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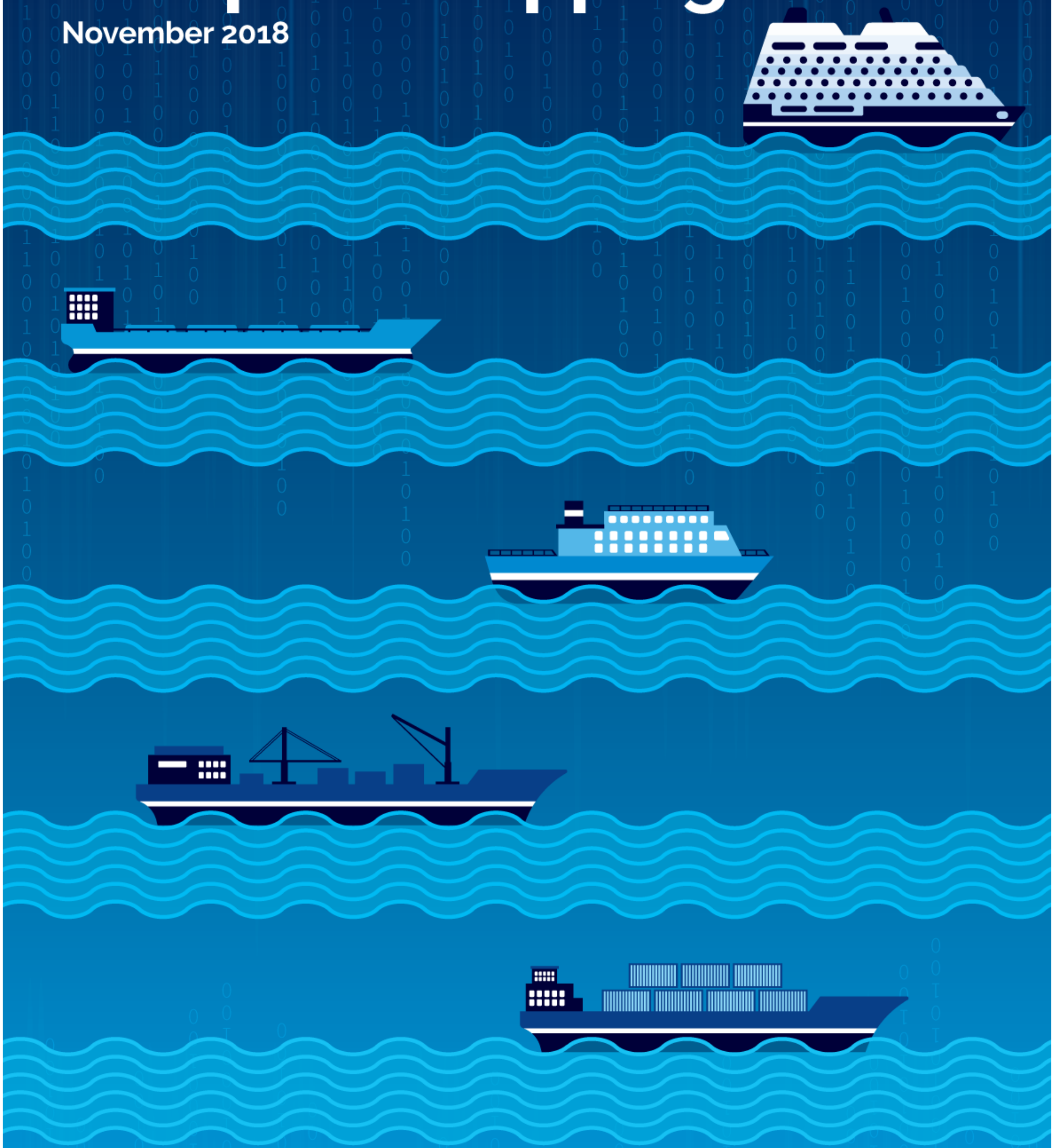
Roadmap to decarbonising European shipping

November 2018



a study by
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Executive Summary

Shipping is one of the largest greenhouse gas (GHG) emitting sectors of the global economy, responsible for around 1 Gt of CO_2eq every year.[1] If shipping were a country, it would be the 6th biggest GHG emitter. EU related shipping is responsible for about ⅕ of global ship GHG emissions, emitting on average 200 Mt/year.[2] This report assesses potential technology pathways for decarbonising EU related shipping through a shift to zero carbon technologies and the impact such a move could have on renewable electricity demand in Europe. It also identifies key policy and sustainability issues that should be considered when analysing and supporting different technology options to decarbonise the maritime sector. The basis of the study is outbound journeys under the geographical scope of the EU ship MRV Regulation.

We have not tried to quantify the emissions reductions that specific regulatory measures to be introduced at the IMO or EU level might contribute towards decarbonisation by 2050 because there are too many uncertainties. We have taken a more limited first approach and investigated how zero carbon propulsion pathways that currently seem feasible to decarbonise shipping, would likely affect the future EU renewable energy supply needs.

It is now generally accepted that ship design efficiency requirements, while potentially having an important impact on future emissions growth, will fall well short of what is needed. Further operational efficiency measures, such as capping operational speed, will be important to immediately peak energy consumption and emissions, but will be insufficient to decarbonise the sector or reduce its growing energy needs. In this context, this study assumes that with all the likely immediate measures adopted, energy demand for EU related shipping will still grow by 50% by 2050 over 2010 levels. This is within the range of the 20-120% global BAU maritime energy demand growth estimate.[3]

The decarbonisation of shipping will require changes in on-board energy storage and use and the necessary accompanying bunkering infrastructure. This study identifies the technology options for zero emission propulsion that, based on current know-how, are likely to be adopted. It is not exhaustive nor prescriptive because the ultimate pathways will likely depend on both the requirements of the shipping industry in terms of cost, efficiency and safety, and on the future renewable electricity sources that the shipping sector will need to compete for.

Literature is nascent on the different techno-economic options likely to be available to decarbonise shipping and individual ships[4], but almost completely lacking on the possible impacts of maritime decarbonisation on the broader energy system(s). Understanding these impacts is nevertheless essential, because it will influence financial and economic decision making by the EU and member states, including those related to investment in future renewable energy supplies and new ship bunkering infrastructure.

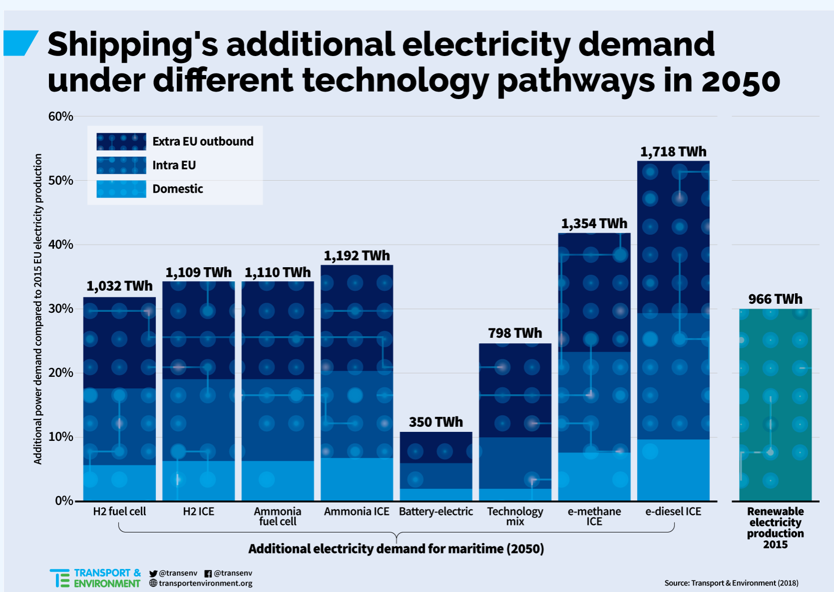
With this in mind, the report aims to provide a preliminary first answer to the following question: Under different zero emission technology pathways, how much additional renewable electricity would be needed to cater for the needs of EU related shipping in 2050?

[1] 3rd IMO GHG study, 2014.
[2] Ricardo-AEA, Technical annex: support for the impact assessment of a proposal to address maritime transport greenhouse gas emissions, Ref: CLIMA.B.3/SER/2011/0005, 2013.
[3] CE Delft, Update of Maritime Greenhouse Gas Emission Projections, 2017
[4] E.g. Zero-Emission Vessels 2030. How do we get there?, Lloyd's Register & UMAS, 2017; Decarbonising Maritime Transport by 2035, ITF, 2018.

Main findings & recommendations

Maritime transport is only one of the many sectors of the European economy that will need to rely on renewable energy in order to decarbonise. Together with other sectors, shipping will add additional stress on European renewable electricity production, around the order of magnitude of the current EU power sector, which itself is yet to fully decarbonise. It is therefore essential in our view that any regulatory and economic policies to support any of the shipping technology pathways analysed in this report take account of this impact and prioritise those minimising the impact on renewable energy demand while maintaining the highest sustainability criteria. From this viewpoint:

- We recommend to prioritise battery-electric and hydrogen (pure and/or in the form of ammonia) technologies from sustainable renewable sources to decarbonise shipping. Although battery-electric propulsion appears to be the most efficient use of primary energy, a tech mix - battery, hydrogen, ammonia - is a more likely pathway for the different segments of EU shipping - domestic, intra-EU and extra-EU. Varying combinations of battery-electric and carbon-free fuels are likely to be pursued depending on the available renewable energy.
- Even though a technology mix of batteries, liquid hydrogen and ammonia appears to be an optimal solution, the impact on the future EU renewable electricity production should not be underestimated. A very considerable level of additional investment will be required not only in the renewables sector, but also in electricity transmission grids, shore-side charging stations, hydrogen/ammonia production plants, new ship propulsion and energy storage designs and the widespread provision of new port bunkering infrastructure. This speaks to the absolute necessity of including maritime transport in the development of an EU 2050 economy-wide decarbonisation strategy and the subsequent financial, investment and regulatory decisions that will be needed.
- The complete decarbonisation of EU-related shipping in 2050 would require 11-53% additional renewable electricity generation across the EU28 over the 2015 levels. This range is estimated on the assumption that EU maritime emissions will grow by around 50% between 2010 and 2050, taking into account the deployment of a range of short & mid-term measures, EEDI & SEEMP, speed reduction and wind propulsion.



- In the technology mix pathway, which under T&E assumptions uses liquid hydrogen and liquid ammonia in addition to battery electric propulsion, decarbonising EU shipping would require around 25% of additional electricity generation over and above the EU 2015 levels.
- In terms of different segments of EU related shipping, the least additional renewable electricity demand would likely be associated with EU short-sea shipping (SSS) - ships mostly engaged in domestic and some intra-EU shipping. Ostensibly, this is due to smaller ships and shorter individual journeys associated with SSS. This suggests that immediate EU regulatory focus on decarbonising SSS would be preferable in order to smooth the transition to zero emission shipping with gradual increase in additional renewable electricity demand.
- The least additional demand on renewable electricity supply would likely be associated with decarbonising EU short-sea shipping (SSS). These are typically smaller ships mostly engaged in coastal shorter individual journeys. The technology is readily available to start this process and range can be extended as technology matures. Such an initial focus would be preferable by involving a more gradual increase in additional renewable electricity demand.
- We found the least energy efficient technology pathways to decarbonise shipping to be those based on synthetic hydrocarbons - electro-methane and electro-diesel, using CO_2 from air capture. These pathways would require around 42% and 53% respectively of additional renewable electricity generation in the EU28 over 2015 levels.
- In addition, since synthetic methane and synthetic diesel would still emit GHG at the vessel level, the practical enforcement of their use under any emission reduction requirement could be very challenging, if not impossible for port/flag authorities. This because these synthetic fuels have very similar chemical characteristics to their fossil equivalents making it very difficult to easily distinguish between them (especially when blended); and since synthetic fuels are an order of magnitude more expensive than their fossil equivalents, the large price difference would provide a strong incentive for operators to cheat on any regulatory requirement to use these synthetic fuels thus creating a large competitive distortion.
- Furthermore, the theoretical climate neutrality of synthetic methane would not be achieved if, as with LNG, methane leakage and slip were to take place during the transportation, bunkering and on-board combustion of the fuel. Technology pathways delivering zero GHG emissions at the vessel level would seem to be preferable.
- There are also implications for the current investment in fossil LNG bunkering infrastructure for ships, which it is claimed could be used in the future for synthetic methane bunkering. Since synthetic methane is one of the least sustainable and enforceable technology pathways for shipping, this report also warns against public investment in LNG bunkering infrastructure with the hope that it would underpin synthetic methane uptake in the future.
- Although this report hasn't quantified biofuel pathways for shipping, the enforcement and sustainability problems we have identified involving synthetic methane seem to be applicable to biofuels, too. Shipping's unique global refuelling patterns make it impossible to apply strict sustainability criteria for biofuels nationally/regionally due to the "collective action" problem and the mobility of bunker fuel suppliers in avoiding strict regulation. Port-state control of sustainability would be problematic too, as sustainable and non-sustainable biofuels would have similar apparent physical properties and be difficult to differentiate without mass spectrometry analysis in high-tech laboratories. The latter are not necessarily at hand everywhere and it would be economically unsustainable to test every ship. Blending and mixing along the fuel supply chain and tank mingling with other fuels, would create even further difficulties for those port-state controls deciding to perform random checks. These all come in addition to sustainability and availability issues surrounding biofuels. Therefore, we recommend to reserve any available sustainable biofuels to the aviation sector.

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1. The problem

Transport is now the largest sectoral emitter of CO_2 and global shipping emitted almost 1 billion tonnes of GHG in 2015, equal to 2.6% of all anthropogenic CO_2 emissions related to energy use. Shipping emissions have grown by some 70% since 1990 and are projected to increase by between 50% and 250% by 2050.[5] This means that on a business-as-usual pathway, total shipping emissions could account for about 18% of worldwide greenhouse gas emissions by 2050.[6]

Shipping also emits a range of air and water pollutants causing a range of health and environmental issues. Ship engines, which predominantly burn heavy fuel oil (HFO), contribute to emissions of sulphur dioxides (SO_2), nitrogen oxides (NO_x) and particulate matter (PM). The latter includes soot/black carbon (BC), which is not only the second most powerful climate forcer after CO_2, but also particularly harmful to human health. Both NO_x and SO_x are precursors to secondary PM. NO_x is also a precursor of ground-level ozone (O_3), a gas that has severe negative impacts on human health. Sulphur oxide and sulphur dioxide (SO and SO_2) are toxic gases that are both harmful to human health, plant vegetation and the fabric of buildings. The Danish Centre for Energy, Environment and Health (CEEH) found that European ship emissions were responsible for around 50,000 premature deaths every year.[7]

Nitrogen oxides are formed during fuel combustion in the engine and have a significant eutrophication effect on freshwater bodies, soils and coastal areas. Studies show that ultrafine particles are the most health harming fraction of PM and are emitted in tremendous numbers when diesel is burnt with no exhaust after treatment[8], as is the case for shipping. The World Health Organization (WHO) published a report in July 2012 confirming that BC from diesel combustion is as carcinogenic as asbestos.[9]

2. The political context

Addressing ship emissions is complicated by long-standing lack of agreement at UNFCCC level on their attribution to countries. Ship emissions are currently reported as a memo item in inventories submitted to the UNFCCC based on national fuel sales. These reports do not correctly reflect emissions arising from ship voyages either departing or arriving at countries as oceangoing ships can travel for weeks before needing to refuel. This mobility prevents individual countries from imposing fuel taxes as ships can easily bunker elsewhere or from taking unilateral action on their registered ships as individual ships can change flag by simply sending an overnight email.

Harmonised regulation at the global level through the IMO is therefore regarded as the preferable approach. But with little real progress so far. The 1997 Kyoto Protocol Article 2.2 assigned responsibility to reduce maritime bunker emissions to Annex 1 countries working through the International Maritime Organisation (IMO) - a UN specialised agency, but it was only in November 2003 that the IMO Council tasked its Marine Protection Environment Committee (MEPC) to consider measures to control ship emissions as a matter of priority. In 2011 the IMO Energy Efficiency Design Index (EEDI) was agreed setting a mandatory energy efficiency standard for all new ships constructed from 2013. Following various studies[10] as to its efficacy, the IMO commenced in 2015 a review of elements of the EEDI's stringency. That review is ongoing and no changes have yet been made. The EEDI was agreed in 2011 amid parallel discussions on possible market

[5] 3rd IMO GHG Study, 2014.
[6] EP, Emission Reduction Targets for International Aviation and Shipping, 2016 [access link]
[7] Assessment of health-cost externalities of air pollution at the national level using the EVA model system (March 2011). By J. Brandt et al. CEEH Scientific Report No 3. Centre for Energy, Environment and Health [access link]
[8] Terzano, C. et al. (2010), Air pollution ultrafine particles: toxicity beyond the lung, European Review for Medical and Pharmacological Sciences, 14: 809-821; Bhardawaj, A. et al (2017), A Review of Ultrafine Particle-Related Pollution during Vehicular Motion, Health Effects and Control, Journal of Environmental Science and Public Health, 1 (4): 268-288
[9] IARC, Diesel engines exhaust carcinogenic, 2012 [access link]
[10] Abbasov, F. (2017), Statistical analysis of the energy efficiency performance (EEDI) of new ships, Transport & Environment.

based measure to tackle emissions from the existing fleet, not just new ships. But these talks fell victim to arguments over technical assistance for developing countries to implement the EEDI. Shortly before the Paris Climate Conference convened in 2015, the IMO Secretary General summed up in public the prevailing view of the sector: shipping was already the most efficient form of transport and its emissions could not be capped because shipping was the servant of world trade and would need to continue to grow with it.

However, the Paris Agreement itself and mounting pressure from South Pacific nations on the frontline of climate change impacts did indeed lead to a significant change in direction. Industry, led by the International Chamber of Shipping (ICS), eschewed previous attempts at denial and embraced the need for the shipping sector to act. Amid mounting pressure from a coalition of high ambition states and civil society, the logjam at the IMO was broken. In April 2018 concerted efforts culminated in a landmark agreement calling for the shipping sector to reduce its GHG emissions by at least 50% by 2050 and to improve energy efficiency by at least 40% by 2030. Reductions higher than 50% were sought by many, so the reference to 'by at least by 50%' was accompanied by a commitment to see short term measures agreed, in place and already contributing to emissions reductions by 2023. The April agreement, importantly, directed at the shipping sector achieving the reductions itself – in-sector reductions - thereby taking pressure off shipping's available 2050 carbon budget and giving time for mid/longer term solutions essentially focussing on new low/zero carbon fuels to be developed.

The IMO is now embarking on a process to develop, agree and implement a suite of short, medium and long term regulatory measures to achieve the goals agreed last April. Options for short term measures include mandatory requirements on individual ships to improve operational carbon intensity based on carbon intensity metrics yet to be agreed or based on mandatory ship speed reductions. Lesser measures involving better ship management and mandatory retrofits have also been proposed. The longer term challenge is more fundamental as decarbonising shipping will effectively depend on a shift to zero carbon fuels/propulsion technologies: electrification, hybridisation and hydrogen/ammonia fuels. This transition is a veritable revolution that will depend on many variables – regulatory aspects within and outside the remit of the IMO, the wider transition to renewable electricity production worldwide, further technological improvements, ship designs and investment in port infrastructure.

This challenge coincides with moves in Europe to strengthen its commitment to the Paris Agreement by developing a strategy to decarbonise the entire European economy. The commitment to a 40% emissions reduction by 2030 has been incorporated in the EU's Paris agreement NDC, but shipping is the one industrial sector that has been excluded. This is despite long standing European pressure on the IMO to take action and repeated warnings that regional action at the EU level would have to be taken instead. Plans for shipping to follow aviation and be included in the EU ETS were in fact already being drawn up when the EEDI was agreed in 2011. However, the EU MRV Regulation agreed in 2015 was limited to an emissions reporting requirement on all ships calling at EU ports from 2018. The first emissions reports are to be submitted by the first quarter of 2019.

The EU ship MRV was itself the key driver for industry to finally agree to a global ship emissions data collection system. Less detailed than the EU MRV, the IMO DCS (data collection system) also protects individual ship efficiency performance from being made public event though it is widely accepted that lack of transparency of such information is a barrier to improving ship efficiency. Pressed by the European Parliament, EU states are keeping open the possibility of a second step; the imposition of a mandatory reduction measure on all ships calling at EU ports by, for example, including shipping in the EU ETS or requiring all ships within the EU MRV scope to contribute to a Maritime Shipping Fund as a condition of entry to EU ports. European pressure on the IMO remains.[11] EU ETS legislation for the post 2021 period contains provisions for the shipping sector to be included in reduction measures at the EU level should IMO outcomes

[11] EU ETS Directive, 2017 [access link]

prove unsatisfactory, particularly related to the IMO commitment to implement short term measures by 2023.

3. Zero emission technologies for ships

Ships require energy both for propulsion (delivered by main propulsion engines/motors), on-board electricity generation (delivered by auxiliary engines) and on-board heating and cargo operations (delivered by boilers). While the main engines are switched off at berth, auxiliary engines and boilers are kept running to sustain on-board operations. For example, a typical large ocean going cruise ship could burn around 220 MWh worth of fuel per 10-hour port call in order to satisfy on-board energy demand. As a comparison, the main (propulsion) engines of the same ship could use 220 MWh energy (fuel) to sail some 100 km out in the sea.[12]

Historically, ships have been using heavy fuel oil (HFO) and marine gas/diesel oils (MGO/MDO) propulsion and on-board operation purposes which emit, inter alia, greenhouse gases (GHG) contributing to global climate change. Energy currently provided to ships by HFO/MGO/MDO can in the future be replaced by energy stored in batteries or synthetic (electro) fuels such as liquid hydrogen or ammonia which generate no GHG emissions at the vessel level. In addition, marine diesel or methane can also be synthetically produced from renewable H_2 and CO_2 air capture and used as a replacement for the HFO/MGO/MDO of fossil origin (table 1).

Table 1: Classification of electrofuels for shipping

Carbon free (non-hydrocarbon)	Carbon containing (hydrocarbon)
Liquid hydrogen	Synthetic (electro-) methane
Liquid ammonia	Synthetic (electro-) diesel

Due to technical characteristics (table 2), including conversion inefficiencies of each technological pathway, the implications on the primary energy production (upstream) will be different, i.e. increase with each conversion step.

Table 2: Summary of technological pathways

Technology	Propulsion	Energy storage	Energy transformation
Battery ships	Electric motor	Batteries	Directly from batteries to electric motor
Hydrogen fuel-cells	Electric motor	Liquid H_2	Electrochemical via fuel-cells
Hydrogen ICE	Internal combustion engine (ICE)	Liquid H_2	Direct combustion of liquid H_2 in ICE
Ammonia fuel-cells	Electric motor	Liquid ammonia	Extraction of H_2 from ammonia via on-board reformers and electro-chemical transformation via fuel-cells
Ammonia ICE	ICE	Liquid ammonia	Direct combustion of liquid ammonia in ICE
Electro-methane	ICE	Synthetic methane from electricity	Direct combustion of electro-methane in ICE
Electro-diesel ICE	ICE	Synthetic diesel from electricity	Direction combustion of electro-diesel in ICE

3.1. Battery-powered ships (BPSs)

This refers to ships propelled by electric motors, which are powered exclusively by electricity stored in batteries on board (similar to battery electric cars). Battery technology is likely to be the cornerstone of future hybrid and/or fully electric technologies for ships. Regardless of the source of electricity, the tank-to-wake (battery-to-wake) GHG and other emissions of these ships are always zero.

[12] T&E estimates based on the luxury cruise ship Symphony of the Seas, sailing at full capacity with a speed of 18 knots.

Well-to-wake (grid-to-battery) emissions on the other hand depend on the carbon footprint of the national/regional electricity grids that are used to charge the on board batteries. However, from the viewpoint of climate policy this is not an inhibiting factor for the shift to battery-powered ships. Electricity generation is included in many of the national pledges to the Paris Agreement. In the EU for example, the power sector is covered under the EU Emissions Trading Scheme (ETS), which sets an absolute cap for emissions from the sector independent of the growth in demand for power generation. So there is likely to be only a limited margin for increasing emissions from the power sector to meet the likely additional demand for electricity from battery powered ships. Such extra electricity demand will likely have to be met by renewables or other low/zero-carbon means of power production in the not too distant future.

Electrical motors to power battery ships can be of different types, with synchronous and induction[13] (AC) motors being more widely accepted for a variety of marine applications. Industry leaders such as ABB and Siemens claim up to 99% efficiency for their synchronous motors. However, AC motors also require the DC current from the batteries to be further converted to AC current for the motor resulting in additional conversion losses. Appendix II provides a (non-exhaustive) list of battery-powered and battery-hybrid ships that are in operation or under construction across the globe.

3.2. Hydrogen Fuel-Cells

This technology converts energy stored in fuels (e.g. liquid hydrogen) directly to electricity via an electrochemical process in fuel-cells, which in turn powers electric motors. Generally, liquid H_2 is used directly in the fuel cells, which produce electricity and water as a by-product. Hence, on a tank-to-wake basis, H_2 fuel cells are climate neutral, not causing any emissions apart from water.[14] There are different fuel-cells technologies, with different levels of technological maturity, electrical efficiencies and resulting emissions depending on the fuel choice (Appendix III).

3.3. Hydrogen in ICE

There is also emerging literature discussing the possibility of using liquid H_2 (or boil off hydrogen gas) directly in modified ship internal combustion engines.[15] However, T&E is not aware of any practical application so far of such propulsion systems in existing commercial ships; however, several pilot projects will likely be realised in the near future providing further evidence to shipowners, scientists and regulators alike.

3.4. Ammonia Fuel-Cells

Similar to methane, ammonia is a gas at normal temperature and atmospheric pressure. But it becomes liquid under ~10 bars at 24ºC temperature (or -33ºC at atmospheric pressure). Since liquid ammonia has more energy density than in its gaseous form, it can be stored in liquid form and re-gasified when in use.

An ammonia molecule consists of one atom of nitrogen and three atoms of hydrogen (NH_3). Because ammonia does not contain any carbon molecule, during combustion it produces only nitrogen and water vapour.

$$4NH_3 + 3O_2 = 2N_2 + 6H_2O$$

[13] Kirtley, James L., Arijit Banerjee, and Steven Englebretson. "Motors for Ship Propulsion." Proc. IEEE 103, no. 12 (December 2015): 2320–2332

[14] Other fuels, notably, LNG, methanol, diesel, etc., can also be used but need first to be converted in the on-board reformers to extract H_2, which is then used in the fuel cells to produce electricity. As a result, total on-board emissions associated with the use of LNG, methanol and diesel are CO_2 (from on-board converter) and water (from the fuel cells). For this reason, only non-carbon based alternative fuels are used for the purpose of this analysis.

[15] Funding secured for UK's First Hydrogen Injection system on a Ferry, Ferguson Marine [access link]; Seddiek, S.I. et al. (2015), The hydrogen-fuelled internal combustion engine for marine applications with a case study, Brodogradnja 66(1): 23-38 [access link]

Ammonia can be used as a hydrogen storage (hydrogen carrier) for fuel cells. Ammonia has a higher volumetric hydrogen density (10.7 kg H_2 /100L)[16] than liquid hydrogen itself so, for example, a litre of liquid ammonia contains ~50% more hydrogen than the same volume of liquid hydrogen. Ammonia has to be split via on-board reformers before the released hydrogen can be supplied to fuel cells. However, several technological challenges for on-board reforming of ammonia remain.

Notably, decomposition (splitting) of ammonia into hydrogen and nitrogen is energy intensive and involves high temperatures (up to 1000 °C). At these high temperatures it becomes difficult for the reactor materials, including the catalyst to sustain exposure to this environment.[17] Additionally, current fuel cells (except alkaline fuel cells) have very low tolerance thresholds (< 0.1 ppm) to ammonia. Therefore, extensive purification is required if fuel cells are to use hydrogen produced from ammonia. This appears to remain both a technical and economic challenge. However, Australia's CSIRO (Commonwealth Scientific and Industrial Research Organisation) has made recent strides into membrane-based hydrogen separation from ammonia, which, if commercialised, could fill the required technology gap. The CSIRO recently announced[18] the successful development of an ammonia-to-hydrogen transformer for hydrogen fuel-cell cars.

It should also be noted that some research points to the possibility of ammonia being used directly in an alkaline fuel cell (FC) without the necessity of the prior splitting of ammonia into hydrogen and nitrogen.[19] Ostensibly, this would solve the efficiency and fuel cell contamination problems associated with PEMFCs.

It is important to note that ammonia is a toxic substance and its spill would be hazardous to the environment. These aspects of ammonia need to be seriously investigated and strict safety rules would need to be put in place before ammonia as a ship fuel/energy source is deployed.

3.5. Ammonia ICE

Ammonia can be used in current ICEs with some modifications. Since the fuel does not contain carbon molecules, on-board emissions are free of CO_2 and other greenhouse gases (GHG).

However, ammonia has a very high resistance to auto-ignition (651°C - ammonia[20] vs. 210/225°C diesel vs. 246/280°C gasoline[21]) and narrow flammability limits (16-25% by volume in air). Therefore, ammonia does not compression ignite and requires blending with a certain amount of another (high-cetane) fuel – e.g. MDO.

This means that on-board CO_2/GHG, SO_x and PM emissions would still take place in proportion to the amount of "other" fuels blended with ammonia. Combustion of ammonia blends can also lead to considerable NO_x and soot emissions depending on the engine load.[22] These emissions could however be controlled using after-treatment technologies, such as SCR and DPF.

With regard to spark-ignition engines, on the other hand, narrow flammability limits and low flame speed causes incomplete combustion of ammonia. To overcome this, ammonia can be blended with hydrogen or gasoline. In the latter case, ammonia-gasolines blends will lead to GHG emissions and other pollutants, notably NO_x.[23]

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[16] Potential Roles of Ammonia in a Hydrogen Economy (2006), U.S. Department of Energy [access link]
[17] ibid.
[18] ABC news, Hydrogen fuel breakthrough in Queensland could fire up massive new export market, 2018 [access link]
[19] Rong Lan and Shanwen Tao (2010), Direct Ammonia Alkaline Anion-Exchange Membrane Fuel Cells, Electrochemical and Solid-State Letters, 13 8, B83-B86
[20] Ammonia- Wikipedia [access link].
[21] Fuels and Chemicals - Auto Ignition Temperatures [access link].
[22] Kong S.C., (2008): Ammonia combustion in diesel engines for reducing greenhouse gas emissions, Technical Report, Iowa State University, USA [access link].
[23] Kong et al., Characteristics of an SI Engine Using Direct Ammonia Injection, Presentation, University of Iowa [access link].

Ammonia-fuelled combustion turbines and oxidation turbines that produce low or zero GHG and minimal conventional emissions are also under development, with significant R&D initiatives in Japan, the Netherlands, and elsewhere.[24]

3.6. Synthetic diesel

Similar to liquid ammonia and hydrogen, diesel fuel can also be synthetically produced using renewable hydrogen from electrolysis and CO_2 capture from air.[25] The resulting fuel is still carbon-based, hence its combustion emits CO_2 (and NO_x); but since the CO_2 is originally captured from the atmosphere, such a synthetic diesel fuel would be carbon neutral on a full life cycle basis provided the energy/electricity used for electrolysis and fuel synthesis was carbon free. Electro-diesel fuels would have similar physical and combustion properties to fossil diesel, so could be used with existing on-board ship machinery and bunkering infrastructure.

3.7. Synthetic methane

Electro-methane, to be subsequently liquefied, can be synthesised using the methanation chemical process to combine hydrogen (H_2) from electrolysis with carbon dioxide (CO_2) to produce methane (CH_4). In the methanation reaction, H_2 and CO_2 are reacted in the presence of a catalyst (generally nickel)[26]:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

The resulting electro methane could then be a direct substitute for compressed or liquefied natural gas.

3.8. Role for biofuels?

Renewable fuels of biological origin are also put forward as one of the possible alternatives to decarbonise shipping, as with other sectors. T&E's recent report concluded that "*advanced biofuels could play a role in substituting fossil fuel demand in aviation. However, strict sustainability safeguards are needed to ensure advanced biofuels offer genuine emission savings - these are not yet in place. If fuels with poor environmental and climate credentials would be excluded, the potential supply of advanced biofuels would be very limited. [...] biofuels could play a role - meeting up to 11.4% of the remaining 2050 fuel demand in our scenario - but alone won't be available in the quantities needed. This is partly because non-transport sectors will also have a claim to biomass feedstocks, reducing availability*".[27] With this in mind it is more advisable to use the available sustainable biofuels in a more difficult to decarbonise sector such as aviation.

Moreover, the use of biofuels in shipping would create unique sustainability and enforcement challenges, which do not arise in other transport modes and would appear to be insurmountable from a regulatory point of view. Ocean-going ships usually bunker in specific ports where fuel is cheap; hence, they do not need to refuel every time they make a port call to take up or discharge cargo. Such a unique refuelling pattern of shipping makes the application of strict sustainability criteria for biofuels - in order to prevent the use of crop-based biofuels that have higher life-cycle emissions than the fossil fuels that they would be replacing - extremely challenging. A unilateral application of strict sustainability criteria by one or even a group of neighbouring bunkering ports would create a "collective action" problem, whereby other ports would be incentivised to go easy on unsustainable biofuels in order to attract more bunkering. A global and

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[24] E.g., Michinari Hamaguchi, Japan Science and Technology Agency, Development of Carbon-Free Hydrogen Value Change (2016); Hideaki Kobayashi, Ammonia Direct Combustion: Thermal Power Generation Using Carbon-Free Fuel (2017); Holland Renewable Energy Technologies BV, From Waste Gas to Sustainable Energy: Oxidation of NH3 Without Formation of NO_x, Presentation (2017) [access link].
[25] See Chris Malins, What role is there for electrofuel technologies in European transport's low carbon future?, 2017 for electro-fuels for road transportation and aviation. Arguably, shipping diesel would follow a similar pathway as road and aviation fuels.
[26] Götz, M. et al. (2016), Renewable Power-to-Gas: A technological and economic review, Renewable Energy, Volume 85: 1371-1390.
[27] T&E, Roadmap to decarbonising European aviation, 2018 [access link]

uniform application of sufficiently strict sustainability criteria - via for example the IMO or another framework - would require a global consensus agreement, which is improbable because of the interests of large bio-energy producing countries such as Brazil, Argentina, the US, Colombia, Indonesia, Malaysia, etc. Some of these countries have already threatened the EU with WTO action because EU will discontinue subsidising crop-based biofuels beyond 2030.[28]

Even if such a global consensus on applying strict environmental criteria was reached uniform enforcement would be an additional and equally insurmountable challenge. Port-state control of sustainability would itself be complex and difficult, because sustainable and non-sustainable biofuels would have similar apparent physical properties and be difficult to differentiate without mass spectrometry analysis in high-tech laboratories. Such laboratories are not necessarily at hand everywhere and it would be economically unsustainable to test every ship. Blending and mixing along the fuel supply chain and tank mingling with other fuels, would create even further difficulties for those port-state controls deciding to perform random checks.

For these reasons, we consider that in addition to availability problems, enforcement of sustainable fuels in shipping would be herculean task with a high potential to create an uneven playing field for industry. Policy-makers should steer away from considering biofuels to decarbonise the maritime industry.

4. Implications on the primary energy demand for renewable electricity

Whether ships are powered by batteries to be charged at ports, or by electrofuels to replace HFO/MGO/MDO, this change will increase demand for (renewable) electricity production on land. To analyse the implications of these different technological pathways on EU primary electricity demand, 7 scenarios/pathways have been analysed for different segments of EU shipping for the year 2050. The main segments of EU shipping have been defined as I) domestic shipping, II) intra-EU international shipping, III) inbound extra-EU shipping and IV) outbound extra-EU shipping.

Technology scenarios/pathways[29]:

1. Full H2 fuel-cell (H2_FC)
2. Full H2 ICE (H2_ICE)
3. Full ammonia fuel-cell (Ammonia_FC)
4. Full ammonia ICE (Ammonia_ICE)
5. Full battery-electric
6. Technology mix - assumes domestic shipping choose batteries; intra-EU shipping half battery, half H2_FC; outbound extra-EU half H2_FC and half Ammonia_FC
7. Full electro-methane (e-methane_ICE)
8. Full electro-diesel (e-diesel_ICE)

The rationale behind the technology in the "technology mix" scenarios is four-fold:

1. Domestic shipping in many European countries is already experimenting with battery-electric propulsion, and we assume this trend will continue due to the segment's relatively short sailing distances, smaller ships and the cost-effectiveness of deploying battery-electric propulsion.
2. Intra-EU shipping could use both battery electric and other (including hybrid) technology pathways. It is assumed that most of the passenger ferries and smaller cargo ships will prefer battery electric propulsion in short-sea shipping, while other ships in this segment will choose hybrid or full hydrogen fuel cell propulsion.

[28] Reuters, Malaysia trade ministry to approach WTO on EU move to limit palm oil use [access link]

[29] "Full" refers all ships switching to the propulsion technology in question.

3. This analysis does not contain cost effectiveness (or safety/handling aspects) of the technology choices from the ship-owner/operator's point of view. It is assumed that the choice between hydrogen and ammonia based technology pathways is determined by a) the well-to-wake energy (conversion) efficiency of the available propulsion options (as a proxy for energy costs) and b) their volumetric energy density which is important for space considerations (as a proxy for opportunity costs). In this regard, since H_2 fuel cells appear to be more energy efficient, it is assumed half the ships on intra-EU journeys will choose H_2 fuel cells.
4. Furthermore, since ammonia has twice the volumetric energy density of H_2, it is assumed that large ships on long-distance (outbound extra-EU) journeys will chose ammonia fuel-cells over H_2.

4.1. Results & Discussions

Table 3 and figure 1 below summarise the results, which are presented for each technological pathway identified above, but also in relation to different shipping segments. To put our findings into a policy context, 2050 primary energy demand for EU shipping has been compared to 2015 EU electricity generation. As it can be seen below, under the 50% maritime growth assumption towards the mid-century, only the full battery-electric and technology mix pathways would result in additional primary energy demand (in 2050) inferior to that of total EU28 renewable electricity generation in 2015. All other options would require significantly more renewable energy than was generated in 2015 in the EU, with synthetic methane and diesel even requiring up to double the 2015 RES capacity.

When compared to historical EU total electricity generation, different maritime technology pathways would result in additional electricity generation of some 11-53% over 2015 levels. Synthetic methane and synthetic diesel would have the highest (worst) impact on the primary energy demand requiring respectively 42% and 53% additional energy demand due to high inefficiencies of these pathways. In contrast, battery-electric (although with a caveat - see below) and technology mix would have a much lower impact on the additional primary energy demand.

Table 3: Impact on primary energy demand under different 2050 technology mix scenarios (TWh)

	Additional electricity demand for maritime (2050)								EU28 total electricity generation (2015)	EU28 RES electricity generation (2015)
	Full H2_FC	Full H2_ICE	Full ammonia_FC	Full ammonia_ICE	Full battery electric	Tech mix	Full e-methane_ICE)	Full e-diesel_ICE)		
Domestic	188	202	202	217	64	64	246	312		
Intra EU	384	412	413	443	130	257	503	639		
Extra EU inbound*	0	0	0	0	0	0	0	0		
Extra EU outbound	461	495	495	532	156	478	604	767		
Total	1,032	1,109	1,110	1,192	350	798	1,354	1,718	3,234	966
Compared to EU28 electricity generation (2015)	32%	34%	34%	37%	11%	25%	42%	53%		

Source: T&E estimations; for conversion efficiencies see Appendix I. Figures for electricity: EU Energy Statistical Pocketbook, 2017.
* it is assumed that ships will bunker outside the EU on in-bound journeys

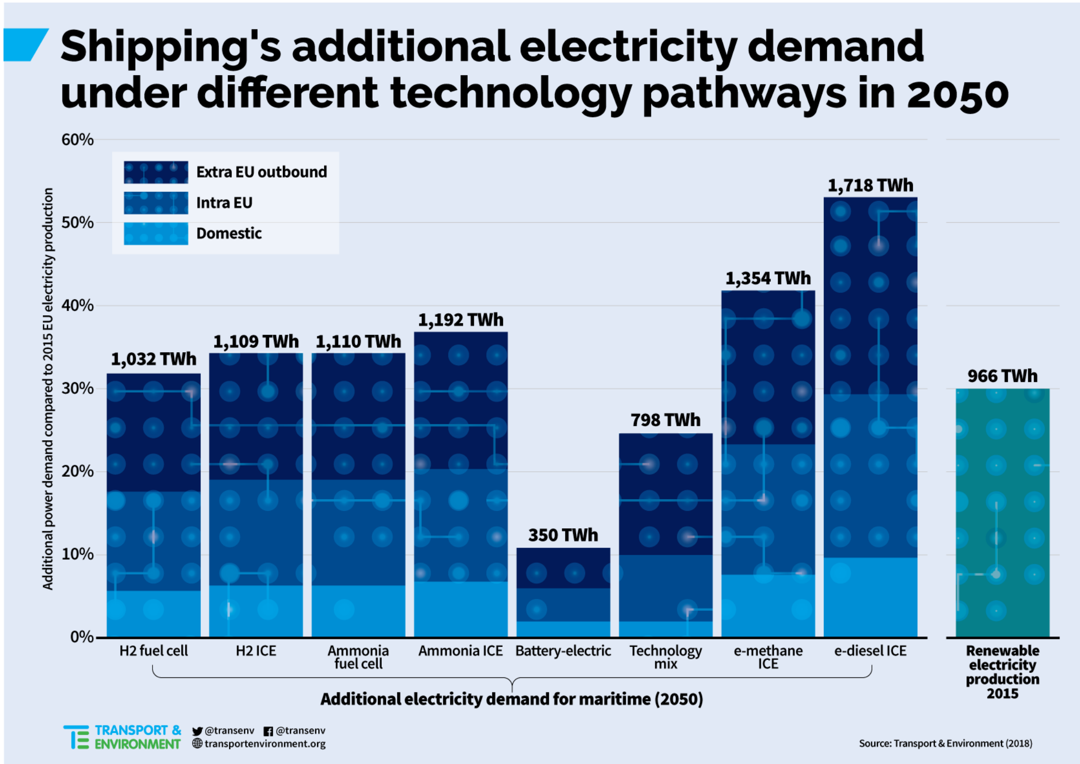

Figure 1: Impact on renewable electricity demand under different 2050 technology scenarios (TWh)

4.1.1. Battery-electric

Battery-electric propulsion is the most energy efficient technology pathway. However, this conclusion does not take into account the potential cargo space lost by accommodating the batteries, which could negate some of energy saving gains particularly for larger ships on long journeys because additional ships could be needed to make up for the lost cargo space in order to maintain transport supply. Battery propelled ships have increased in numbers in recent years and more and more marine technology providers appear to be investing in this technology. According to T&E analysis, despite the inferior (specific) energy density of batteries compared to liquid hydrogen, battery-electric propulsion could actually be more cost-effective for small and mid-size ships, notably roll-on/roll-off ships, that are mostly engaged in short-sea coastal shipping. Figure 2 below compares the real world (propulsion related) operational costs per journey of an existing diesel passenger ferry with the hypothetical battery-electric and hydrogen fuel-cell versions of the same ship under the identical operational conditions. In shorter journeys this cost difference can be explained by 3 factors:

1. Battery-electric propulsion enjoys a superior total tank-to-wake energy conversion efficiency (>80%), i.e. conversion of energy stored in batteries into rotational-mechanical energy delivered to the propellers. As a result, the amount of levelised energy needed to sail the same ship is half as much for a hypothetical battery ship, as opposed to its diesel-ICE or H_2 FC equivalents. For example, an existing ferry - Pride of Burgundy - would require respectively 20,780 kWh, 10,715 kWh and 19,341 kWh energy for diesel, battery-electric and H_2 FC propulsion modes in order to complete a single Calais-Dover journey (table 4).
2. The levelised (i.e. kWh for kWh) cost of electricity today is cheaper than the current liquid hydrogen prices leading to higher per journey energy costs for an H_2 FC ship.

3. FC still remain an expensive technology. Although some FC technologies (e.g. alkaline) are considerably cheaper than others (e.g. PEM), any analysis needs to also take into account the lifetime of the technology; hence its replacement rate over the ship's operational lifetime; and Alkaline FC appears to have a shorter lifetime than PEM FC.[30]

Table 4: Energy requirements under different technology pathways for a Calais-Dover journey

	Existing diesel-ICE Pride of Burgundy	Battery-powered Pride of Burgundy	H_2 fuel-cell Pride of Burgundy
Energy/journey (kWh)	20,780	10,715	19,341
Energy mass (tonnes)	2.6	86	<1
Energy weight - DWT ratio (/journey)	0.04%	1.47%	0.01%
Energy volume (m^3)	2.40	75	11
Energy volume - GT ratio (/journey)	0.002%	0.0533%	0.008%

Key density assumptions[31]:
Battery pack[32]: gravimetric - 175 Wh/kg; volumetric - 200 kWh/m^3
Liquid hydrogen: gravimetric - 33,330 Wh/kg (LHV); volumetric - 71 kg/m^3

Despite this higher efficiency, battery electric ships are only viable over shorter distances unless considerable improvements are achieved in battery specific energy densities in the future. For this reason, it would be reasonable to expect battery technology to be used mostly by ships sailing in domestic and intra-EU traffic. It is also possible that batteries could be deployed as auxiliary power sources or in hybrid modes with other technologies for deep sea shipping.

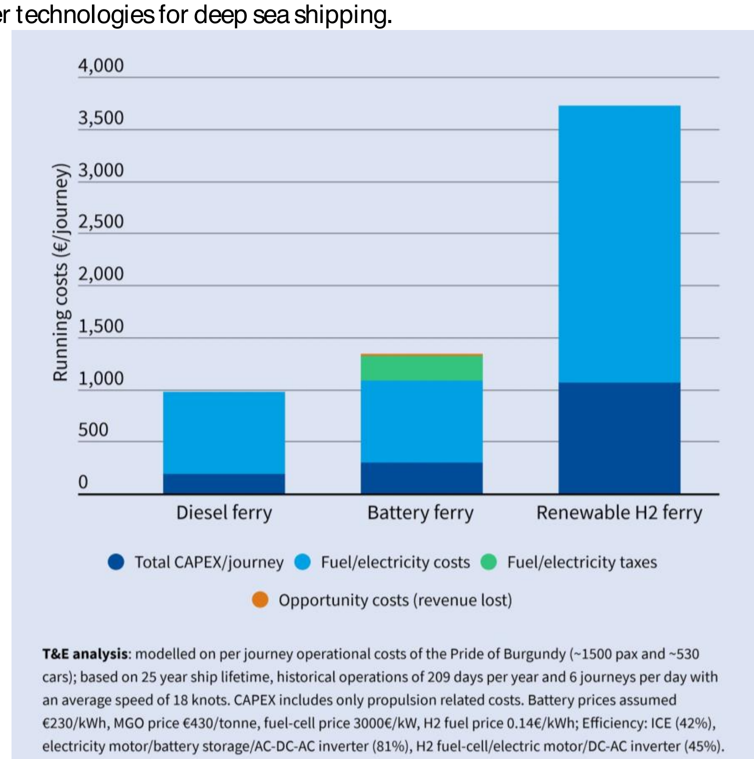

Figure 2: battery electric and H_2 fuel-cell ship in real operational conditions for short-sea shipping

[30] Technology Roadmap: Hydrogen and Fuel Cells, IEA, 2015
[31] Battery technology is still evolving and further density improvements are expected in the near future. Some manufactures for road vehicles already claim achieving >200 Wh/kg gravimetric battery density, which allows us to assume that current shipping battery density can be further improved. See e.g. "BMW i3 gets a 100 kWh battery pack for 435 miles of range as a proof-of-concept by Lion Smart", 2018 [access link]; "IAA Commercial Vehicles: AKASOL is showcasing a wide range of solutions for hybrid and electric mobility", 2018 [access link]
[32] See e.g. XALT Energy systems for marine application [access link]

4.1.2. Hydrogen and Ammonia

These appear to be the second most efficient methods of energy provision followed by hydrogen ICE and ammonia fuel cells. But the total energy efficiency of hydrogen fuel cells/ICE could actually be inferior to that of ammonia fuel-cells/ICE in real life, because of the inferior (volumetric) energy density of H_2 compared to ammonia as a fuel or hydrogen carrier. As a result, more cargo space in the largest ships sailing on longer voyages could be compromised if H_2 was chosen over ammonia, necessitating more H_2 ships to maintain transport supply. But the choice of H_2 over ammonia would also likely be influenced by other factors, such as journey distance, higher fuel costs of ammonia over hydrogen, potential additional energy losses that might result from on-board splitting of ammonia into H_2 (for FC), as well as additional safety standards that would be required for either fuel.

Therefore, even though it is possible that some of the largest ships sailing long distances would prefer ammonia over H_2[33], some large ships sailing shorter distances could potentially favour H_2 over ammonia as the preferred fuel/energy storage choice.

There do not appear to be huge differences (in terms of impact on the primary energy demand) between H_2/Ammonia FC on the one hand and H_2/Ammonia ICE on the other.

4.1.3. Synthetic methane and diesel

Although synthetic methane and diesel are technically viable fuels and can be used in current shipping infrastructure and engines, their use would appear to suffer from a number of pitfalls, some of which may be insurmountable:

1. The synthetic diesel followed by synthetic methane pathways place the highest (worst) demands on renewable energy supplies due to the excessively high amounts of energy needed to produce them. For example, today around 1.94MJ, 2.29MJ, 2.59MK and 3.2MJ of energy is needed to produce 1MJ of H_2, ammonia, synthetic methane and synthetic diesel, respectively.[34] As a result, even with assumed efficiency improvements towards 2050 (table 6), T&E estimations suggest that up to twice as much primary energy would be required if shipping adopted synthetic methane and synthetic diesel as opposed to the technology mix pathway described above (figure 1.)
2. Synthetic methane and diesel (and/or blends thereof with existing fuels) would have similar physical properties to fossil LNG and marine distillates. This would create almost insurmountable regulatory challenges for port and flag states to ensure compliance, especially as synthetic methane and diesel would be an order of magnitude more expensive than their fossil equivalents[35] creating a significant incentive to cheat. Requiring synthetic fuels (and other carbon-based synthetic alternatives) to decarbonise shipping could become practically unenforceable and the risks of creating an unequal playing field would be great. Investing (especially from public coffers) today in LNG bunkering infrastructure[36] in the hope that it could be used in the future for synthetic methane bunkering would seem to set the industry and the whole energy system on an expensive, unsustainable and potentially unenforceable pathway.
3. Synthetic methane and diesel pathways could also create policy complacency and a denial of responsibilities between technology and fuel providers, shipowners/operators and different regulatory institutions. This pathway could be, indeed, would be interpreted as a "no-action-needed" from shipowners as they could argue that it would be entirely up to fuel suppliers to produce these synthetic fuels and in sufficient quantities.
4. Regulatory and political difficulties of attempting to decarbonise fuels (as opposed to the means of transport) is a well-known challenge, especially in Europe. Efforts to reduce the carbon intensity of

[33] Raucci, C. et al. (2017), Zero-Emission Vessels 2030. How do we get there?, UMAS/Lloyd's Register.
[34] Malins, C. (2018), What role for electromethane and electroammonia technologies in European transport's low carbon future.
[35] Malins, What role for electromethane and electroammonia technologies in European transport's low carbon future, 2018.
[36] Domagoj, B. et al. (2018), LNG as a marine fuel in the EU, Market, bunkering infrastructure investments and risks in the context of GHG reductions, UMAS [access link]; T&E, CNG and LNG for vehicles and ships - the facts, 2018 [access link]

road fuels through the Fuel Quality Directive has created significant sustainability issues over the past decade and has often lead to higher emissions on a full life-cycle basis. The nature of international shipping would suggest that such regulatory issues and hurdles involving marine fuels would be significantly magnified in shipping.

For these reasons, whatever is the specific technological pathway for shipping, for sustainability and enforcement purposes, it should deliver zero GHG emissions at the vessel level.

5. Conclusions

This report analyses the possible impacts of decarbonising EU related shipping on the primary renewable energy production and concludes that a mix of alternative zero emission technologies including battery-electric, liquid hydrogen and ammonia would cause the least additional strain on the broader energy system. Synthetic fuels such as electro-methane and electro-diesel, on the other hand, would be the least optimal for the broader energy system and also extremely difficult to monitor and enforce.

Maritime transport is only one of the many sectors of the economy that will need to rely on primary renewable energy in order to decarbonise. Together with other sectors this will add tremendous additional stress on the renewable electricity production, possibly an order of magnitude higher than the current electricity production sector, which itself is yet to fully decarbonise. In addition to improving the efficiency of shipping as much as possible, it is therefore essential in our view that any regulatory and economic policies to support any of the technology pathways analysed in this report take account of this impact and prioritise those which minimise the impact on primary energy demand.

Appendix I: Detailed Methodology

As the basis of analysis, this report has used CO_2 data (Ricardo-AEA, 2013) from ships calling at EU ports in 2010 in the four above-mentioned shipping segments related to the EU. This scope corresponds to the definition of EU-related shipping ship in the EU 2015 ship MRV Regulation and this study assumes that ships only on domestic, intra-EU and extra-EU outbound journeys would bunker in the EU. Extra-EU inbound journeys would likely bunker outside the EU; hence have been excluded from the current analysis.

Using CO_2 data, energy consumption by ships has then been back calculated assuming 72% - HFO and 28% MGO historical use (Ricardo-AEA, 2013). The final energy demand has then been projected to 2050 using a 50% maritime trade growth assumption, which is within the 20-120% growth range forecast by CE Delft (2017) for international shipping. It is also assumed that a 50% growth rate is a reasonable assumption after taking into account the likely emissions reductions to be realised by short and mid-term climate measures taken at IMO level, such as further improvements to the EEDI & SEEMP, and potentially speed regulation and deployment of wind propulsion.[37]

With the 2050 energy demand estimated, the total well-to-wake expended energy requirements for each technology pathway were calculated using well-to-tank and tank-to-wake efficiency ratios between conventional ICE-based fossil energy consumption and each of the 7 technology pathways identified-above (tables 5, 6, 7).

Table 5: On board efficiency losses (energy/energy) †

	ICE (fossil baseline)	Battery-electric	H2 Fuel-Cell	H2 ICE	Ammonia fuel-cell	Ammonia ICE	ICE (e-diesel)
Fuel energy content	100%	100%	100%	100%	100%	100%	100%
Inversion AC/DC (%)		95%					
Battery charge efficiency (%)		95%					
Fuel-cell efficiency (%)*			50%		50%		
Inversion DC/AC (%)		95%	95%		95%		
ICE/E-Motor efficiency (%)**	42%	95%	95%	42%	95%	42%	42%
Power deliver to shaft	42%	81%	45%	42%	45%	42%	42%
Efficiency as a ratio to ICE	1.00	1.94	1.07	1.00	1.07	1.00	1.00

† This table uses lower bounds of claimed FC and ICE efficiency ranges.
* Alkaline/PEM FC are claimed to have 50-60% electrical efficiency: https://goo.gl/A26eFg
** Wärtsilä claims 42-50% efficiency range for its diesel engines: https://goo.gl/TcsLCM
ABB and Siemens, major synchronous AC motor producers for marine sector claim up to 99% efficiency of AC motors: https://bit.ly/2okRbY; https://sie.ag/2MDg7 (this analysis assumes 95%)

Table 6: Upstream expended energy needs (MJ/MJ)

	ICE (fossil)	Electricity (incl. transmission losses)	Liquid H2FC (2050)	Liquid Ammonia (2050)*	e-methane (2050)*	e-Diesel (2050)*
Production/transmission/storage/delivery	1.00	1.05	1.72	1.85	2.10	2.67

* 2018 expended energy for ammonia 2.29 MJ/MJ, for e-diesel 3.3 MJ/MJ and for e-methane 2.6 MJ/MJ (C. Malins, 2018). 2050 projections assume efficiency improvements proportionate to expected improvements in H_2 (table 7).

[37] CE Delft, Study on the analysis of market potentials and market barriers for wind propulsion technologies for ships, 2016 [access link]

Table 7: Upstream expended energy for liquid H_2 production with low temperature electrolyzers (Alkaline and Proton exchange membrane) *

	2015	2020	2030	2040	2050
Electrolysis energy Requirements(kWh/kWh) [1]	1.74	1.53	1.50	1.41	1.41
Liquefaction (kWh/kWh)	0.30	0.30	0.30	0.30	0.30
Maintaining in liquid form for 30 days (kWh/kWh) [2]	0.01	0.01	0.01	0.01	0.01
Total (kWh/kWh)**	2.05	1.84	1.81	1.72	1.72

* H_2 energy content 33.3 kWh/kg (LHV)

Sources:

[1] Schmidt, P. R., Zittel, W., Weindorf, W., & Raksha, T. (2016). Renewables in Transport 2050 - Empowering a sustainable mobility future with zero emission fuels from renewable electricity. Frankfurt: Ludwig Bölkow Systemtechnik GmbH (LBST), p.68-69.
[2] Jeffrey Ralph Bartels (2008) A feasibility study of implementing an Ammonia Economy, Iowa State University

Appendix II: Battery-electric, hybrid & hydrogen ships

Battery-electric and hybrid systems

1. Norway: Future of the Fjords, an all-electric tourist ferry,
2. Norway: Vision of the Fjords, a hybrid electric tourist ferry,
3. Norway: Ampere, all electric first passenger ferry (120 cars and 360 pax),
4. Norway: YARA Birkeland, all electric and autonomous chemical tanker, huge 9MWh battery,
5. Norway: Karoline, battery electric fishing cutter,
6. Denmark: e-Ferry, EU Commission funding an all-electric passenger ferry,
7. Finland: Aranda, an old ship being retrofitted into a battery-hybrid propulsion system,
8. Belgium-Netherlands: Port-Liner, EU subsidised battery barges,
9. Norway: Hurtigruten, battery-hybrid cruise ship,
10. Norway: Fjord 1, orders new battery-electric ferries
11. Denmark-Sweden: Tycho Brahe, massive 4.2MWh battery pack with automated shore-side charging,
12. Denmark-Sweden: Aurora, massive 4.16MWh battery pack with automated shore-side charging,
13. Denmark: Maersk says batteries could be deployed on container ships by 2020
14. Italy: Grimaldi shipyard building 6 battery-hybrid RoRo ships,
15. Turkey: Zero Emissions Electric Tugboat with a huge 1.5MWh battery pack (in development),
16. China: all electric ferry with massive 2.4MWh battery pack,
17. China: HYTug, a battery-hybrid tugboat,
18. Canada: RAlly 1600-E, a battery-electric pilot boat (at design stage),
19. Canada: BC Ferries, looking for battery-hybridisation,
20. US: Puyallup, Wenatchee & Tacoma, ferries carrying 2500 pax & 202 cars in Washington state,
21. US: Bend Ferry, to be retrofitted into battery electric propulsion,
22. Germany: Damen shipyard developing battery-electric and battery-hybrid propulsion solutions.

Hydrogen systems

1. France: Energy Observer, autonomous hydrogen fuel cell propelled vessel
2. United Kingdom: Hyseas III, Sea-going Hydrogen Ro-Pax ferry
3. Saudi Arabia: Taba RoRo Cargo vessel trialling Hydrogen internal combustion engine
4. Germany: Zemships, hydrogen fuel cell powered 100 person passenger vessel launched in 2008 - now out of service

Appendix III: Fuel-Cell technologies

Table 8: Fuel cell technologies: types, efficiencies, emissions and fuels used.[38]

Type	Temp	Fuel	Efficiency	Tech. maturity/ marine experience	Module Power levels (kW)	Emissions (with different fuels)
Alkaline Fuel Cell (AFC)	Low	High purity hydrogen	50-60 % (electrical)	High/ yes (NASA)	<500 kW	- water/nitrogen
Proton Exchange Membrane Fuel Cell (PEMFC)	Low	Hydrogen	50-60% (electrical)	High/ yes	<120 kW	- water
High Temperature Proton Exchange Membrane Fuel Cell (HT-PEMFC)	High	Hydrogen, LNG, methanol, diesel (via internal reformers*)	50-60% (electrical)	Low/ yes	<30 kW	- water (H_2); - CO_2, low NO_x (carbon fuels**)
Solid oxide fuel cell (SOFC)	High	Hydrogen, LNG/CNG, methanol, ethanol, diesel (via internal reformers), ammonia (directly)	60% (electrical); 85% (with heat recovery)	Moderate / yes	<20-60 kW	- water (H_2); - CO_2, low NO_x (carbon fuels); - water & NO_x (ammonia)
Molten carbonate fuel cell (MCFC)	High	LNG, methanol, hydrogen	50% (electrical); 85 % (with heat recovery)	High/ Less-mature	<500 kW	- water (H_2); - CO_2, low NO_x (carbon fuels)

[38] Tronstad et al., EMSA Study on the use of Fuel Cells in Shipping, 2017.