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

Economic Opportunities from Low and Zero Emission Shipping. A Report for the Department for Transport

July 2019

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EXECUTIVE SUMMARY

Shipping is responsible for substantial emissions of greenhouse gases and air pollutants. Current regulations and incentives mean that without further intervention shipping emissions are expected to increase in an unsustainable way, with associated climate change impacts and damage to human health.

The Department for Transport (DfT) published Maritime 2050 in January 2019 (DfT, 2019). This included a commitment that the UK will actively drive the transition to zero emission shipping in its waters by 2050. This is with the intention to address the negative impacts of emissions and to allow the UK to capitalise on the potential economic benefits associated with the transition (DfT, 2019).

This report provides a framework for assessing the current and future potential scale of economic opportunities for the UK from the design, development and commercialisation of technologies and low emission fuels that reduce UK shipping emissions (together referred to as 'abatement options') and that are expected to be critical to achieving zero emission shipping. The framework is then applied to assess the economic opportunities for the UK from a selection of specific abatement options which were chosen using agreed criteria.[1]

For each selected abatement option, this report provides a mapping of the relevant supply chain; an assessment of the current global uptake of those abatement options along with the economic footprint of the UK firms in the supply chain; and the UK's share of global exports of those abatement options. It then considers the UK's potential to be a global player in the design, development and commercialisation of those abatement options by assessing the UK's current capability and competitive advantage. An illustrative assessment is provided of the potential scale of the global future market for those technologies and low emission fuels, using plausible scenarios. This is used to infer the potential scale of the UK market, given its capability and competitive advantage.

Eleven abatement options were shortlisted for this analysis. Each is expected to play a material role in facilitating the transition to zero emission shipping. Figure 1 and Figure 2 set out the shortlisted abatement options along with the key findings from the analysis in terms of a preliminary assessment of the UK's current competitive position and the estimated potential future global market size by the middle of the century. These estimates of the potential market size are based on the assumption that policies and incentives are put in place to deliver a 50-100% reduction in global shipping greenhouse gas emissions by the middle of the century relative to emissions in 2008. All modelling results are sensitive to the assumptions used to estimate future scenarios, as described in Frontier et al. (2019c).

The UK's competitiveness rating for each option is scored on a scale of 1-5, based on the best available evidence and expert judgement. A score of 1 indicates that the UK has little or no relevant activity and no basis for competitive advantage while a score of 5 implies that the UK is a global leader across all activity areas and has a very strong basis for competitive advantage.

[1] These are described in full in the main report.

The future global market size for all fuel production technologies is presented as a single estimate for two reasons:

1. The likely mix of these low carbon fuels in the future is uncertain and depends on how the cost effectiveness of each fuel type evolves over time; and
2. Ammonia and, in some cases, methanol require hydrogen as a feedstock. Additional detail is provided in the abatement option annexes contained in Frontier et al. (2019a).

Figure 1 Overview of shortlisted abatement options (fuel production technologies): UK competitive advantage and potential global scale of market by the middle of the century

Option	Assessment of UK competitive position (rating 1 to 5)	Estimated future global market size by the middle of the century[2] ($m per year)
1. Hydrogen production technologies	4/5	11,000-15,000[3]
2. Methanol production technologies	3/5	
3. Ammonia production technologies	4/5	
4. Bio-LNG production technologies	3/5	

Source: Frontier, E4tech

Note: Figures are rounded to the nearest billion and are in 2016 prices. The estimated future global market size represents only those stages of the value chain in which the UK has a particular competitive advantage (such as the upfront design or intellectual property (IP) intensive aspects of fuel production technologies).

In relation to fuel production, the UK generally has strengths in the upfront design and IP-intensive stages of the relevant value chains. The estimate of the future global market size for fuel production technologies in Figure 1 includes only these particular aspects of the value chain (i.e. this is a relatively small part of the market for low carbon fuel supplied for shipping). These particular stages of the value chain are where the UK stands a greater chance of building and/or maintaining market share as the volume of these low carbon options grows worldwide.

The transition to low carbon fuels for shipping also presents a potential opportunity for the UK to increase its market share in the actual production of these fuels. This is an important opportunity associated with wider UK decarbonisation and clean growth strategies. This would benefit from further consideration. However, it is outside of the scope of this study and does not feature in the estimated market size estimates.

Around 0.7-1 billion tonnes of alternative fuel sources are estimated to be used annually by the global shipping fleet by the middle of the century, based on scenario analysis (Frontier et al. 2019c). The modelling suggests that ammonia and methanol will make up the bulk of this volume. Usage of hydrogen and Bio-

[2] Assuming a 50-100% reduction in shipping emissions by the middle of the century relative to 2008 levels.

[3] This includes all four alternative fuel production technologies.

LNG is expected to be relatively limited in the sector. However, this is subject to significant uncertainty.

Figure 2 provides an estimate of the potential future markets for the non-fuel technologies explored in this report.

Figure 2 Overview of shortlisted abatement options (non-fuel technologies): UK competitive advantage and potential global scale of market by the middle of the century

Option	Assessment of UK competitive position (rating 1 to 5)	Estimated future global market size by the middle of the century[4] ($m per year)
5. Low carbon shore power	2/5	100-200
6. Onboard hydrogen technology	3/5	-
7. Batteries for electricity storage onboard	4/5	0-100
8. Electric engines	4/5	0-600
9. Air lubricants	3/5	2,600-3,500
10. Wind propulsion	3/5	2,600-2,900
11. Exhaust Gas Recirculation and Selective Catalytic Reduction (EGR/SCR)	3/5	500-700

Source: Frontier, E4tech

Note: Figures are rounded to the nearest 100 million. All financial values are in 2016 prices and reflect capital costs for new installations[5] and annual recurring costs for new and existing installations.

The implied UK potential market across all 11 shortlisted abatement options (both fuel and non-fuel) could be **$650-890 million** per year by the middle of the century, if the UK were able to maintain its current export market share (this is approximately equivalent to 4% of the relevant global markets). Focusing just on fuel production the implied UK potential market across could be **$490-690 million** per year by the middle of the century (approximately equivalent to 4.6% of the relevant global markets). Importantly, this assessment is indicative only because future export market shares are inherently uncertain and could rise or fall relative to current levels.

Figure 1 and Figure 2 show that the competitive position of the UK is assessed as having a rating of least 2 out of 5 across all 11 abatement options. This suggests that there are significant economic and commercial opportunities for the UK across all abatement options considered, with some currently relatively stronger than others.

Firms are currently operating successfully in the UK within specific niches related to each of the abatement options. In addition, although not assessed within this report, a further key strength of the UK, which cuts across the abatement options, is its position as a global leader in maritime professional services. The UK has extensive expertise in finance, vessel chartering, insurance, legal and educational

[4] Assuming a 50-100% reduction in shipping emissions by the middle of the century relative to 2008 levels.

[5] The number of new installations was estimated as the annual average number of installations over 2046 to 2051.

services (Maritime UK, 2018). These services are likely to continue to be important for the industry going forward, both in the UK and overseas.

Overall, the analysis suggests that low carbon fuel production technologies offer a relatively greater commercial opportunity for the UK, particularly in relation to **hydrogen and ammonia**. Importantly, these two options are inter-related as hydrogen production technologies are a key input to the production of ammonia fuel. **Batteries and electric engines** also offer a strong potential competitive advantage.

However, as noted above, given that the UK has some level of competitive advantage across all 11 options and acknowledging the inherent uncertainty when considering future market opportunities, policy measures that are technology agnostic are likely to be prudent. Further work is recommended in this area to carry out a more detailed competitive assessment of the UK across the entire shortlist.

For the UK to maximise its potential commercial opportunity, policy intervention may be required to overcome barriers that could otherwise hinder its progress in this space. Key barriers identified in Frontier et al. (2019d) that would merit policy attention are:

1. **Externalities**: this highly prevalent barrier is of significant importance due to the fact that the price of fossil fuels does not currently reflect the social costs of climate change nor damage to human health and ecosystems from air pollution, which are known as negative externalities. This affects the relative price of fuels in the market and therefore the incentives to invest in their development. Low carbon fuels are currently relatively expensive compared to conventional fuel sources. This is partially because the technologies associated with such fuels are still nascent. However, the price differential is also partially due to the negative externalities which are not currently included in the price of fossil fuels. Policy could address this through the use of various price-based market mechanisms, for example.

2. **Policy landscape stability**: the policy landscape is an important barrier in relation to the development of and incentives to take up low carbon fuels. Significant financial investment is likely to be required for the development and widespread uptake of abatement options, along with associated infrastructure, if zero emissions shipping is to be achieved by around 2050. This requires a stable policy landscape that is able to provide the market with sufficient confidence that the market opportunities will be sustainable over the longer term. Where policy is uncertain or unstable, this could be a significant barrier. The UK has a number of strengths in relation to cutting edge R&D of electric propulsion, for example, so ongoing incentives to encourage applied research and skills development are likely to add value.

3. **Organisational barriers:** interdependencies across various actors in the shipping market mean that there are likely to be barriers to the widespread development and uptake of low carbon fuels and other abatement options if there is no supporting co-ordination. For example, the ability of one set of organisations to implement changes is often dependent on the activities of others. Policy incentives could be designed in a way which recognises

these interdependencies by targeting actors appropriately across the supply chain.

4. **Structural barriers**: some abatement options, such as on-shore power, have particular infrastructure requirements at ports which need investment from the port and others in the supply chain, such as those operating the regional or national grid. Co-ordination of activities and the provision of appropriate incentives may be required. For example, ship owners may not want to invest in alternative fuel technologies until ports put in place the supporting infrastructure. However, ports may not want to invest in the supporting infrastructure until the demand can be credibly demonstrated. These co-ordination issues could be partially overcome if governments, trade bodies or international representative groups can organise, promote and facilitate the diffusion of abatement options, especially through an inter-government body like the International Maritime Organisation.

5. **Split incentives:** related to the co-ordination issues above, split incentives are an important barrier and derive from the fact that ship owners often have little incentive to invest in fuel efficiency or emissions abatement options, because it is likely to be the charterer that benefits from the fuel savings. These could be addressed through, for example, exploring mechanisms which facilitate co-ordination and some sharing of the benefits across the parties involved in decision-making.

1 INTRODUCTION

Shipping is responsible for substantial emissions of greenhouse gases (GHGs) and air pollutants. Shipping (both international and domestic) is currently responsible for 3.4% of the UK's overall GHG emissions (DfT, 2019) and generates emissions of several pollutants harmful to human health. In 2016, domestic shipping accounted for 11% of the UK's total domestic nitrogen oxide (NO_x) emissions, 2% of particulate matter (primary $PM_{2.5}$) emissions and 7% of sulphur dioxide (SO_2) emissions (DfT, 2019). As emissions from other sectors decrease in line with UK commitments and action on climate change, without further intervention the contribution of the maritime sector will increase. Shipping emissions are associated with climate change impacts and damage to human health.

The Department for Transport (DfT) published Maritime 2050 in January 2019 (DfT, 2019). This includes a commitment that the UK will actively drive the transition to zero emission shipping in its waters by 2050. This is with the intention to address the negative impacts of emissions and to allow the UK to capitalise on the potential economic benefits associated with the transition (DfT, 2019). The Clean Maritime Plan (CMP), to be published later in 2019, will provide detail on what this means for the UK and how policy can support this ambition.

Not only does the commitment to zero emission shipping imply substantial benefits to the UK in terms of reduced damage to health from cleaner air and by making a valuable contribution towards the UK's legally binding climate change targets for 2050, but such a transition also offers economic and commercial opportunities to the UK. More specifically, the transition to zero emission shipping will require the wide-scale adoption of low emission technologies and fuels. For some options, the UK could be a global player in their design, development and commercialisation.

To inform the CMP, this report provides evidence on the potential scale of the economic and commercial opportunities to the UK from the transition to zero emission shipping. In particular, it sets out:

- Chapter 2: a framework for identifying the low emission shipping technologies and fuels (i.e. 'abatement options') that are likely to offer a material commercial opportunity for the UK;
- Chapter 3: the shortlist of abatement options on which this report focuses;
- Chapter 4: the application of the framework to each of the shortlisted abatement options, synthesising the findings to identify the options that are likely to provide the greatest economic opportunity to the UK and the potential scale of that opportunity given the UK's competitive strengths; and
- Chapter 5: where policy intervention could usefully focus to support the UK in becoming a global player in low emission technologies and fuels for shipping.

A separate report provides additional detail on each individual abatement option considered in this report (Frontier et al., 2019a).

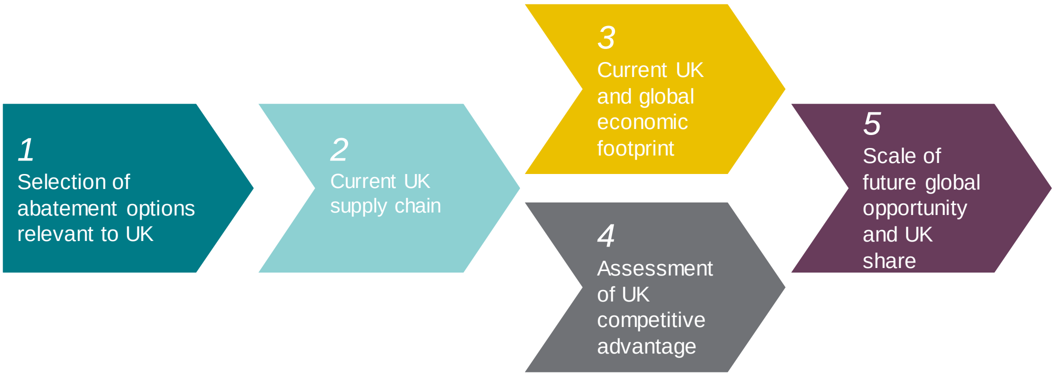
2 FRAMEWORK FOR ANALYSIS

An overarching framework for identifying the shipping emissions abatement options that offer the greatest potential economic opportunity to the UK is set out in Figure 3. The aims of the framework are to provide:

- an approach for identifying a shortlist of abatement options on which analysis could most fruitfully focus, in a proportionate and tractable way;
- a method for articulating a definition of the shortlisted abatement options along with their supply chains;
- a transparent approach for assessing the current deployment of these shortlisted abatement options for shipping and the UK's current share of relevant export markets;
- a coherent approach for assessing the competitive advantage of the UK in relation to each shortlisted abatement option; and
- an illustrative assessment of the potential global demand for the shortlisted abatement options for shipping and the scale of potential opportunity for the UK.

Each of the steps is then described in the sections below.

Figure 3 Analytical framework



Source: Frontier, E4tech

2.1 Step 1: Selecting shortlisted technologies

To make this analysis tractable, **Step 1** provides an approach for selecting a short list of abatement options on which to focus. Previous work has identified 38 potential abatement options for shipping (Frontier et al., 2019b). It is not practical to assess each option in this report, particularly as not all abatement options will offer a commercial opportunity for the UK. Criteria are therefore used to provide a coherent and transparent framework for the selection of an appropriate shortlist. Shortlisted abatement options are identified based on the extent to which they:

- are likely to make a material contribution to shipping emissions reduction by 2050;
- have the potential to be cost effective; and
- are those for which there is readily available data to inform the analysis.

On the basis of a high-level qualitative assessment, 11 abatement options pass each criterion. Assessment of each option against the criteria is partially based on previous analysis (Frontier et al., 2019b) as well as on a preliminary exploration of the UK's competitive position, which is explored further in subsequent sections.

The criteria and resulting shortlist are presented in Chapter 3.

2.2 Step 2: Identification of supply chains

Step 2 takes each of the shortlisted options and maps its UK supply chain. In order to assess the options, it is necessary to disaggregate the supply chains into the main sub-technologies which correspond to current and potential UK industrial activities. The nature of the commercial and economic opportunity for the UK could derive from one or more stages of the supply chain, and not necessarily the whole chain. Breaking it down in this way helps to be specific about where the opportunity may exist and what form of activity it involves.

In addition, the sub-technologies inter-connect rather than existing in isolation. Mapping out the full supply chains helps to illustrate this. Chapter 4.2 contains the results of the supply chain mapping.

2.3 Step 3: Current deployment and UK economic footprint

Step 3 of the framework presents current uptake rates of the shortlisted abatement options across the global fleet; illustrates the current economic footprint of key UK firms in the relevant supply chain; and uses published trade data to estimate the UK's current share of the relevant global export market for proxy or related technologies.

This is based on three primary data sources:

1. Information on current implementation of abatement options from modelling work carried out by UMAS and summarised in Frontier et al. (2019c). This analysis estimates the global take-up of each of the abatement options across each ship type at the start of the 2020s and in the middle of this century.
2. The current economic contribution of key UK firms active in the relevant supply chains, using data from sources such as Companies House (2019), annual reports and engagement with sectoral experts.
3. International export data from the United Nations International Trade Statistics Database (also known as Comtrade), the largest depository of international trade data. Comtrade provides data on the value of imports and exports (including re-imports and re-exports) by country-pair and commodity (UN, 2019). Comtrade data is useful for approximating the current market share of the UK in each sub-technology industry by looking at trade in proxy or related technologies, and identifying the countries that are most likely to be the largest exporters of those technologies in that industry. However, there are a number of important caveats that should be noted in drawing inference from this data for this study:

a. Comtrade data is organised by six-digit Harmonised System commodity codes (HS6). In some cases, these closely describe the relevant sub-technology well (e.g. the Hydrogen Fuel: Electrolyser sub-technology maps to HS code 854330, which includes 'machines & apparatus for electroplating/electrolysis/ electrophoresis'). In other cases, these provide only a rough proxy of the sorts of products that are likely to be included in the sub-technology. For these sub-technologies, the share of global export estimates is likely to be less precise. This is particularly the case for niche technologies (e.g. the Hydrogen Storage technology maps to HS codes 841869 and 841430, which cover a range of related products including 'Refrigerating/freezing equip. n.e.s. in 84.18; heat pumps' and 'Compressors of a kind used in refrigerating equip') and nascent technologies that do not yet have established export markets (e.g. the Wind Propulsion technology maps to HS code 630630, which include sails for all vessel types). Where the proxy has been judged by experts to be too weak, Comtrade data has not been used to estimate export market shares.

b. Comtrade data does not account for production of the abatement options that is consumed domestically; rather it reports only the value of goods traded internationally. Where a country has a substantial domestic market, relative to its level of production, using Comtrade data might underestimate its market share. Likewise, if a country exports all of its production, using Comtrade data might overstate its market share.

c. Comtrade data only accounts for goods exports, rather than all goods and services exports. Where a country has a substantially higher share of services exports, using Comtrade may understate its market share.

d. For the above reasons, using the Comtrade data to approximate export *market shares* is likely to be more precise than using it to estimate the absolute value of the global product market.

Chapter 4.3 presents an overview of current uptake rates and export data for each of the 11 technologies. As examples, the contributions of three particular abatement options are illustrated. Additional detail on all other abatement options is provided in the abatement option annexes contained in Frontier et al. (2019a).

2.4 Step 4: UK competitive advantage

To help understand the potential future commercial opportunities for the UK for each of the shortlisted abatement options and sub-technologies, **Step 4** describes how to assess the UK's current competitive position relative to key rivals and hence its competitive advantage. This analysis considers several dimensions of competitive advantage. Specifically, the assessment draws on academic models of competitive advantage (Porter and Kramer, 2002) and considers how the UK fares in terms of input factors (such as access to highly skilled labour), technology factors (such as existing IP) and access to markets (see Figure 4).

Figure 4 Competitive advantage framework

Source: Frontier, E4Tech based on Porter and Kramer (2002)

The competitive position of the UK is assessed individually for each option based on a range of data sources. The results of the competitiveness assessment are presented in Chapter 4.4. Additional detail is provided in the abatement option annexes contained in Frontier et al. (2019a).

2.5 Step 5: Future global opportunities for the UK

Step 5 provides a method for assessing the potential future scale of the global commercial opportunity of each shortlisted technology and sub-technology. This draws on modelling carried out by UMAS and summarised in Frontier et al. (2019c) which forecasts take-up of abatement options across the global shipping fleet, assuming global shipping emissions are reduced by 50-100% by the middle of this century.[6] This analysis is illustrative only, given the significant uncertainties when projecting over a 30-year period. Its purpose is to provide a relative order of magnitude of scale, rather than implying any spurious accuracy.

Estimates of the future export market size draw on scenario analysis undertaken by Frontier et al. (2019c). These reflect the indicative annual capital and annual recurring costs associated with each non-fuel technology. For fuel production technologies, the UK generally has strengths in the upfront design and IP-intensive stages of the relevant value chains. Therefore, the contribution of these stages of the value chain only are assessed for fuel production technologies. All modelling results are sensitive to the assumptions used to estimate future scenarios, as described in Frontier et al. (2019c). Finally, the scale of the potential UK opportunity is considered by applying an estimated potential market share. Where appropriate, this draws on the analysis in Steps 3 and 4. Chapter 4.5 contains the results of this analysis. Additional detail is provided in the abatement option annexes contained in Frontier et al. (2019a).

[6] The proportional reductions are measured relative to 2008.

3 STEP 1: SELECTING SHORTLISTED TECHNOLOGIES

3.1 Introduction

As described in Chapter 2, the first step of the framework is to select a shortlist of low emission technologies and fuels on which to focus the analysis. This chapter starts with the long list of options identified in previous analysis (Frontier et al., 2019b) and then it develops and applies criteria to identify a shortlist.

3.2 Longlist of abatement options and criteria for shortlisting

In total, 38 options were identified in a separate report (Frontier et al., 2019b). The full longlist is presented in Annex A. The potential uptake of all 38 options has been comprehensively modelled in a separate report (Frontier et al., 2019c).

A transparent set of criteria have been developed in discussion with DfT to filter down the options into a shortlist. They are intended to target the relevant aspects when considering the extent to which the abatement options offer a commercial opportunity for the UK in future decades. The longlist was then filtered down based on the criteria listed below:

- Potential to make a material contribution to shipping emissions reduction by 2050. In keeping with the analysis presented in Frontier et al. (2019b), the scales of both GHG abatement and abatement of local air pollutants are considered. The magnitude of abatement[7] 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. Longlisted options which are only expected to have a low impact on both GHG and local air pollutant emissions were not included in the shortlist.
- Potential to be cost effective. Expert judgement was used to determine whether an option would be cost effective in 2050, meaning they have the potential to be competitive with other low emission options. Any longlisted options which do not have a significant chance of becoming cost effective by the middle of the century are excluded. A short narrative around those options deemed to have potential to be cost effective is included below.
- Availability of data on the abatement option to inform the analysis. The data sources used vary according to the specific abatement option. Sources include:
  - Engagement with sector experts;
  - Patent data (European Patent Office, 2019);
  - Comtrade data (UN, 2019);
  - Companies House data (Companies House, 2019);
  - Academic databases (British Library, 2019); and

[7] On a per vessel basis.

- Sector reports (Maritime UK, 2018).

If there is sufficient relevant information currently available on an abatement option, it is considered for inclusion on the shortlist. Other options will be excluded from further consideration as part of this report.

3.3 Shortlist

To identify a shortlist for the focus of this report, each of the longlisted options was qualitatively assessed against the criteria, drawing on previous work (Frontier et al., 2019b), on the expertise of academic experts at University College London and the input of DfT maritime policy and analysis officials. Figure 5 summarises the results of this selection process. A shortlist of 11 abatement options was chosen, all of which meet the three criteria listed above and have been agreed with DfT. In a number of cases, multiple longlist options were combined into a group which was then included as part of the shortlist. These abatement options will be subject to in-depth analysis throughout the rest of this report. Additional detail is provided in the abatement option annexes contained in Frontier et al. (2019a).

Figure 5 Shortlisted abatement options

Option	Description	GHG abatement	Local air pollutant abatement [8]	Cost effectiveness	Data availability
1. Hydrogen production technologies	Hydrogen can be produced via a number of methods. Electrolysis and steam methane reformation (SMR) with carbon capture and storage (CCS) are considered here.	High	Medium	Currently high cost but potential to reduce in future depending on the production pathway used. [9]	Sufficient data available
2. Methanol production technologies	Methanol is considered to be produced from synthetic gas + CCS or from green hydrogen + waste/atmospheric CO_2 source.	High	Medium	Currently competitive relative to traditional fuel sources when produced from fossil. Low emission methanol cost from the routes considered here is linked to the hydrogen production technologies and will have a higher price point.	Sufficient data available
3. Ammonia production technologies	Ammonia is produced from combining nitrogen with hydrogen.	High	Medium	Expensive due to hydrogen (H_2) component. Ammonia conversion is currently inexpensive compared to H_2 production cost. Ammonia cost will decrease in line with H_2 cost in future.	Sufficient data available
4. Bio-LNG production technologies	Bio-LNG refers to liquefied methane from biomass. It can be derived from harvested biomass or from the organic fraction of wastes, such as municipal solid waste and manure.	High	Medium	Currently more expensive than LNG but could be competitive with other fossil fuels in the future on an energy basis.	Sufficient data available

[8] Local air pollutant abatement for fuels assumes use via an internal combustion engine. All fuels covered here can also be used in fuel cells, which would eliminate operational air pollution. See Option 6.

[9] Potential for cost reduction is from technology improvement and economies of scale for both SMR+CCS and electrolysis technologies. Electrolysis may also benefit from increased utilisation and the potential for reducing fuel costs from renewable electricity generation.

Option	Description	GHG abatement	Local air pollutant abatement [8]	Cost effectiveness	Data availability
5. Low carbon shore power	Enables vessels to avoid the use of their engines in port to run onboard generators.	High	High	Electricity price high compared to fossil fuels. Further reduction in renewable electricity cost expected.	Sufficient data available
6. Onboard hydrogen technologies	Hydrogen requires specialist equipment for it to be used and stored on a vessel. This includes hydrogen storage and fuel cells to convert hydrogen to electricity.	N/A[10]	High[11]	Higher cost than traditional fuel storage due to special materials. Fuel cells currently expensive but significant cost reduction expected through scale-up of technology.	Sufficient data available
7. Batteries for electricity storage onboard	As with other types of vehicle, some vessels can adopt battery power.	Low-high[12]	High	High cost due to low energy density. More economic for smaller vessels. Continued improvement in cost and performance expected in the future.	Sufficient data available
8. Electric engines	Electric propulsion systems substitute combustion engine of a conventional vessel with an electric motor. In road vehicle terms they can be compared with series hybrids.[13]	N/A[14]	High[15]	Generally more expensive than traditional combustion engines but higher efficiency.	Sufficient data available
9. Air lubricants[16]	Use of air to reduce the frictional resistance of a ship's hull in the water.	Medium	Low	Currently cost effective for high-fuel consumption vessels.	Sufficient data available

[10] GHG abatement is not associated with the fuel cell or hydrogen storage technology but is a property of the fuel itself.

[11] Hydrogen storage has no effect on air pollution, but fuel cells eliminate the presence of operational air pollutants that are produced when combusting the same fuels in combustion engines e.g. NO_x.

[12] Realised GHG emissions reductions for batteries depend on route length and battery application.

[13] Series hybrids are vehicles where the electric motor is the only propulsion driving the drivetrain. This is compared to a parallel series where both internal combustion engine and electric motor are connected directly to the drivetrain. In series, any mechanical energy is converted into electricity before being used in

Option	Description	GHG abatement	Local air pollutant abatement [8]	Cost effectiveness	Data availability
10. Wind propulsion	Onboard use of sails, rotors and kites as an auxiliary propulsion source.	Medium	Low	Currently cost effective for certain vessels (those with sufficient deck space) operating on certain routes (those with suitable wind speed and direction).	Sufficient data available
11. EGR/SCR	Exhaust Gas Recirculation and Selective Catalytic Reduction to reduce the nitrogen oxides in the exhaust of vessels.	Low-negative[17]	High	Significant additional cost. (capital and additional fuel). Some improvements possible over time, as found in automotive sector.	Sufficient data available

Source: Frontier, E4tech, UMAS

Note: GHG abatement and cost reduction are presented in Frontier et al. (2019b).

As set out above, each of the selected abatement options has the potential to either reduce GHG emissions in the future or reduce emissions of local air pollutants, or both. The precise extent to which this is true varies across the 11 shortlisted options. Specifically, options such as hydrogen production could have a ***high*** impact on GHG emissions, as vessels powered by hydrogen would not emit any GHGs at the point of use (Frontier et al. 2019b). Wind propulsion is expected only to have a ***medium*** impact, as this technology may in some cases only serve as an auxiliary power source and some other form of propulsion may also be needed.[18] The Exhaust Gas Recirculation (EGR) and Selective Catalytic Reduction (SCR) option is focused on air quality and has the potential to have a ***high*** impact on local air pollutants. This option may need to be used in combination with other options (such as alternative fuel sources) to also achieve significant GHG abatement.

Longlisted options such as propeller modifications and engine modifications, which are expected to only have a ***low*** impact on both GHG abatement and local air pollutant abatement, are excluded from the shortlist.

the electric motor, i.e. a gasoline engine would run a generator (in series) instead of connecting straight to the drivetrain itself (parallel).

[14] Electric engines have no operational GHG emissions directly but energy conversion to electricity on board vessels may include GHG emissions.

[15] Electric engines have no operational air pollutant emissions but energy conversion to electricity on board vessels may include air pollutant emissions.

[16] Included as part of Ship Design options in Frontier (2019b).

[17] The use of these technologies to reduce air pollutants can increase fuel consumption and therefore increase GHG emissions depending on the characteristics of the technology installed, fuel type used and journey.

[18] IMO SOLAS Convention allows use of wind as long as the vessel does not solely rely upon it. Source: DNV-GL (2018) 'Assessment of Selected Alternative Fuels and Technologies' p33

Liquefied Natural Gas (LNG) is considered as an alternative fuel for shipping in Frontier et al. (2019b) but is not included here because of its low GHG abatement and partial abatement of air pollution. However, Bio-LNG is included as it offers greater GHG abatement (Frontier et al., 2019b). Bio-LNG was selected for this analysis as a representative biofuel. Other biofuels apart from Bio-LNG were not considered on advice from DfT maritime policy officials, as the shipping sector is currently not seen as a primary recipient of biofuel resource.[19] However, this does not rule out the use of biofuels in the sector.

There is also some variation between the abatement options in terms of cost effectiveness. The production of some alternative fuels such as hydrogen is expensive currently, but this cost is expected to fall in the future following more widespread adoption.[20] Other new technologies such as air lubrication have the potential to be cost effective currently for certain vessels, although this depends on current fuel prices among other factors.

In general, data and information are currently available on each option, which allows for a preliminary assessment to be carried out. The quantity of relevant existing work that has been carried out does vary from option to option. For example, the Low Carbon Coordination Group's (2014) Hydrogen Technology Innovation Needs Assessment provides a rich source of information regarding hydrogen production in the UK. Equivalent detail is not always available for all other options. However, no abatement option is classified as 'insufficient' according to this criterion, which implies that there is enough data available to carry out a meaningful analysis in each case.

These shortlisted options are the focus for the remainder of this report.

[19] See for example https://www.theccc.org.uk/publication/biomass-in-a-low-carbon-economy/

[20] See for example, https://doi.org/10.1016/j.ijhydene.2017.10.045

4 STEPS 2-5: OVERARCHING FINDINGS

4.1 Introduction

This chapter takes the shortlisted options derived above in Chapter 3 and applies the framework Steps 2-5 that were outlined in Chapter 2 to each option. Additional detail is provided in the abatement option annexes contained in Frontier et al. (2019a).

4.2 Step 2: Identification of supply chains

The shortlisted shipping abatement options comprise a number of sub-technologies which combine to facilitate clean shipping. In order to assess the options it is necessary to disaggregate the supply chains into the main sub-technologies which correspond to UK current and potential industrial activities. For example, Bio-LNG comprises sources of biomass or waste which can be converted by two very different technologies (gasification or anaerobic digestion), each with its own industrial sector. Once converted, the gas needs to be liquefied, which involves another sector.

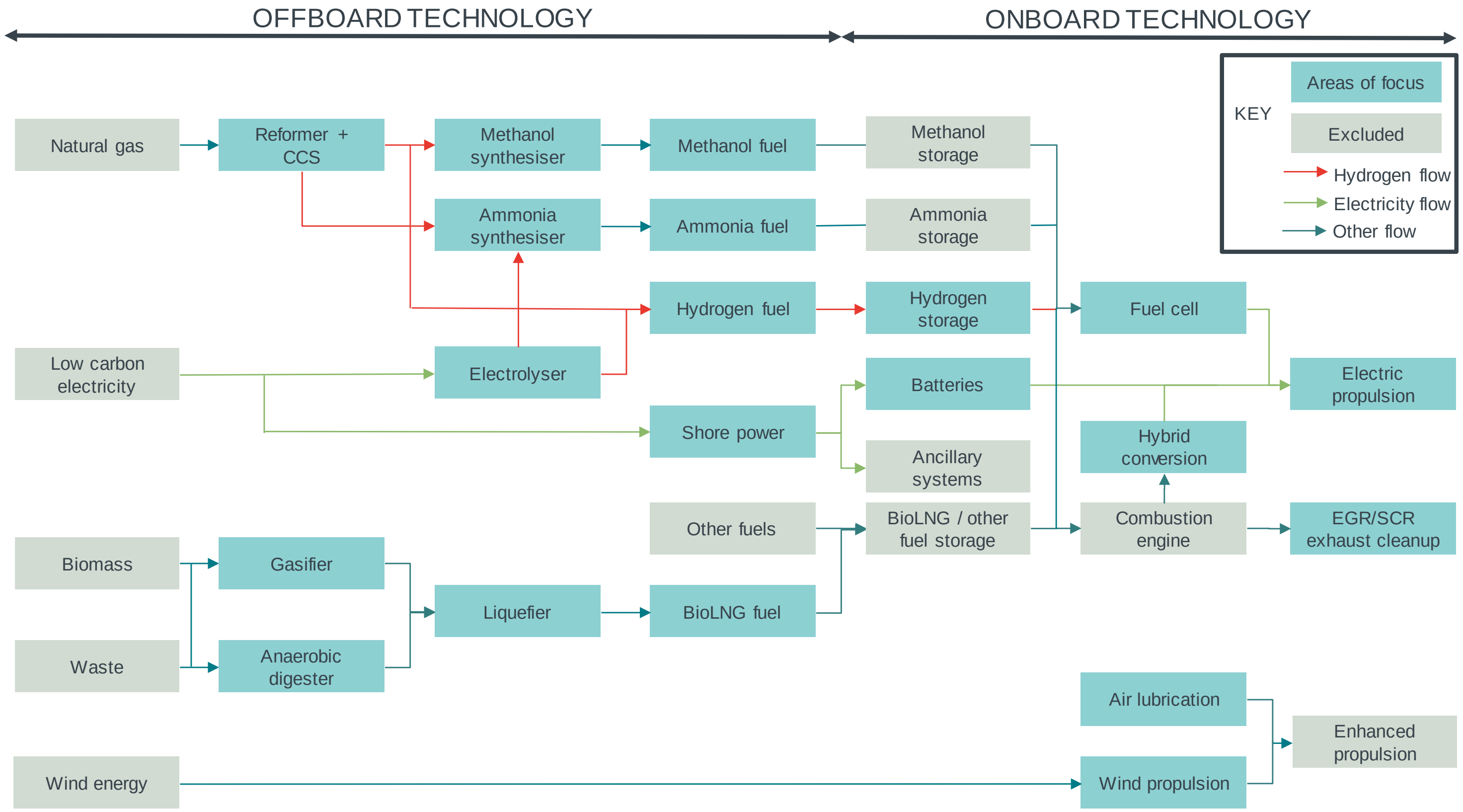
The disaggregation used in this report is shown in Figure 6, which depicts the high-level supply chains for all options. Each sub-technology is classified as either offboard or onboard. The main relationships between each sub-technology are then represented. It should be noted that the interactions are complex since many of the options feature key primary energy building blocks on the left-hand (upstream) side of the supply chain (see Figure 6), notably hydrogen and low carbon electricity. On the right-hand (downstream) side of the supply chain, combustion engines and/or electric propulsion are common to all applications. Not all of the sub-technologies shown are within the scope of this report, which focuses on areas where the UK is likely to have the greatest opportunities, specifically the shortlisted 11 abatement options and their sub-technologies. Other sub-technologies are not considered in detail but they are shown in Figure 4 for completeness. The reasons for not including these sub-technologies are:

- Primary energy or electricity production are not included as there is already a suite of policies and regulations (both international and domestic) that address upstream energy system emissions.
- Storage of methanol, ammonia, Bio-LNG or other liquid fuels was not included as the opportunities were deemed limited due to the similarities with existing liquid and LNG fuel storage.
- Similarly, combustion engines and auxiliary systems are currently in widespread use and offer little opportunity for an increase in value to the UK during the progression to low emission and potentially non-combustion engine vessels.

More detailed supply chains can be shown for each abatement option individually. For example, low carbon hydrogen (Option 1) can be produced from either natural gas through reforming with CCS or from low carbon electricity through the electrolysis of water.[21] The hydrogen produced then needs to be stored. It is assumed that for maritime applications hydrogen is stored as liquid hydrogen, to achieve the highest energy density. This requires specific materials and technology. Hydrogen could also be stored by other methods, for example in compressed form or by conversion to carrier fuels such as ammonia. The stored hydrogen can then be used either in a combustion engine, which is tailored to hydrogen injection and combustion, or in a fuel cell to produce electricity. If used in a fuel cell, the electricity produced can be used to power an electric motor for propulsion or for auxiliary systems on board the vessel. Additional detail is provided for each option in the annexes contained in Frontier et al. (2019a).

[21] Other pathways, such as gasification of biomass or coal, exist but are not included here.

Figure 6 Supply chains for shortlisted abatement options



Source: E4tech

Note: This figure is not exhaustive of technologies or pathways.

4.3 Step 3: Current deployment and UK economic footprint

As described in Chapter 2, **Step 3** of the framework involves an exploration of current global market sizes for each shortlisted abatement option and consideration of the current economic footprint of key UK firms in the supply chain.

There is no straightforward way to assess the market size for shortlisted abatement options as some of the sectors are, as yet, nascent and in other cases the technology or alternative fuel has only been operationalised in contexts other than shipping. Therefore, this analysis triangulates across multiple sources of information to help inform an assessment of the current deployment of options and UK activity. This does mean that all estimates are necessarily subject to considerable uncertainty.

Firstly, trade data is used to approximate the current market share of the UK in each sub-technology industry. In addition, scenario analysis carried out by Frontier et al. (2019c) projects uptake rates for each abatement option across the global fleet in 2021[22] under business as usual (i.e. meeting agreed regulations only, with no additional incentives for ship owners to invest in abatement options).

Thereafter, three case studies are presented, each of which focuses on UK activity related to an individual abatement option. The three case studies were chosen because they cover a wide spectrum of abatement options including alternative fuel sources, onboard technologies and non-traditional engine types. The lessons highlighted within these three cases studies will therefore have wider relevance across other abatement options. Additional detail across all 11 options is provided in the annexes contained in Frontier et al. (2019a).

4.3.1 Current market size

International trade data

The United Nations International Trade Statistics Database (Comtrade) provides data on the value of imports and exports by country-pair and product (UN, 2019). As discussed in Chapter 2, Comtrade data can be used to estimate the market share of the UK for each sub-technology and identify the largest global exporters. These results are described in Figure 7. Importantly, these figures in most cases reflect the market exports of **proxy or related technologies,** as in many cases the markets are currently nascent.

The UK's approximate share of the global market is estimated to range from 0% (for methanol synthesis) to 9% (for reformer and CCS). For context, the largest exporter in each sub-technology industry is generally estimated to have 10-25% of global exports.[23]

[22] The model projects uptake in five-year intervals. 2021 uptake was chosen as it is closer to the current date than any other modelled period.

[23] China does have market shares of 30-40% for Bio-LNG gasifiers, hydrogen fuel cells and onboard batteries.

The Comtrade data suggests that **the UK is the second largest exporter of reformer + CCS technology (for hydrogen, methanol and ammonia production) and a top-five exporter of Bio-LNG liquefiers and electric propulsion**.

The Comtrade data also shows that **China, Germany, the USA, Russia and the Netherlands are large exporters of the 11 technologies, along with the UK, Japan, Mexico, South Korea and Hong Kong**.

As described in Chapter 2, these estimates are approximations only. This is because:

a. Comtrade data is organised by six-digit Harmonised System commodity codes (HS6) and in some cases these provide only a rough proxy of the sorts of products that are likely to be included in the sub-technology.
b. The data covers goods exports only and excludes services exports.
c. The data covers exports only and not the sale of products that are made and sold within any individual country.

Estimates are not presented for methanol synthesis, ammonia synthesis, ammonia direct production, air lubricants and wind propulsion as Comtrade does not have an appropriate proxy.

Figure 7 Estimated UK market share based on exports of proxy or related sub-technologies

Technology	Sub-technology	Estimated UK market share
1. Hydrogen production technologies	Reformer + CCS	9%
1. Hydrogen production technologies	Electrolyser	2%
2. Methanol production technologies	Reformer + CCS	9%
2. Methanol production technologies	Electrolyser	2%
2. Methanol production technologies	Methanol synthesis	N/A
3. Ammonia production technologies	Reformer + CCS	9%
3. Ammonia production technologies	Electrolyser	2%
3. Ammonia production technologies	Ammonia synthesis	N/A
3. Ammonia production technologies	Direct production	N/A
4. Bio-LNG production technologies	Gasifier	3%
4. Bio-LNG production technologies	Anaerobic digester	2%
4. Bio-LNG production technologies	Liquefier	6%
5. Low carbon shore power technologies	-	2%
6. Onboard hydrogen technology	Hydrogen storage	1%
6. Onboard hydrogen technology	Hydrogen fuel cell	4%
7. Onboard batteries	-	1%
8. Electric propulsion	-	3%
9. Air lubrication	-	N/A
10. Wind propulsion	-	N/A
11. EGR & SCR engine exhaust technologies	EGR and/or SCR	3%

Source: Frontier analysis of UN Comtrade data

Notes: Based on 2017 export data. Estimated UK market share is listed as N/A where there is not a sufficiently robust proxy for the sub-technology in the UN Comtrade data.

Current deployment of abatement options

Figure 8 describes the outputs for non-fuel options from the scenario analysis carried out by Frontier et al. (2019c), which projects uptake rates for each abatement option across the global fleet in 2021 under business as usual (i.e. meeting agreed regulations only, with no additional incentives for ship owners to invest in abatement options).[24] The model projects that uptake of low-carbon fuel technologies by 2021 will be very limited, so no outputs for low-carbon fuel technologies are provided.[25]

This analysis involves:

- the **number of vessels in the global fleet that are expected to have the technology installed** by 2021;
- the estimated **global market size in 2021.** The global market size estimate is based on the value of the annual capital costs and annual running costs; and
- the **estimated UK market potential in 2021.** This is calculated by multiplying the estimated annual global market size by the estimated UK market share (as in Figure 7).

Further details on the modelling methodology are available in Frontier et al. (2019a).

Figure 8 Indicative market size for non-fuel technologies in 2021

[24] The model projects uptake in five-year intervals. 2021 uptake was chosen as it is closer to the current date than any other modelled year.

[25] The combined fuel production technologies cover hydrogen production technologies, methanol production technologies, Bio-LNG fuel production technologies and ammonia production technologies.

Technology	No. of vessels with the technology globally (% of global fleet)	Annual global market size ($m)	Implied annual UK market potential ($m)
5. Low carbon shore power technologies	1,800 (4%)	100	2
6. Onboard hydrogen technology	-	-	-
7. Onboard batteries	400 (1%)	1,000	6
8. Electric propulsion	1,100 (2%)	100	4
9. Air lubrication	<100 (0%)	2,300	60
10. Wind propulsion	<100 (0%)	400	10
11. EGR & SCR engine exhaust technologies	8,300 (17%)	1,200	31

Source: Frontier et al. (2019c)

Note: Vessel numbers are rounded to the nearest hundred; global market size is rounded to the nearest 100 million, UK market size is rounded to the nearest million. All monetary estimates are in 2016 prices and reflect capital costs for new installations[26] and annual recurring costs for new and existing installations.

These projections estimate that under business as usual, in 2021 the global annual market for the 11 abatement options could be in approximately **$5 billion**, implying an estimated UK market potential of approximately **$110 million**. The total number of installations is estimated to be fewer than 500 vessels for four of the abatement options, which reflects the fact that the technology areas are still expected to be nascent. However, this does not imply that there will be no examples of uptake across the entire global fleet. Very limited deployment has in some cases already occurred.

4.3.2 Case studies

Three case studies, each of which focuses on UK activity related to a specific abatement option, are presented below. The three selected abatement options cover a range of solutions and alternative fuel types which relate to both offboard and onboard technologies. Each case study introduces the individual abatement option, considers the main UK actors and considers current deployment.

[26] The annual figure for the number of new installations in 2021 reflects the average annual number of installations of each technology over 2021 to 2026. Hence for those technologies that are likely to experience a sharp increase in uptake, the 2021 estimate of the number of new installations in that year will be over-estimated.

Equivalent detail for all 11 abatement options is provided in the annexes contained in Frontier et al. (2019a).

4.3.3 Case study: Air lubrication technology

Introduction

The Wärtsilä Encyclopaedia of Marine Technology (2015) defines air lubrication technology as systems that: '…provide constant flow of air bubbles to lubricate the flat bottom area of a ship's hull which requires minimal structural changes'. These systems inject air into the turbulent boundary layer (between the stationary and moving water), which helps to reduce the frictional resistance of a vessel by improving a ship's hydrodynamic characteristics (GloMEEP, 2019).

Very few air lubrication systems have been fitted to active vessels to date. However, the technologies have the potential to make a material contribution to reduced emissions. Academic research suggests that under certain assumptions net energy savings of 10-20% are possible when an air lubrication system is successfully implemented (Mäkiharju et al., 2012). Importantly, air lubrication technology can be deployed regardless of the propulsion mechanism used.

There are several stages involved in the development of an air lubrication system. This starts with upfront design work and modelling to determine likely performance, followed by manufacture of the hardware, installation and, finally, ongoing operations and maintenance.

Main actors

In the UK, the only company active in this area is Silverstream.[27] This is a UK-based firm and air lubrication is currently 100% of its activity. Silverstream currently carries out the upfront design and modelling work in-house. The air release units[28] tend to be manufactured near the shipbuilding sites (which are all outside the UK). Silverstream is currently in negotiations to establish agreements for the manufacture of its units in different locations around the world.[29] This will ensure that Silverstream has the ability to service customers in different locations, in particular in those countries where shipbuilding is a vibrant industry.

Manufacture of compressors for Silverstream currently takes place in the EU. However, there are UK firms active in this area who Silverstream is aware of.[30] Likewise, the air control systems are currently manufactured in the EU but there are other UK providers.

Silverstream's first system was retrofitted in 2014 on a tanker owned by the Danish shipping company Dannebrog Rederi, with net efficiency savings of more than 5% from multiple sea trials.[31] More recently, the Silverstream system was installed on

[27] https://www.silverstream-tech.com/

[28] The hull installations from which air is pulled to coat the bottom of a vessel.

[29] This includes locations in Asia, the EU and the UK. The UK firm is Responsive Engineering, which is part of the Reece Group. https://responsive-engineering.com/

[30] See for example https://lontra.co.uk/blade-compressor-lontra/

[31] See for example https://www.wartsila.com/encyclopedia/term/air-lubrication

a Norwegian Cruise Lines vessel in 2016,[32] and in 2017 a Silverstream air lubrication system was successfully retrofitted onto a Carnival cruise ship. Silverstream claimed net efficiency improvements of over 5%.[33] Both cruise ship companies are headquartered in the USA. In 2018, it was announced that the Silverstream Technologies system would be installed on 12 new Grimaldi Group[34] ro-ro vessels. Grimaldi is headquartered in Italy (see Figure 9 below). The CEO of Grimaldi expects fuel savings of between 6% and 10%.[35] Silverstream currently has 12 UK-based employees.[36]

Figure 9 Silverstream sales locations

4.3.4 Case study: Ammonia

Introduction

As shown in Figure 6, ammonia could serve as a marine fuel, either for combustion engines or fuel cells, although it is in its infancy for marine applications.

Ammonia is one of the most abundantly produced chemicals globally for use in fertiliser (see Figure 10).[37] To date, ammonia has been widely produced from combining nitrogen (from air) with hydrogen (from natural gas) through the Haber-Bosch process.[38] In the future, the hydrogen input could also be produced through electrolysis of water (and the electricity source for this process could be renewable).

[32] Source https://www.silverstream-tech.com/norwegian-joy-christened/

[33] Source http://www.seatrade-cruise.com/news/news-headlines/diamond-princess-retrofitted-with-silverstream-air-lubrication-system.html

[34] Source https://www.grimaldi.co.uk/AgencyUK/

[35] Source https://www.motorship.com/news101/engines-and-propulsion/silverstream-air-lubrication-for-grimaldi-fleet

[36] Source https://www.silverstream-tech.com/about-us/

[37] Source http://www.catalystgrp.com/wp-content/uploads/2018/04/PROP-Ammonia-Production-April-2018.pdf

[38] Source https://www.britannica.com/technology/Haber-Bosch-process

There are no operational GHG emissions when using ammonia as a fuel, as it does not contain carbon.[39] The upstream GHG emissions depend on the hydrogen source and the process used to make it. More novel methods, which enable the direct synthesis of ammonia from water and air using renewable electricity, are being developed.

Figure 10 Fertiliser production and green ammonia demonstration

Source: www.cffertilisers.co.uk and https://ammoniaindustry.com/green-ammonia-pilot-plants-now-running-in-oxford-and-fukushima/

Ammonia is a potential marine fuel since it serves as a store of hydrogen. This hydrogen can be accessed by converting the ammonia on board the vessel.[40] Ammonia can also be burned directly in a combustion engine. However, there are currently some unresolved challenges in combusting neat ammonia[41] and dual fuel operation is more likely, meaning that some carbon dioxide (CO_2) emissions could also result from the use of fossil fuels to aid combustion.[42]

Main actors

Several UK companies work on products which are or could be relevant to ammonia's use in maritime applications. Few or none of their current activities are currently focused on marine applications of ammonia. The location of these firms is illustrated in Figure 11. The revenue, EBITDA[43] and employment values stated below give an indication of the company size and activity. Where possible this is segmented into UK and/or specific activities to give greater clarity. However, the data availability and granularity does not allow for specific figures on the contribution to these firms from solely ammonia production.

The specific position and activities undertaken by these firms varies:[44]

- CF Fertilisers is the largest producer of UK fertilisers and supplies liquefied ammonia. CF Fertilisers has two UK plants, in Billingham and Ince (these account for 10% of the global volume of the parent company, CF Industries). CF Fertilisers produces 40% of the UK's fertiliser needs. CF Industries' revenue

[39] Ammonia is toxic and this should be considered as a wider environmental impact.

[40] Ammonia cracking dissociates the ammonia into hydrogen and ammonia using a catalytic reaction. http://www.syngen.it/wp-content/uploads/2013/02/Ammonia-crackers_V.-Hacker-and-K.-Kordesch.pdf

[41] These challenges include low flammability, high NO_x emissions and low radiation intensity. Kobayashi et al. (2019) https://doi.org/10.1016/j.proci.2018.09.029

[42] Source https://nh3fuelassociation.org/wp-content/uploads/2018/12/0900-Ammonia_vision-Rene-Sejer-Laursen-MAN.pdf

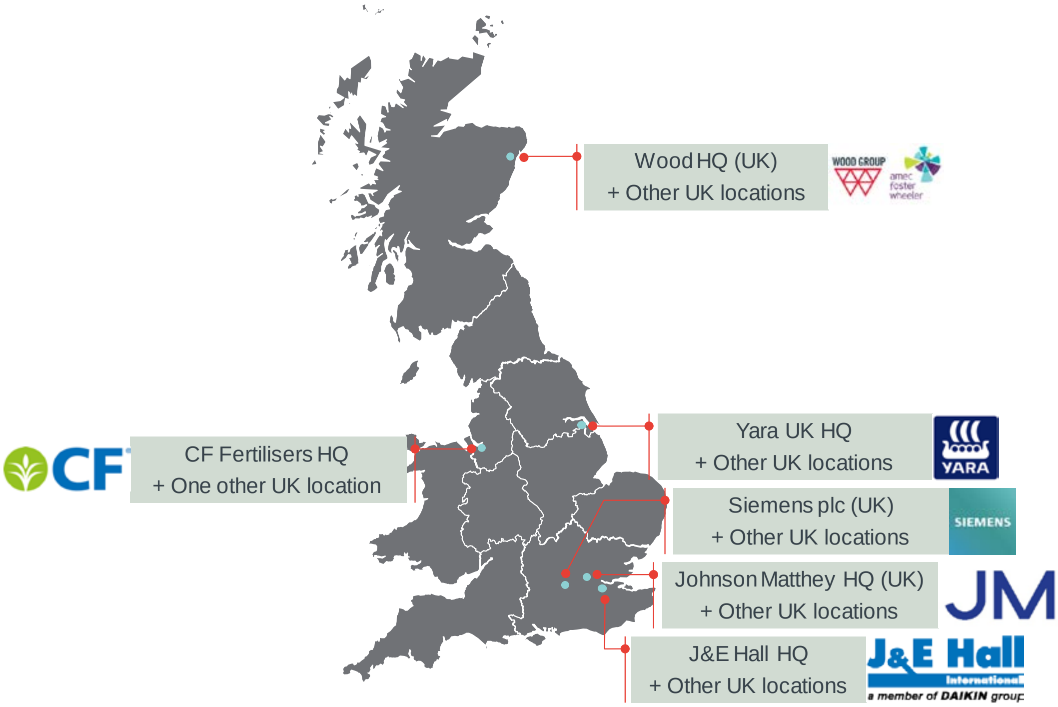
[43] Earnings before interest, tax, depreciation and amortisation.

[44] Data is taken from UK Companies House as well as company financial statements and website information. Data was the latest available on 07/02/19.

is $4 billion and its EBITDA is $900 million, of which 10% could be considered relevant to the UK.

- Eneus Energy is a small UK business that specialises in integrating technology to convert excess renewable electricity directly into ammonia.
- J&E Hall is a UK- based specialist in oil and gas refrigeration, with applications for ammonia storage.
- Johnson Matthey (UK) is a global science and technology firm which is a world leader in ammonia synthesis. Current revenue is £14 billion with EBITDA of £680 million.
- Siemens plc is a global engineering firm, currently leading a green ammonia demonstration project in the UK. Siemens generates an annual revenue of €83 billion, of which the power-to-gas segment is €12.4 million (an estimated 6% of the power-to-gas figure is relevant to the UK). The company employs 42,782 people in Europe – 25% of these employees are in Germany and the remainder are spread across Europe.
- The Wood Group is a large UK engineering firm which has run projects in ammonia production worldwide. The group has 36,000 employees, and a revenue of £5.44 billion, of which less than 1% is related to CCS directly.
- Yara UK runs fertiliser plants in the UK and is exploring ammonia as an energy vector. There is a large UK arm (350 employees) of the Global YARA Group, which has had 170 years of business in the UK in plant nutrient products and 50 years in liquid fertiliser production. The UK arm specialises in low carbon footprint nitrogen fertilisers.

Figure 11 Primary location of selected UK firms who are relevant to ammonia's use in maritime applications



Source: E4tech

4.3.5 Case study: Electric propulsion

Introduction

As shown in Figure 6, electric drive is relevant for pure electric or combustion engine vessels. This case study considers the hybrid conversion and electric drive aspects of electric propulsion (not batteries, fuel cells or combustion engines).

Integrated electric propulsion systems substitute the combustion engine of a conventional vessel drivetrain with an electric motor and related electronic controls connected to an energy store and converter (battery, fuel cell or flywheel) or more likely engine or turbine-based generator (see Figure 12). Diesel-electric drive systems have been used for many years (e.g. QE2 or Canberra from the 1960s) offering improved redundancy and manoeuvrability. They are now widely used in vessels that have to position themselves accurately, such as tugs, oilfield support vessels and drill ships. Parallel drives also exist (e.g. Type 26 frigates[45]), combining direct engine drive or electric drive.

Figure 12 Electric propulsion system

Source: www.wartsila.com/products/marine-oil-gas/power-systems/electric-propulsion/electric-propulsion-systems

The use of integrated electric propulsion simplifies the propulsion system, reducing maintenance costs. This means designers have more flexibility in siting engines, noise and vibration are reduced as the engine need not be directly connected to the hull, and ancillary loads are more easily served. Overall, electric propulsion offers potential for higher efficiency as engines can be operated more constantly and hull forms optimised. However, the systems are more expensive upfront and are less efficient than two stroke engines for vessels which have long, constant speed cruising passages.[46]

Main actors

Several UK companies work on products which are or could be relevant to electric propulsion's use in maritime applications. The data shown below is not therefore confined to marine activities, but, where relevant, data specific to maritime

[45] Source https://ukdefencejournal.org.uk/guide-type-26-city-class-frigate/

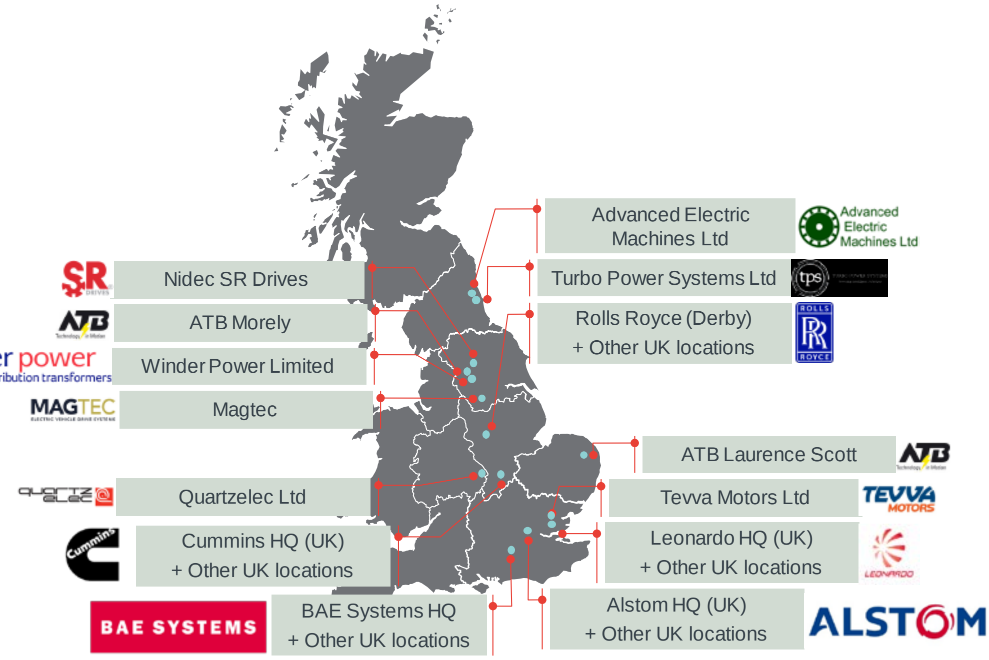
[46] Source https://www.marineinsight.com/marine-electrical/electric-propulsion-system-for-ship-does-it-have-a-future-in-the-shipping/

applications has been isolated.[47] The location of these firms is illustrated in Figure 13 below.

- Advanced Electric Machines is a UK SME specialising in high performance electric machines for heavy duty vehicle applications.
- Alstom is a global rail specialist with a presence in the UK, which has developed electric propulsion systems for hydrogen trains. Alstom is part of a group with a total annual revenue of €7 billion. This includes turnover of £300 million related to the UK transport sector.
- ATB Laurence Scott is a UK-based specialist supplier of high and low voltage AC and DC electric motors.
- ATB Morely is a global supplier of heavy duty electric machines for industrial applications. It is a subsidiary of ATB Austria called Antriebstechnik AG, with an annual revenue relevant to electric machines of £17 million.
- BAE Systems is a large UK-based global defence firm, offering marine hybrid propulsion systems. 39% of the firm's revenue is directly attributed to marine and naval defence projects.
- Cummins is a global firm with UK distribution, aiming to be a leader of electrified power in commercial and industrial transport markets.
- Leonardo is a company which supplies products for the defence industry, including electric machines for power generation and vehicle propulsion.
- Magtec is a UK-based electric machine system designer and manufacturer for heavy duty transport applications.
- Nidec SR Drives is an electric machine producer in the UK, focusing on switched reluctance (high torque, low speed) technology. Nidec employs approximately 80 staff and has an annual turnover of £10 million.
- Quartzelec is a leading UK engineering service provider and an expert in large rotating machines. Quartzelec's annual turnover is £68 million, of which the majority is in the UK. Currently, the firm employs 650 people.
- Rolls Royce is a large UK-based multinational engineering firm, producing electric machines and power systems for marine applications.
- Tevva Motors is a UK SME, manufacturing electric machines for its light duty vehicles.
- Turbo Power Systems is an electric machine designer and manufacturer for various applications, specialising in generators for gas turbines. 50% of the group's revenue is from sales in the UK.
- Winder Power is a UK supplier of exciter machines (electromagnetic coils) to major global manufacturers of large synchronous generators and motors.

[47] Data is taken from UK Companies House as well as company financial statements and website information. Data was the latest available on 07/02/19.

Figure 13 Primary location of selected UK firms who are relevant to electric propulsion's use in maritime applications



Source: E4tech

4.4 Step 4: UK competitive advantage

To help understand the potential future commercial opportunities for the UK for each of the shortlisted low emission technologies and sub-technologies, **Step 4** describes how to assess the UK's current competitive position relative to key rivals and hence its competitive advantage. This section applies Step 4 to the shortlisted abatement options and sub-technologies.

Competitive advantage refers to the ability of the UK to develop and produce products and services in a way which gives the UK an advantage relative to international competitors. This could be because the UK activity is higher quality or lower cost than other countries. These advantages can then translate into jobs, taxation and multiplier effect benefits to the UK economy. If the UK has a basis for competitive advantage then it can be inferred that the UK's share of the abatement technology markets of the future will be maintained and, where the UK is highly competitive, the UK's share would be expected to grow relative to the market shares of other countries.

This analysis considers several dimensions of competitive advantage. Specifically, the assessment draws on academic research on international competitiveness (Porter and Kramer, 2002) and considers how the UK fares in terms of input factors (such as access to highly skilled labour), technology factors (such as existing IP) and access to markets. The framework used to assess competitiveness is shown in

Figure 14.

Figure 14 Competitiveness framework

Competitiveness category	Competitiveness measure	Evidence
Technology advantages	IP position of firms	Existing patents. Known activities of innovative players in the technology area.
Technology advantages	National R&D environment	Assessment of innovation landscape and R&D capacity. Current research landscape.
Technology advantages	Adjacent technology activity	Presence of industries that use similar technologies. Potential for spillovers between sectors. This could include UK-based organisations such as the National Oceanography Centre[48] which provides marine science and technology for a variety of businesses including shipping companies.
Factor advantages	Production scale/cost	Current volume of supply and potential to expand. Potential to exploit economies of scale.
Factor advantages	Supply chain	Access to inputs that provide an advantage. Links to processes in other parts of the supply chain.
Factor advantages	Skills	Workforce characteristics such as the number of appropriately trained employees relative to industrial need. Quality of academic institutions.
Market advantages	Access to markets	Location of customers. Existence of maritime support services such as finance and legal.
Market advantages	Supporting policy and regulation	National and international policy including the tax environment, government initiatives to link different actors in the maritime sector, export support policies and consistency of policy positions.

Source: Frontier, E4tech

[48] https://noc.ac.uk/files/documents/business/Shipping.pdf

This evidence has been synthesised and the UK competitive position for each shortlisted abatement option is indicatively assigned an overall rating. Some factors will apply across multiple abatement options. For example, the UK is a global leader in maritime professional services, with extensive expertise in finance, vessel chartering, insurance, legal and educational services (Maritime UK, 2018). A report by PwC (2016) concluded that the maritime business sector supported around 10,000-11,000 jobs across the UK. The presence of these support services will benefit the UK's competitive position across several shortlisted options.

It is important to note that the rating is not intended to reflect an absolute measure but is intended to provide a relative assessment of the UK's strengths when considered alongside other competing nations. The ratings draw on best available evidence and expert judgement and range from 1 to 5, and are explained below in Figure 15.

Figure 15 Competitiveness rating out of 5

Rating	Explanation
1	UK has little or no relevant activity; *no basis* for competitive advantage
2	UK has pockets of relevant activity; *some basis* for competitive advantage
3	UK has several areas of relevant activity which are internationally strong; *moderate basis* for competitive advantage
4	UK has several areas of relevant activity which are on par with global leaders; *strong basis* for competitive advantage
5	UK is global leader across all activity areas; *very strong basis* for competitive advantage

Source: E4tech, Frontier

Note that, inevitably, judgement has been applied. This is particularly the case in nascent sectors where there is still large uncertainty about the size and direction of the industry. The assessment of the abatement options is shown in the appendices and a summary is shown in Figure 16. This summarises the UK's main strengths and weaknesses, competitor nation activities and provides an overall assessment of the UK's competitive basis for advantage.

The UK's rating is at least 2 out of 5 for all options, but most ratings are 3 or 4 out of 5, implying that there are significant economic and commercial opportunities for the UK across the entire shortlist. Firms are currently operating successfully in the UK within specific niches related to each of the areas listed above. The UK currently has a more widespread competitive advantage in relation to four specific options: hydrogen production, ammonia production, onboard batteries and electric propulsion. However, given that the UK has some advantages across all 11 options and acknowledging the inherent uncertainty when considering future market opportunities, policy measures that are technology agnostic are likely to be the best first step. Further work is recommended in this area to carry out a more detailed competitive assessment of the UK across the entire shortlist.

The UK also has some key strengths which cut across multiple options. For example, the UK policy direction on shipping emissions is ambitious, as demonstrated by initiatives such as the Clean Maritime Council.[49] Maritime Research & Innovation UK (MarRI-UK) is a new national initiative that is expected to provide a collaborative innovation platform for UK industry and academia to work jointly in tackling major challenges such as green shipping. It will be led by shipping companies, universities and trade associations (Maritime UK, 2018). This is intended to help strengthen links between technology providers and world-class academic expertise. This area is likely to be an important strength of the UK going forward.

The UK is also the global leader in maritime professional services, with extensive expertise in finance, vessel chartering, insurance, legal and educational services ((Maritime UK, 2018). An Oxera report produced for DfT concluded that the UK has a market-leading 26% of global maritime insurance premia (Oxera, 2015).

A 2018 report assessing the size of approximately 50 financial centres around the world concluded that the UK finance industry (not limited to shipping) was ahead of all other European countries and in second place overall to the USA.[50]

[49] See for example https://www.gov.uk/government/news/clean-maritime-revolution-starts-voyage

[50] Source https://newfinancial.org/financial-centres-index/

Figure 16 Summary of UK competitiveness

Option	UK strengths and weaknesses	Main competitors	Overall assessment	Rating
1. Hydrogen production technologies	UK has extensive experience in natural gas reformer technology. There is growing interest and activity in CCS where the UK is one of the frontrunners globally. Electrolysis activities are directly relevant for use with low carbon power and the UK is a leader. UK scientific research is strong in supporting areas.	Natural gas reformation is led by major oil and gas suppliers in USA, Germany, Japan. In water electrolysis there are a few large players in USA, Canada, Germany, Japan.	Hydrogen energy is nascent so there is still much to play for. UK technology companies are well positioned, particularly in reformer and CCS technology areas. The high level of competitiveness within the global electrolyser industry could impact the scale of UK activity. UK CCS technology will require continued development. The cost of hydrogen is currently relatively high compared with conventional fuels.	4/5
2. Methanol production technologies	Related to the UK's strengths in natural gas reformer technology, there is a strong domestic position in methanol catalyst supply. UK also has strong R&D in use of waste CO_2, which could be applied. UK scientific research is strong in several supporting areas.	UK is not currently a large-scale methanol producer. The industry and overall synthesis technology supply is led by major industrial economies such as Germany, China and USA.	Methanol is a well-established industry globally and the UK position is strong only in catalyst supply. However, early UK moves into CO_2 utilisation and low carbon hydrogen production provide a basis for growth in low carbon methanol. The lack of a UK bulk methanol industry may be a key barrier going forward. The cost of methanol is currently relatively high compared with conventional fuels.	3/5
3. Ammonia production technologies	Related to the UK's strengths in natural gas reformer technology, there is a strong domestic position in ammonia catalyst supply. Ammonia-based fertiliser is produced in volume in the UK. A novel 'green ammonia' production process is also being demonstrated in the UK, featuring UK scientific research which is generally strong in this area.	The global ammonia industry is centred on low cost gas producers with technology supplied by countries such as Italy, Germany, USA and Denmark. Green ammonia is a topic of interest in several countries, with notable programmes in Japan, Italy and USA as well as those with strong electrolyser industries.	The UK's conventional ammonia industry is strong in catalyst supply. Novel low carbon production techniques are at an early stage and UK has a relevant technology position which could be the basis for growth of a large industry. UK ammonia production is currently modest. Increasing scale of production may be important for realising the UK's potential opportunity. The cost of ammonia is currently relatively high compared with conventional fuels.	4/5
4. Bio-LNG production technologies	The UK has a good research and early-stage technology position in biomass gasifiers and gas liquefaction, but only modest size technology companies working in these areas and none with a Bio-LNG or marine focus. The UK's position is well behind the leading players.	Gasification technology is led by major industrial countries with hydrocarbon processing industries such as the USA, China and Germany. Biomass-specific gasification also has strong players from forested countries such as Austria and Sweden. Anaerobic digester technology is generally less complex and is led by Germany, the USA and China.	Some technology strengths in parts of the supply chain, though competition is likely to come from established players if Bio-LNG picks up. Uptake of Bio-LNG relies on supporting infrastructure for LNG, which is currently at low levels of deployment.	3/5
5. Low carbon shore power technologies	The UK has several manufacturers of relevant electrical equipment though most are now headquartered outside UK and relatively little R&D is conducted domestically. The technologies involved in low carbon shore power are fairly mature so the UK innovation opportunity is modest overall.	Innovation is led by major companies in Japan, Germany, Korea and USA, with manufacturing spread across global industrial countries.	The electrical supply industry has hollowed out in UK, leaving only a small number of innovators and mainly foreign ownership of manufacturers. Establishing port connections can be challenging due to the involvement of multiple stakeholders and weak distribution networks to ports.	2/5

Option	UK strengths and weaknesses	Main competitors	Overall assessment	Rating
6. Onboard hydrogen technology	While it does not have dominant fuel cell companies, the UK is a significant player in high-value components. High temperature (non-hydrogen) fuel cells are a pocket of strength. For hydrogen storage, the UK has carbon fibre technology and novel storage solutions such as solid-state hydrides. A strong materials and electrochemistry R&D environment supports this sector.	Leading hydrogen fuel cell countries also feature automotive industries with a strong hydrogen push, notably Japan, Korea and to a lesser extent Germany and USA. The small hydrogen tank industry is largely North American, and more novel storage technologies are spread widely.	As mentioned above, use of hydrogen is nascent and the assessment must be viewed in that context. The main opportunity for the UK is in the high value components of fuel cell supply chain (catalysts and membranes), innovative high temperature fuel cells and the commercialisation of more novel hydrogen storage technologies. UK hydrogen technology is not yet proven at suitable scale for vessels which could pose a barrier going forward.	3/5
7. Onboard batteries	UK research is strong in the fundamentals of battery chemistry. Innovative UK companies are developing 'next generation' chemistries that either evolve or go beyond lithium ion. Batteries have been recognised as central to the UK automotive sector's future, and the Faraday Challenge is a core feature of UK industrial policy, providing support for research, industrial development and scale-up of battery technology in UK.	Lithium ion cell production is concentrated in Japan, Korea and China, which benefit from high technical barriers to entry. It is unlikely that the UK will 'grow its own' lithium ion Gigafactory; rather it will need to compete with other automotive-heavy EU nations to attract an Asian battery cell manufacturer.	Overall the UK remains competitive in early stage technology, much less in volume battery cell manufacture (which needs to be attracted) and on par with others for battery pack assembly if cells can be sourced in volume. The UK battery pack supply industry is currently niche.	4/5
8. Electric propulsion	The UK large-scale (1MW+) electric machine sector has declined, with three significant players left after several moved operations to Europe. The UK is recognised as having a strong research base in relevant technology areas, especially materials. Integration of electrical drives into vessels remains a UK strength, notably for more specialist vessels. Stephenson Challenge set up to drive UK industrial strategy in this area.	The UK faces tough competition in large electric machine design and manufacture, notably from leading exporters France, Sweden, Germany, China and USA. The UK also lacks general purpose vessel design.	Overall, the UK remains on par with other industrial nations for innovation and manufacture of large electric machines, given the technology base. The UK also has relevant strengths in design of electric propulsion systems for vessels. However, manufacture of more standardised, low-cost e-machine designs are harder for the UK to compete in due to the UK's cost base. This could act as a barrier for the UK going forward.	4/5
9. Air lubrication	The UK has one of the only firms active in this technology area which is currently filling orders. The UK is well placed to carry out upfront design work. This is due to existing academic expertise and the domestic skill base. In addition, air lubrication providers will also be attracted to the UK due to the concentration of maritime financing activity. Manufacturing and installation of the technologies are likely to be less of an opportunity for the UK. The lack of large-scale shipbuilding in the UK does constitute a barrier. However, this does not preclude UK firms from carrying out initial modelling work required prior to manufacture.	There are a small number of other major international players involved in air lubrication technology. They are based in Japan, Korea and Finland. Manufacturing of component parts can take place in a number of locations around the world.	Overall, the UK is well placed in this area due to the domestic tradition of maritime innovation and London's status as a global shipping hub. The lack of domestic shipbuilding in the UK relative to key competitors could pose a challenge.	3/5

Option	UK strengths and weaknesses	Main competitors	Overall assessment	Rating
10. Wind propulsion	The UK has several firms who are developing technologies in this area. It is also home to the International Windship Association which facilitates and promotes wind propulsion for commercial shipping worldwide and brings together all relevant parties. The UK's maritime R&D base is strong in related areas. However, other international players are currently more established. The relatively high cost base of UK manufacturing may pose a barrier. R&D work could still take place in the UK. The UK is also well placed in terms of offshore wind capability. Currently the UK has the largest operational offshore wind capacity of any country.[51] This may lead to some positive spillovers.	Major international players are based in Finland and the USA.	UK advanced manufacturing techniques and R&D capabilities will attract technology providers. The UK's large shipping and maritime finance sector will also be a considerable advantage. There are other international players who may be in a stronger position currently and the cost base of UK manufacturing may pose a challenge.	3/5
11. EGR & SCR engine exhaust technologies	The UK has a strong presence in engine design and manufacture including large diesels, though not at ship scale. Many of these firms are expert in developing EGR. UK chemical companies are active in exhaust gas clean-up systems and catalysts, which are sold via system integrators. UK research is also strong in relevant aspects of mechanical engineering, chemical and material science.	Marine EGR leaders are those countries with large ship engine industries such as Germany and Japan. SCR systems are also offered by some of the engine companies, but also by urea companies (neither of which the UK has leading players in).	Overall, the UK is not well positioned for supply of large scale EGR but can bring relevant technology and innovation skills to medium and smaller diesel engines. In SCR the UK has a strong position in catalysis. The UK has limited marine engine scale technology capability for full system supply, which could act as a barrier in this specific market segment.	3/5

Source: E4Tech, Frontier

[51] https://www.renewableuk.com/news/410144/UK-Offshore-wind-capacity-set-to-double-following-Government-announcement-.htm

4.5 Step 5: Future global opportunities for the UK

This final step in the framework considers how uptake of the shortlisted abatement options could evolve under particular scenarios. As described in Chapter 2, this draws on modelling carried out by UMAS and summarised in Frontier et al. (2019c). This analysis is illustrative and provides a relative order of magnitude of scale of the markets for abatement technologies and low carbon fuels for shipping, if uptake rates were consistent with achieving between 50% and 100%[52] decarbonisation of global shipping by the middle of the century.[53]

As described above, estimated future market size values (Figure 17 and Figure 18) reflect the annual capital and annual recurring costs associated with each technology for non-fuel abatement options. For low carbon fuel abatement options, the estimated market value reflects only those stages of the value chain in which the UK has a competitive advantage (such as the upfront design and IP-intensive stages).

The scale of the potential UK opportunity is estimated based on combining the current export market shares presented above (Figure 7) with the estimated future annual global market size.[54]

All fuel production technologies are combined into one category for two reasons:

1. The mix of these low carbon fuels in the future is still uncertain and depends on how the cost effectiveness of each fuel type evolves over time; and
2. Ammonia, and in some cases methanol, requires hydrogen as a feedstock. Additional detail is provided in Frontier et al. (2019a).

Figure 17 Indicative market size by the middle of the century based on projected uptake of low carbon fuels assuming 50-100% reduction in greenhouse gas emissions[55]

Technology	No. of vessels with the technology globally (thousands) (% of global fleet)	Estimated annual global market size by the middle of the century ($m)	Implied annual UK market potential by the middle of the century ($m)
1-4. Combined fuel production technologies[56]	49-60 (55-68%)	11,000-15,000	490-690

Source : Frontier et al. (2019c)

[52] The proportional reductions are measured relative to 2008.

[53] The modelling projects uptake in five-year intervals. Estimates for 2051 are therefore presented throughout this section as this is the closest year to the middle of the century that has been modelled.

[54] The analysis of export market shares covers export of goods only and not the sale of products that are made and sold within any individual country. It also assumes that the observed market shares for proxy sectors remain constant over time.

[55] The proportional declines are measured relative to 2008.

[56] This includes hydrogen, ammonia, methanol and Bio-LNG.

Notes: *Vessel numbers are rounded to the nearest thousand; global market size is rounded to the nearest billion; UK market size is rounded to the nearest 10 million. All monetary estimates are in 2016 prices.*

The estimated future global market size represents only those stages of the value chain in which the UK has a particular competitive advantage (such as the upfront design or IP-intensive aspects of fuel production technologies).

Figure 18 Indicative market size by the middle of the century assuming 50-100% abatement[57]

Technology	No. of vessels with the technology globally (thousands) (% of global fleet)	Annual global market size by the middle of the century ($m)	Implied annual UK market potential by the middle of the century ($m)
5. Low carbon shore power technologies	43-47 (50-55%)	<1,000	<10
6. Onboard hydrogen technology	-	-	-
7. Onboard batteries	3-9 (5-10%)	<1,000	<10
8. Electric propulsion	2-6 (0-5%)	<1,000	0-20
9. Air lubrication	13-16 (15-20%)	3,000-4,000	70-90
10. Wind propulsion	37-40 (40-45%)	2,000-3,000	70-80
11. EGR & SCR engine exhaust technologies	74-75 (80-85%)	<1,000	10-20

Source: *Frontier et al. (2019c)*

Notes: *Vessel numbers are rounded to the nearest thousand; global market size is rounded to the nearest billion; UK market size is rounded to the nearest 10 million. All monetary estimates are in 2016 prices and reflect capital costs for new installations[58] and annual recurring costs for new and existing installations.*

The implied UK potential market across all 11 shortlisted abatement options (both fuel and non-fuel) could be **$650-890 million** per year by the middle of the century, if the UK were able to maintain its current export market share (this is approximately equivalent to 4% of the relevant global markets). Focusing just on fuel production the implied UK potential market across could be **$490-690 million** per year by the middle of the century (approximately equivalent to 4.6% of the relevant global markets). Importantly, this assessment is indicative only because future export market shares are inherently uncertain and could rise or fall relative to current levels.

[57] The proportional declines by 2050 are measured relative to 2008.

[58] The number of new installations was estimated as the annual average number of installations over 2046 to 2051.

5 IMPLICATIONS FOR POLICY

This report finds that two abatement options currently offer the most significant economic and commercial opportunities for the UK. These are options where the UK has a relatively widespread competitive advantage (see Figure 16) and the modelling has shown that future take-up is expected to be considerable (see Figure 17 and Figure 18):

- The UK is well placed in relation to **hydrogen production technologies.** The UK's extensive experience in natural gas and reformer technologies would be a key advantage here. In addition, the UK is already a world leader in electrolysis activities, which are directly relevant to hydrogen production for zero emission shipping. It is estimated that the UK currently has around a 9% global export market share of reformer and CCS technologies, which are likely to be important elements of hydrogen production for zero emission shipping. Both China and the USA currently have market shares in excess of 10% in this area.

  There is currently no take-up of hydrogen fuel in the global fleet. If policies and incentives are in place to move towards zero emission shipping by the middle of the century, hydrogen fuel usage may increase or remain low depending on future cost effectiveness. However, hydrogen production technologies are an important input to ammonia and in some cases methanol fuel which may have substantial expected take-up.

- The UK also has a strong competitive position in relation to **ammonia production technologies**. In particular, the UK has a strong domestic position for ammonia catalyst supply, and ammonia-based fertiliser is produced in volume in the UK. This is important because catalyst supply is a high-value part of the supply chain. The current take-up of onboard ammonia fuel technologies is relatively low so this is a nascent market at present.

Batteries and electric engines also offer strong potential competitive advantage.

However, given that the UK has some advantages across all 11 options, and acknowledging the inherent uncertainty when considering future market opportunities, policy measures that are broadly technology agnostic are likely to be the best first step. Further work is recommended in this area to carry out a more detailed competitive assessment of the UK across the entire shortlist.

Although not assessed in detail as part of the technology assessment in this report, a further key strength of the UK which cuts across the abatement options is its position as a global leader in maritime professional services, with extensive expertise in finance, vessel chartering, insurance, legal and educational services (Maritime UK, 2018). These services are likely to continue to be important for the industry going forward, both in the UK and overseas.

For the UK to maximise its potential commercial opportunity, policy intervention may be required to overcome barriers that could otherwise hinder its progress in this space. Key barriers identified in Frontier et al. (2019d) that are relevant here and would merit policy attention are:

1. **Externalities**: this highly prevalent barrier is of significant importance due to the fact that the price of fossil fuels does not currently reflect the social costs of climate change or damage to human health and ecosystems from air pollution, which are known as negative externalities. This affects the relative price of fuels in the market and therefore the incentives to invest in their development. Section 4.4 highlighted that low carbon fuels are currently relatively expensive compared to conventional fuel sources. This is partially because the technologies associated with alternative fuels are still nascent. However, the price differential is also partially due to the negative externalities which are not currently included in the price of fossil fuels. Policy could address this through the use of various price-based market mechanisms, for example.

2. **Policy landscape stability**: the policy landscape is an important barrier in relation to the development of and incentives to take up low carbon fuels. Significant financial investment is likely to be required for the development and widespread uptake of abatement options, along with associated infrastructure if zero emissions are to be achieved by around 2050. This requires a stable policy landscape that is able to provide the market with sufficient confidence that the market opportunities will be sustainable over the longer term. Where policy is uncertain or unstable, this could be a significant barrier. For example, there is evidence from the National Audit Office that uncertainty regarding CCS projects could have led to two prospective bidders cancelling their project (National Audit Office, 2017). On the other hand, Maritime 2050 (DfT, 2019) and, more generally, the 2008 Climate Change Act[59] help by providing certainty of ambition. Section 4.4 noted that the UK has a number of strengths in relation to cutting edge R&D of electric propulsion, for example. Therefore, ongoing incentives to encourage applied research and skills development are likely to add value.

3. **Organisational barriers:** interdependencies across various actors in the shipping market mean that there are likely to be barriers to the widespread development and uptake of low carbon fuels and abatement technologies if there is no supporting co-ordination. For example, the ability of one set of organisations to implement changes is often dependent on the activities of others. The supply chain set out in Section 4.2 highlights these interdependencies. Policy incentives could be designed in a way which recognises these interdependencies by targeting actors appropriately across the supply chain.

4. **Structural barriers**: As noted in Section 4.4, some abatement options, such as on-shore power, have particular infrastructure requirements at ports which need investment from the port and others in the supply chain, such as those operating the regional or national grid. Co-ordination of activities and the provision of appropriate incentives may be required. For example, ship owners may not want to invest in alternative fuel technologies until ports put in place the supporting infrastructure. However, ports may not want to invest in the supporting infrastructure until the demand can be credibly demonstrated. These co-ordination issues could

[59] See http://www.legislation.gov.uk/ukpga/2008/27/contents

be partially overcome if governments, trade bodies or international representative groups can organise, promote and facilitate the diffusion of abatement options, especially through an inter-government body like the International Maritime Organisation.

5. **Split incentives:** related to the co-ordination issues above, split incentives are an important barrier and derive from the fact that ship owners often have little incentive to invest in fuel efficiency or emissions abatement options because it is likely to be the charterer that benefits from the fuel savings. These could be addressed through, for example, exploring mechanisms which facilitate co-ordination and some sharing of the benefits across the parties involved in decision-making.

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ANNEX A LONG LIST OF ABATEMENT OPTIONS

Figure 19 Long list of abatement options

Option
Rudder bulb
Pre-swirl propeller ducts
Trim optimisation
Vane wheel
Contra rotating propeller
Twisted rudders
Boss cap fin
Hull coating management
Air lubrication bubbles
Block coefficient reduction
Sails and Flettner rotors
Kites
Steam waste heat recovery
Organic Rankine waste heat recovery
Turbo-compounding in series
Solar power
Hotel systems
Fuel cells for auxiliary system
Draft/displacement optimisation
Port turnaround optimisation
Energy saving lighting
Shore power
Engine derating
Energy storage battery + power take off
Energy storage battery (small ships)
2 stroke diesel
4 stroke diesel
Diesel electric
4 stroke spark ignition (liquified natural gas)
Fuel cell with hydrogen
Fuel cell with ammonia
Fuel cell with liquified natural gas
4 stroke spark ignition (ammonia)
Internal combustion engine with hydrogen (retrofit)
Internal combustion engine with hydrogen (new build)
Internal combustion engine with ammonia (retrofit)
Methanol 2 stoke (retrofit and new build)
Methanol 4 stoke (retrofit and new build)

Source: Frontier et al. (2019b)

www.frontier-economics.com