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ISWG-GHG 3/3
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FURTHER CONSIDERATION OF HOW TO PROGRESS THE MATTER OF REDUCTION OF GHG EMISSIONS FROM SHIPS

The costs of GHG reduction in international shipping

Submitted by IMarEST

SUMMARY

Executive summary:	In order to contribute to the temperature goals of the Paris Agreement, a global emissions pathway is needed for international shipping in which emissions start declining as soon as possible. This can be achieved through a combination of energy efficiency improvements and the use of low and zero-emission (GHG emission) technologies and fuels. This document discusses recent evidence on several different zero-emission technologies and fuels, and examines their relative competitiveness for implementation from 2030. The document also examines recent evidence on the production and prices for key zero-emission fuels, and uses this to produce updated Marginal Abatement Cost Curves (MACC). The results show that the prices of zero-emission fuels are likely to dominate the cost of decarbonization of international shipping, and that depending on how prices evolve for renewable electricity in coming decades, 100% absolute reduction of shipping GHG by 2050 appears achievable for a marginal abatement cost of 100 to 500 US$/t.
Strategic Direction, if applicable:	3
Output:	3.2
Action to be taken:	Paragraph 44
Related documents:	MEPC 71/WP.5; MEPC 65/5/1; ISWG-GHG 2/4 and ISWG-GHG 1/INF.2

Introduction

1 ISWG-GHG 1 and MEPC 71 undertook initial discussions on the IMO Roadmap. Document MEPC 71/WP.5 describes the discussion on among other topics "costs and benefits". On this topic, the group agreed (paragraph 37.1) that:

> "[…] there is a need for information on updates on the MACC to have an understanding of the cost and development of technology and low-carbon fuels […]"

2 This document is a continuation of the submission ISWG-GHG 2/4 which presented some of the evidence from literature, as well as some initial findings from ongoing work on the technologies and fuels for the decarbonization of international shipping, in order to understand potential costs associated with the decarbonization of international shipping.

Energy efficiency, renewable energy and zero-emission fuels

3 There are a multitude of technical and operational modifications that can be applied to reduce the carbon intensity of shipping. These can be approximately divided between two groups: improving energy efficiency and reducing the carbon factor of the energy source.

4 Improving energy efficiency for a given size and type of ship is ultimately limited by the laws of physics. The hydrodynamic resistance of a hull, the efficiency of a propeller and the efficiency of an internal combustion engine are impossible to improve beyond certain limits (i.e. the laws of physics and thermodynamics). As those limits are approached, the improvements have increasingly diminishing returns, and become challenging from a cost-effective perspective. So whilst every effort should be made to identify and incentivize further improvements in energy efficiency to reduce the amount of energy needed in shipping, efficiency improvements alone cannot decarbonize shipping.

5 The ultimate cost of the decarbonization of international shipping is partly influenced by the cost of energy efficiency technologies, but is ultimately capped by the cost of the zero CO_2 emissions fuels and technologies as also indicated in document ISWG-GHG 2/4.

6 For these reasons, this document focuses on the estimation of the potential future costs of zero CO_2 emission fuels and technologies. It is recognized that depending on the specification, there can be other operational and upstream emissions and that these also need to be taken into consideration, as they have been in a number of studies, including document ISWG-GHG 1/INF.2. For brevity and because of the focus on CO_2 emissions as the dominant source of shipping's GHG and climate impact, this document will refer generically to these options as "zero-emissions".

Candidate zero emissions fuels and technologies

7 Recent activity in the shipping industry illustrates a number of different candidate zero emissions fuels and technologies that the sector considers could be viable. A non-exhaustive but illustrative list of activity is provided in table 1.

Table 1: Examples of recent activity in the shipping industry, related to zero emissions fuels and technologies

Type of Activity	Parties	Nature of activity
Shipowner Activity and Ship Designs	CMB	The **Hydroville** was launched in 2017 and is the first passenger shuttle that has received class approval to operate with diesel and hydrogen.
	Caledonian Maritime Assets Ltd	CMAL have undertaken a feasibility study and are actively involved in the continued project development for the operation of a zero emission ro-pax ferry to operate with hydrogen and fuel cell technology.
	Energy Observer	The **Energy Observer** was launched in 2017 and is the first autonomous zero emission and energy self-sufficient hydrogen-powered catamaran.
	FutureShip	FutureShip have developed a zero emission passenger ferry concept design that is intended to operate within the Baltic, incorporating hydrogen and fuel cell technology in addition to wind energy harvesting systems.
	Germanischer Lloyd	The "ZERO" is a zero emission container feeder ship concept design that is intended to operate in Northern Europe with liquid hydrogen and fuel cell technology.
	Hangzhou Modern Ship Design & Research Company	The construction of a zero emission, fully electric, battery-powered inland bulk cargo ship has been completed by the Guangzhou Shipyard Company International, which is intended to operate on an inland section of the Pearl River.
	Nippon Yusen Kaisha (NYK) Line	The "Super Eco Ship 2030" is a container ship concept design that achieves an overall CO_2 emissions reduction of 69% and is intended to provide a development basis for a zero emission ship by 2050.
	Norled	The **Ampere** commenced commercial operations in 2015 within the Sognefjord and is a zero emission, fully electric, battery-powered car and passenger ferry, constructed by the Fjellstrand Shipyard of Norway in collaboration with Siemens and Norled.
	Sandia National Laboratories	Sandia National Laboratories have undertaken feasibility studies for the design, construction and operation of a zero emission high speed passenger ferry, the "SF-BREEZE", and a coastal class research vessel, the "ZERO/V", both of which operate with hydrogen and fuel cell technology.
	Stena Line	The **Stena Germanica** was made operational in 2015 following conversion, servicing the route between Gothenburg and Kiel, and is the first ro-pax ferry to operate with methanol as an alternative fuel.
	Viking Cruises	Viking Cruises has announced the intention to build the World's first cruise ship to operate with fuel cell technology and liquid hydrogen, in collaboration with the Norwegian Maritime Authority.
	Yara International & Kongsberg	The **Yara Birkeland** is a zero emission, fully electric, battery-powered autonomous feeder container ship that is intended for construction and operation during 2018.

	Wallenius Wilhelmsen Logistics (WWL)	The "E/S Orcelle" is a zero emission car carrier concept that is designed to operate exclusively with renewable energy sources, including wind, solar and wave power, in addition to hydrogen and fuel cell technology.
Machinery and Fuels	ABB	ABB have been involved in a number of activities and associated projects, including the following; The development of measures for the reduction of port area emissions, through the provision of shore-to-ship power solutions. The development of electric power and propulsion systems and conversion of the **Tycho Brahe** and **Aurora** to zero emission, fully electric ferries. The development of fuel cell technology for application within the maritime environment, with a pilot system intended for installation on board a cruise ship.
	e4ships	e4ships - fuel cells in marine applications is a cooperative venture between leading researchers, manufacturers, shipyards and operators within Germany, with the intention to drive polymer electrolyte membrane and high temperature fuel cell technology development through projects such as "Toplaterne", "Pa-X-ell" and "SchIBZ".
	Engie	Engie has announced the intention to make the necessary alterations to all commercial gas operations to enable the adoption of second generation biogas and renewable hydrogen by 2050, the company being currently involved in a considerable number of international biogas projects and having expressed an interest in the commercial production of hydrogen through electrolysis in areas that have a suitable solar energy availability potential.
	FellowSHIP Project	The "FellowSHIP" project is a joint industry research and development undertaking with the intention to develop fuel cell technology as a method of propulsion, resulting in the incorporation of a molten carbonate fuel cell within the duel fuel diesel electric propulsion plant of the "**Viking Lady"**, capable of operation on liquefied natural gas and reconfiguration for methanol.
	GoodFuels	The provision and supply of sustainable second generation biofuels to the maritime industry, which are produced from waste or residue feedstock and do not influence competition for land use.
	ITM Power	ITM Power is a hydrogen technology provider that specializes in the manufacture of integrated hydrogen production systems that utilize renewable energy sources, such as electrolysers powered by tidal energy, with an aim of provision of hydrogen within ports for the supply of maritime transportation.
	Kawasaki Heavy Industries & Royal Dutch Shell	Kawasaki Heavy Industries have formed a partnership with Royal Dutch Shell for the development of the ships and technology necessary for the maritime transportation of hydrogen, with the intention to launch a pilot operation by 2020.

	Norsepower	Suppliers of the Norsepower Rotor Sail Solution, a form of auxiliary wind propulsion device that has been developed from the Flettner Rotor, that achieves fuel and emission reductions by enabling available wind energy to be harnessed by the vessel.
	Royal Dutch Shell & ITM Power	Confirmation of a joint project between Royal Dutch Shell and ITM Power was announced at the beginning of 2018 for the construction of the World's largest hydrogen electrolysis plant, a 10MW polymer electrolyte membrane electrolyser, to be located at the Rhineland Refinery in Germany.

8 Partly informed by this recent activity, a study by Lloyds Register and UMAS entitled *Zero-emission vessels 2030. How do we get there?* sought to explore how competitive some of these candidates were, and what might still be needed if they were to be developed by 2030. The study developed detailed assumptions on the specifications and costs of seven combinations of zero emissions fuels and machinery that had the potential to become available to shipping following further R&D from 2030. These are listed in table 2. Specifications were worked up for each of the seven fuel and machinery combinations for five case study ship types and sizes, as listed in table 3.

Table 2: The seven potential zero-emission fuel and machinery combinations considered

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

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

Table 3: The five ship types and sizes considered as case studies for the study

Ship type	Bulk carrier	Containership	Tanker	Cruise	RoPax
Representative ship size category	53,000 dwt	9,000 TEU	110,000 dwt	3,000 dwt	2,250 dwt

9 The study was not intended to be exhaustive, but to use an investigation of some of the potential options in order to get indicative information on cost. There are many further options that were not considered. These include the use of wind-assisted technology as a source of renewable power, the use of other "power to liquid" fuels which are manufactured rather than extracted, and the use of carbon capture on board a ship in combination with a fossil fuel, with its subsequent storage. Depending on how these technologies develop over time, they could become significant in setting the cost of shipping's decarbonization.

10 Biofuel is one option for which it is difficult to define equivalence to a synthetic zero CO_2 emission fuel, given issues related to the sustainability and carbon intensity of its production and transportation. For the purposes of the study it was assumed equivalent to non-carbon fuels, and that it could meet strict sustainability specifications enabling it to achieve "net zero" CO_2 emissions whereby CO_2 emissions emitted during combustion were cancelled out by CO_2 absorbed in production (the growth of biomass).

11 Taking into account the capital cost of machinery, the capital cost of fuel storage, the lost cargo carrying capacity (due to additional volume/weight of fuel needed), and fuel prices, the study analysed the profitability of these different options for each ship type. Assumptions were derived both from currently available data in the industry and academic literature on performance specifications, costs and prices, and some conservative projections of how these costs and specifications might evolve by 2030. Details on the derivation of assumptions can be found in the LR and UMAS study *Zero-emission vessels 2030. How do we get there?* Three different scenarios were defined across which a variation of assumptions were incorporated in order to represent the uncertainty. Under the different scenarios of assumptions used, and across the range of ship types considered, the relative profitability of these options can be seen in figure 2.

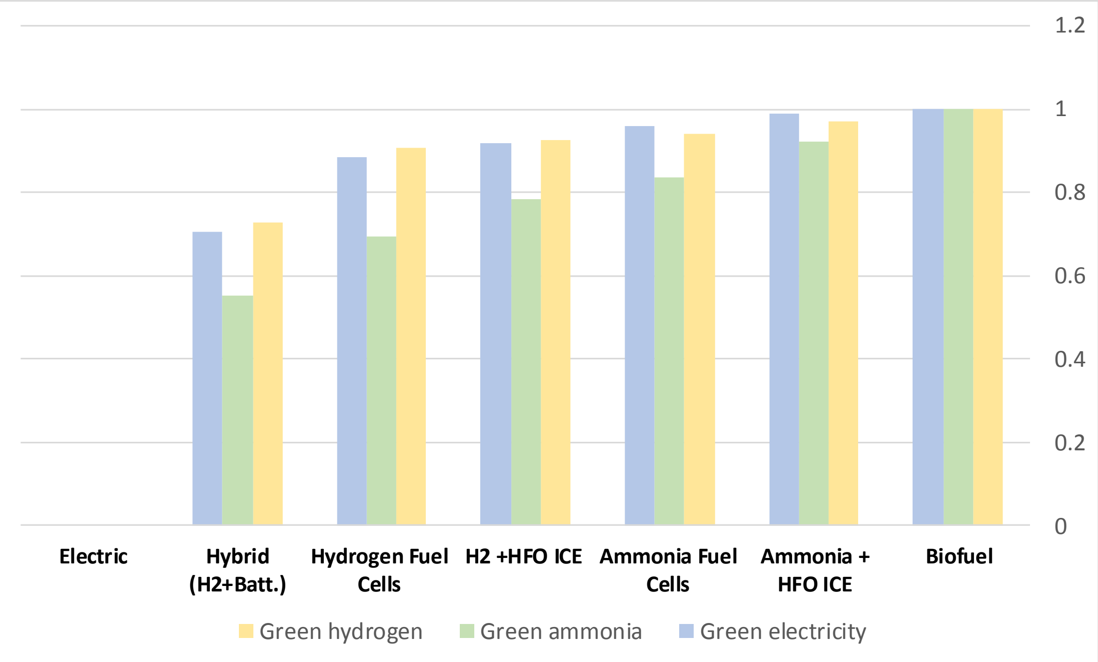


Figure 2: The relative profitability of seven zero emissions options in three scenarios defined in the study and representing different projections on the future costs of fuel and technology. Definitions of machinery and fuel combinations can be found in table 2. Profitability is calculated relatively to biofuel (normalized to 1).

12 Biofuel consistently appeared to be the most profitable and therefore competitive option, with the synthetic fuels of ammonia and hydrogen appearing to be second most competitive. Full electric and hybrid hydrogen (hydrogen fuel cell and battery electric) appeared consistently the least competitive, at least for the ship types considered.

13 The conclusion that battery-electric propulsion appears to be least competitive could be considered counter-intuitive when looking at some of the electric ships currently entering into service. The explanation for this result in the study is predominantly due to the range requirements of the ships considered (endurance on one "tank" of fuel) and the capital costs of the batteries required to achieve this range – ships' ranges were considered to be equivalent to those of ships designed today. Ships with battery-electric propulsion as a cost-competitive solution are all comparatively short-range to the predominantly deep-sea ships considered in the study. Variations in the assumption on a ship's range were applied and showed that this could improve the relative competitiveness of battery solutions. It is also not inconceivable that progress on materials science and technology developments could further reduce battery capital costs.

14 Whilst hydrogen is well known as a potential future marine fuel, ammonia is less known and an interesting result was that for certain ship types, ammonia appears to outperform hydrogen. Ammonia (NH_3), is in essence a hydrogen rich molecule and "vector" of hydrogen's chemical energy. One of the explanations for ammonia outperforming hydrogen in profitability terms was the fact that the capital costs for storage of the quantities needed on board were significantly lower. Hydrogen must either be stored as a high pressure gas, or in liquid form (at similar but even lower temperatures than LNG). Ammonia on the other hand can be stored in liquid form at low pressure.

15 Capital cost estimates for all systems were obtained using the best available estimates from current literature. The actual costs will be strongly dependent on further marine-specific R&D. Strong potential for future capital cost reduction is possible, especially on emerging fuel cell and catalyst technologies.

16 Whilst all the zero emissions propulsion solutions were theoretically considered technologically viable, none appeared to be as economically competitive as the baseline conventional propulsion systems (HFO/MDO and internal combustion engine) under the projected 2030 assumptions and scenarios considered. Capital costs were the key factor determining the relative profitability of battery-electric, hydrogen and fuel cell propulsion solutions relative to conventional propulsion. Fuel costs were the key factor determining the relative profitability of biofuel and ammonia relative to conventional propulsion.

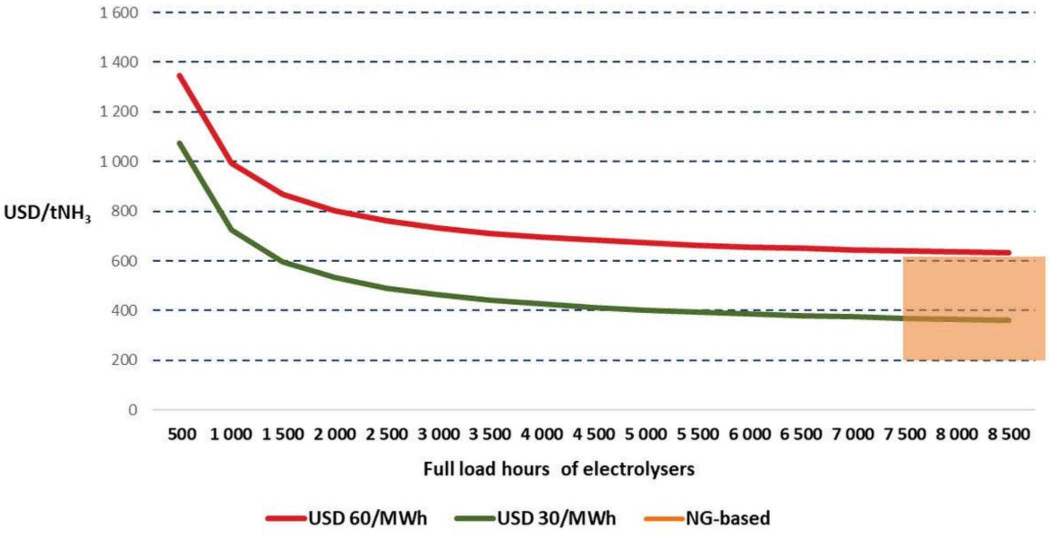
Zero-emission production of zero-emission fuels, and associated cost scenarios

17 A significant and justified concern associated with the adoption of any alternative marine fuel is the risk of increased life-cycle emissions relative to current marine fuels, e.g. increased emissions associated with upstream and downstream fuel production and disposal processes. Biofuel, ammonia, hydrogen and electricity are all currently often dependent on fossil fuel whether directly as a feedstock or as an energy source for production and transportation processes.

18 Ammonia and hydrogen are both produced by chemical processes for which a fossil fuel (most often natural gas) is the feedstock, and therefore significant CO_2 emissions can occur upstream from their use due to their production. Similarly, electricity, if produced from fossil fuels, can have a significant upstream CO_2 emissions. All these production processes could theoretically be coupled to Carbon Capture and Sequestration (CCS) technology as a means to continue to use fossil fuels whilst reducing upstream CO_2 emissions.

19 Alternatively, ammonia, hydrogen and obviously electricity can also all be produced from 100% renewable or nuclear energy. Ammonia and hydrogen can both be produced through electrolysis, a process for which only water, air and electricity are the required inputs. The combination of decarbonization policy in the wider energy system, and the increasingly low cost of renewable electricity, is already making "green" zero-upstream-emissions versions of these fuels competitive to their alternative fossil-derived production processes.

20 The recent OECD/IEA report *Renewable Energy for Industry* analysed the potential costs of production of both "green" renewable electricity derived hydrogen and ammonia to understand the costs associated with replacing their current fossil-dependent processes. It was found that for both of these potential fuels, cost scenarios were bounded by renewable electricity prices. Furthermore, the report identifies the potential for even lower cost production of these fuels when very low marginal price electricity was available from electricity grids with high renewables penetration (e.g. due to unmanageable variability in the availability of wind and solar).



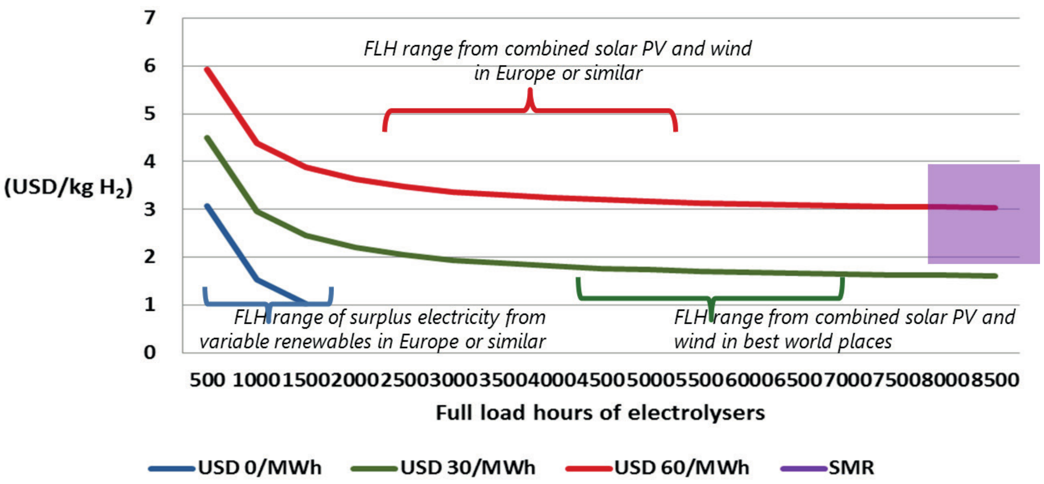


Figure 3: The cost of hydrogen and ammonia production at various electricity prices and electrolyser load factors

Source: figure 7, page 28 and figure 12, page 33 of *Renewable Energy for Industry*, IEA/OECD, 2017

21 Currently global hydrogen production is approximately 60 Mt/y, and global ammonia production is approximately 150 Mt/y (~20 Mt/y is traded by ship). As well as a shift to zero-emission production, the volumes produced would need to scale up to become significant bunker fuels (given expected continued demand from industry). The geographical potential for scalability of production of renewable hydrogen and ammonia, whether for use as a bunker fuel near the point of production, or for transport/trade for bunkering elsewhere, can be seen in figure 4.

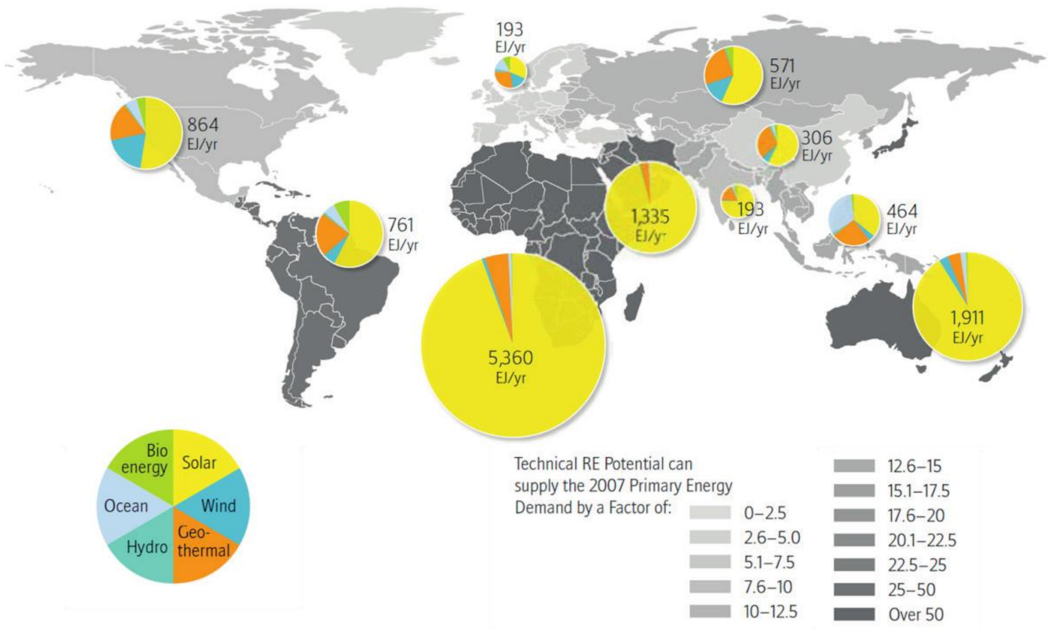


Figure 4: renewable energy potential in various parts of the world
Source: figure 20 page 52 of *Renewable Energy for Industry*, IEA/OECD 2017

Updated calculations of shipping sector MACCs

22 In order to gain some insight into the cost of the decarbonization of international shipping, assumptions were derived from the above studies in order to update estimates of international shipping's MACC.

23 The method used was to calculate the MACCs which followed the most detailed and reliable method as described in ISWG-GHG 2/4: "using simulation models that estimate the future technological and operational development of shipping by estimating the combination of modifications selected over time, and the evolution of the global fleet, in response to both regulatory and market conditions". The specific model used is GloTraM, which has been used in multiple earlier submissions including documents ISWG-GHG 1/INF.2 and ISWG-GHG 2/4. A detailed description of the modelling method, assumptions and some more detailed results from similar scenarios can be found in document ISWG-GHG 1/INF.2.

24 The model used (GloTraM) includes assumptions on the cost and performance of most currently known options for energy efficiency improvements, as well as a variety of alternative machinery (e.g. fuel cells, electric motors, etc.) and alternative fuel options. Ship operating speed is also a parameter that is used within the model, so the average speeds of different ship types are calculated and can increase or decrease. Investment and operational (speed) decisions are modelled for each ship type, size and age category, which potentially could maximize a shipowner's profits under a given regulatory and macroeconomic environment.

25 The MACCs are formulated as a composite for absolute GHG reduction on 2008 levels of CO_2 emissions for five ship types (container ship, oil tanker, bulk carrier, chemical tanker, gas carrier) for the years 2030 and 2050. The input assumptions listed for the scenarios in some instances contain projected cost reductions of certain technologies (in 2030) taken from current literature. Beyond this, the MACC model and analysis does not assume any technology cost learning for the machinery/technologies due to e.g. the increase in production volumes, or as a consequence of further R&D and technological developments. They can therefore be considered likely to be conservative estimates of the abatement cost.

26 Significant uncertainty remains on the overall availability of sustainable biofuel, prices of fuels (conventional fossil fuels and alternative zero-upstream / zero-emissions fuels), and the capital costs of equipment. Therefore a number of different sets of assumptions were derived as foreseeable scenarios and are listed in table 4. Global experts in this field have high agreement on the sustainable availability of a total of 100 EJ's of biofuel by 2050 (see http://onlinelibrary.wiley.com/doi/10.1111/gcbb.12205/full). The scenarios test two different levels of availability for international shipping – a central case (4EJ), and a high case (11EJ).

Table 4: Scenarios and assumptions

	2030			2050		
	Bio avail (EJ)	**FO price $/t (HFO, MDO, LSHFO, LNG)**	**Other fuel price $/t (H2, NH3)**	**Bio avail (EJ)**	**FO price $/t (HFO, MDO, LSHFO, LNG)**	**Other fuel price $/t (H2, NH3)**
Scenario A (bio central, high fuel price & capex)	1.71	514, 747, 598, 546	3,025, 666	4	664, 943, 754, 744	3,764, 829
Scenario B (bio high, high fuel price & capex)	4.7		1,857, 338	11		2,311, 421
Scenario C (bio central, low fuel price & capex)	1.71		1,857, 338	4		2,311, 421
Scenario D (bio high, low fuel price & capex)	4.7		3,025, 666	11		3,764, 829

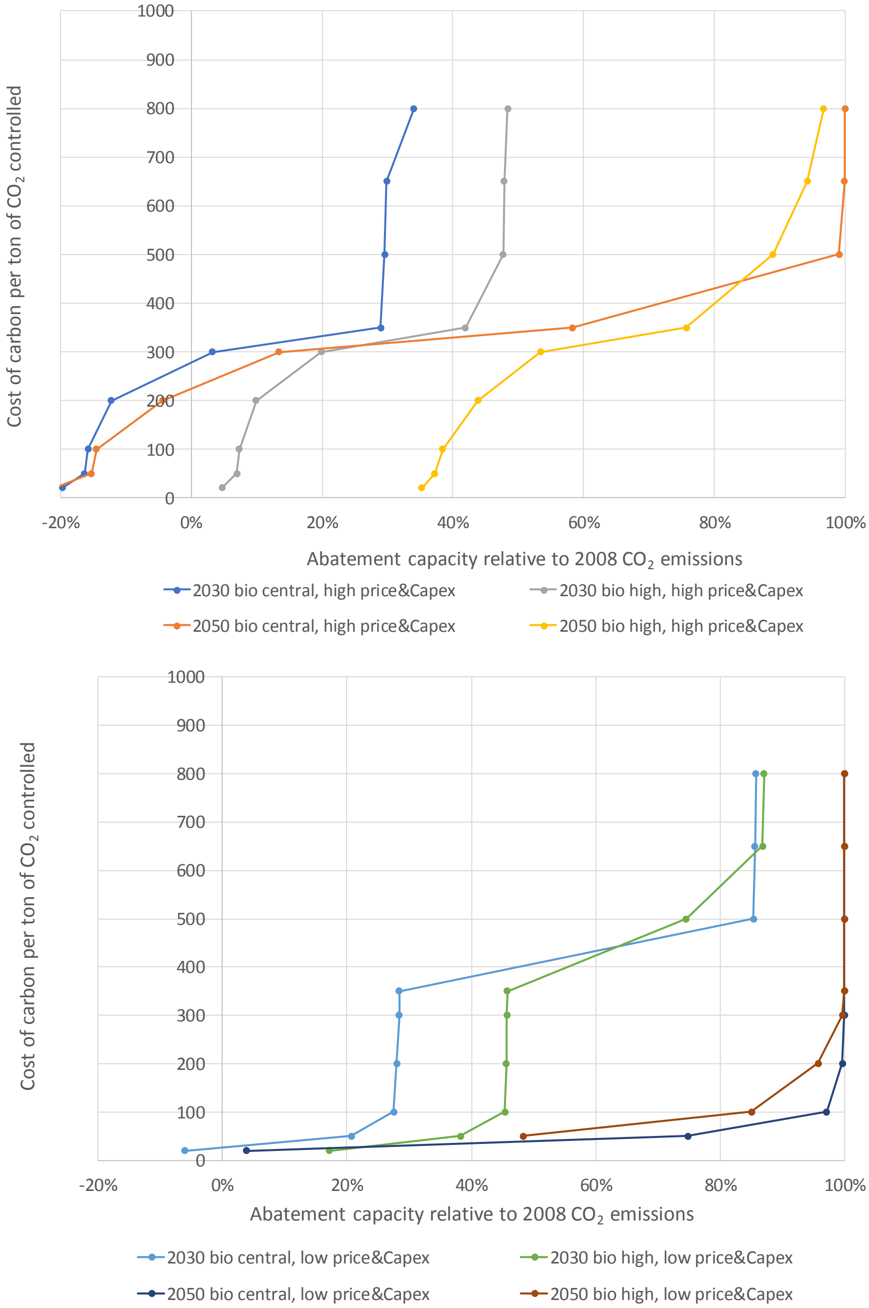


Figure 5 – Results for the MACC (in US$/t) produced using GloTraM and under different scenario assumptions, as listed in table 4

27 Figure 5 shows the estimated MACCs. The shapes of the MACCs in figure 5 are consistent with the shape of the MACC in figure 2 of document ISWG-GHG 2/4 in a way that after initial increases in abatement cost, the cost curve reaches a "plateau" at a value which represents the carbon price needed to make zero-emissions technologies competitive with conventional propulsion.

28 In Scenario A, which has the most challenging input assumptions for decarbonization (central estimate of bio energy availability and high fuel price and capex), emissions in 2030 and 2050 start higher than in the baseline year 2008, consistent with expectations that for BAU scenarios CO_2 emissions from international shipping are expected to increase (MEPC 67/INF.3).

29 Significant absolute emissions reductions are achieved even at low marginal cost of carbon ($50/t), because of the assumption about the availability of bioenergy which in these scenarios is significant relative to international shipping's total demand for energy. In this modelling, bioenergy is assumed to enter the fuel mix as a substitute for fossil fuels and therefore at the same price as the fossil fuel equivalent and is not dependent on additional carbon price to stimulate its take-up.

30 These results are qualitatively consistent with the findings in document ISWG-GHG 2/4 that the shape of the MACC for shipping is monotonically increasing but with a "plateau" at which significant further CO_2 reduction is achieved with low increase in marginal carbon cost. Or in other words, that beyond a certain level of absolute GHG reduction, significant further GHG reduction can be achieved with only small increases in cost. This result is the consequence of the cost-ceiling associated with zero-emissions fuels and associated technology and machinery. This is importantly different from the MACCs produced earlier (e.g. in the *Second IMO GHG Study 2009*), which did not include zero-emissions fuels/technologies.

31 The MACC for 2030 shows a significant further increase in carbon price after the "plateau" which is associated with the cost of achieving very low or zero carbon intensity for the fleet built with conventional technology (e.g. the current specification of internal combustion engines) and without an expectation of having to achieve such high rates of decarbonization. The plateau occurs at the price point that the zero emission fuel/machinery becomes viable. For example, ships built before 2020, which would only be 10 years old in 2030. This finding highlights the risks for shipping if costly technology is incentivized now (for example LNG as a marine fuel), which ultimately is not economically viable throughout the life of the ship if it "locks" the ship into using fossil fuel at a time when the sector transitions away from fossil fuel, and therefore necessitates either premature scrappage or expensive retrofitting.

32 The MACCs for 2050 consistently show that given a 30 year lead time (e.g. from 2020 to 2050), greater than 90% absolute GHG reduction is possible, with a negligible marginal cost increase, relative to achieving 40% absolute GHG reduction.

33 The results show that in scenarios where higher amounts of sustainable biofuels are available to shipping at the prices assumed, marginal carbon costs are lower for the same level of absolute GHG reduction. However, even if there is not high availability of biofuels, high levels of absolute GHG reduction are possible.

34 Beyond the input assumptions, the modelling approach used in GloTraM, does not incorporate any cost reductions resulting from R&D spent, innovation or from the increased production of technologies. In this respect, the model is conservative and as these are all factors that would normally be expected to reduce technology capital costs, and zero-emission fuel production costs would be expected to reduce the magnitude of the marginal abatement costs as calculated. Specific examples of the scale of cost reduction over time, which have become apparent in many low carbon technologies, can be found in document ISWG-GHG 2/4.

35 The different scenarios show significant variations in marginal carbon cost, and the potential for shipping's decarbonization to be significantly lower cost than the initial estimated in document ISWG-GHG 2/4. This shows the sensitivity of the MACCs to assumptions used about the prices of future shipping energy sources, particularly electricity, biofuel, hydrogen and ammonia. It also illustrates how rapidly the evidence is evolving on how low these energy prices can become, as the energy system increasingly shifts towards renewable energy sources.

Concluding remarks

36 Improving ship's energy efficiency and increasing the use of alternative low and zero-emission marine fuels are essential for shipping's decarbonization. The exact combination of these options, and the pathway for the sector remains uncertain. However, scenario analysis and modelling can help to produce some guidance on the range of marginal abatement costs that can be expected for a range of levels of CO_2 reduction.

37 Several specific zero emissions fuels and technology options exist for ships. These include hydrogen and ammonia either with fuel cells or combustion engines, biofuels and batteries and motors. The options were studied in detail for several case study ship types in a recent study by LR and UMAS.

38 Whilst all the zero-emission propulsion solutions were theoretically considered technologically viable by 2030, none appeared to be as economically competitive as the baseline conventional propulsion systems (HFO/MDO and internal combustion engine) under the projected 2030 assumptions and scenarios considered. Capital costs were the key factor determining the relative profitability of battery-electric, hydrogen and fuel cell propulsion solutions relative to conventional propulsion. Fuel costs were the key factor determining the relative profitability of biofuel and ammonia relative to conventional propulsion.

39 Some of these options for zero-emission propulsion may have safety or other emissions (e.g. air pollutant) issues which will need detailed consideration as they are further developed. This emphasizes the need for an approach that considers GHG reduction in parallel to safety, sustainability and air quality.

40 Since the LR and UMAS analysis, further evidence has become available for potential fuel price scenarios for two of the key fuels studied: ammonia and hydrogen. These price scenarios show that developments in renewable electricity and electrolysis enable production of zero-emission production of zero-emission fuels ammonia and hydrogen at prices competitive with, and in some circumstances, lower than the prices currently available by using fossil fuel feedstocks.

41 Incorporating both the work from the LR and UMAS analysis of zero-emissions fuel and machinery options for shipping, and the recent evidence on renewable ammonia and hydrogen price scenarios, a family of MACCs were produced using the model GloTraM. The results confirm earlier findings that shipping's decarbonization pathway and cost is likely to be largely defined by the costs of zero-emission fuels and technologies.

42 The findings show that 70 to 100% absolute reductions in GHG emissions by 2050 can be achieved for a marginal carbon cost currently conservatively estimated to range from 100 to 500 US$/t, depending on the scenario.

43 The lower bound marginal carbon cost scenarios for shipping under high levels of ambition GHG reduction, are more consistent with those carbon prices estimated in recent literature (ISWG GHG 2/4), for the economy as a whole (80 to 100$/t in 2030).

Action requested of ISWG-GHG 3

44 The Group is invited to note the information provided in this document and take action as appropriate.