple individual private decisions by ship builders, owners, operators, financiers and insurers are likely to make it a reality.

In addition, the IMO can force progress through the **legally-binding energy efficiency standards** which it has applied to newly built ships since 2011, as measured by its Energy Efficiency Design Index.

Achieving the IMO's 50% emissions reduction objective by 2050 will require a reduction of 70% in the carbon intensity of shipping



Source: Lloyd's Register & UMAS (2017), *Zero-Emission vessels 2030*

Exhibit 20

[24] UCL (2018), *The IMO's 2018 climate agreement explained* & Lloyd's list maritime intelligence (2018), *IMO agrees to cut emissions by at least 50% by 2050*

However significant further work will be required to ensure that the objectives are achieved, and there may still be important political barriers to the imposition of adequately tough policy measures:

- While the agreement committed to achieve some GHG reduction by 2023, **detailed actions have not yet been agreed** to make this short-term commitment clearly credible.
- Further work is needed to agree **specific policy measures**. These could include (i) further tightening of the energy efficiency standards for new build ships, (ii) operational efficiency standards for new build and existing ships, or (iii) measures to encourage the adoption of low- and zero-carbon fuels.
- Since analysis suggests that alternative low carbon fuels will represent a cost penalty, effective policy will at some stage need to include **some form of carbon pricing** (i.e. a levy on fossil fuel HFO) **or a mandatory standard** (i.e. an increasing percentage of fuel produced from zero or low carbon sources). But it may be difficult to achieve international agreement to such measures, given that, while the policy objective was endorsed by an overwhelming majority, it was opposed by two important nations, Saudi Arabia and the United States.

Box 2 – Call for action from the Global Maritime Forum

Progressive voices from the shipping industry are increasingly being heard: the Global Maritime Forum orchestrated, in October 2018, the signature of a call for action in support of decarbonization from 34 CEOs from across the maritime industry. The CEOs recommend that the IMO's Roadmap for transition to a new zero-emission future be aligned to 7 core principles[25]:

- **Ambitious**: The strategy should be consistently in line with the Paris agreement's temperature goals.
- **Predictable**: Regulations should provide long-term certainty for financiers, builders, owners and charterers to make the required investments in low-carbon technologies.
- **Market-oriented**: Emissions reduction objectives should be met at the lowest possible cost, and the industry should explore the use of carbon pricing and other mechanisms that can create economic value from GHG emission reductions.
- **Technology-enabling**: The strategy should accelerate the use of low-carbon technologies and fuels by encouraging significant funding flows for research and development.
- **Urgent**: Certain mid- and long-term measures will require work to commence prior to 2023, including the development of zero-emission fuels to enable implementation of decarbonization solutions by 2030.
- **Coherent**: Solutions implemented should build on and reinforce existing technical, operational, and energy efficiency measures whilst maintaining or enhancing safety standards. In this context it is critical that all IMO environmental regulations be compatible with future 2050 regulations.
- **Enforceable**: Legally binding, enforceable actions set by the IMO and enforced by member countries are required to compel the industry to shift. ambitious (in line with the Paris agreement's temperature goal).

[25] Global Maritime Forum (2018), *34 maritime CEOs sign call for action in support of decarbonization*

8. RECOMMENDATIONS

The fragmented, heterogeneous and international nature of the shipping industry creates complex challenges in the implementation of a decarbonization strategy, but these can be overcome if the different parties – major ship owners/operators, industry associations, national governments and the IMO – coordinate and play complementary roles. The end objective should be a set of regulations, carbon prices, or fuel standards which deliver increased efficiency and the gradual adoption of low/zero-carbon fuels, supported by research and development to help reduce the cost of these technology options.

A. RESEARCH AND DEVELOPMENT

Public and private RD&D efforts should focus on three priorities:

- **Continued improvements in the energy efficiency of ship and engine design**, including consideration of innovative developments such as the use of wind assistance;
- Achieving cost reductions in **green ammonia** production from zero-carbon hydrogen – here the key challenge is to reduce the cost of hydrogen produced from electrolysis, which requires reductions in the capital cost of electrolysis equipment (e.g. from today's $850 per kilowatt to $400 or well below) – as well as perfecting the engineering of the storage and use of ammonia as a shipping fuel;
- **Achieving cost reduction in biofuels** produced from truly sustainable waste, lignocellulosic or algae sources, including through a greater efficiency of the biomass-to-biofuels refinery process.

The first priority – energy efficiency and shipping – is specific to the shipping industry itself and must primarily be driven by individual shipping company research and development, but national governments of major ship operating nations should also provide public support to help drive innovation.

The development of zero-carbon fuel alternatives, by contrast, is important to other sectors of the economy apart from shipping. Zero-carbon hydrogen is likely to play a major role in the decarbonization of heavy industry and of long-distance trucking. Sustainable biofuels are likely to be essential for the decarbonization of aviation. Public-private joint research and development initiatives should therefore be used to drive these vital cross-sectoral technology developments, with finance coming from both public and private sources, including from major shipping companies and from other user segments.

B. PUBLIC POLICY

THE IMO: TURNING OBJECTIVE INTO DETAILED STRATEGY

The fragmented and international nature of the shipping industry makes the role of the IMO particularly crucial. Building on its commitment to an emissions reduction of "at least 50%" by 2050, it should now:

- **Develop a detailed roadmap** of how this objective can be achieved:
    - Setting out a possible balance between energy efficiency improvements and a shift to low/zero-carbon fuels;
    - Developing more granular estimates of the additional costs which would be faced in shifting to zero-carbon fuels today;

    - Describing how these might be reduced through research, development and large-scale production;
    - Identifying the possible impact of increased fuel costs and other additional costs (capital costs, revenue loss due to space taken by energy storage…) on freight rates.
- **Define and agree the key policies needed** to ensure that the 50% target will be achieved, considering in particular:
    - The gradual tightening of the Energy Efficiency Design standard for new built ships;
    - The imposition of a similar energy efficiency standards to be applied to existing ships;
    - The imposition and gradual increase of a carbon tax on heavy fuel oil imposed across the world and/or at the most significant refueling ports;
    - The enforcement of an international "green fuel" mandate, requiring shipping companies to use a gradually increasing percentage of low-carbon fuels, with companies which fall below the percentage purchasing "offsets" from other companies overachieving the target.

GOVERNMENTS AND REGIONAL COALITIONS: LEADERSHIP BEYOND THE INTERNATIONAL STANDARD

While there are limits to how far national governments can impose carbon taxes or fuel mandates without provoking some shift in refueling location, there are still wide degrees of freedom for national governments or regional organizations, such as the European Union, to take measures ahead of international agreement.

Coalitions of governments could therefore:

- Impose tight regulatory standards and green fuel mandates on domestic or regional Ropax, river freight, coastal and shorter-distance freight and cruise ships, seeking to make these sectors the drivers of innovation and early adoption of low/zero-carbon solutions;
- Impose modest carbon taxes on HFO picked up in major ports (e.g. Port of Rotterdam), setting tax rates which will provide a useful stimulus to early action but will not be sufficiently high to make avoidance strategies economic;
- Provide support (potentially financed from such taxes) for research, development and early deployment of technologies which can reduce the eventual costs of decarbonization.

C.INDUSTRY COLLABORATION AND COMMITMENTS

Industry associations and major shipping companies can play a powerful role as agents of change not only by arguing for and supporting strong action by the IMO, but also by:

- Defining sub-sectoral (e.g. for cruising) or regional specific roadmaps to achieve more rapid progress than required by IMO agreements and regulations;
- Defining investment guidelines to help investors distinguish between investments that are Paris compatible and those that are not, to channel financing to lower-carbon investment;
- Supporting research, development and early deployment of key technologies.

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