REDUCING THE MARITIME SECTOR'S CONTRIBUTION TO CLIMATE CHANGE AND AIR POLLUTION

Maritime Emission Reduction Options

A Summary Report for the Department for Transport

July 2019

Authors:
Dr. Tristan Smith (UCL/UMAS), Chester Lewis (E4tech), Jasper Faber (CE Delft), Cavin Wilson (Frontier Economics) and Kat Deyes (Frontier Economics). We are grateful for the expert advice of Alison Pridmore (Aether).

Department for Transport

Great Minster House

33 Horseferry Road

London SW1P 4DR

Telephone 0300 330 3000

General enquiries https://forms.dft.gov.uk

Website www.gov.uk/dft

CONTENTS

1 INTRODUCTION

The science is becoming ever clearer about the harmful effects of greenhouse gas emissions (GHGs) due to their contribution to climate change (IPCC, 2018) and of air pollutants due to their adverse impacts on human health and ecosystems (Defra, 2019). Domestic and international shipping is responsible for substantial quantities of both types of emissions in the UK, and action is needed to curb those emissions and ensure that the maritime sector plays its part in meeting environmental objectives.

A myriad of abatement options exist for reducing maritime GHG and air pollutant emissions. This report is intended to provide a high-level overview for policy makers of the range of options currently available, and those that are likely to be available in the future, to generate meaningful emissions reductions. The purpose of this report is not to go into detail on every individual abatement option. Rather, it provides an overarching summary of the categories of options available, the role they could play in reducing emissions and the extent to which they are market ready. A range of other important issues are also discussed. These include: the ship types for which the abatement options are relevant; the extent to which the abatement options can be combined and how this affects their abatement potential; interdependencies with wider infrastructure and the energy system; and a commentary on current and potential future uptake.

This report is structured as follows:

- Section 2 summarises the current levels of UK shipping emissions and their main drivers and influences;
- Section 3 summarises the range of maritime abatement options, along with key information about each category of options;
- Section 4 discusses implementing abatement options in practice; and
- Section 5 discusses the abatement options in terms of their levels of deployment and adoption timescales.

2 CURRENT LEVELS OF UK SHIPPING EMISSIONS AND THEIR MAIN DRIVERS AND INFLUENCES

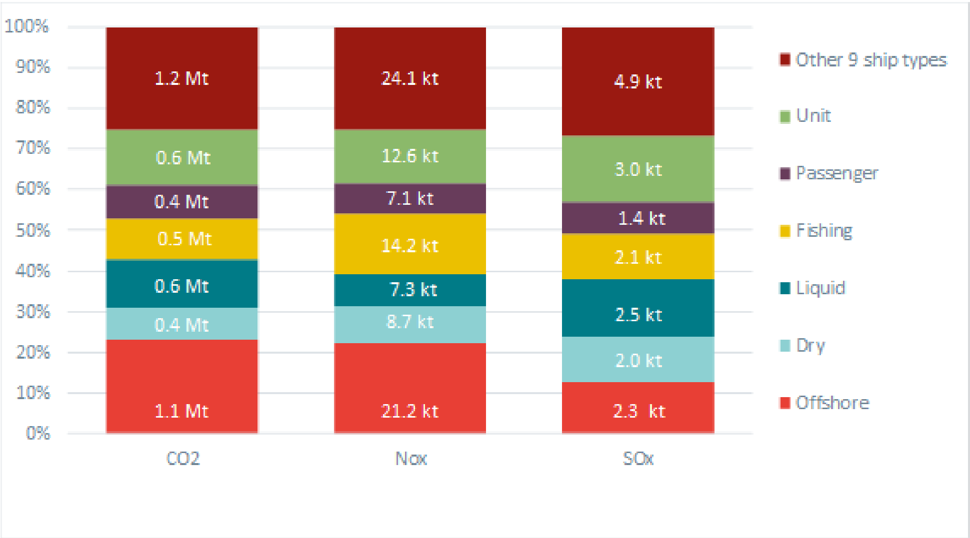
The UK's domestic shipping emissions, both GHG and air pollutant emissions,[1] are estimated to be dominated by six ship types: fishing, offshore, passenger, unitised cargo carriers ('unit'), liquid tankers ('liquid') and dry bulk carriers ('dry') (see Figure 1). In 2016, domestic shipping, defined here as ships that only move freight and passengers between UK ports, accounted for 11% of the UK's total domestic NO_x emissions, 2% of primary $PM_{2.5}$ and 7% of SO_2 (DfT, 2019) and the impact of these emissions is particularly pertinent to certain port cities (Ricardo Energy and Environment, 2017).

The emissions that arise from the UK's international shipping are significantly greater than domestic shipping emissions (irrespective of the estimation method used),[2] and are estimated to be dominated by just three ship types: unitised cargo carriers ('unit'), liquid tankers ('liquid') and dry bulk carriers ('dry') (see Figure 2).

Many of the air pollutant emissions occur in deep sea, though emissions that occur near land are of greater concern due to their impact on human health and coastal ecosystems.

Options for abating these emissions are considered in the next section.

Figure 1 UK domestic and Crown dependency shipping emissions by vessel type, 2014



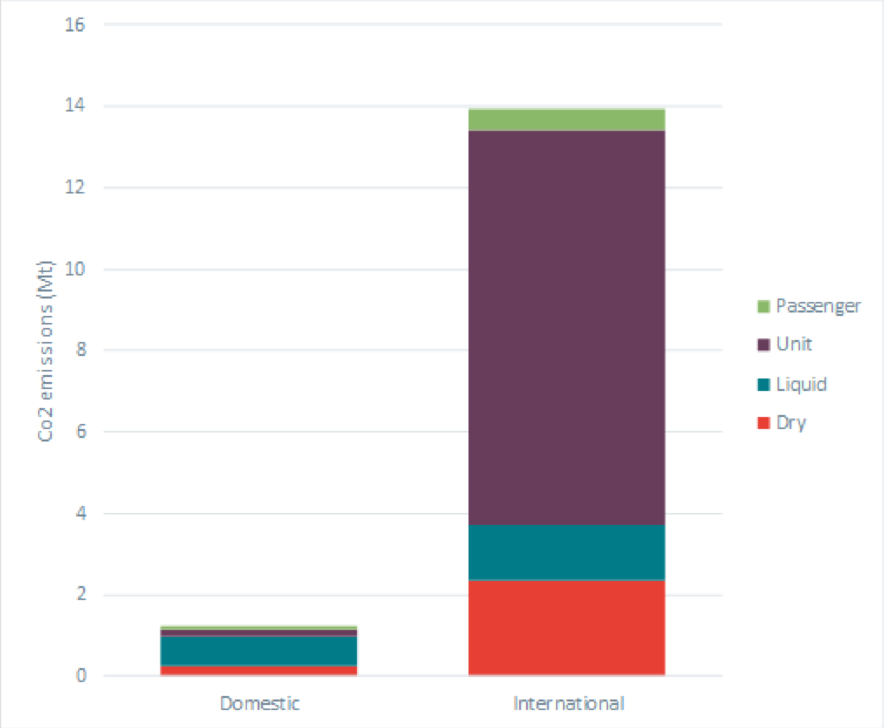
Source: Ricardo Energy and Environment (2017) A review of the National Atmospheric Emissions Inventory (NAEI) shipping emissions methodology: final report.

[1] Air pollutant emissions considered in this report include: nitrogen oxides (NO_x), sulphur oxides (SO_x), ammonia (NH3), primary particulate matter ($PM_{2.5}$) and volatile organic compounds (VOCs). For shipping, CO_2 is the dominant GHG, but accountancy includes CH_4 and N_2O emissions.

[2] There is no international standard or agreement on the way global international shipping emissions might be allocated or apportioned to individual countries. Different options exist, including methods based on sales of marine fuels, levels of trade and levels of shipping activity. Each method provides a different estimate of absolute emissions for individual countries.

Note: Figure 1 may not be fully consistent with the final NAEI (for example, totals may not match up due to rounding).

Figure 2 UK domestic and international shipping CO_2 emissions, 2010



Source: UMAS (2014) Support to Energy Technology Institute's Heavy Duty Vehicle Programme: Marine.

Note: The estimate of UK domestic emissions in Figure 2 is significantly less than the estimate presented in Figure 1. This is because the method used to produce the estimate shown in Figure 2 has since been superseded. However, the split between the different ship types for international shipping and the relative scale of domestic and international shipping emissions remains valid. As a result of method differences, Figure 2 is also not consistent with the NAEI figures on CO_2 emissions.

3 A SUMMARY OF MARITIME ABATEMENT OPTIONS

3.1 Categories of abatement options

The different options for reducing GHG and air pollution from both domestic and international shipping are, for the most part, the same. These options can be considered in four categories:

- Technologies that can increase energy efficiency;
- Operational or behavioural change that can increase efficiency;
- Technologies specific to the capture/treatment of exhaust emissions (GHG and air pollutant emissions); and
- Alternative fuels and energy sources and related machinery.

Each of these categories is discussed in this section, though some contextual points are useful to bear in mind.

Firstly, there are many available technologies and operational changes that can increase efficiency and could be used now for both new and existing ships (i.e. retrofits). However, these will not be able to achieve deep reductions in GHG and air pollutant emissions on their own, and so new fuels (with associated machinery) will be needed (UMAS, 2016). In order to meet the International Maritime Organisation's (IMO's) Initial GHG Strategy objectives, these new fuels are expected to be widely adopted by the middle of the century and fully in use by 2100 (UMAS, 2016).

Secondly, as well as new fuels and machinery, additional technology for controlling air pollutant emissions may also be required. This is because the rate of introduction of new fuels and machinery may not be high enough to sufficiently displace continued use of the existing fuels and machinery and, by association, their higher levels of air pollutant emissions (EEA, 2013). In many cases, there are co-benefits from the use of such technologies because some options that reduce GHG emissions also reduce air pollutant emissions. However, some options that reduce air pollutant emissions can reduce energy efficiency and therefore increase GHG emissions.

Thirdly, the climate benefits of reducing GHG emissions are the same, wherever those reductions take place geographically. However, for maritime air pollutants, the location of those emissions is important as they have the greatest adverse impacts when the ship is near population centres due to the risk to human health. This would be likely when the ship is at berth, but also when at anchor or manoeuvring to the berth near urban areas. For this reason, in the assessment below, we consider the impact of an abatement option on both the local air quality (e.g. when at berth or manoeuvring, defined here as within two nautical miles of the berth) and the air quality at sea (e.g. when at sea and under way).

The impacts of the abatement options presented below are summarised as a total reduction potential per annum for each category of abatement options (as described above) for example if all individual options within a given category were applied to a given representative average ship. The scale of possible impacts is categorised as: low impact on emissions (e.g. 0-10% reduction), medium (10-30% reduction) and high (30%+ reduction), relative to today's levels. There is a 'full' impact category, which corresponds to an option that fully abates an emission. There is also a 'negative' impact category, where an option that abates one type of emission causes an increase in another.

In addition to indicating the potential impact of an option on abatement, the assessment identifies an option's commercialisation features. This includes:

- The estimated level of maturity (or 'technology readiness level' (TRL))[3] for widespread implementation (e.g. across the fleets that are significant contributors to UK GHG and air pollutant emissions). TRLs identify the readiness such that a high TRL (e.g. 9) indicates that the technology is mature and available, and lower values are associated with full-scale demonstrators, pilots or laboratory prototypes.
- The expected date by which the category of options is expected to be commercially available. This indicates the number of years from now that the option is currently anticipated to reach full commercial readiness (e.g. TRL 9), if it is not already commercially available.
- The 'cost reduction potential', which is an estimate of the potential for further research, development and demonstration effort to achieve significant cost reductions (whether reductions in capital or recurring costs). Cost reductions are categorised approximately as low (0-20% reduction), medium (20-50% reduction) and high (50%+ reduction) relative to today's levels.

The next sections explore each of the four categories of abatement options described above. The different options that exist are described generally, and then grouped and described in a table with a high-level summary of their impacts or benefits, and current commercialisation status. The information summarised in the tables has been compiled from a number of studies and publications.[4]

3.1.1 Category 1: Technologies that increase energy efficiency

There are a number of devices and technologies that are options for increasing the energy efficiency of ships, summarised in Figure 3. These either improve the efficiency of an existing component (e.g. the engine or the propeller) or reduce the drag/resistance of the hull. They reduce GHG and air pollutant emissions by reducing the amount of fuel needed, and, depending on the fuel price, they may already have a positive net present value (i.e. create a commercially viable return on investment) even if, for other reasons (such as market failures or other barriers), they have not yet entered widespread use. Most of these options, with the exceptions of the more substantial ship design changes (e.g. an increase in the ship's length relative to its beam (width), or change to the curvature of the aft sections (the sections towards the back) of the hull), can be applied to the existing

[3] Technology Readiness Levels (TRLs) in the Project Lifecycle, https://publications.parliament.uk/pa/cm201011/cmselect/cmsctech/619/61913.htm

[4] UMAS (2016), Rehmatulla (2015), OCIMF (2011), LR and UMAS (2017), Smith et al. (2014), Winnes et al. (2016) and Faber et al. (2016).

fleet as retrofits, and many already have been. However, take-up currently remains low overall and therefore these options continue to present an opportunity for further marginal gains in efficiency.

Figure 3 Technologies that increase energy efficiency

Options	Impacts/benefits			Commercialisation		
	GHG abatement	**Local air pollutant abatement**	**At sea air pollutant abatement**	**TRL**	**Expected commerc. date**	**Future cost reduction potential**
Propulsion devices, including modifications to the propeller and adjacent area (ducts, fins etc.)	Low	Low	Low	TRL9	Currently available	Low
Ship design (changes in the shape of the hull, addition of bulbous bows etc.)	Medium	Low	Medium	TRL9	Currently available	Medium
Main machinery & engine modifications (design improvements to the diesel engine, energy recovery from waste heat etc.)	Low	Low	Low	TRL7-9	Up to 10 years	Medium
Auxiliary (energy management and recovery systems, design improvements and control systems for machinery such as pumps etc.)	Low	Medium	Low	TRL7-9	Currently available	Medium

3.1.2 Category 2: Operational or behavioural change that can increase energy efficiency

In addition to technology changes that can improve the energy efficiency of ships, there are a number of ways in which behavioural changes and modifications to operations can improve energy efficiency. These are summarised in Figure 4. Reducing ship speed in particular can have, and has already had, significant efficiency impacts. It has been argued that there could still be potential for further speed reduction in certain fleets,[5] hence its inclusion in this list. Other options have also been adopted in a few instances but are not widespread despite being ready and mature. This is due to a variety of reasons and therefore these options continue to present an opportunity. Operational energy efficiency improvements can be applied to the existing fleet and new ships and are generally fast to implement.

[5] Clean Shipping Coalition (2018). 'The Regulation of Ship Operational Speed: An Immediate GHG Reduction Measure to Deliver the IMO 2030 Target', IMO publication ISWG-GHG 4/2/8

Figure 4 Operational or behavioural change that can increase energy efficiency

Options	Impacts/benefits			Commercialisation		
	GHG abatement	**Local air pollutant abatement**	**At sea air pollutant abatement**	**TRL**	**Expected commerc. date**	**Future cost reduction potential**
Speed/voyage optimisation related	Medium	Low	Medium	TRL9	Currently available	Low
Condition related (trim, hull coating selection and maintenance etc.)	Medium	Low	Medium	TRL9	Currently available	Low
Port related (just in time arrival/turnaround at berth)	Low	Medium	Low	TRL9	Currently available	Low

3.1.3 Category 3: Technologies specific to the capture/treatment of exhaust emissions (GHG and air pollutant emissions)

Technology specific to the capture/treatment of exhaust emissions includes treatments that 'purify' the exhaust from the machinery or capture (and store) a component within the exhaust. These are summarised in Figure 5. Technologies that capture/treat the exhaust tend to be focused on specific air pollutant emissions and therefore may need to be used in combination with other options, depending on the fuel. It is possible to retrofit all these options onto existing ships, but there can be operational and technical issues on some ships, and the systems are typically slightly cheaper to integrate on a new ship. There are already some drivers for adoption of some of these technologies, including IMO regulation on air pollutant emissions both globally and within the emission control areas (ECAs), which currently include the English Channel and the North Sea. The take-up of exhaust gas cleaning systems has accelerated since the IMO confirmed that the sulphur content of marine fuel would be limited to 0.5% from 1 January 2020. It is anticipated that the Tier III NO_x controls which apply to new ships operating inside an ECA will gradually incentivise the use of NO_x abatement technologies (such as selective catalytic reduction and exhaust gas recirculation systems).

Figure 5 Technology specific to the capture/treatment of exhaust emissions

Options	Impacts/benefits			Commercialisation		
	GHG abatement	Local air pollutant abatement ***	At sea air pollutant abatement ***	TRL	Expected commerc. date	Future cost reduction potential
NO_x emissions control: Selective catalytic reduction (SCR) and Exhaust gas recirculation (EGR), exhaust gas technology, water in fuel (emulsion fuels)	Negative-Low	High	High	TRL9	Currently available	Medium
SO_x emissions control: Exhaust gas cleaning systems	Negative	High	High	TRL9	Currently available	Medium
Particulate matter (PM) (including black carbon (BC)) control: diesel particulate filters for reducing PM and BC, diesel oxidation catalyst for reducing SO_x, PM and BC, electrostatic precipitator	Negative-Low	High	High	TRL8*	Currently available **	Low
Methane catalysts for removal of methane (CH_4) in exhaust	High	Low	Low	TRL 5	Approximately 5 years	Medium
On board carbon capture, for storage and sequestration (CCS)	High	Low	Low	TRL 4	Approximately 10 years	Medium

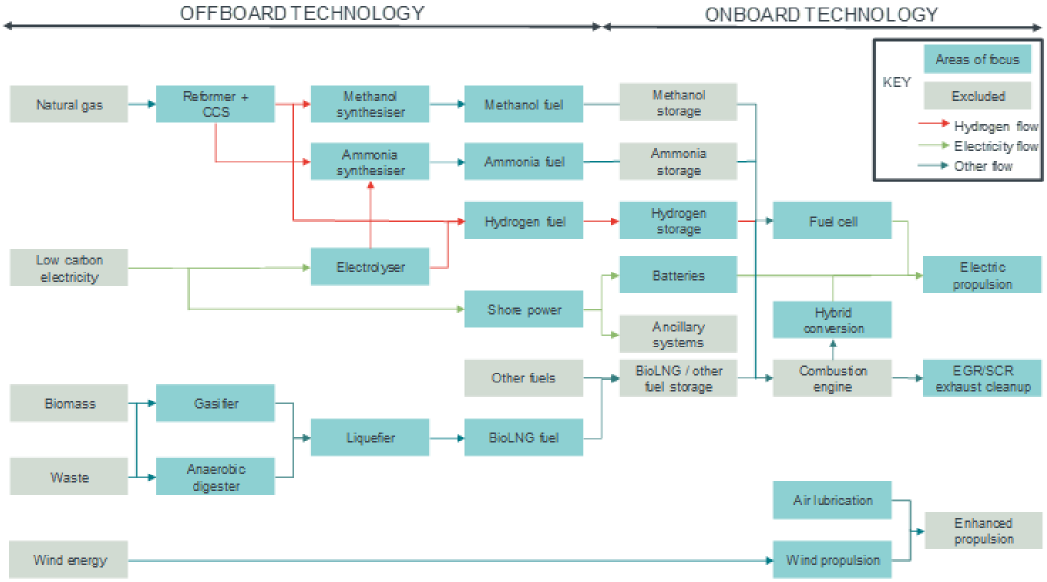
*Note: * for 4-stroke diesel engines. ** Applications in smaller vessels, more developed applications in trains and tractors, which can be marinized (made suitable for the marine environment). *** The abatement estimation is specific to the emissions that the technology is designed to abate (as specified in the row header).*

3.1.4 Category 4: Alternative fuels and energy sources, and related machinery

The fuel or energy source (summarised in Figure 7) has a large impact on the operating emissions in shipping. For this reason, international and national emission regulation has already started to provide the incentive for shifts towards alternative fuels. Regulation has so far focused on air pollutant emissions, such as SO_x, NO_x and particulate matter (PM). It is possible for low sulphur versions of incumbent fuels, such as low sulphur heavy fuel oil, and emission reduction technologies to comply with these air pollution regulations, but they will not act to reduce GHG emissions. Therefore, alternative fuels that reduce all emission types are outlined below.[6] A summary of these changes is included in Figure 6.

[6] There are other alternative energy sources and fuels not covered here such as LPG and alcohols such as ethanol, fossil methanol and fossil ammonia. These were excluded as their future use in shipping and effectiveness for emission reduction have been deemed limited by other literature. Nuclear is also excluded on the basis that the costs are not expected to be competitive and the technology would pose significant limitations on operability.

Figure 6 Summary of future energy technologies and machinery for shipping[7]



Natural gas in the form of liquefied natural gas (LNG) or compressed natural gas (CNG) offers the potential for large reductions in all air pollutant emissions but limited GHG savings when compared to incumbent fuels (heavy fuel oil, marine diesel oil). LNG was originally used for propulsion in LNG carriers and has been the most commonly considered alternative fuel for the shipping sector since regulations on air pollutant emissions started. Such regulations were initially in the ferry sector and short-sea shipping, and now have several applications in deep-sea, international shipping.[8] The UK domestic fleet has not been a strong early adopter of LNG as availability and infrastructure have developed more slowly than in other countries (DNV GL, 2015).

Hydrogen (sometimes stored as ammonia) is another option that produces very few or no air pollutant emissions, depending on the machinery it is used with (internal combustion engine or fuel cell, see below). When used as a shipping fuel, it can be stored in liquid form (LH_2) or via a hydrogen carrier fuel, such as ammonia, for storage and transportation reasons. No operational GHG emissions are produced from using hydrogen. However, there may be upstream[9] GHGs, depending on how it is produced, and these may need to be considered. Hydrogen from steam methane reforming (SMR) produces more GHGs in its lifecycle than incumbent shipping fuels, but hydrogen produced from renewable electricity via an electrolyser can reduce lifecycle GHGs to negligible levels.[10] Carbon capture and

[7] Elements of the supply chains shaded in blue are considered in more depth in Frontier et al (2019).

[8] International Maritime Organisation MARPOL Annex VI 'Regulations for the Prevention of Air Pollution from Ships' – Regulation 14.

[9] Upstream emissions are defined here as those involved with producing or processing the fuel. Although the emissions involved with producing the equipment to process the fuel are not included. (i.e. equivalent of Scope 2 emissions and Scope 3 emissions are not included). For example, the upstream emissions associated with hydrogen produced from electrolysis would be the emissions created from the electricity used in the production process.

[10] DNV GL (2018). Assessment of Selected Alternative Fuels and Technologies - reference value for fossil fuel liquid in shipping 83.8 gCO_2e/MJ. Source: Annex V, Renewable Energy Directive (2009) https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009L0028

storage (CCS) could also be used with SMR to reduce the GHG emissions of hydrogen production from a fossil fuel route.

Electro-fuels (or power-to-gas/liquids) is a general term for fuels produced from combining hydrogen derived from electrolysis with a carbon source to form low carbon versions of conventional fossil fuels i.e. e-diesel, e-methanol or e-methane. They can also have net zero operational GHG emissions, assuming the carbon source is taken from the atmosphere or as part of a sustainable cycle. As in the case of hydrogen and hydrogen carrier fuels, such as ammonia, production of synthetic fuels is energy intensive. To achieve lifecycle reductions in emissions, it is therefore important that their production's energy requirements are met with renewable or nuclear electricity. Low carbon methanol or methane can be made from a power-to-liquid/gas process but can also be produced from bio-based routes and, in that case, are categorised as biofuels (see paragraph below).

Batteries can store electricity on board the vessel for use for all of the operations (full electric), some of the operation (e.g. like a plug-in hybrid car), or to help manage variations in power demand (like a hybrid car). Electricity can also be used on board ships through **shore power** connections, supplying auxiliary power when the vessel is in port. This is sometimes referred to as 'cold ironing'. There are no operational emissions (GHG or air pollutant emissions) from using electricity on ships but, as for hydrogen and electro-fuels, the upstream emissions can be significant if the electricity used to charge the batteries has not been decarbonised.

Biofuels is a general term for many different fuels with different properties, production pathways and compatibility with current shipping engines. All biofuels have low sulphur oxide (SO_x) and PM emissions (Gilbert et al., 2018). The operational GHG emissions from the combustion of biogenic fuels are considered zero, as policy (e.g. IPCC guidelines) assumes that the fuel only releases carbon that is extracted from the atmosphere by the biomass. However, there are upstream emissions associated with the production of biofuels. Biofuels can be split into two categories: crop-based and waste-based. Crop-based biofuels, produced from food and energy crops, generally have higher lifecycle GHG emissions (36-68% reduction)[11] and greater issues with sustainability than waste-based biofuels. Waste-based biofuels have lower lifecycle emissions (70-95% reduction)[12] and less sustainability issues with feedstocks. Most liquid biofuels can be 'blended'[13] with liquid fossil fuels that have similar characteristics, as is currently carried out in road transport (European Commission, 2017). Similarly, biomethane (with similar properties to natural gas) can be produced from biogas[14] and liquefied to give bio-LNG.

Alternative primary renewable energy sources such as **wind propulsion** or **solar** cannot be used as the sole energy source but can be used to reduce the need for

[11] Straight vegetable oil (SVO), hydro-treated vegetable oil (HVO), FAME (Biodiesel). GHG values do not include waste feedstocks – reference value for fossil fuel liquid in shipping 83.8 gCO_2e/MJ. Source: Annex V, Renewable Energy Directive (2009) https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009L0028

[12] Fischer-Tropsch diesel, pyrolysis oil, bio-methanol – reference value for fossil fuel liquid in shipping 83.8 gCO_2e/MJ. Source: Annex V, Renewable Energy Directive (2009) https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009L0028

[13] Term used to describe the mixing of biofuel with fossil fuel with similar characteristics.

[14] Biogas is commonly produced from the anaerobic digestion of waste, for example manure. It contains CO_2, which is removed to produce biomethane.

consumption of energy from other sources (e.g. fuels or electricity), reducing emissions. **Wind propulsion** includes the use of fixed sails, Flettner rotors and kites to reduce the fuel consumption of the vessel and therefore the emissions. Solar can help power auxiliary systems and reduce the electrical demand from the engine.

What implications are there for storage and handling of alternative fuels?

Many alternative fuels result in the need to change onboard storage and port infrastructure. The gaseous alternative fuels such as natural gas and hydrogen require compression or liquefaction, resulting in new infrastructure and storage equipment. However, even with compression or liquefaction, the energy densities of these fuels are lower than liquid fossil fuels, requiring more storage space and reducing the available cargo space for vessels. Batteries suffer from a similar issue: the size and weight required for battery powered ships means that their range is limited, and they are not a compatible option with the larger ship types.

Alternative fuels like LNG, hydrogen and methanol have low flash points[15] and will need to comply with appropriate safety regulations. Additionally, methanol and ammonia are toxic and add complications to the handling of the fuel.

Liquid drop-in fuels like electro-fuels and some biofuels can be used in current storage and infrastructure without modification. However, compliance with existing fuel specifications needs to be considered for high biofuel blends.

How do these options influence machinery choices?

An advantage of some of the biofuels and electro-fuels is that they need no (or very little) modification to current marine diesel engine designs to function.

Other alternative fuels require, or significantly benefit from, new machinery options. Fuel cells and batteries, when used as the main energy source for propulsion, require an electric motor instead of an internal combustion engine, and are therefore more suited to new-build ships. Fuel cells can be used with fuels such as hydrogen, LNG, ammonia and methanol. These convert the fuel into electricity to be used with electric propulsion, similar to batteries. Fuel cells have the benefit of a higher efficiency compared to combusting the same fuels in internal combustion engines. However, fuel cell powered vessels have so far only been tested at the ~1MW size, limiting the power of propulsion. This propulsion power can be used in smaller vessels but is currently one to two orders of magnitude away from being the primary power for propulsion of larger ship types (DNV GL, 2017). Electric propulsion motors with suitable power outputs are technologically and commercially mature and have been used for some time in the defence, cruise and offshore supply vessel fleets. There are several competing fuel cell technologies. The most mature (proton exchange membrane) is available commercially at smaller scale, though efficiency improvements and cost reductions are expected through further technological development.

[15] The flash point of a fuel is the lowest temperature at which the flammable vapour of the fuel will ignite from an ignition source.

LNG/CNG and hydrogen (gaseous fuels) can be used in gas turbines,[16] spark ignition internal combustion engines[17] or multi-fuel internal combustion engines.[18] These machinery types would require retrofitting to existing vessels, as most vessels currently use marine diesel engines. It is possible to convert some marine diesel engines to use these fuels in a dual-fuel setup, but the conversion is costly. When also considering the required changes in storage, gaseous fuels are more suited to new-builds. Methanol can be used in similar engine configurations to gaseous fuels, although the corrosive and toxic nature of the fuel requires redesigned parts or chemical additives to reduce engine wear. Gas turbines, spark ignition and multi-fuel machinery options are all at TRL 9, and commercially mature. Gas turbines are in use in many military craft and there are also limited examples in the cruise ship sector. Many ships currently using LNG have multi-fuel engines.

Hybrid vessels using batteries and diesel are a viable option in new-build and retrofit, especially for ship types with power requirements that vary, for example vessels that have lots of changes in speed or manoeuvring, compared to vessels that go at constant speed from one port to another. Hybrid vessels are technologically and commercially mature and currently in use in several ship types (tugs, offshore vessels and cruise ships).

[16] Gas turbines are often used in shipping applications to burn gas and produce electricity, through the same process that is used in gas power plants on land.

[17] Spark ignition combustion engines differ from diesel (compression ignition) engines commonly found in vessels. Spark ignition are required for fuels that have high self-ignition temperatures, such as petrol or gaseous fuels, whereas fuels like diesel can self-ignite through compression.

[18] Multi-fuel (commonly dual-fuel) can use both a self-ignition fuel, such as diesel, heavy fuel oil, marine diesel oil etc. with a fuel such as LNG to overcome the issue of high self-ignition temperatures.

Figure 7 Alternative fuels and energy sources, and related machinery[19]

Options	Impacts/benefits			Commercialisation		
	GHG abatement ***	Local air pollutant abatement	At sea air pollutant abatement	TRL	Expected commerc. date	Future cost reduction potential
Wind propulsion	Medium	Low	Medium	TRL7-8	Next 5 years	High
Solar	Low	Low	Low	TRL9 **	Currently available	Medium
Battery	Low-Full*	High	Low-High*	TRL8-9	Currently available	High
Shore power (cold ironing)	Low	High	N/A	TRL9	Currently available	Medium
LNG/CNG	Low-Medium	Medium	Medium	TRL9	Currently available	Low
Biofuels (crop-based)	Full	Medium	Medium	TRL9	Currently available	Low
Biofuels (waste-based)	Full	Medium	Medium	TRL4-8	Next 5 years	Medium
Renewable hydrogen (including when stored as ammonia)	Full	Medium	Medium	TRL6-8	Next 5 years	High
Electro-fuels (including methanol)	Full	Medium	Medium	TRL5-8	Next 5 years	High

*Note: * Dependent on route length and battery application e.g. load levelling or full propulsion. ** Seen in sailing boats but not in commercial shipping. *** These assessments are for GHG emissions in operation, some options can have significant upstream emissions, see discussion in text.*

[19] This table refers to alternative fuels and energy sources i.e. energy technologies and their respective impacts and commercialisation parameters when deployed in combination with compatible machinery.

4 IMPLEMENTING ABATEMENT OPTIONS IN PRACTICE

4.1 Uncertainties prevalent when considering maritime abatement options

Category 1 (technologies that can increase energy efficiency) and category 2 (operational or behavioural change that can increase efficiency) options have uncertainties in terms of their impacts (benefits) and costs. The individual technologies often have small impacts/benefits, and these can vary as a function of the design of the ship that they are applied to and the way that ship is operated, and can even vary on the same ship from one year to the next. Overall, these uncertainties are not significant to the total expected savings from this group, but the uncertainty can influence the accuracy of estimates for individual ships and is one of the barriers that can hinder take-up. Their commercialisation is well known.

Category 3 options (technologies specific to the capture/treatment of exhaust emissions (GHG and air pollutant emissions)) have generally low uncertainty in terms of their impacts (benefits) as they can easily be tested and monitored both in laboratory environments and at sea. There is uncertainty as to whether there will be further innovations and new concepts developed, including from other sectors managing similar emissions.

Category 4 options (alternative fuels and energy sources and related machinery) are some of the most uncertain, primarily because, although the concepts are known and in many cases demonstrated, the scaling-up of some of the machinery, the production processes and supply chains has not been carried out and this could change the landscape of the impacts/benefits of these options. The uncertainty is not driven by a lack of technological readiness, but more by the lack of certainty about which of the options is likely to prove most commercially competitive in the long run. Each option has different supply chains and infrastructure requirements and could benefit from economies of scale if they achieve a significant share of future energy/technology markets. In particular, there remains uncertainty about the timescale over which the fuel options will become globally available without significant upstream emissions.

4.2 Variations by ship type/size/operation/route

Technologies that can increase energy efficiency and options for operational or behavioural change that can increase efficiency are generally applicable to all type/size/operation/route variations, but the total amount by which they reduce emissions can vary. Certain options, for example speed reduction and waste heat recovery, are most applicable to ships that spend a lot of time at constant speed, which is typically deep-sea shipping (e.g. containerships, tankers, ro-ros and bulk carriers). Hybrid technologies and shore power are particularly relevant for ships that are more frequently at berth or experience high variability in power requirements as a function of their operations (e.g. offshore ships, ferries and some fishing vessels).

Wind propulsion is an option that is naturally suited to areas with high wind speeds and the viability can also be influenced by wind direction relative to the route taken. It can also be very difficult to integrate the equipment (sails/rotors) on certain ships either because of a lack of deck space (such as for some offshore vessels) or the need for access of cranes and equipment during loading/unloading operations (such as for some dry bulk carriers).

Most of the alternative fuel and energy options require more space for energy storage than existing fossil fuels. In extreme cases (e.g. current battery technologies), this can be prohibitive for certain ship types that sail long distances and therefore need to store a large quantity of energy. Viability for most of these options will therefore be greatest initially for the ships that spend the shortest time at sea between access to shore for grid connection or regular refuelling.

4.3 Abatement choices that work well in combination and those that do not

Most technology/operational options can be used in combination. The savings realised in combination are less than those achieved by summing the savings potential of individual options. This is because the energy efficiency improvements are applied to a diminishing magnitude of energy consumption, and because some of the options have physical interactions (e.g. some propulsion and hull form options, waste heat recovery technology and some air pollution exhaust treatment technologies) which reduce their effectiveness. Furthermore, many of the air pollution abatement options are exhaust treatments. This means that they add resistance to the flow of exhaust gases, which in turn creates a small (e.g. 1-3%) reduction in the efficiency of the main propulsion engine.

The different technologies for controlling air pollutant emissions are fuel/machinery dependent and need to be considered in combinations (e.g. fuel, machinery, pollution abatement technology). This is because there are drivers related to GHG abatement which will ultimately cause a shift away from current fuel and machinery, so specific abatement technology installations suited to current fuels and machinery may subsequently become obsolete. For example, SCR/EGR technology could be used to abate NO_x emissions on the fishing fleet's machinery (currently using diesel fuel and internal combustion engines), but this technology would not be required if the fleet were to subsequently convert to using hydrogen/ammonia and fuel cells. This is an issue that would be relevant to all ship types, but particularly so for ship types that are the likely early adopters of zero-emission fuels/energy, such as some of the ferries and short-sea shipping segments.

Changing fuel and machinery can also affect the viability of some energy efficiency options, for example those associated with the main machinery like waste heat recovery, which can be effective with internal combustion engines but may not be as suitable for use with fuel cells. Options that should produce emissions reductions through efficiency improvements (irrespective of the underlying fuel and machinery choices, e.g. hull and propulsion improvements, wind propulsion, and solar), should continue to be effective regardless of the specific fuel and machinery which is subsequently adopted.

4.4 Dependencies on wider infrastructure and energy system developments

A large-scale change is needed generally to enable even a sub-section of the fleet to use a low emission alternative fuel or energy source. This is because, as well as there being issues of compatibility with existing fleet machinery, air pollution technology and energy storage technology, the land-side infrastructure and supply chains for the fuels need to be in place and widely available. However, there may be synergies that arise if other parts of the energy system move to use the same fuel or energy source, for example passenger vehicles switching to electrification, heavy goods vehicles switching to hydrogen, or hydrogen production used to supply grid gas.

Even shore power connections for ships to use when in berth place significant extra and variable power demands on the grid and therefore require further infrastructure development.

In some cases, air pollution technologies can require land-based disposal processes. For example, some scrubbers for reducing SO_x emissions create a waste stream that then subsequently needs to be received at the port and disposed of, adding to port-side developments and infrastructure needs.

5 ABATEMENT OPTIONS: CONCLUDING COMMENTARY

Overall, the assessment in the previous sections shows that there are a number of different options which are not yet in widespread use for abating emissions from domestic and international shipping. With the exception of two options – batteries and wind propulsion – all the options could, from a standpoint of technical considerations, be applied to all ship types and therefore have the technical feasibility to become fully deployed. Due to their low energy density, batteries may be technically infeasible to use for some deep-sea shipping without a technological breakthrough. Wind propulsion is constrained because for some ship types there is not sufficient deck space to warrant its use.

The options are all currently available and mature or are expected to be available in the near term (e.g. the next ten years). Therefore, their maturity is no reason to significantly delay initiation of the action needed to control the sector's GHG and air pollutant emissions. Furthermore, many options have potential for reductions in their cost of implementation and use which could be facilitated if there were significant levels of take-up in UK or global fleets.

There are several options that enable marginal GHG reductions to be achieved in combination with significant reductions in air pollutant emissions, which would all be compatible with the current fuels and machinery, for example the technology or behavioural change options. However, the solutions for achieving significant GHG reductions (biofuels, hydrogen and ammonia, and synthetic fuels) will all require a switch to a different fuel, which may also require (or make commercially viable) a switch to different machinery.

Given this availability and maturity information, if the barriers to uptake were to be addressed, all ship types could technically achieve zero operational GHG and pollutant emissions by 2050 through full adoption of alternative fuels and associated machinery. Given the long life of many shipping assets, which can make it slow for new technology to reach high take-up, this would imply a transition away from fossil fuels starting soon (such as in the 2020s) and with strong drivers (commercial and/or regulatory) for adoption from as soon as is feasible. If action is taken early enough, the transition can be driven primarily by changes in the new-build specifications, but an accelerated transition can be achieved using options (e.g. biofuels and synthetic fuels) that can also be used with minimal modification to existing ships. For this not to create unintended consequences of significant upstream emissions or sustainability impacts, this would also require sustainable supply chains and pathways for the production of low GHG and low air pollution fuels. Many of the energy efficiency options could be stimulated from now onwards and would still be relevant in the event of fuel switching. This adoption would help to reduce energy demand and make the supply and cost of fuel switching more manageable.

If the transition away from fossil fuels starts much later than 2030, and with weaker drivers to encourage take-up of the options to reduce GHG emissions, the period to 2050 will likely require more use of air pollution abatement technologies due to a sustained use of the incumbent fossil fuels and internal combustion machinery.

Under weaker commercial or policy drivers, the switch away from fossil fuels would be expected to be more gradual, and full penetration in the sector of zero emissions options might then be expected to be achieved between 2050 and 2100 (with the point in time determined by commercial and policy drivers).

6 REFERENCES

Defra, 2019. Clean Air Strategy. [Online] Available at: https://www.gov.uk/government/publications/clean-air-strategy-2019

DfT (Department for Transport), 2019. Maritime 2050: Navigating the Future. [Online] Available at: https://www.gov.uk/government/publications/maritime-2050-navigating-the-future

DNV GL, 2015. In Focus – LNG as Ship Fuel. [Online] Available at: http://production.presstogo.com/fileroot7/gallery/dnvgl/files/original/124feddb807045969b3071a55f73c80b/124feddb807045969b3071a55f73c80b_low.pdf

DNV GL, 2017. Study on the Use of Fuel Cells in Shipping. EMSA. [Online] Available at: http://emsa.europa.eu/csn-menu/download/4545/2921/23.html

EEA (European Environment Agency), 2013. The Impact of International Shipping on European Air Quality and Climate Forcing. EEA Technical Report No. 4/2013. [Online] Available at: https://www.eea.europa.eu/publications/the-impact-of-international-shipping

European Commission, 2017. Report in Accordance with Article 9 of Directive 98/70/EC Relating to the Quality of Petrol and Diesel Fuels. [Online] Available at: https://ec.europa.eu/transport/sites/transport/files/com20170284-evaluationreportfuelqualitydirective.pdf

Faber, J., Ahdour, S., 't Hoen, M., Nelissen, D., Singh, A., Steiner, P., Rivera, S., Raucci, C., Smith, T., Muraoka, E., Ruderman, Y., Khomutov, I. and Hanayama, S., 2016. Assessment of Fuel Oil Availability. MEPC 70/INF.6. [Online] Available at: http://www.imo.org/en/OurWork/Documents/MEPC%2070-INF.6%20-%20Assessment%20of%20fuel%20oil%20availability.pdf

Frontier Economics, E4tech and UMAS (2019) Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution: Economic Opportunities from Low and Zero Emission Shipping.

Gilbert, P, Wash, C, Traut, M., Kesieme, U., Pazouki, K. and Murphy, A.2018. Assessment of Full Life-cycle Air Emissions of Alternative Shipping Fuels. Journal of Cleaner Production, 172 pp. 855-866.

IPCC, 2018. Summary for Policymakers. In: V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds), 'Global warming of 1.5°C'. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Geneva: World Meteorological Organization.

LR and UMAS, 2017. Zero-Emission Vessels 2030. How Do We Get There? [Online] Available at: http://www.lrs.or.jp/news/pdf/LR_Zero_Emission_Vessels_2030.pdf

OCIMF, 2011. GHG Emission-Mitigating Measures for Oil Tankers (MEPC 63/INF.7) [Online] Available at: https://www.transportstyrelsen.se/contentassets/4b0bec76d2c74c95a37181b5fe45a921/63-inf7.pdf

Ricardo Energy and Environment, 2017. A Review of the NAEI Shipping Emissions Methodology: Final Report. [Online] Available at: http://naei.beis.gov.uk/reports/reports?report_id=950

Rehmatulla, N., 2015. Assessing the Implementation of Technical Efficiency Measures in Shipping. Survey Report. [Online] Available at: https://www.ucl.ac.uk/bartlett/energy/sites/bartlett/files/shipping_survey.pdf

Smith, TWP, Day, S. Bucknall, R. Mangan, J. Dinwoodie. J. Landamore, M. Turan, O. Robel, P., 2014. Low Carbon Shipping A Systems Approach, Final Report. London: University College London.

UMAS, 2014. Support to Energy Technology Institute's Heavy Duty Vehicle Programme: Marine.

UMAS, 2016. CO2 Emissions from International Shipping, Possible Reduction Targets and their Associated Pathways. [Online] Available at: https://u-mas.co.uk/LinkClick.aspx?fileticket=na3ZeJ8Vp1Y%3D&portalid=0

Winnes, H., Fridell, E., Yaramenka, K., Nelissen, D., Faber, J. and Ahdour, S., 2016. NOx controls for shipping in EU Seas. [Online] Available at: https://www.transportenvironment.org/sites/te/files/publications/2016_Consultant_report_shipping_NOx_abatement.pdf