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

Economic Opportunities from Low and Zero Emission Shipping. Technical Annexes

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Authors:

Matthew Bell (Frontier Economics), Kat Deyes (Frontier Economics), Nick Fitzpatrick (Frontier Economics), Cavin Wilson (Frontier Economics), Adam Chase (E4tech) and Chester Lewis (E4tech). Expert advice was provided by Dr Tristan Smith (UMAS). The authors would like to thank David Connolly who provided technical advice relating to specific abatement options, particularly air lubrication. David is a technical advisor to University Maritime Advisory Services (UMAS) and is employed by Silverstream Technologies which is one of the companies referred to in this report.

Department for Transport

Great Minster House

33 Horseferry Road

London SW1P 4DR

Telephone 0300 330 3000

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

Website www.gov.uk/dft

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1 INTRODUCTION

To inform the Clean Maritime Plan, this report provides evidence on the potential scale of the economic and commercial opportunities to the UK from the transition to zero emission shipping. Eleven abatement options are considered individually – these have been selected using the method described in the Summary Report (Frontier et al., 2019a), which synthesises the evidence presented in this report and should be read first.

ANNEX A contains additional detail related to the modelling work undertaken to illustrate the size of the relevant global export markets for each technology and sub-technology, and the UK's estimated shares of these markets. Each abatement option is then considered individually in ANNEX B to ANNEX L. In general, a common approach has been undertaken for each abatement option. Slight differences in the presentation of each Annex section do occur due to variation in the level of information relating to each of the 11 abatement options. This variation occurs because some of the areas under consideration are still nascent. As a result, the level of detail contained in the following sections varies significantly. In addition, the authors listed above all contributed to the Summary Report (Frontier et al., 2019a) and this document. However, individual team members contributed more to certain sections, reflecting their areas of expertise. ANNEX J and ANNEX K are both onboard technologies that do not connect with the offboard system and therefore are treated slightly differently in certain respects.

In all cases, every effort was made to ensure that relevant information was reviewed and incorporated.

ANNEX A TECHNICAL ANNEX

A.1 Description of Comtrade data and mapping

Comtrade data (UN, 2019) has been used to estimate the scale of the export market for the selected abatement options. This source provides data on the value of exports (and imports) in each year in current US dollar prices for a large number of products, each of which is assigned a code known as an HS6 code.[1]

These codes do not match neatly to the eleven abatement options and associated supply chain elements that are the focus of this analysis. Therefore, in order to construct a version of the Comtrade dataset that could provide insight into the UK's market share and the size of the global market, the HS6 codes that most closely match each sub-technology were identified using the expert judgement of industry specialists.

In some cases, these HS6 codes closely describe the relevant sub-technology (e.g. the Hydrogen Fuel: Electrolyser sub-technology maps to HS code 854330, which includes 'machines & apparatus for electroplating/electrolysis/ electrophoresis'). In other cases, they 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 '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 relevant, technologies have been used that reflect the most relevant similar market – this is to allow the analysis to demonstrate the extent to which the UK has a market presence in similar markets, and hence has potential to move into the marine market.

Where the proxy has been judged to be too weak to provide insight into the potential market share of UK firms, Comtrade data has not been used to estimate export market shares.

Figure 1 summarises whether the appropriateness of the proxy is high, medium or low for each sub-technology. This assessment is based on the share of the sub-technology that is likely to be accounted for by the HS6 code (in some cases the HS6 code is only a sub-set of the sub-technology), and the share of the HS6 code that is likely to be accounted for by the sub-technology (in other cases, the HS6 code includes goods that are not covered by the sub-technology). Where Comtrade data has not been used, N/A is given.

Figure 1 Appropriateness of mapping from options to Comtrade HS6 codes

Technology	Sub-technology	Appropriateness rating
1. Hydrogen production technologies	Reformer + carbon capture and storage (CCS)	Low

[1] This analysis uses data from 2008-2017 – the latest data available.

Technology	Sub-technology	Appropriateness rating
1. Hydrogen production technologies	Electrolyser	Medium
2. Methanol production technologies	Reformer + CCS	Low
2. Methanol production technologies	Electrolyser	Medium
2. Methanol production technologies	Methanol synthesis	N/A
3. Ammonia production technologies	Reformer + CCS	Low
3. Ammonia production technologies	Electrolyser	Medium
3. Ammonia production technologies	Ammonia synthesis	N/A
3. Ammonia production technologies	Direct production	N/A
4. Bio-LNG production technologies	Gasifier	Low
4. Bio-LNG production technologies	Anaerobic digester	Low
4. Bio-LNG production technologies	Liquefier	Medium
5. Low carbon shore power technologies	-	Medium
6. Onboard hydrogen technology	Hydrogen storage	Low
6. Onboard hydrogen technology	Hydrogen fuel cell	Low
7. Onboard batteries	-	Medium
8. Electric propulsion	-	Medium
9. Air lubrication	-	N/A
10. Wind propulsion	-	N/A
11. Exhaust Gas Recirculation and Selective Catalytic Reduction (EGR/SCR)	-	Low

The HS6 codes that have been used for each sub-technology are described in Figure 2.

Figure 2 Mapping from options to Comtrade HS6 codes

Option	Sub-technology	HS6 code	HS6 code description
1. Hydrogen production technologies	Reformer + CCS	840510	Producer gas/water gas generators, with/without their purifiers; acetylene gas generators & similar water process gas generators, with/without their purifiers

Option	Sub-technology	HS6 code	HS6 code description
1. Hydrogen production technologies	Reformer + CCS	840590	Parts of the producer gas/water gas generators/acetylene gas & similar water process gas generators of 8405.10
1. Hydrogen production technologies	Electrolyser	854330	Machines & apparatus for electroplating/electrolysis/electrophoresis
2. Methanol production technologies	Reformer + CCS	840510	Producer gas/water gas generators, with/without their purifiers; acetylene gas generators & similar water process gas generators, with/without their purifiers
2. Methanol production technologies	Reformer + CCS	840590	Parts of the producer gas/water gas generators/acetylene gas & similar water process gas generators of 8405.10
2. Methanol production technologies	Electrolyser	854330	Machines & apparatus for electroplating/electrolysis/electrophoresis
2. Methanol production technologies	Methanol synthesis	N/A	N/A
2. Methanol production technologies	Reformer + CCS	840510	Producer gas/water gas generators, with/without their purifiers; acetylene gas generators & similar water process gas generators, with/without their purifiers
3. Ammonia production technologies	Reformer + CCS	840590	Parts of the producer gas/water gas generators/acetylene gas & similar water process gas generators of 8405.10
3. Ammonia production technologies	Electrolyser	854330	Machines & apparatus for electroplating/electrolysis/electrophoresis
3. Ammonia production technologies	Ammonia synthesis	N/A	N/A
3. Ammonia production technologies	Direct ammonia production	N/A	N/A
3. Ammonia production technologies	Direct ammonia production	N/A	N/A
4. Bio-LNG production technologies	Gasifier	841940	Distilling/rectifying plant, whether/not electrically heated
4. Bio-LNG production technologies	Anaerobic digester	841989	Machinery, plant & equip., n.e.s. in Ch.84, other than for making hot drinks/for cooking/heating food, whether/not electrically heated
4. Bio-LNG production technologies	Anaerobic digester	841990	Parts of machinery, plant/laboratory equipment, whether/not electrically heated (excl. furnaces, ovens & other equipment of heading 85.14), for the treatment of materials by a process involving a change of temperature such as heating, cooking, roasting

Option	Sub-technology	HS6 code	HS6 code description
4. Bio-LNG production technologies	Liquefier	842139	Filtering/purifying machinery & apparatus for gases, other than intake air filters for internal combustion engines
5. Low carbon shore power technologies	-	850410	Ballasts for discharge lamps/tubes
5. Low carbon shore power technologies	-	850421	Liquid dielectric transformers having a power-handling capacity not >650kVA
5. Low carbon shore power technologies	-	850422	Liquid dielectric transformers having a power-handling capacity >650kVA but not >10000kVA
5. Low carbon shore power technologies	-	850423	Liquid dielectric transformers having a power-handling capacity >10000kVA
5. Low carbon shore power technologies	-	850432	Electrical transformers (excl. dielectric) having a power-handling capacity >1kVA but not >16kVA
5. Low carbon shore power technologies	-	850433	Electrical transformers (excl. dielectric) having a power-handling capacity >16 kVA but not >500kVA
5. Low carbon shore power technologies	-	850434	Electrical transformers (excl. dielectric) having a power-handling capacity >500kVA
5. Low carbon shore power technologies	-	853521	Automatic circuit breakers, for a voltage of <72.5kV
6. Onboard hydrogen technology	Hydrogen storage	841869	Refrigerating/freezing equip. n.e.s. in 84.18; heat pumps
6. Onboard hydrogen technology	Hydrogen storage	841430	Compressors of a kind used in refrigerating equip.
6. Onboard hydrogen technology	Hydrogen fuel cell	850161	AC generators (alternators), of an output not >75kVA
6. Onboard hydrogen technology	Hydrogen fuel cell	850720	Electric accumulators, incl. separators therefor, whether/not rectangular (incl. square), lead-acid (excl. of 8507.10)
7. Onboard batteries	-	850750	Electric accumulators; nickel-metal hydride, including separators, whether or not rectangular (including square)
7. Onboard batteries	-	850760	Electric accumulators; lithium-ion, including separators, whether or not rectangular (including square)
8. Electric propulsion	-	850162	AC generators (alternators), of an output >75kVA but not >375kVA
8. Electric propulsion	-	850163	AC generators (alternators), of an output >375kVA but not >750kVA

Option	Sub-technology	HS6 code	HS6 code description
8. Electric propulsion	-	850164	AC generators (alternators), of an output >750kVA
8. Electric propulsion	-	850300	Parts suit. for use solely/principally with the machines of 85.01/85.02
9. Air lubrication	-	N/A	N/A
10. Wind propulsion	-	N/A	N/A
11. EGR & SCR engine exhaust technologies	-	841950	Heat exchange units, whether/not electrically heated
11. EGR & SCR engine exhaust technologies	-	841350	Reciprocating positive displacement pumps (excl. of 8413.11-8413.40)
11. EGR & SCR engine exhaust technologies	-	841459	Fans, other than table/floor/wall/window/ceiling/roof fans, with a self-contained electric motor of an output not >125W
11. EGR & SCR engine exhaust technologies	-	848180	Taps, cocks, valves & similar appliances for pipes/boiler shells/tanks/vats/the like, incl. thermostatically controlled valves, n.e.s. in 84.81

Source: Frontier analysis of HS6 codes

Using the HS6 codes described above, the UK's export share of the global proxy technology areas was estimated for the latest available year (2017). Shares were similarly calculated for the overall technologies. The results of this stage are presented in Figure 7 of the Summary Report (Frontier et al., 2019a).

A.2 Estimated scale of potential future markets

A.2.1 Business as usual modelling

Information on short-term deployment of the 11 abatement options across the global fleet was taken from modelling work carried out by University Maritime Advisory Services (UMAS) and summarised in Frontier et al. (2019b). This analysis estimates short-term projections for uptake of each abatement option assuming business as usual policy and market conditions prevail. The assumptions which underpin this model are described in detail below in Section A.3.

The modelling provides information on:

- **The number of vessels in the global fleet expected to have each abatement option installed by 2021**.[2] To estimate this figure across the entire fleet, it was necessary to aggregate deployment across 10 ship types which are further subdivided according to vessel size. The ship types are presented below in Figure 3. Similarly, it was necessary to map from the long-list of abatement options used in the model to the 11 technologies examined in this report. This mapping is presented below in Figure 4.

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

Figure 3 Vessel types used in UMAS modelling

Vessel type
Bulk carrier
Container
Oil tanker
Cruise
Ferry-RoPax
Ro-ro
Service – tug
Offshore
Service – other
Miscellaneous – other

Source: UMAS

Figure 4 Mapping of abatement options

Technology	Modelled abatement options
1. Hydrogen production technologies	Hydrogen fuel
2. Methanol production technologies	Methanol fuel
3. Ammonia production technologies	Ammonia fuel
4. Bio-LNG production technologies	Bio-LNG fuel
5. Low carbon shore power	Shore power
6. Onboard hydrogen technology	FC+H2
7. Batteries for electricity storage onboard	Energy storage battery + PTO
8. Electric engines	Diesel electric_HFO Diesel electric_LSHFO Diesel electric_MDO
9. Air lubricants	Air lubrication bubbles
10. Wind propulsion	Wind assistance (rotors/sails/wings) Wind assistance (kites)
11. Exhaust Gas Recirculation and Selective Catalytic Reduction (EGR/SCR)	NOx device

Source: UMAS

Notes: Full descriptions of each modelled abatement option is available in Table 4 of Frontier et al. (2019b). Technology 4, Batteries for electricity storage onboard, includes 'energy storage battery (small ships)'.

- **The estimated global annual cost of these installations in 2021**. To estimate the total cost for non-fuel options, two cost fields from the modelling output were used.
  - The non-recurring capital costs associated with installing each technology on a new-build ship, or retrofitting an existing ship. This figure was multiplied by the estimated number of new installations of that abatement option in 2021.
  - The annual recurring cost for new and existing installations. This reflects the value of market activity associated with servicing the operation of each

installed technology. This figure was multiplied by the estimated number of new and existing installations of that technology in 2021.

Non-recurring and recurring cost data was used for each technology, vessel type and vessel size. The model further disaggregated costs by the original build-year of the vessel, however this variation was not substantial and so was not accounted for in the cost estimates. This analysis used the costs associated with the oldest ships of each respective ship type and size. These estimates reflect the final costs incurred by the ship owners/operators who will be responsible for installing and running the new technology. As such, it provides an indicative, order-of-magnitude estimate of the potential overall market size. This is because the total costs incurred by ship owners/operators will reflect the total scale of activity across each intermediate stage of production included within the overall supply chain.

Three particular assumptions used for estimating the global market potential are:

- The number of new installations in 2021 was estimated as the annual average number of installations over 2021 to 2026 (i.e. by subtracting the number of ships with the particular technology installed in in 2021 from the number of ships with the particular technology installed in 2026, and dividing by five). While the actual number of new installations in 2021 may be higher or lower than the five-year average, this number was not available in the model. The five-year average is the best available estimate. The five year average from 2021 to 2026 is considered a better estimate than the five year average from 2016 to 2021 because 2016 to 2021 includes modelling calibration that is not reflective of the long-run rate of change consistent with the policy scenarios considered.
- In some instances, the number of vessels of a particular size and type with a particular abatement option is lower in 2026 than in 2021 (due to vessels retiring). Where this is the case, the number of new installations was assumed to be zero rather than a negative value to avoid undercounting.
- In some instances, recurring and capital cost data was not available for a particular abatement option for a particular vessel type and size. In these instances, costs were interpolated based on the costs available for the same vessel type of the nearest vessel size. If all costs of a particular abatement option for a particular vessel type were zero or not available, no inference was made (though this is in a negligible number of instances). This approach is consistent with the approach used in the GloTraM modelling.

- **Projected fuel consumption volumes and unit costs in 2021**. Fuel volumes (tonnes) and unit costs (USD per tonne) are combined to estimate the annual fuel costs for the four fuel options: hydrogen, methanol, ammonia and Bio-LNG. Fuel options are combined into a single renewable fuel option for reporting purposes due to modelling uncertainty regarding the fuel mix.

The next stage of the analysis involves combining the UK's export market share estimates, computed using Comtrade data with the estimated annual global market size for each abatement option from the business as usual modelling.

- **For non-fuel technologies**, the estimated annual global market size is proxied by final annual capital and annual recurring costs.
- **For fuel production technologies**, the estimated annual global market size is the product of a) total fuel volumes in tonnes per year, b) unit costs in USD per tonne for the respective year, and c) a 2.6% scaling factor. The scaling factor reflects the fact that the UK generally has strengths in the upfront design and intellectual property (IP) intensive stages of the relevant value chains. The estimate of the future global market size for fuel production technologies therefore 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.[3]

  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 is not included in the estimated market size estimates.

Multiplying the estimate of future potential global market size for each abatement option with the UK's estimated current market share in technologies which are similar to the abatement option provides an estimated UK market potential. This calculation is outlined in Figure 5.

Figure 5 Combining Comtrade data with uptake modelling

Source: Frontier, E4tech

Estimates of the number of vessels expected to have each abatement option installed globally by 2021, the annual global market size for each abatement option in 2021 and the UK market potential for each abatement option in 2021 are presented in Figure 8 of the Summary Report (Frontier et al., 2019a).

A.2.2 Scenario modelling to the middle of the century

Long-term deployment projections for the 11 abatement options across the global fleet were generated by modelling work carried out by UMAS and summarised in Frontier et al. (2019b). Take-up of abatement options across the global fleet was estimated assuming global shipping greenhouse gas emissions are reduced by

[3] The scaling factor was calculated for ammonia production on the basis of expert judgement from industry stakeholders and applied to other fuel types for consistency and because there is insufficient evidence on other fuel types and ammonia production is judged to be a good proxy. The cost of catalysts for ammonia production (which will be open to competition) is approximately 0.6% of total cost per tonne of ammonia (the catalyst is not often replaced; it just deteriorates over time). In addition to this, the IP value (which is also open for competition) is likely to be approximately 2% of the revenue from the plant's total annual production (measured in royalties).

50-100% (relative to 2008) by the middle of this century (Frontier et al. 2019b). 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. Further limitations are discussed in detail in Section A.3.

As with the short-term business as usual projections, the modelling provides an estimate of the number of vessels in the global fleet expected to have the technology installed by 2051[4] (using the same 10 ship types), the estimated global annual cost of these installations in 2051 and the estimated total global fuel costs in 2051, using the same approach to aggregating and compiling recurring and non-recurring costs specified in section A.2.1.[5]

Using the same process described above, it is then possible to provide a range of estimates for future uptake of each option and the associated potential market size. The final step is again to combine the estimate of UK export market share, estimated using Comtrade data, with the potential global market size estimate from the scenario modelling to estimate a potential UK market size.

These estimates are presented in Figures 17 and 18 of the Summary Report (Frontier et al., 2019a).

A.3 Limitations and assumptions

The analysis presented in the accompanying Summary Report (Frontier at al., 2019a) and discussed in this document is subject to a number of limitations. In general, the quantitative estimates presented, both the current UK export market share for the relevant technologies and the estimated scale of the global market for the relevant technologies in 2021 and 2051, are subject to uncertainty but the analysis is considered reasonable for the purposes of this work.

In relation to the estimated current export market share of the UK for the relevant technologies, particular limitations are:

- Data does not exist for some products and technologies because the markets are currently nascent. In such cases, the most relevant proxy products or technologies have been used because this demonstrates the UK's potential to expand into marine-related technologies of a similar nature.
- Comtrade data is for exports and imports only – no data is available on the scale of the product or technology markets that serve domestic consumers. This will underestimate the global market size if considerable domestic activity is omitted.

In relation to the estimate of the potential future scale of the UK market for relevant technologies in 2051, there are inevitable uncertainties when projecting over a 30-year period. Therefore, the analysis is intended to provide a relative order of magnitude of scale rather than implying any spurious accuracy. The method used

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[4] The modelling projects uptake in five-year intervals. 2051 was used as it the closest modelled year to the middle of the century.

[5] For the purposes of estimating the annual non-recurring capital costs for new installations, the number of new installations in 2051 was estimated by subtracting the number of installations in 2046 from the number of installations in 2051, and dividing by five.

is transparent and avoids unnecessary complexity. The analysis requires use of Comtrade data to generate a current UK market share of exports for the relevant technologies, alongside data from complementary modelling of scenarios which assess the potential uptake of technologies in 2021 and 2051 in order to achieve particular emission reduction targets. This approach has been developed for the purposes of this analysis and has not been employed elsewhere to date. Uncertainty has been handled in a proportionate way. Namely:

- The analysis draws on published Comtrade data for the assessment of UK export market shares, where the relevant technologies and proxy markets were selected and reviewed by internal team experts.
- As outlined above, for some technologies the Comtrade data provides only a proxy of the sorts of products that are likely to be included in the sub-technology. This will affect the precision of the estimated UK export market shares of related technology areas.
- The Comtrade data covers goods exports only and exclude services exports. Where a country has a substantially higher share of services exports, using Comtrade may understate its market share.
- The analysis covers exports only and not the sale of products that are made and sold within any individual country.
- The scenario modelling that provides an assessment of the global uptake of particular technologies by 2021 and 2051 has been carried out by UMAS using one of the leading global models of shipping (GloTraM). Its outputs have been extensively peer reviewed. It does, however, rely on a number of assumptions. In particular:
  - The modelling assumes that shipowners/operators always make decisions which will allow them to maximise profits. The accuracy of the results depends on the ability of the model to simulate actual decision-making behaviour of ship owners and operators.
  - The accuracy of the results also depends on key inputs to the business as usual scenario, such as the assumed fuel prices, the costs and performance of the abatement options and appropriate characterisation of UK domestic and international fleets. These have all been validated wherever feasible with experts or rely on government guidance (in relation to fuel costs).
- The scenario modelling to the middle of the century carried out by UMAS using GloTraM, and used in this analysis, focuses on two specific scenarios which forecast take-up of abatement options across the global fleet, assuming global shipping emissions are reduced by 50-100%[6] by the middle of this century (Frontier et al. 2019b). Alternative scenarios would lead to a different rate of abatement option deployment depending on the assumptions used.
- The UMAS projections cover a 30-year period. Long-term forecasting of this nature is inherently uncertain especially when considering the usage of nascent technologies – no account has been taken of practical barriers to the update of those technologies, such as the infrastructure requirements (though capex is

[6] Relative to 2008.

included). In addition, the analysis provides an illustration of the scale of potential UK market if it were to achieve the same export market share as the present day, for the purposes of illustration. The actual market share could, of course, be higher or lower.

In relation to the assessment of competitive advantage:

- The data and evidence underpinning the assessment was derived from a combination of desk-based research of published papers, annual reports, Companies House data, academic databases and interviews with industry experts. The assessment is qualitative in nature and hence the assessment of the relative competitive advantage of the UK relies in part on expert judgement, informed by the evidence.
- The work underpinning the Summary Report (Frontier, 2019a) was carried out over a short period of time (approximately six weeks over January and February 2019). The work that was carried out was proportionate to the time available.

A.4 Quality assurance statement

As described above, the time available to carry out this work was short. Every effort has been made to quality assure the work in a proportionate manner in line with the agreed timescales. Further detail is provided below, aligned with the requirements of the Department for Transport's (DfT) Analytical Assurance Framework.[7]

A.4.1 Reasonableness of the analysis / scope for challenge

The technology options analysed at detail in this study were shortlisted using a high-level qualitative approach across a set of criteria. Importantly, the criteria used captured the objectives of this individual study and the wider programme of work for DfT to inform the Clean Maritime Plan. A proportionate approach was applied to assess the potential abatement options against the criteria, using input from previous analysis, expert judgement as well as input from DfT officials.

A supply chain analysis was mapped for each of the 11 shortlisted technologies to disaggregate them into sub-technologies that correspond to UK current and potential industrial activities. This was determined through input from experts in the 11 shortlisted technologies and supported by desk research. The supply chain was then validated by the study team, UMAS, DfT officials and external stakeholders. This method was used to gain both a high level of insight and efficient use of resource.

The robust framework for assessing the UK's competitive advantage for each of the sub-technologies was developed by drawing on existing competitive advantage academic models and methodologies (Porter and Kramer, 2002). The data used for this process was gathered from a variety of sources and sense-checked with subject-matter experts. Where published data was not available, the input of subject-matter experts was used and sense-checked with secondary sources.

7 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/353372/strength-in-numbers.pdf

Findings from the analysis were also cross-checked with findings from alternative sources where available.

The draft report and findings were critiqued by the DfT officials as well as officials in relevant other government departments such as the Department for Business, Energy and Industry Strategy (BEIS).

The reasonableness of the qualitative analysis is considered high. This is because the findings have been sense-tested against other assessments of competitive advantage (such as the BEIS Technology Innovation Needs Assessments) and overall findings have been tested with stakeholders from industry and government.

The reasonableness of the quantitative analysis is also considered high. UMAS scenario modelling, which has been subject to rigorous testing, was used as a primary input to this analysis. Sense-checking has been carried out in the form of testing emerging findings with industry via three stakeholder events (held on 14 February 2019, 4 March 2019 and 11 March 2019).

A.4.2 Risk of error / robustness of the analysis

Quality assurance of the quantitative modelling was provided through three main processes:

1. Immediate quality assurance and error-checking of analysis to ensure the work is as robust as possible.
2. Project Manager review of quantitative outputs to ensure consistency across all outputs and accuracy of findings.
3. Project Director oversight of key outputs to test emerging findings.

In addition, the results of all modelling work carried out as part of this piece of work were sense-checked by analysts at UMAS to ensure the findings are consistent with Frontier et al. (2019b). All staff who carried out the quantitative modelling have considerable expertise carrying out complex analytical work and have extensive experience using appropriate modelling tools.

The scenario modelling work carried out by UMAS to input to this analysis was subject to its own quality assurance process. A proportionate approach was employed here to mitigate potential modelling input and calculation errors. Further detail is available in the Technical Annex which accompanies Frontier et al. (2019b).

The time available for this analysis has been tight, so quality assurance has necessarily been proportionate but is considered adequate for the purposes of the analysis. The robustness of the assessment of competitive advantage is considered high; the assessment of market shares and future scale of global and UK markets is considered medium.

ANNEX B HYDROGEN PRODUCTION TECHNOLOGIES

B.1 Introduction

This Annex applies the analysis framework set out in the Summary Report to hydrogen production technologies. Firstly, a brief description of hydrogen production technologies is provided, and the technologies are then assessed against the criteria for selection (Step 1).

The subsequent sections present the supply chain for hydrogen production technologies (Step 2) and explore relevant firms' current contribution to the UK economy, as well as presenting current levels of global deployment (Step 3). UK competitiveness is then assessed (Step 4) and future opportunities within the global market for hydrogen production technologies are considered (Step 5).

This Annex has been prepared using a combination of desk research, expert knowledge and discussions with industry, which have been referenced within the text where appropriate.

B.1.1 Technology description

Hydrogen used as a fuel has unique characteristics. Namely, when it is combusted or utilised in a fuel cell it does not emit any carbon dioxide (CO_2) and has no operational greenhouse gas (GHG) emissions.

Hydrogen can be produced through steam methane reforming (SMR) using natural gas[8], with or without Carbon Capture and Storage (CCS), water electrolysis[9] or from gasification of coal or biomass,[10] which can also feature CCS. The upstream emissions associated with the fuel depend on the method chosen. For example, electrolysis of water using renewable electricity is considered 'green hydrogen' with the lowest GHG emissions. On the other hand, SMR from natural gas produces large amounts of GHGs and needs CCS to be a viable option for creating low carbon hydrogen (Committee on Climate Change, 2018).[11]

B.1.2 Justification for inclusion in technology shortlist

Two main potential sources of economic value have been identified in the production of hydrogen:

- development and sale of electrolyser technology; and

[8] Steam methane reforming is a mature technology that has been used globally for many years to produce hydrogen. Carbon dioxide (CO_2) can be captured and stored to prevent its emission, using additional technology that can be added to the production process. In the UK, the largest plant is based in Teesside and is owned by BOC Linde. Source: E4tech and Element Energy (2014) Tees Valley and North East Hydrogen Economic Study.

[9] Electricity is used to split water across a membrane into hydrogen and oxygen. This is analogous to the reverse process in a fuel cell.

[10] Coal or biomass is heated to release carbon monoxide (CO) and hydrogen (H_2), otherwise known as syngas. The syngas is upgraded, separating the hydrogen and converting the CO to CO_2 in the process. The carbon dioxide (CO_2) can be captured and stored to prevent its emission using additional technology that can be added to the production process.

[11] https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf

- development and sale of methane reformer and CCS technology.

Economic opportunities may derive from the UK’s potential to develop and export technologies related to fuel production. It is possible that value could also be gained from additional supply of primary energy, such as renewable electricity or natural gas. However, there are already a suite of policies focusing on the economic opportunities for primary energy resources in the UK. Further value may be derived from operating UK fuel production facilities, regardless of the source of technology. However, these activities may be displacing existing operations such as conventional refining. This assessment therefore focuses on fuel production technologies.

B.2 Further detail on supply chain

An outline of the supply chain for hydrogen for shipping is shown in Chapter 4 of the Summary Report (Frontier et al., 2019a). Electrolyser technology has its own component supply chain, which mainly comprises specialist material and catalyst manufacturers. Similarly, methane reforming with carbon capture also requires specialist equipment, materials and catalysts that are an important part of the value chain.

Expert opinion was used to identify key actors in important parts of the related component supply chains in order to identify significant strengths and weaknesses for the UK, where appropriate.

B.3 UK economic footprint and share of global export market

This section presents evidence on the estimated market shares of the UK for relevant sub-technologies using data from the United Nations International Trade Statistics Database (Comtrade). This provides information on the value of imports and exports by country-pair and product (UN, 2019). These results are presented below and described in the Summary Report. This section also discusses the key actors in the UK.

B.3.1 Global export market size and UK share of proxy markets

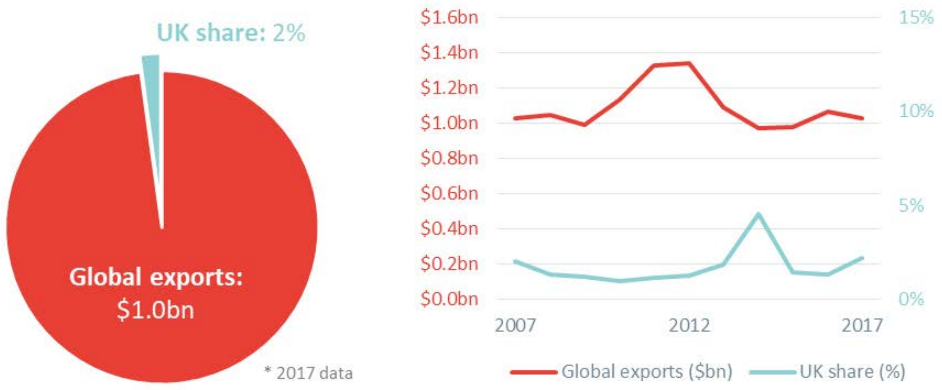
Figure 6 shows the export market for SMR and CCS technologies using the proxy of the HS6 codes 840510 and 840590 (see Annex A). The value of the global export market has decreased since 2007, but during this time the UK share of global exports has increased, indicating a stable or strengthening position for the UK in the global market.

Figure 6 International trade: reformer and CCS technologies

Source: Comtrade, Frontier analysis

Figure 7 shows the export market for electrolyser technologies using the proxy of the HS6 code 854330 (see Annex A). The proxies here give a larger global export market value when compared to reformer and CCS technologies. However, the UK has a smaller and, historically, mostly stable share at approximately 2%.

Figure 7 International trade: electrolyser technologies



Source: Comtrade, Frontier analysis

B.3.2 Key actors in the UK

Selected key actors in the electrolysers and SMR + CCS technologies are outlined below. The relevance of these companies to the UK economy and the technology is described. Also, the current activity or, in the absence of current activity, the readiness for activity in the technology is outlined.

Figure 8 Reformer and CCS UK actors

Actor	Parent company	Relevance	Activity or readiness
Amec Foster Wheeler PLC	John Wood Group PLC	Large global engineering firm with experience in gas and chemicals, as well as CCS. Currently working to develop CCS projects. Amec Foster Wheeler has numerous locations spread across the UK. Across all sectors, it has 36,000 employees,[12] and a revenue[13] of £5.44bn, of which <1% related to CCS directly.	Current early-stage activity in CCS and also has technology for reforming hydrogen from various fossil products.
Air Products plc	Air Products and Chemicals, Inc	Air Products is a world leader in industrial gases, with 75 years' experience. With a UK presence, Air Products is the global leader of technical options for capturing CO_2 from fossil fuel conversion such as natural gas reforming, gasification and oxyfuel coal combustion before it reaches the atmosphere.	Air Products received funding for a project in the US, for CCS on SMR for hydrogen production. Other innovations related to CCS through sorption enhanced water gas shift (SEWGS) demonstrated in Europe by the CACHET project coordinated by BP.

Source: Expert knowledge, company websites, company financial statements, UK Companies House

Figure 9 Electrolyser UK actors

Actor	Parent company	Relevance	Activity or readiness
ITM Power		Medium-sized UK power to gas company which specialises in manufacture of integrated hydrogen energy systems, refuelling and electrolyser technology. Demonstrated generation projects using renewable energy including tidal power. £14.1m revenue, of which £3.3m is product sales.	Active in selling electrolyser systems and demonstrating, with deployments in Europe and studies underway worldwide. Growing 53% by revenue (including funding) and 35% increase in headcount in 2018.

[12] Number of full-time equivalent employees (FTEs).

[13] Total income for the company from activities e.g. sales of product or grant funding.

Actor	Parent company	Relevance	Activity or readiness
Johnson Matthey plc (JM)		Large global science and technology firm with a vision for sustainable energy. JM has the technology and capability to enter hydrogen generation from electrolysis owing to experience in catalysts. £14bn revenue, with £680m EBITDA,[14] across all sectors.	Not directly active in electrolyser market but has the ability to enter market easily. However, active more broadly in hydrogen technologies. Johnson Matthey Technology Centre is hosting directly relevant research and participating in the UKH2Mobility project.
Inovyn	INEOS Group	Subsidiary of INEOS, a large international firm where the focus is on petrochemicals. Inovyn specialises in chlor-alkali products and electrolysers, where hydrogen is a co-product. INEOS group has 7,000 employees and a revenue of €15.2bn, of which Inovyn revenue is £412m.	Inovyn is actively selling and deploying technology across 45 plants worldwide, with 35 years' experience in membrane electrolysers. Involved in multiple partner projects in the UK relating to hydrogen production.
Siemens plc	Siemens AG	Large global engineering and manufacturing corporate with electrolyser products and 62 UK-based subsidiaries. Siemens generated revenue of €83.0bn, of which power to gas segment has €12.441bn (estimated 6% relevant to UK). The company employs 42,782 in Europe (25% Germany, 75% rest of Europe).	Siemens is currently producing two sizes of electrolyser products (SILYZER 200 and SILYZER 300) and is involved with UK and European projects.
Toshiba UK	Toshiba Global	Toshiba is a large Japanese corporation with offices in the UK. Its diverse product and service range includes information and communication, and power systems. Involved previously in a pilot project in Scotland, providing its hydrogen energy management system (H2 EMS).	Toshiba UK is not known for involvement in hydrogen, but the project in Scotland demonstrates some capability for a niche system required for hydrogen storage and grid balancing.

[14] Earnings before interest, tax, depreciation and amortization.

Actor	Parent company	Relevance	Activity or readiness
PV3 Technologies		UK-based SME specialised in the manufacturing and development of electrochemical materials, including catalysts and coated electrodes.	Specifically developed electrochemical materials for proton-exchange membrane (PEM) and alkaline water electrolysers. It would need to be involved with a system integrator to develop and deliver a electrolyser product.

Source: Expert knowledge, company websites, company financial statements, UK Companies House

B.4 UK competitiveness

B.4.1 Technology advantages

The UK's strength in electrolyser technology is not as high as that in the conversion of fossil fuels to hydrogen (SMR + CCS). The former is a relatively immature and sparsely populated sector in the UK, though with pockets of strength. Conversely the UK actors in SMR technology are well established and, although the ecosystem for CCS is still developing, UK companies are among the emerging leaders. A few countries such as the USA and Germany could claim stronger positions in both technology fields, particularly through the involvement of large companies.

The UK does benefit from government support for fuel cells and related technologies such as electrolysers.[15] This support was successful in creating some global leading advances in performance (Carbon Trust, 2014).[16] However, other countries such as the USA, Korea, Japan, China and Germany have also been supporting hydrogen and fuel cell-related R&D.[17]

In steam reforming technologies, the UK has strong IP and lots of experience. For example, Johnson Matthey has 80 years of steam reforming experience, ranging from catalysis to process engineering and is the world-leading exporter of reformer IP through licensing (Johnson Matthey, 2016).[18] CCS needs to be applied for the GHG emissions to be reduced to a level that can be considered a low carbon source of hydrogen. The UK's planned CCS demonstration programmes and long history in the processing of hydrocarbons make it credible that the UK could be one of the world leaders in CCS (Carbon Trust, 2014).[19].

However, the USA, China and Canada accounted for 60% of all the carbon dioxide utilisation (CDU) patents globally in the years 1980-2017 (Norhasyima and Mahlia, 2018).[20] Chemical and fuel production is the largest category of CDU.

[15] UK Hydrogen and Fuel Cell Association http://www.ukhfca.co.uk/did-you-know/

[16] https://www.carbontrust.com/media/593904/h2-for-transport-summary-report.pdf

[17] UK Hydrogen and Fuel Cell Association http://www.ukhfca.co.uk/did-you-know/

[18] https://www.technology.matthey.com/pdf/263-269-jmtr-oct16.pdf

[19] https://www.carbontrust.com/media/593904/h2-for-transport-summary-report.pdf

[20] www.sciencedirect.com/science/article/pii/S2212982018301616

B.4.2 Factor advantages

The UK has some electrolyser companies at SME size with world-leading technology performance. This niche is complemented by fuel cell companies who also have high-quality technology and could in principle produce electrolysers if the market became more attractive. The UK also has leading components suppliers for both electrolysers and fuel cells.

The UK has world-leading electrochemistry research. This has mostly focused on battery and fuel cell groups, rather than electrolysers. However, the skills and knowledge could be easily applied to electrolysers if either policy or the market became more attractive (Carbon Trust, 2014).[21].

While the UK is well positioned with technology in SMR and CCS, competing nations are benefiting from strong education in areas such as materials and advanced process engineering. Engineering UK cites a shortfall of 20,000 engineers per year, posing a risk to the continued competitiveness of the UK (Engineering UK, 2017).[22]

B.4.3 Market advantages

While the skills and technology base in the UK are good for electrolysers, safety and reliability are critical, which makes buyers tend to favour larger (e.g. German) suppliers, making life harder for SMEs and novel tech developers. This is especially true of the non-EU markets for the smaller UK players (Carbon Trust, 2014).[23]

Reformer + CCS has both a good technology and supply chain base, funnelling this through reputable large organisations such as Johnson Matthey, giving the industry access to global markets.

Domestic policy for hydrogen production is currently in development, although there has been recent policy support for the development of CCS capabilities that will enable the reforming + CCS route. Support for electrolysis is currently focused upon supporting the development of the technology through demonstration projects at hydrogen refuelling stations for fuel cell vehicles.[24] More generally, while there has been general support for R&D for hydrogen technologies in the UK, there is not the same level of support for deployment of hydrogen as there is in some other countries, such as Japan, Korea and China.

Internationally, countries such as Japan and Korea have committed to using hydrogen in their national energy policy and have been developing technology capabilities in accordance with this (E4tech, 2018).[25]

B.4.4 International competitors

For electrolysis technologies the main competitors internationally, in no particular order, are Germany, China, the USA and Norway.[26] This is based on a relative

[21] https://www.carbontrust.com/media/593904/h2-for-transport-summary-report.pdf

[22] https://www.engineeringuk.com/media/1355/enguk-report-2017.pdf

[23] https://www.carbontrust.com/media/593904/h2-for-transport-summary-report.pdf

[24] www.itm-power.com/news-item/8-8m-olev-funding-for-refuelling-infrastructure

[25] http://www.fuelcellindustryreview.com/

[26] Expert consultation.

assessment of the industrial landscape, including technology, factor and market advantages, as well as the maturity of the companies and supply chain.

Many industrial countries have strength in SMR technologies, but CCS is a developing technology with limited skills globally. In CCS, the competitors to the UK in development are the USA and China, with other fossil fuel-abundant countries such as Norway, Australia and Canada having high development activity (Staffell et al., 2018).[27]

[27] https://www.drax.com/energy-policy/energy-revolution-global-outlook/

ANNEX C METHANOL PRODUCTION TECHNOLOGIES

C.1 Introduction

This Annex applies the analysis framework set out in the Summary Report to methanol production technologies. Firstly, a brief description of methanol production technologies is provided, and the technologies are then assessed against the criteria for selection.

The subsequent sections present the supply chain for methanol production technologies, explore relevant firms' current contribution to the UK economy and present current levels of global deployment. UK competitiveness is then assessed.

This Annex has been prepared using a combination of desk research, expert knowledge and discussions with industry, which have been referenced within the text where appropriate.

C.1.1 Technology description

Methanol is currently produced primarily for use by the chemical industry. Specifically, it is one of the key feedstocks for the production of plastics, solvents and other chemicals. It can also be used as a fuel.

Methanol can be produced from synthesis gas,[28] made from natural gas (through steam reforming) or by gasification of oil, coal or biomass (to form biomethanol). Methanol can also be produced from the combination of hydrogen and a carbon source – commonly known as e-methanol. The carbon source can be a concentrated waste CO_2 source or CO_2 captured from atmosphere, for the best GHG reductions. The fossil feedstocks have high associated GHG emissions, unless CCS is used in the process. Biomethanol and e-methanol have high GHG reduction potential. Methanol from high GHG routes is not considered here, as it will not bring GHG savings of the scale needed. Similar reasoning means that LNG is not considered but Bio-LNG is (see Annex E).

C.1.2 Justification for inclusion in technology shortlist

Two main potential sources of economic value were identified:

- production of hydrogen (covered in Annex B); and
- methanol synthesis from synthesis gas (or hydrogen).

Economic opportunities are judged to derive from the UK's potential to develop and export technologies related to methanol fuel production. It is possible that value could also be gained from additional supply of primary energy, such as renewable electricity or natural gas. However, these activities may be displacing existing operations such as conventional refining. This assessment therefore focuses on fuel production technologies.

[28] Synthesis gas is an in intermediate gas that is made up of hydrogen and carbon monoxide.

C.2 Further detail on supply chain

Methanol synthesis technology has its own component supply chain, which mainly comprises specialist material and catalyst manufacturers, as well as process equipment supply.

Expert opinion was used to identify key actors in important parts of the related component supply chains in order to identify significant strengths and weaknesses for the UK, where appropriate.

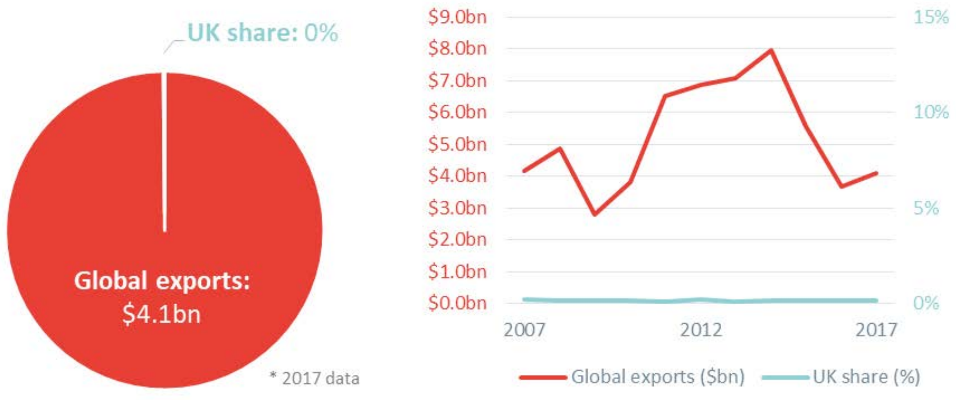
C.3 UK economic footprint and share of global export market

This section presents evidence on the estimated market shares of the UK for relevant sub-technologies using data from the United Nations International Trade Statistics Database (Comtrade). This provides information on the value of imports and exports by country-pair and product (UN, 2019). These results are presented below and described in the Summary Report. This section also discusses the key actors in the UK.

C.3.1 Global export market size and UK share of proxy markets

Figure 10 shows the export market for methanol synthesis technologies using the proxy of the HS6 code 290511 (see Annex A).

Figure 10 International trade: methanol synthesis technologies



Source: Comtrade, Frontier analysis

The apparent zero share of global trade is at odds with the reality that Johnson Matthey is a major supplier to the industry worldwide (see below), suggesting that the Comtrade category is not well aligned for this specific area of technology. For this reason, the Comtrade proxy for methanol synthesis was not used to estimate the UK market share of the methanol technology.

C.3.2 Key actors in the UK

Some key actors in the methanol synthesis technologies are outlined below. The relevance of these companies to the UK economy and the technology is described. Also, the current activity or, in the absence of current activity, the readiness for activity in the technology is outlined.

Figure 11 Methanol synthesis UK actors

Actor	Parent company	Relevance	Activity or readiness
Amec Foster Wheeler PLC (AmecFW)	John Wood Group PLC	Large global engineering firm with experience in gas and chemicals, particularly in syngas production for chemical use, and gas-to-liquids including methanol synthesis. It has 36,000 employees, and a revenue of £5.44bn, of which <5% estimated to be directly related to methanol production.	With a global presence, methanol synthesis is typically from fossil fuel-based resources. However, AmecFW has a new technology for substitute natural gas (SNG).
Johnson Matthey plc (JM)		Large global science and technology firm with a vision for sustainable energy. JM is one of the world's leading methanol technology and catalyst providers, with over half of the world's licensed methanol plants based on its Davy technology. £14bn revenue, with £680m EBITDA,[29] across all sectors.	Able to license its Davy technology and further develop a suite of technology options to deliver methanol processes for optimised production.

Source: Expert knowledge, company websites, company financial statements, UK Companies House

C.4 UK competitiveness

C.4.1 Technology advantages

The UK has world-leading strength in methanol synthesis technology. Johnson Matthey claims that over 50% of methanol plants globally use its technology (Johnson Matthey Technology Review, 2017).[30] However, the UK's domestic chemical sector has been declining and this makes it difficult to maintain momentum in methanol synthesis and the related chemistry domestically.

C.4.2 Factor advantages

The UK is well positioned for technology supply despite it lacking potential as a volume producer, due to its limited (low-cost) natural gas reserves, whereas countries with low-cost coal, natural gas or shale gas will benefit from the use of these technologies to produce large quantities of methanol fuel (IHS Markit, 2017).[31] This has also resulted in a lack of actors in the UK that construct large-scale methanol. However, the UK may be well placed for production of e-methanol

[29] Earnings before interest, tax, depreciation and amortization

[30] https://www.technology.matthey.com/article/61/3/172-182/

[31] https://ihsmarkit.com/products/methanol-chemical-economics-handbook.html

through renewable electricity, due to its large on- and offshore wind potential. The UK strength in technology is in part because of its well-developed catalyst supply chain, and this is supported by good levels of advanced scientific skills.

C.4.3 Market advantages

Historically, the UK has a strong market position in methanol technology and the market has high barriers to entry. It is worth noting however, that a lot of growth in the methanol market is outside of the UK (75% of global capacity additions in the 2012-17 period have been in China alone) (IHS Markit, 2017).[32] Unhindered access to these international markets is key to maintaining the UK's share of the global market.

Methanol production is not supported specifically in the UK. There is indirect funding for research and innovation in science, which covers many of the key areas associated with continued development of synthesis technology.[33] Large industrial economies with petrochemical sectors will also benefit from the opportunity to scale new technology quickly. Fast-growing economies or those with a large industrial basis should be seen as the strongest competitors and these include China, the USA and Germany.

C.4.4 International competitors

The section above outlines the type of UK competitors and the reasons for competition. The fast-growing economies or those with a large industrial basis should be seen as the strongest competitors and these include China, the USA and Germany.

[32] https://ihsmarkit.com/products/methanol-chemical-economics-handbook.html

[33] https://gow.epsrc.ukri.org

ANNEX D AMMONIA PRODUCTION TECHNOLOGIES

D.1 Introduction

This Annex applies the analysis framework set out in the Summary Report to ammonia production technologies. Firstly, a brief description of ammonia production technologies is provided, and the technologies are then assessed against the criteria for selection.

The subsequent sections present the supply chain for ammonia production technologies, explore relevant firms' current contribution to the UK economy and present current levels of global deployment. UK competitiveness is then assessed.

This Annex has been prepared using a combination of desk research, expert knowledge and discussions with industry, which have been referenced within the text where appropriate.

D.1.1 Technology description

Ammonia is one of the most abundantly produced chemicals globally and the majority is used in the agriculture industry as fertiliser. Approximately 146 million tonnes of ammonia were produced globally in 2016.[34] Ammonia is most commonly produced from combining nitrogen, an inert gas, with hydrogen through the Haber-Bosch process.[35]

Ammonia is considered a hydrogen carrier and can be used directly in internal combustion engines (with specific designs or modification) or in fuel cells (Kobayashi et al., 2019).[36]

Like hydrogen, there are no operational GHG emissions when using ammonia as a fuel, as it does not contain carbon in its molecular structure. The upstream GHG emissions depend on the production route of the hydrogen (commonly natural gas) and the process requirements of synthesising ammonia from hydrogen, through the Haber-Bosch process (TCG, 2018).[37] More novel electrochemical methods enable the direct production of ammonia from water and air through electrolysis, using renewable electricity.[38]

The use of ammonia in combustion engines can produce high NO_x emissions due to the nitrogen content of the fuel. This can be mitigated by the use of emission abatement technologies (see Annex L), multi-stage combustion or through optimising the combustion process for lower NO_x formation, for example by decreasing the temperature of combustion. Ammonia is a required chemical in the process of selective catalytic reduction, meaning there could be benefits from using

[34] http://www.essentialchemicalindustry.org/chemicals/ammonia.html

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

[36] https://doi.org/10.1016/j.proci.2018.09.029

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

[38] https://nh3fuelassociation.org/wp-content/uploads/2012/05/howarduniv1.pdf

it both as a fuel and also in emission reduction – for example, shared storage. The use of ammonia for fuel cells does not emit any NO_x emissions.

D.1.2 Justification for inclusion in technology shortlist

Three main potential sources of economic value were identified in the production of ammonia:

- production of hydrogen (see Annex B);
- ammonia synthesis using Haber-Bosch (catalytic route); and
- direct ammonia synthesis using electrolysis.

Economic opportunities are judged to derive from the UK's potential to develop and export technologies related to fuel production. It is possible that value could also be gained from additional supply of primary energy, such as renewable electricity or natural gas. However, these activities may be displacing existing operations such as conventional refining. This assessment therefore focuses on fuel production technologies.

D.2 Further detail on supply chain

Ammonia synthesis technology has its own component supply chain, which mainly comprises specialist material and catalyst manufacturers, together with more general process equipment.

Expert opinion was used to identify key actors in important parts of the related component supply chains in order to identify significant strengths and weaknesses for the UK, where appropriate.

D.3 UK economic footprint and share of global export market

This section presents evidence on the estimated market shares of the UK for relevant sub-technologies using data from the United Nations International Trade Statistics Database (Comtrade). This provides information on the value of imports and exports by country-pair and product (UN, 2019). These results are presented below and described in the Summary Report. This section also discusses the key actors in the UK.

D.3.1 Global export market size and UK share of proxy markets

Figure 12 shows the export market for ammonia synthesis technologies, using the proxy of the HS6 codes 281410 and 281420 (see Annex A). While the value of the global export market for ammonia technologies has had lots of fluctuation over the last 10 years, the UK share of the export market has been around 1-3%.

Figure 12 International trade: ammonia synthesis

Source: Comtrade, Frontier analysis

The Comtrade proxy for ammonia synthesis was not considered to be sufficiently robust for it to be used to estimate the UK market share of the ammonia technology.

There are currently no separate Comtrade commodity codes for direct ammonia technology due to the early stage of development and the similarities with the electrolyser technology.

D.3.2 Key actors in the UK

Key actors in ammonia synthesis technologies and direct ammonia production technologies are outlined below. The relevance of these companies to the UK economy and the technology is described. Also, the current activity or, in the absence of current activity, the readiness for activity in the technology is outlined.

Figure 13 Haber-Bosch ammonia synthesis UK actors

Actor	Parent company	Relevance	Activity or readiness
Amec Foster Wheeler PLC (AmecFW)	John Wood Group PLC	Large global engineering firm with experience in gas and chemicals particularly in syngas production for chemical use, and gas-to-liquids, including project management of ammonia synthesis plants. It has 36,000 employees and a revenue of £5.44bn, of which <5% is related to general project management activities directly.	With a global presence, AmecFW has had recent success in ammonia and urea projects in Russia, USA and Brazil, particularly focusing on project management consultancy. Independent of technologies and would need to work with a technology licensor.

Actor	Parent company	Relevance	Activity or readiness
CF Fertilisers UK Group Limited	CF Industries	Now the largest UK producer of fertilisers and bought 'GrowHow' from Yara, which has 2 plants in Billingham and Ince with approximately 1m tonnes ammonia production capacity (10% of CF industries' volume). CF fertilisers produces 40% of the UK's fertiliser needs. CF industries has a revenue of $4bn and EBITDA[39] of $900million, of which an estimated 10% could be considered relevant to the UK.	CF industries manufactures liquid ammonia and supplies it in both premium and standard grades, being primarily used for NO_x abatement for industries and power generation.
Eneus Energy		Small UK business that specialises in integrating technology to convert excess renewable electricity directly into ammonia.	Opportunity to further develop if the market signals an increased demand for ammonia from renewable energy.
Johnson Matthey plc (JM)		Large global science and technology firm with a vision for sustainable energy. JM is one of the world's leading catalyst providers, based on more than 80 years' experience with Imperial Chemical Industries (ICI) and 100 years' experience with BASF. £14bn revenue, with £680m EBITDA across all sectors.	JM is a technology leader in the fertiliser industry, supplying ammonia synthesis catalysts (named KATALCO) and providing further engineering support on ammonia plant operation (e.g. with Thyssenkrupp and Uhde).
J&E Hall	Daikin Industries Ltd.	J&E Hall is a refrigeration equipment manufacturer in the UK, specialised in tailor-made upstream and downstream refrigeration packages specifically for the oil and gas industries. Member of the Daikin group.	Ammonia storage is an important factor for widespread use as a fuel, and the UK has expertise in refrigeration for high-pressure storage with J&E Hall.

Source: Expert knowledge, company websites, company financial statements, UK Companies House

[39] Earnings before interest, tax, depreciation and amortization

Figure 14 Electrochemical ammonia production UK actors

Actor	Parent company	Relevance	Activity or readiness
Siemens plc	Siemens AG	Large global engineering and manufacturing corporate with electrolyser products. It has 62 UK-based subsidiaries. Siemens generated revenue of €83.0bn, of which power to gas segment has €12.441bn (estimated 6% relevant to UK). The company employs 42,782 in Europe (25% Germany, 75% rest of Europe).	Siemens is participating in an all-electric ammonia synthesis and energy storage system demonstration programme at Rutherford Appleton Laboratory, near Oxford and is supported by Innovate UK. Collaborators include the University of Oxford, Cardiff University and the Science & Technology Facilities Council.
Yara UK	Yara International ASA	Large UK arm (350 employees) of the Global YARA Group, with 170 years of business in the UK with plant nutrient products. Liquid fertiliser production for 50 years, specialising in low carbon footprint nitrogen fertilisers. The YARA Group, is a global leader in ammonia, producing approximately 7,500m tonnes of ammonia, with revenues of ~£8.3bn.[40] The production sector (including ammonia production) is responsible for 50% of revenues.	Yara has plants across the UK. Longer-term perspectives include circular economy offerings, as well as de-carbonising ammonia production. Yara has developed a relationship with a Japanese strategic innovation programme and is preparing to initiate commercial negotiations on the use of such ammonia as an energy vector.

Source: Expert knowledge, company websites, company financial statements, UK Companies House

D.4 UK competitiveness

D.4.1 Technology advantages

The leading companies in the Haber-Bosch process are Clariant (Switzerland), Casale (Italy), ThyssenKrupp (Germany), Johnson Matthey (UK), Haldor Topsoe (Denmark), BASF (Germany), KBR (US) and Linde (Germany) (TCG, 2018).[41] Johnson Matthey in the UK claims a leading position in this technology, providing catalysts and related technology for all steps of the main production process.[42] This is mainly for large-scale plants producing ammonia from hydrogen production by natural gas steam reforming. Siemens UK has an all-electric 'green ammonia' demonstration plant operating in Harwell, Oxfordshire, where electrolytic hydrogen

[40] Converted from Norwegian Krone at 1 NOK = 0.088 GBP

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

[42] https://matthey.com/markets/agrochemicals-and-fertilisers/ammonia

is converted into ammonia using an electrified thermochemical Haber-Bosch process powered only by renewable electricity.[43]

The UK has some R&D strengths in these technologies, with pockets of commercial activity outside of Johnson Matthey and strong fundamental science and technology research in related areas. Electrochemical production of ammonia is not yet commercialised, but leading research is being conducted by the University of Oxford and Siemens UK.[44] Other leading commercial research on this technology is being conducted by Bettergy, Molecule Works Inc., Giner and Ceramatec in the USA (TCG, 2018).[45]

D.4.2 Factor advantages

The UK is well positioned for technology supply despite it not being a volume producer. Countries with low-cost natural gas or shale gas will benefit from the use of these technologies to produce large quantities of ammonia. This has also resulted in a lack of actors in the UK that construct ammonia plants on this scale. However, the UK may be well placed for production of ammonia through renewable electricity, given its large on- and offshore wind potential.

The UK strength in these technologies is in part because of its well-developed catalyst supply chain, and this is supported by good levels of advanced scientific skills. The UK supply chain can support low- to mid-volume production, but, it will become less competitive at high volumes due to relatively high labour and other input costs. Additionally, the UK is putting efforts into developing skills in electrochemistry, currently focused on batteries,[46] but with transferable skills that could benefit electrochemical ammonia production.

D.4.3 Market advantages

Historically, the UK has strong market position in ammonia technology and the market has high barriers to entry. Despite this, the UK does not have many large-scale ammonia production plants and only contributes approximately 3% of global ammonia production.[47] These UK production facilities are not UK owned. The largest producers globally benefit from low natural gas prices and well-developed industrial capabilities (Centre for European Policy Studies, 2008).[48] Therefore, it is worth noting though that most of the growth in the technology market is outside of the UK and unhindered access to international markets is key to maintaining the UK's share of the global market.

Ammonia production is not supported specifically in the UK but there is indirect funding for research and innovation in science, which covers related areas.[49] Large industrial economies producing ammonia have strong incentives to increase competency in this technology and they will benefit from the opportunity to scale new technology quickly.

[43] http://www.energy.ox.ac.uk/wordpress/wp-content/uploads/2016/03/Green-Ammonia-Hughes-8.3.16.pdf

[44] http://www.energy.ox.ac.uk/wordpress/wp-content/uploads/2016/03/Green-Ammonia-Hughes-8.3.16.pdf

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

[46] Explained further in Annex H.

[47] Comtrade data.

[48] https://ec.europa.eu/docsroom/documents/4165/attachments/1/translations/en/renditions/pdf

[49] https://gow.epsrc.ukri.org

D.4.4 International competitors

China, India, Russia, the USA, Trinidad and Tobago, and Indonesia are the largest ammonia producers (by annual volume produced).[50] These countries all benefit from low-cost (fossil) feedstocks. In technology and IP, the UK's main competitors are Germany and the USA (TCG, 2018).[51] For direct ammonia production, the international competition is very early stage, but the USA, Japan and Germany have active players.

Overall, the UK is a global leader in producing technology for both the Haber-Bosch process and in the development of electrochemical ammonia production. This builds on its common strength in low-volume and high-value technology manufacture. However, the UK is not well placed for the construction of large-scale ammonia plants or the large-scale production of the fuel, due to high input costs (Centre for European Policy Studies, 2008).[52]

[50] https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2018/fertilizer-industry-handbook-2018.pdf/

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

[52] https://ec.europa.eu/docsroom/documents/4165/attachments/1/translations/en/renditions/pdf

ANNEX E BIO-LNG PRODUCTION TECHNOLOGIES

E.1 Introduction

This Annex applies the analysis framework set out in the Summary Report to Bio-LNG production technologies. Firstly, a brief description of Bio-LNG production technologies is provided, and the technologies are then assessed against the criteria for selection.

The subsequent sections present the supply chain for Bio-LNG production technologies, explore relevant firms' current contribution to the UK economy and present current levels of global deployment. UK competitiveness is then assessed.

This Annex has been prepared using a combination of desk research, expert knowledge and discussions with industry, which have been referenced within the text where appropriate.

E.1.1 Technology description

'Bio-LNG' is the (somewhat inaccurate) shorthand for liquefied methane from biological sources, also known as liquefied biomethane (LBM). However, the term LNG is widely understood in the shipping industry so Bio-LNG will be used here.

Bio-LNG can be produced from biological sources in the form of harvested biomass (for example trees, thinnings or forestry waste) or from the biological fraction of municipal solid waste (for example, food waste). Different conversion technologies are applicable, depending on the feedstock. For woody biomass or dry waste, gasification is most suitable, whereby the carbonaceous content is converted into carbon monoxide, hydrogen and carbon dioxide (known as syngas). This is achieved by reacting the material at high temperatures (>700 °C), without combustion (i.e. burning), with a controlled amount of oxygen and/or steam. A further methanation step converts the syngas into methane and carbon dioxide. Gasification can also be used for non-biological feedstocks such as coal or mixed wastes containing plastics, but these do not result in a low carbon fuel. Gasifiers are (typically) large-scale continuous processes which require accurate process control.

Figure 15 Plasma gasifier component

Source: AlterNRG[53]

[53] https://ecoandsustainable.com/2014/08/31/waste-to-energy/

For wet feedstocks such as waste water, animal or food waste, anaerobic digestion (AD) is more appropriate. AD is the breakdown of organic material by micro-organisms in the absence of oxygen to produce biogas, a methane-rich gas. This is then purified for use as methane fuel. AD plants comprise large sealed tanks operating at around 35°C on a batch production basis.

Figure 16 Farm-scale AD plant

Source: Farmers weekly[54]

Gaseous methane, produced via either gasification or AD, does not have high enough energy density (on a volume basis) to provide adequate range for most vessels. Methane becomes a liquid at -160ºC and so can be liquefied using a cryogenic expander which employs the cooling effect of gas expansion (Tybirk et al., 2018).[55] The resulting liquid has 600 times the volumetric energy density of uncompressed gas.[56] This Bio-LNG can then be transported from the point of production to the port for vessel fuelling, or temporarily stored in vacuum-insulated spheres. Note that, as there cannot be perfect insulation, Bio-LNG boils off from bulk storage at a rate of around 0.05-0.15%/day.[57] This boil-off could be used on the storage site for on-site energy use.

E.1.2 Justification for inclusion in technology shortlist

Familiarity with bulk LNG led the makers of LNG carriers several decades ago to develop LNG-fuelled engines which utilise the boil-off from the cargo. As environmental sensitivity has risen, so LNG has become a widely used fuel for vessels with frequent port visits, typically ferries and cruise liners (a quarter of new build cruise ships use LNG – (Maritime Executive, 2018).[58] Latterly, other areas of coastal shipping have turned to LNG in view of the tightening sulphur limits and lower cost of LNG compared to low sulphur gas oil (one ferry operator claims a 50% reduction in operating costs[59]). Bio-LNG extends the environmental benefits of LNG (which eliminates SO_x, particulates and 90% of NO_x in comparison with gasoil) to CO_2 reduction.

[54] https://www.fwi.co.uk/news/8m-farm-biogas-plant-powering-2500-homes-approved

[55] https://www.biogas2020.se/wp-content/uploads/2018/03/a-study-on-lbg-productionfinal.pdf

[56] Engineering toolbox, available from: https://www.engineeringtoolbox.com/fossil-fuels-energy-content-d_1298.html

[57] Peak shaving plant boil-off 0.05% http://www.unece.org/fileadmin/DAM/trans/doc/2011/wp29grpe/LNG_TF-02-06e.pdf, typical bulk LNG carrier rate 0.15% www.wartsila.com/encyclopedia/term/boil-off-rate-(bor)

[58] www.maritime-executive.com/blog/lng-to-become-the-fuel-of-choice-for-shipping

[59] BC Ferries cited in Reuters 2018 https://uk.reuters.com/article/us-gas-conference-shipping/marine-shipping-sector-eyes-lng-to-meet-clean-fuel-rules-idUKKBN1JO1FD

However, Bio-LNG faces challenges in terms of sustainable resource availability and cost. There is competition for feedstocks that do not interfere with food production and this can lead to high costs (ICCT, 2016).[60] Also, LNG (and Bio-LNG) requires specialist bunkering facilities at ports, which are not yet widespread and impose an upfront cost on port operators.

Three main potential sources of economic value to the UK were identified in the production of Bio-LNG:

- gasification technology;
- anaerobic digestion; and
- liquefaction.

Economic opportunities are judged to derive from the UK's potential to develop and export technologies related to fuel production. Further value may be derived from *operating* UK fuel production facilities, regardless of the source of technology. However, a strict view of value addition suggests that, as these activities would be displacing conventional refining, this is not additional value. This assessment of value therefore focusses on fuel production technologies.

E.2 Further detail on supply chain

Gasification and AD to produce Bio-LNG have their own component supply chains comprising, for example, high-temperature process equipment (for gasification); tanks, pumps, microbes and gas clean-up (for AD); and cryogenic expanders and storage vessels (for liquefaction).

Expert opinion was used to identify key actors in important parts of the related component supply chains in order to analyse significant strengths and weaknesses for the UK, where appropriate.

E.3 UK economic footprint and share of global export market

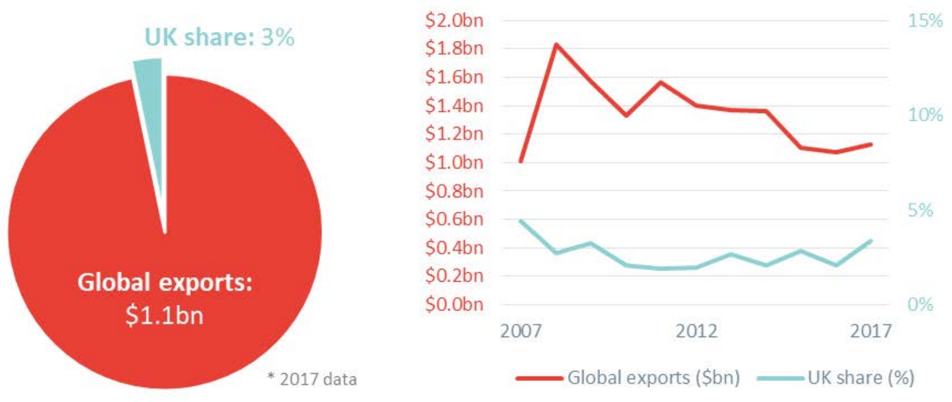
This section presents evidence on the estimated market shares of the UK for relevant sub-technologies using data from the United Nations International Trade Statistics Database (Comtrade). This provides information on the value of imports and exports by country-pair and product (UN, 2019). These results are presented below and described in the Summary Report. This section also discusses the key actors in the UK.

E.3.1 Global export market size and UK share of proxy markets

Figure 17 shows the export market for gasification technologies using the proxy of the HS6 codes 841940 (see Annex A). While the value of the global export market for gasification technologies has varied over the last 10 years, the UK share of the export market has mostly remained in the 2-4% range.

[60] https://www.theicct.org/sites/default/files/publications/ICCT_competing-uses-biomass_20160613.pdf

Figure 17 International trade: gasification technologies



Source: Comtrade, Frontier analysis

Figure 18 shows the export market for AD technologies using the proxy of the HS6 codes 841989 and 841990 (see Annex A). While the value of the global export market for AD technologies has seen several cycles over the last 10 years, the UK share of the export market has been fairly stable at around 2%.

Figure 18 International trade: anaerobic digestion technologies

Source: Comtrade, Frontier analysis

Figure 19 shows the export market for methane liquefaction technologies using the proxy of the HS6 codes 842139 (see Annex A). The value of the global export market for liquefaction technologies has seen fairly steady growth in the last 10 years, and the UK's share of this export market has also risen in the latter years from around 4% to 6%.

Figure 19 International trade: liquefaction technologies

Source: Comtrade, Frontier analysis

E.3.2 Key UK actors

Certain key actors in gasification and liquefaction technologies are outlined below; note that UK actors in AD were reviewed but none appeared to offer UK-developed systems, as explained below. The relevance of these companies to the UK economy and the technology is described. Also, the current activity or, in the absence of current activity, the readiness for activity in the technology is outlined.

Figure 20 Gasification technologies UK actors

Actor	Parent company	Relevance	Activity or readiness
Advanced Plasma Power Limited (APP)		APP claims to be the world leader in waste-to-energy and advanced fuels technology. APP has developed the Gasplasma advanced waste-to-energy and fuels technology (combination of gasification and plasma treatment).	APP's Gasplasma technology is modular and scalable. It generates a hydrogen-rich syngas, which can be used directly as a fuel in gas turbines to produce SNG which can be upgraded for injection into the grid, treated for use in fuel cells or converted into liquid fuels. APP demonstration project is in the UK. It has contracts for work in Europe and North America.
Velocys plc		Velocys, formerly Oxford Catalysts Group, has a partnership with TRI (a US process engineering firm) turning waste into drop-in transportation fuels.	Velocys has developed proprietary and commercially proven Fischer-Tropsch technology that can produce low carbon fuels from a variety of waste materials. Velocys is currently developing biorefineries in the UK and USA.

Actor	Parent company	Relevance	Activity or readiness
KEW Technology (KEW)		KEW is a technology company aiming to promote use of solid wastes for fuels. KEW operates small-scale plants as compact modular solutions.	Since 2014, KEW has been working with the Energy Technology Institute to demonstrate its technology

Source: Expert knowledge, company websites, company financial statements, UK Companies House

Figure 21 Liquefaction technologies UK actors

Actor	Parent company	Relevance	Activity or readiness
Cryo pur (not UK)		Cryo pur is a small developing business in France, with projects across the UK.	Cryo pur use a sub-brand called Cryo fuel which liquefy biogas into Bio-LNG & bio-CO_2.
Gasrec Ltd		Gasrec is a provider of the UK's natural gas and biogas refuelling infrastructure. Working closely with automotive Original Equipment Manufacturers (OEMs).	Gasrec can offer solutions for LNG and Compressed Natural Gas (CNG), based on tanker delivery design. Gasrec has new stations opening around the UK in 2019.

Source: Expert knowledge, company websites, company financial statements, UK Companies House

E.4 UK competitiveness

E.4.1 Technology advantages

Gasifiers

The UK features a number of developers seeking to gasify waste and biomass into methane or hydrogen. For example, Advanced Plasma Power has constructed a pilot-scale gasifier using its proprietary plasma gasification technology.[61] KEW Technology is also developing gasification plants using its own technology.[62] However, there remain challenges of scaling up gasification technology using biomass or waste feedstocks and there have been notable project failures, such as Air Products' Teesside gasifier, which was to be the largest waste-to-energy facility in the world (including some hydrogen production) but was never successfully commissioned (Waste Management World, 2016).[63] The UK's strengths in process engineering research are also highly relevant to gasification technology development.[64]

[61] Advanced Plasma Power, Launch of BioSNG Commercial Plant, Available from: https://advancedplasmapower.com/blog/latest-news/launch-gogreengas-biosng-pilot-plant/

[62] Kew technology, Our Technology, Available from: https://www.kew-tech.com/

[63] https://waste-management-world.com/a/air-products-to-ditch-plasma-gasification-waste-to-energy-plants-in-teesside

[64] UK Research Excellence Framework 2014. https://www.ref.ac.uk/2014/

AD

AD technology is widely deployed in the waste and water sectors, though there are few UK developers of systems and so this is imported or the processes licensed from other developers.[65] A review of the UK Anaerobic Digestion and Bioresources Association technology supplier database[66] lists 34 AD equipment or plant suppliers; however, only two of these appear to be UK-headquartered companies, with the majority supplying equipment from Germany, Austria and Denmark. On examining the two listed, they, like many others in the database, appear to be suppliers of components of AD systems. From this it can be concluded that the UK has a relevant supply chain for aspects of the AD supply chain but little activity in the integration and supply of systems.

Liquefaction

Within the UK there is substantial activity and capability from major oil companies such as Shell and BP and industrial gas companies such as BOC and Air Products, which are strong players in LNG and cryogenic technology. However, the LNG R&D efforts of these firms have largely migrated outside the UK (BOC is now part of German cryogenic technology leader Linde (Gasworld, 2006)[67] who announced a merger in 2018 with US firm Praxair). The UK is home to one specialist liquid biomethane company – Gasrec – which covers the full chain from landfill to vehicle refuelling.[68] It is also worth noting that the UK is a global leader in very low temperature cryogenics thanks to the scientific and satellite technology sectors which are clustered south of Oxford, typically employing liquid helium (-270°C) (Science & Technology Facilities Council, 2015).[69]

E.4.2 Factor advantages

As an island nation with a large population, the UK is faced with waste challenges, especially as it seeks to avoid the use of landfill (DEFRA, 2018, SEPA, n.d.).[70][71] UK sustainable woody biomass resources, though having potential to scale up (Whitaker, 2018),[72] are not on the same scale as the biomass resources in Scandinavia and North America – these being the most common sources of imports for biomass power projects, for example.

[65] Carbon Trust (2012), supported by E4tech, conducted a Technology Innovation Needs Assessment for UK bioenergy, finding that for AD 'the UK is assessed to have low medium competitive advantage as the majority of the UK's technology is imported from abroad' https://www.carbontrust.com/media/190038/tina-bioenergy-summary-report.pdf

[66] UK ADBA supplier database http://adbioresources.org/member-directory/category/ad-equipment-or-plant-supplier/anaerobic-digester-system-suppliers

[67] https://www.gasworld.com/linde-/-boc-merger-complete/1018.article

[68] Gasrec, Available from: https://www.gasrec.co.uk/solutions-your-company/

[69] https://stfc.ukri.org/files/cryogenics-impact-summary-report/

[70] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/765914/resources-waste-strategy-dec-2018.pdf

[71] https://www.sepa.org.uk/regulations/waste/landfill/biodegradable-municipal-waste-landfill-ban/

[72] https://www.theccc.org.uk/publication/steps-to-scaling-up-uk-sustainable-bioenergy-supply-ceh/

E.4.3 Market advantages

The UK offers a generally supportive environment for biogas production with the Renewable Heat Incentive (RHI) available to biomethane injected into the gas grid (Ofgem, 2018)[73] and incentives under the Renewable Transport Fuel Obligation (RTFO) available if biomethane from AD or gasification is used in the road transport sector (UK Government, 2018).[74] Hydrogen produced from biomass via gasification would also be eligible for support under the RTFO, although none has been supplied to date (DfT, 2018).[75]

E.4.4 International competitors

Gasification

Large-scale capital-intensive R&D favours large industrial economies, and China, the USA and Germany are all strong players in gasification technology.[76] These players are well positioned to pivot towards biomass gasification given the right signals. Indeed, the majority of biomass gasification plants currently operational or planned are in the EU, USA, China, Japan and Canada.[77] Access to feedstock makes biomass gasification particularly attractive in forested countries such as Austria, Sweden and Canada.

AD

A strong incentive programme in the last decade led Germany to develop a large biogas sector with widespread activities in technology and project development (Lehuhn et al., 2014).[78] The USA and China are also strong players in AD technology and some UK plants are developed through a Chinese joint venture.

Liquefaction

Conventional large-scale LNG technology is led by Germany and the USA. The UK's technology position in cryogenic gas technology is a sound base to build upon, but with only one Bio-LNG developer there is only modest application so far. LNG vehicle development is emerging in continental Europe led by Iveco, Volvo, Scania and Mercedes.[79]

Overall, the UK has a good research and early-stage technology position in biomass gasifiers and gas liquefaction, but only modest size companies working in these areas and none with a marine focus. The AD sector in the UK is very active but employing non-UK technology since the UK's position is behind the leading players.

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[73] https://www.ofgem.gov.uk/system/files/docs/2019/01/guidance_volume_1_oct_2018.pdf

[74] https://www.gov.uk/government/publications/renewable-transport-fuel-obligation-rtfo-guidance-year-11

[75] https://www.gov.uk/government/statistics/biofuel-statistics-year-10-2017-to-2018-report-4

[76] Global Syngas Technologies Council, The Gasification Industry, Available from: https://www.globalsyngas.org/resources/the-gasification-industry/

[77] E4tech confidential internal database of advanced biofuel plants. Includes plants gasifying biomass and municipal waste.

[78] https://core.ac.uk/download/pdf/81860626.pdf

[79] https://www.broadviewenergysolutions.com/lng-distribution/lng-road-transport/

ANNEX F LOW CARBON SHORE POWER TECHNOLOGIES

F.1 Introduction

This Annex applies the analysis framework set out in the Summary Report to low carbon shore power technologies. Firstly, a brief description of low carbon shore power technologies is provided, and the technologies are then assessed against the criteria for selection.

The subsequent sections present the supply chain for low carbon shore power technologies, explore relevant firms' current contribution to the UK economy and present current levels of global deployment. UK competitiveness is then assessed.

This Annex has been prepared using a combination of desk research, expert knowledge and discussions with industry, which have been referenced within the text where appropriate.

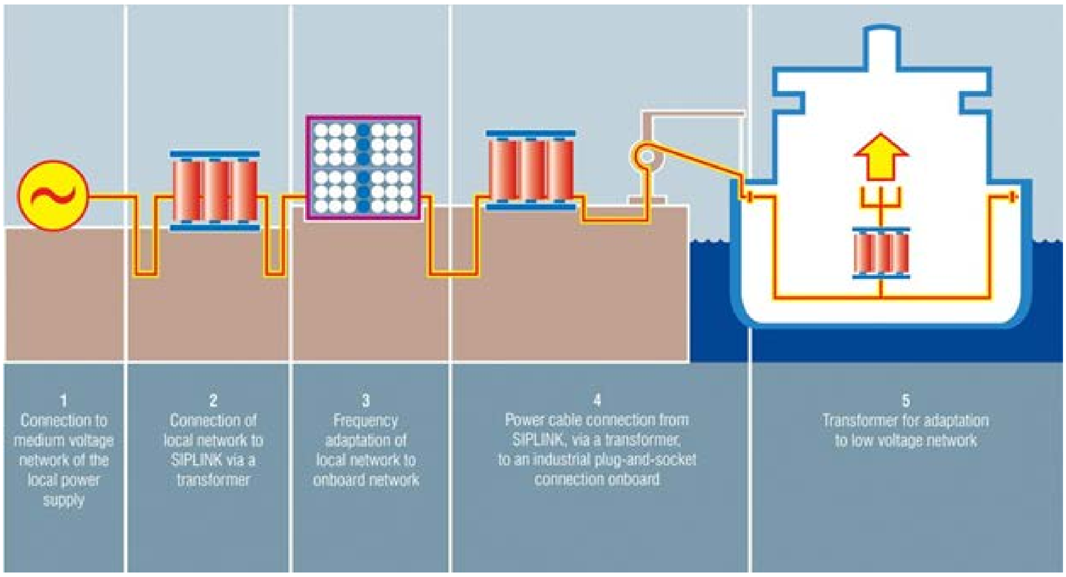
F.1.1 Technology description

Low carbon shore power encompasses a wide range of component technologies which enable vessels to avoid use of their engines in port to run onboard generators. This is known as alternative marine power or cold ironing. Also, for any vessels that move to battery power, then such connections will be essential for recharging.

The offboard technologies include substations, switchgear and power connections. Further upstream there may also be power network reinforcement or local generation if the port is in a poorly connected location. Onboard the vessel there is a cable reel, connection boxes, switchgear, transformer and control panel. The connections can be sizeable – a large container ship requires around 3.4 megawatt (MW) to operate its ancillary loads, a large cruise liner 13MW (Massachusetts Port, 2016).[80] (equivalent to approximately 3,400 and 13,000 houses respectively at average load).

[80] https://docplayer.net/48064776-Massport-shore-to-ship-power-study-august-5-2016.html

Figure 22 Low carbon shore power process



Source: Siemens[81]

F.1.2 Justification for inclusion in technology shortlist

Low carbon shore power was initially demanded of the cruise industry as a condition for operating in sensitive marine environments, such as the Arctic, in the early 2000s. Now it is being widely adopted by larger ports in the USA, Europe and Asia. Vessel makers are fitting the relevant onboard equipment to new vessels but retrofit is not always straightforward or economic (Massachusetts Port, 2016).[82]

The benefits of avoiding use of engines in port are the obvious reduction in pollution and CO_2. There is also a noise benefit, especially important for ports that are close to city centres.

Low carbon shore power is not without challenges though:[83]

- The onboard equipment is expensive, and the benefits do not accrue to the ship owner or operator.
- The charges for shore power can be high in order to recoup investment costs, which does not compete well with untaxed fuel-fired generation.
- The cost of offboard equipment and network upgrades mean that ports can be reluctant to invest. This is aggravated by the competitive aspect of shipping, meaning that ports which allow operators to continue to use (lower-cost) engine generation could win business from those that mandate cold ironing.
- Ports in different countries supply different voltages and frequencies, yet ships are designed for one system (UK EU ships are 50Hz, US ships are 60Hz). This difference imposes additional cost to convert onboard.

Economic opportunities are judged to derive from the UK's potential to develop and export technologies related to providing connections for vessels in port and technologies for the vessels themselves to be able to connect. Further value may

[81] www.portstrategy.com/news101/products-and-services/siemens_powers_down_with_145cold_ironing146
[82] https://docplayer.net/48064776-Massport-shore-to-ship-power-study-august-5-2016.html
[83] Expert consultation with UMAS.

be derived from generating low carbon electricity, but this is a wider energy system activity, so this is not the focus of this assessment.

F.2 Further detail on supply chain

Shore power technology has its own component supply chain, which mainly comprises electrical system components and some related hardware such as cable reels and cabinets (Marine Insight, 2018).[84]

Expert opinion was used to identify key actors in important parts of the related component supply chains in order to identify significant strengths and weaknesses for the UK, where appropriate.

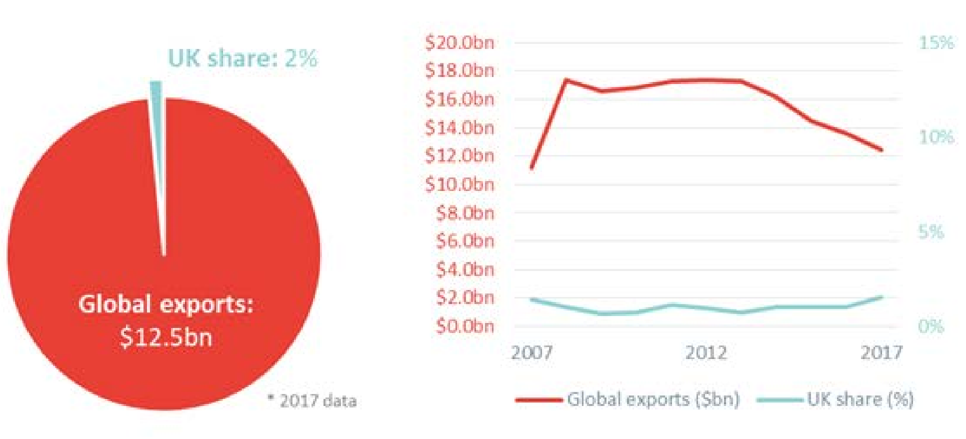
F.3 UK economic footprint and share of global export market

This section presents evidence on the estimated market shares of the UK for relevant sub-technologies using data from the United Nations International Trade Statistics Database (Comtrade). This provides information on the value of imports and exports by country-pair and product (UN, 2019). These results are presented below and described in the Summary Report. This section also discusses the key actors in the UK.

F.3.1 Global export market size and UK share of proxy markets

Figure 23 shows the export market for shore power technologies using the proxy of the HS6 codes 850410, 850421, 850422, 850423, 850432, 850433, 850434 and 853521 (see Annex A). While the value of the global export market for shore power-type technologies has fluctuated over the last 10 years, the UK share of export market has been relatively constant at 1-2%.

Figure 23 International trade: low carbon shore power technologies



Source: Comtrade, Frontier analysis

[84] https://www.marineinsight.com/marine-electrical/what-is-alternate-marine-power-amp-or-cold-ironing/

F.3.2 Key actors in the UK

Key actors in local distribution networks and connector technologies are outlined below. The relevance of these companies to the UK economy and the technology is described. Also, the current activity or, in the absence of current activity, the readiness for activity in the technology is outlined.

Figure 24 Local distribution network UK players

Actor	Parent company	Relevance	Activity or readiness
ABB Limited (ABB)	ABB Group	ABB limited is the UK arm of ABB group, a large global corporate which works as a technology developer with utilities, industry, infrastructure and transportation customers. With a particular interest in sustainable mobility, ABB delivers automotive electric vehicle charging solutions. ABB UK reported a near £700m revenue for 2017.	ABB is involved in products, systems and services across high, medium and low voltage product ranges, with switchgear and transformers. 'ABB Ability' is a pioneer in shore power solutions, and small port integration systems. It demonstrated electrification of ships by shore power for Stena Line in Norway in 2018.
Balfour Beatty plc (BB)		Large UK and international infrastructure group with sectors in power and energy and transportation. It has a reported £1bn revenue for the support services sector, which includes power and distribution among other infrastructure businesses.	BB provides technical engineering solutions to regional, national and international electricity networks. Its experience and expertise cover the whole electricity grid, including overhead lines, cable tunnels and distribution networks.
Cavotec UK		Cavotec, with a UK presence, is a global company committed to minimising environmental impact through innovative technology. It provides connection solutions for ships, aircraft and mobile equipment.	An engineering group which can design and manufacture automated connection and electrification systems for ports, including crane electrification and shore power solutions for both onboard and offboard (dockside).

Actor	Parent company	Relevance	Activity or readiness
Schneider Electric UK	Schneider Electric SE	The UK operation is part of the larger Schneider Electric group. 27% of business is done in western Europe. 18% of revenue is attributed to the medium voltage sector. Schneider also has a marine sector with a suite of products under the EcoStruxure sub-brand.	The medium voltage sector sells products associated with power distribution and grid automation, prefabricated substations, switchgear and transformers. Schneider also manufactures and sells onboard shore power solutions as prefabricated units to connect the vessel to the grid (ShoreBoX).[85]
Siemens plc	Siemens AG	Large global engineering and manufacturing company. It has 62 UK-based subsidiaries. Siemens generated revenue of €83.0bn. The company employs 42,782 in Europe (25% Germany, 75% rest of Europe).	Siemens is actively selling products over high, medium and low voltage ranges, with substations, transmission systems, transformers, switchgear and power transmission lines. It also sells services relating to smart grids and energy automation.
Wilson Power Solutions Ltd.	Wilson Power Solutions Group Ltd.	An independent transformer manufacturer in the UK, engineering power distribution solutions for major UK organisations. It has a revenue of £15m, of which all is applicable to the technology.	Able to design, manufacture and supply a range of distribution transformers for application such as step-down distribution transformers, step-up generation transformers, wind farm transformers, solar photovoltaic farm transformers.
Morrison Utility Connections (MUC)	M Group Services Limited	Part of a group of businesses in the UK with 8,000 employees and £1bn revenue, Morrison Utility Connections is one of the largest ICP[86] operators in the UK, able to build electricity networks to agreed standards and quality required for them to be owned by a Distribution Network Operator (DNO).	MUC has expertise in delivering complete electrical infrastructure projects with ranges from 11kV through to 132kV for both DNO adoptable and Private Wire Network projects.

[85] https://www.schneider-electric.com/en/product-range-presentation/61396-shorebox/

[86] Accredited company that can build electricity networks. Source: https://www.enwl.co.uk/get-connected/competition-in-connections/information-for-customers/what-is-an-icp/

Actor	Parent company	Relevance	Activity or readiness
Mott MacDonald (MM)	Mott MacDonald Group Ltd	MM is a global engineering, management and development consultancy, focused on 'making a sustainable difference'. MM offers a range of services to deliver the development of modern and efficient port and harbour facilities	MM is not known for electrical infrastructure projects related to maritime or ports, but with their experience in engineering and construction, they could be capable of entering the market.
PBSI Group Ltd. (PBSI)		Small UK design innovator with manufacturing centre in Manchester, supporting major utilities suppliers, generators, industrial clients, OEMs,[87] consultants, EPCs[88] and wholesalers globally with medium voltage switchgear and relays. £6m revenue.	Operating with a global network of distributors and other partners, PBSI supports a broad range of clients in multiple sectors, including oil and gas, power generation and renewables.
Winder Power Limited (WP)	Winder Power Group Limited	WP –operational for over 100 years – is a leading UK manufacturer of power and distribution transformers and generator equipment, specialising in design, build and deployment of power transformers and distribution transformers up to 60MVA.[89]	WP provides a total in-house project management solution, bespoke transformer design, manufacturing production, site installation and commissioning. WP focuses on transformer products and encompasses all application areas and sizes.

Source: Expert knowledge, company websites, company financial statements, UK Companies House

Figure 25 Onboard and offboard connections UK actors

Wärtsilä UK Ltd.	Wärtsilä Oyj Abp	Although not UK based, Wärtsilä, has a UK presence, and has acquired several UK marine sector players, e.g. Hamworthy. Wärtsilä is a global leader in smart technologies and complete lifecycle solutions for the marine and energy markets.	Wärtsilä offers a product called SAMCon, a mobile high voltage shore connection for onboard connection the grid.

Source: Expert knowledge, company websites, company financial statements, UK Companies House

[87] Original Equipment Manufacturers are companies that make products from components parts supplied from other companies.

[88] EPCs refers to companies that conduct engineering, procurement and construction services.

[89] Mega Volt Amp (MVA) is a measure of apparent power taking into account resistive and reactive load.

F.4 UK competitiveness

F.4.1 Technology advantages

The UK has a diverse electrotechnical[90] sector comprising many branches of global groups as well as smaller firms. However, few large firms are headquartered in the UK and UK R&D spend in the category is less than 1% of all corporate R&D (Engineering UK, 2017).[91] Although UK electrical engineering research capability is fairly strong,[92] there does not appear to be widespread activity to support development of the relevant technologies. This is perhaps because the component technologies are relatively mature and so the opportunity lies mainly in systems integration (not typically a research-intensive activity).

F.4.2 Factor advantages

The UK industry has hollowed out to a large extent, losing ground to lower-cost locations which are better suited to manufacture of commodity and semi-commodity items.

The UK's position in the wind energy supply chain is a bright spot, notably offshore,[93] [94] offering the potential for UK installers to create wind generation-fed connections at ports.

F.4.3 Market advantages

UK vessel manufacturing remains a strength, but it is largely oriented towards naval, specialist and luxury vessels (UK Marine Industries Alliance, 2014).[95] for which shore power is less of a requirement. The UK has many ports, and where cold ironing is best suited depends on the characteristics of the ports and the policy incentives available.

F.4.4 International competitors

The UK electrotechnical industry faces stiff competition from China, Germany, Mexico and the USA, which are leading exporters.[96] More generally, nations which have large industrial sectors create strong pull-through for electrical engineering and those with low costs are at an advantage for products with limited innovation potential.

Overall, the UK's position for innovation and supply of onboard and offboard equipment is modest, with the exception of wind power connection.

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[90] The study or science of practical and industrial applications of electricity.

[91] https://www.engineeringuk.com/media/1355/enguk-report-2017.pdf

[92] UK Research Excellence Framework 2014. https://www.ref.ac.uk/2014/

[93] UK leads offshore wind deployment https://www.renewableuk.com/news/430793/Record-breaking-amount-of-new-UK-offshore-wind-capacity-installed-in-2018-.htm

[94] UK offshore wind supply chain expanding rapidly https://www.themanufacturer.com/articles/supply-chain-opportunities-in-offshore-wind-power/

[95] https://www.maritimeindustries.org/CoreCode/Admin/ContentManagement/MediaHub/Assets/FileDownload.ashx?fid=121380&pid=12853&loc=en-GB&fd=False

[96] Comtrade data.

ANNEX G ONBOARD HYDROGEN TECHNOLOGY

G.1 Introduction

This Annex applies the analysis framework set out in the Summary Report to onboard hydrogen technologies. Firstly, a brief description of onboard hydrogen technologies is provided, and the technologies are then assessed against the criteria for selection.

The subsequent sections present the supply chain for onboard hydrogen technologies, explore relevant firms' current contribution to the UK economy and present current levels of global deployment. UK competitiveness is then assessed and future opportunities within the global market for onboard hydrogen technologies are considered.

This Annex has been prepared using a combination of desk research, expert knowledge and discussions with industry, which have been referenced within the text where appropriate.

G.1.1 Technology description

Hydrogen fuel requires specialist equipment if it is to be on a vessel. The important technologies for this are:

- hydrogen storage – specific materials and design are needed for hydrogen; and
- fuel cells – electrochemical conversion of hydrogen to electricity for electric propulsion.

G.1.2 Justification for inclusion in technology shortlist

Hydrogen storage and fuel cells were deemed to provide additional value as they were identified as the novel equipment needed on board a vessel.

Economic opportunities are judged to derive from the UK's potential to develop and export technologies related to onboard storage or fuel cells. The value of producing hydrogen is dealt with elsewhere.

G.2 Further detail on supply chain

Both hydrogen storage and fuel cells have their own component supply chains comprising high strength materials, valves and piping (for storage); and membranes, catalysts, precision stampings, pumps, electronic controls (for fuel cells).

Expert opinion was used to identify key actors in important parts of the related component supply chains in order to analyse significant strengths and weaknesses for the UK, where appropriate.

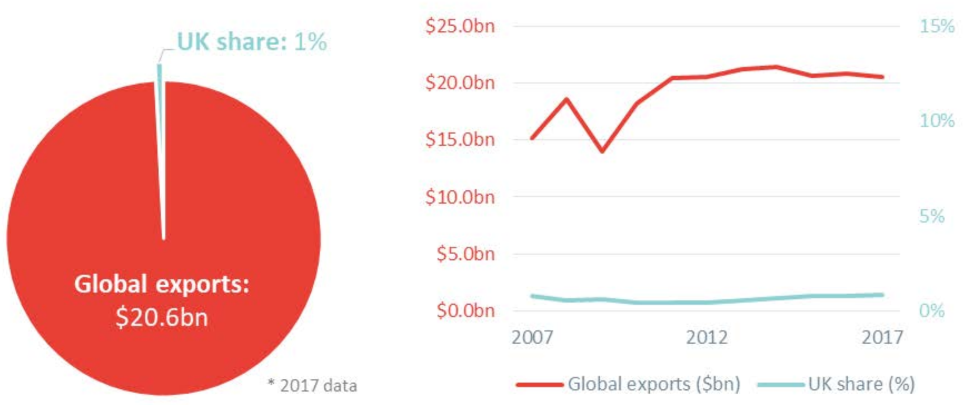
G.3 UK economic footprint and share of global export market

This section presents evidence on the estimated market shares of the UK for relevant sub-technologies using data from the United Nations International Trade Statistics Database (Comtrade). This provides information on the value of imports and exports by country-pair and product (UN, 2019). These results are presented below and described in the Summary Report. This section also discusses the key actors in the UK.

G.3.1 Global export market size and UK share

Figure 26 shows the export market for hydrogen storage technologies using the proxy of the HS6 codes 841869 and 841430 (see Annex A). While the value of the global export market for hydrogen storage has seen an upward trend with some fluctuation over the last 10 years, the UK's share of the export market has stayed close to 1% over the period.

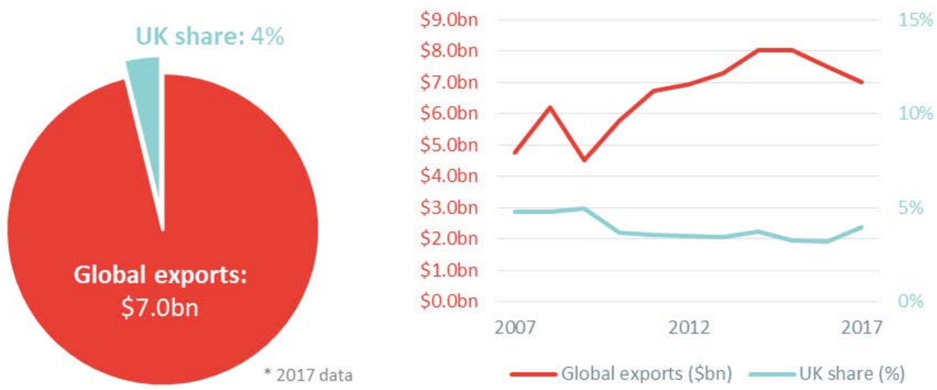
Figure 26 International trade: hydrogen storage technologies



Source: Comtrade, Frontier analysis

Figure 27 shows the export market for fuel cell technologies using the proxy of the HS6 codes 850161 and 850720 (see Annex A). The value of the global export market for fuel cell technologies has pursued a similar path to hydrogen storage over the period, though at absolute values less than half those of storage. Over the same period, the UK's share of global trade has generally declined from around 5% to 3-4%.

Figure 27 International trade: fuel cell technologies



Source: Comtrade, Frontier analysis

G.3.2 Key UK actors

Key actors in hydrogen storage and fuel cell technologies are outlined below. The relevance of these companies to the UK economy and the technology is described. Also, the current activity or, in the absence of current activity, the readiness for activity in the technology is outlined.

Figure 28 Hydrogen storage UK actors

Actor	Parent company	Relevance	Activity or readiness
Air Products plc	Air Products and Chemicals, Inc	Air Products is a world leader in industrial gases, with 75 years' experience. The world leader of LNG process technology and equipment. Very experienced in hydrogen handling.	Air Products has capabilities in gas production, storage and handling equipment and heat exchangers.
BOC	Linde Group	BOC, part of the Linde Group, is the largest UK provider of industrial gases, along with other applications.	BOC distributes gases in cylinders with a range of pressures and sizes, including bulk cryogenic storage vessels particularly for LNG applications.

Actor	Parent company	Relevance	Activity or readiness
CALVERA Hydrogen	Calvera Group	Calvera is a Spanish company, currently headquartered in the UK. Calvera manufactures transport and storage equipment for compressed gas, namely hydrogen and (bio) compressed natural gas.	Working directly with products for hydrogen and biogas, it does not manufacture any specific model of cylinders, but instead designs bespoke solutions for each project. Calvera has wide experience as a partner of innovation projects across a range of fuels.
Chesterfield Special Cylinders (CSC)	Pressure Technologies plc	CSC is an operating subsidiary of Pressure Technologies plc, which designs, manufactures and tests cylinders of volumes up to 3000L and 600bar.	CSC has an extensive list of products for gas containment for multiple applications including naval system, and high-pressure storage vessels for transport of CNG, and hydrogen.
Hexcel Composites	Hexcel Corporation	Hexcel is a leading producer of carbon fibre reinforcements and resin systems, and the world leader in honeycomb manufacturing for the commercial aerospace industry, but is included for consideration for its hydrogen storage development activities. A global business, Hexcel composites is based in the UK, and operates in automotive and marine sectors for composites in general.	Hexcel is working in high-pressure onboard hydrogen storage solutions for the automotive industry, and there is potential to scale up to larger tank designs. This expertise is also combined with knowledge of the marine composites industry.
Luxfer Gas Cylinders	Luxfer Group	Luxfer Gas Cylinders is the world's largest manufacturer of high-pressure aluminium and composite gas cylinders for a wide and growing variety of applications including alternative fuels, industry and aerospace. Luxfer has facilities in the UK, the USA, France, Canada, China and India, with over 50 million cylinders in use.	Luxfer traditionally manufactures smaller storage vessels but has strong IP in design, including high-pressure cylinders.

Source: Expert knowledge, company websites, company financial statements, UK Companies House

Figure 29 Fuel cell UK actors

Actor	Parent company	Relevance	Activity or readiness
AFC Energy		AFC Energy is one of two key players in the alkaline fuel cell technology (the other is GenCell based in Israel). The company is in development and aiming to reach commercialisation of its stationary high-power fuel cell product line.	The AFC technology is still under development and AFC Energy is mainly involved in demonstration projects rather than commercial sales. These projects are mainly stationary with 10kW stacks to create up 1MW systems. AFC technology could be used in a maritime application.
Alstom Transport UK Limited	Alstom SA	With a presence in the UK, Alstom transport focuses on rail and rolling stock. Part of a group with revenues of €7bn. Of this, the UK transport section reported £300m revenue due to high investment of the UK government in the rail infrastructure. Alstom is involved with fuel cell system integration into vehicles, namely trains in Germany.	In 2018, Alstom demonstrated a pioneering fuel cell train project first conceptualised in 2016. Two trains are in regular service. Although developed in Germany and France, the UK arm of the company will benefit from the technology demonstration. There are options to develop the technology for other applications.
Ceimig Limited	Ames Goldsmith UK Limited	Ciemig is a small part of a wider chemical and valuable material production company – Ames Goldsmith. It is a team of catalyst and chemical experts that produces platinum and iridium for fuel cells. Ciemig turns over £0.5m and the wider group £50m.	Ceimig produces high surface area materials for PEM fuel cells. It currently offers cathode and anode catalysts, but also provides custom services for various applications.
Ceres Power plc		Ceres power is a UK-based company with unique low temperature solid oxide technology for stationary power and transport applications. Offices in Japan and Korea. £7m revenue in 2018, up 71% on 2017. Order book of £30m for 2018/19.	Ceres is currently selling into the stationary and vehicle range extender markets but has potential for growth with strong IP. New manufacturing facility to be opening with 2MW capacity in the UK 2019. Ceres attracted investment from Bosch on a joint venture with others including Weichai, Honda and Nissan.

Actor	Parent company	Relevance	Activity or readiness
Intelligent Energy (IE)	Meditor Energy	UK company engineering and developing proton-exchange membrane fuel cell (PEMFC) technology, with 30 years' experience operating in unmanned aerial vehicle (UAV), stationary and automotive markets. The company was bought by a UK investment group for £20m in 2017.	IE has proprietary air cooled fuel cells for smaller applications in UAVs and stationary power. Larger applications for automotive are available up to 100kW. Either series installations or technology scale-up would be required for marine applications.
Johnson Matthey Fuel Cells Limited (JM Fuel Cells)	Johnson Matthey plc	Large global science and technology firm with a vision for sustainable energy. JM Fuel Cells is a dedicated global business for supply of fuel cell components. Fuel cells achieved £24m revenue and employed 180 in 2018 across 6 locations worldwide.	JM Fuel Cells actively sells MEA (membrane electrode assemblies) and is well regarded for its catalyst for fuel cells expertise for a range of applications. JM sells these fuel cell catalysts under the brand HiSPEC.

Source: Expert knowledge, company websites, company financial statements, UK Companies House

G.4 UK competitiveness

G.4.1 Technology advantages

While it does not have dominant fuel cell technology companies, the UK is a significant player in the high-value markets (Carbon Trust, 2014).[97] It is also a leader in some key parts of the supply chain, such as catalyst and membrane production, where the UK's Johnson Matthey is a leading global actor in these components. UK fuel cell manufacturers have some leading IP, for example in low temperature solid oxide fuel cells (Ceres power). For hydrogen storage, the UK has early-stage firms in the supply chain such as carbon fibre, and also for novel storage solutions such as solid state hydrides (Carbon Trust, 2014).[98]

The UK's supply chain strength is supported by a strong materials and electrochemistry R&D environment in the UK. Although the electrochemistry research is mainly focused on battery development, the skills and research base is internationally strong.[99]

G.4.2 Factor advantages

The UK has a good supply chain for low-to-medium volumes but may be less competitive at producing fuel cells and storage technologies at high volumes due to high input costs. Other countries such as China and Japan have large-scale

[97] www.carbontrust.com/media/593904/h2-for-transport-summary-report.pdf

[98] www.carbontrust.com/media/593904/h2-for-transport-summary-report.pdf

[99] UK Research Excellence Framework 2014. https://www.ref.ac.uk/2014/

electrochemical production capabilities and industrial experience to scale up to high volumes.

While the UK has some specialist fuel cell companies, these are mainly SMEs created out of research institutions (e.g. Ceres Power from Imperial College and Intelligent Energy from Loughborough University). Scaling-up has been a common challenge for UK technology companies as they seek to cross the ‘chasm of commercialisation’, whereas several competitor countries benefit from deeper and longer-term pools of funding (e.g. USA, China) (Hauser, 2016).[100]

G.4.3 Market advantages

The UK has a small domestic market for fuel cells and hydrogen storage, and therefore has not developed diverse domestic supply chains at scale. Instead, large global organisations with links to global markets have prevailed within the supply chain. This may present high barriers for entry for earlier-stage companies.

There is no specific policy support for either hydrogen storage or fuel cells. However, the UK offers a generally supportive environment for clean technology innovation, through overarching policy direction such as the Industrial Strategy.[101]

G.4.4 International competitors

Japan, China and Korea have very supportive environments for hydrogen technologies, created by their pro-hydrogen energy policies and their strength in technology development. Japan and Korea have both been driving fuel cell and storage development through their automotive OEMs, whereas China has (for now) been acquiring non-domestic technology to integrate into vehicles. The USA and Germany are also key competitors in fuel cell technology, with good IP and R&D environments (E4tech, 2018).[102]

Overall, the opportunity for the UK is in the high-value components of fuel cell supply chain (catalysts and membranes) and the commercialisation of more novel hydrogen storage technologies, such as metal hydrides.

[100] https://catapult.org.uk/wp-content/uploads/2016/04/Hauser-Review-of-the-Catapult-network-2014.pdf

[101] UK Industrial Strategy https://www.gov.uk/government/topical-events/the-uks-industrial-strategy

[102] http://www.fuelcellindustryreview.com/

ANNEX H ONBOARD BATTERIES

H.1 Introduction

This Annex applies the analysis framework set out in the Summary Report to onboard battery technologies. Firstly, a brief description of onboard battery technologies is provided and the technologies are then assessed against the criteria for selection.

The subsequent sections present the supply chain for onboard battery technologies, explore relevant firms' current contribution to the UK economy and present current levels of global deployment. UK competitiveness is then assessed and future opportunities within the global market for onboard hydrogen technologies are considered.

This Annex has been prepared using a combination of desk research, expert knowledge and discussions with industry, which have been referenced within the text where appropriate.

H.1.1 Technology description

Batteries, or more precisely secondary (i.e. rechargeable) batteries, that could be used in marine applications are likely to be from the lithium-ion technology family. This technology was conceived in the 1970s but the breakthrough came in the 1980s at Oxford University, though the first commercial production was in 1991 in Japan.[103]

A lithium-ion cell comprises positive and negative electrodes and an electrolyte between. Generally, the negative electrode of a conventional lithium-ion cell is made from carbon, the positive electrode is a metal oxide and the electrolyte is a lithium salt in an organic solvent. The electrochemical roles of the electrodes reverse between anode and cathode, depending on the direction of current flow through the cell (charging or discharging).[104]

Battery cells are combined into groups to form modules which, in combination with an electronic battery management system, are multiplied up to form a battery pack. A pack may comprise thousands of cells in a car, many more in a vessel.

Technology improvements focus on increasing energy density and power density per unit of weight and/or volume, improving lifetime and maintaining safety, while reducing cost.

H.1.2 Justification for inclusion in technology shortlist

Lithium-ion batteries are widely established for portable and mobile devices including vehicles. Battery technology is also being applied to a limited extent in rail and marine applications with niches being the entry point.

[103] https://phys.org/news/2015-04-history-batteries.html and http://jes.ecsdl.org/content/164/1/A5019.full

[104] Expert input but described in detail at https://www.energy.gov/eere/articles/how-does-lithium-ion-battery-work

Aside from small electric launches and leisure craft, only a handful of larger vessels have adopted 100% battery power for short-distance defined routes (e.g. ferries) (DNV GL, 2018).[105, 106]

More likely, however, are hybrid applications where the duty cycle matches the ability of batteries to provide either low power drive (e.g. tugs or support vessels in stand-off mode), or additional peak power for short bursts, or even stealth operation (e.g. submarines). The hybrid power could come from a reciprocating engine, gas turbine or fuel cell and – as more electric architectures increase – batteries may 'hang off' an electric network to provide drive or standby power where use of fuel is not desirable.

Figure 30 Electric ferry example

Source: Siemens[107]

Economic opportunities are judged to derive from the UK's potential to develop and export technologies related to battery cells and packs for vessels, which is the focus of this assessment.

H.2 Further detail on supply chain

In the marine context, batteries are linked to low carbon shore power, electric propulsion and, potentially, to other electrical technologies such as fuel cells (or different low carbon power generators).

Batteries have their own component supply chain. Expert opinion was used to identify key actors in important parts of the related component supply chains in order to identify significant strengths and weaknesses for the UK, where appropriate.

H.3 UK economic footprint and share of global export proxy market

This section presents evidence on the estimated market shares of the UK for relevant sub-technologies using data from the United Nations International Trade Statistics Database (Comtrade). This provides information on the value of imports

105 https://www.dnvgl.com/maritime/publications/alternative-fuel-assessment-download.html

106 https://conferences.ncl.ac.uk/media/sites/conferencewebsites/scc2016/1.4.2.pdf

107 https://www.siemens.com/innovation/en/home/pictures-of-the-future/mobility-and-motors/electromobility-electric-ferries.html

and exports by country-pair and product (UN, 2019). These results are presented below and described in the Summary Report. This section also discusses the key actors in the UK.

H.3.1 Global export proxy market size

Figure 31 shows the export market for battery technologies using the proxy of the HS6 codes 850750 and 850760 (see Annex A). The value of the global export market for battery technologies has grown sharply in a manner that suggests that the category may not have been measured before 2011. Despite this, however, the UK share of export market is no more than 1%.

Figure 31 International trade: battery technologies

Source: Comtrade, Frontier analysis

H.3.2 Key actors

Key actors in onboard battery technologies are outlined below. The relevance of these companies to the UK economy and the technology is described. Also, the current activity or, in the absence of current activity, the readiness for activity in the technology is outlined.

Figure 32 Onboard batteries UK actors

Actor	Parent company	Relevance	Activity or readiness
Accutronics Ltd	Ultralife	UK-based SME Accutronics is a battery design, development and manufacturing company for high-performance portable and handheld electronic devices.	Although Accutronics works with smaller applications such as portable electronics, it also has completed projects for large power systems e.g. gensets

Actor	Parent company	Relevance	Activity or readiness
Automotive Energy Supply Corporation (AESC)	Envision	AESC was set up by Nissan Motor Co. to provide battery packs for the Nissan Leaf in the USA and UK. It was recently sold to Envision, a Chinese energy company. AESC has been making cells and battery packs and carries huge expertise in the sector.	Battery production line capable of scaling up to meet demand for major automotive OEMs.
AGM Batteries Ltd		AGM is an SME in Scotland that develops and manufactures advanced lithium battery cells and provides a manufacturing service for client companies, producing cells on their behalf. Operating mainly in the UK but working with international OEMs on research projects.	AGM has the flexibility to manufacture a broad range of chemistries and cell types in pouch or cylindrical formats for clients under sub-contract or as a licensee, and therefore could adopt to a new application.
Cummins UK	Cummins	A US corporation with manufacturing and distribution in the UK. Cummins designs and manufactures medium to large diesel and alternative fuel engines, electrical gensets and related components. In 2018 Cummins UK purchased the battery pack business of Johnson Matthey.	Cummins is targeting the role of leading provider of electrified power in commercial and industrial markets. Its Battery Electric Vehicle system for buses launches in 2019, followed by its Range Extended Electric Vehicle for Buses system in 2020. With a large engine focus, a shift to marine applications is possible.
Denchi Power Ltd		Denchi Power Ltd is a leading supplier and manufacturer of batteries and chargers to the global defence industry. Co-located with AGM Batteries Ltd.	Denchi power has standard products but most of its business is focused on bespoke battery and cell design.
Ilika plc		Ilika is a small UK technology company looking to develop solid state battery technology. Its core abilities are in combinatorial chemistry.	Ilika has proven battery designs in small applications, e.g. medial implants and sensors, and is scaling up by extending its roadmap to develop larger format cells suitable for providing automotive power.

Actor	Parent company	Relevance	Activity or readiness
McLaren Applied Technologies (MAT)	McLaren Group	The research and development arm of the McLaren group and F1 team, MAT works on innovation and sectors undergoing disruption. Public transport and electrification are two areas of interest.	Battery products demonstrated in Formula E, but main strength is R&D, making MAT a potential development partner for battery applications.
OXIS Energy Ltd		UK SME specialising in lithium sulphur battery technology and manufacturing, currently serving the aviation sector. Revenue of £763k, of which 1% is in the UK.	Patented technology with a claimed advantage over other rechargeable battery chemistries. Working with marine sector on development activities.
Potenza Technology Ltd		Potenza Technology specialises in the design and build of prototype and low-volume, high-energy density lithium battery packs.	Niche volume production for automotive activities.
Ricardo plc		Ricardo is included as a technical consultancy for battery technology. It has a large reach in global technology and environmental consultancy, operating across all transport markets. 3,000 employees and £380m revenue globally, of which 34% is attributed to the UK.	Ricardo is well placed as a development partner or to provide technology consultancy for battery technology, among other expertise.
William Advanced Engineering Ltd (WAE)		WAE is a UK-based R&D engineering consultancy, combining cutting-edge technology and engineering expertise to achieve accelerated speed to market. WAE has experience in battery technology and manufacturing, through joint programmes with automotive OEMs and Formula E. Team of 700+ includes F1.	WAE recently announced a collaboration with Unipart - Hyperbat Limited. There are expectations for it to target smaller marine applications with an integrated powertrain in the future.

Source: Expert knowledge, company websites, company financial statements, UK Companies House

H.4 UK competitiveness

H.4.1 Technology advantages

Since the early breakthrough in lithium-ion chemistry, UK research has remained strong in the fundamentals of battery chemistry through universities such as Oxford, Cambridge and Imperial, and a diaspora of mainly early-stage innovative companies such as Ilika and Oxis. Many of these are developing 'next generation' chemistries that either evolve or go beyond lithium-ion, and commercial application remains around 10 years off for many of these (Automotive Council, 2017).[108]

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 the UK (£246m government funding awarded in first phase, second phase in discussion[109]). The next phase of the Faraday Challenge also has involvement from the aerospace sector, and rail and marine could also benefit.

H.4.2 Factor advantages

The UK currently has very few manufacturers of lithium-ion batteries and a handful of battery pack assemblers. This picture may alter as the automotive (and other) sectors are actively seeking to attract an Asian cell manufacturer to establish a 'gigafactory' in UK. These assemblers require local production of batteries to avoid lengthy (risky) long-distance supply of a heavy and high-value component. The UK chemical industry is actively engaged in supporting this, seeing a large growth opportunity in the supply chain (Advanced Propulsion Centre and E4tech, 2018).[110] UK skills are likely to be sufficient, as battery cell production would be highly automated.

H.4.3 Market advantages

The presence of large vehicle manufacturers, aerospace and rail companies, grid storage and other companies in the UK creates an opportunity for UK cell assembly, and the race is on to attract a gigafactory. UK industrial policy is strongly championing this.[111] In principle, the UK has strong pull factors, but several other EU countries are also trying to attract the same Asian manufacturers (Greentech Media, 2018),[112] and Brexit is currently hampering the UK's case.

H.4.4 International competitors

The vast majority of lithium-ion cell production is concentrated in Japan, Korea and China, which benefit from high technical barriers to entry through strong IP and manufacturing scale, low costs and advantaged supply chain and market positions.

[108] https://www.automotivecouncil.co.uk/technology-group-2/automotive-technology-roadmaps/

[109] BEIS 2018 www.gov.uk/government/collections/faraday-battery-challenge-industrial-strategy-challenge-fund

[110] https://www.apcuk.co.uk/app/uploads/2018/06/E4tech_Report_UK-chemical-supply-chain-for-EV-batteries_25June2018-1.pdf

[111] Faraday battery challenge: Industrial Strategy Challenge Fund https://www.gov.uk/government/collections/faraday-battery-challenge-industrial-strategy-challenge-fund

[112] https://www.greentechmedia.com/articles/read/european-battery-manufacturing-to-grow-20-fold-by-2025#gs.rXSptKjn

The related chemical and material supply chains in these countries also reinforce this position (for example, China dominates the mining and processing of several key materials) (Stark, 2018).[113] For these reasons, 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 player. However, the next generation technologies provide more of an opportunity for UK IP to develop and scale up, since no player is yet dominant.

Overall the UK remains competitive in early-stage technology, much less so in volume battery cell manufacture (though this may be attracted) and on par with others for battery pack assembly if cells can be sourced in volume.

[113] https://www.process-worldwide.com/asia-pacific-region-remains-main-supplier-of-lithium-ion-battery-materials-a-715549/

ANNEX I ELECTRIC PROPULSION

I.1 Introduction

This Annex applies the analysis framework set out in the Summary Report to electric propulsion technologies. Firstly, a brief description of electric propulsion technologies is provided and the technologies are then assessed against the criteria for selection.

The subsequent sections present the supply chain for electric propulsion technologies, explore relevant firms' current contribution to the UK economy and present current levels of global deployment. UK competitiveness is then assessed and future opportunities within the global market for onboard hydrogen technologies are considered.

This Annex has been prepared using a combination of desk research, expert knowledge and discussions with industry, which have been referenced within the text where appropriate.

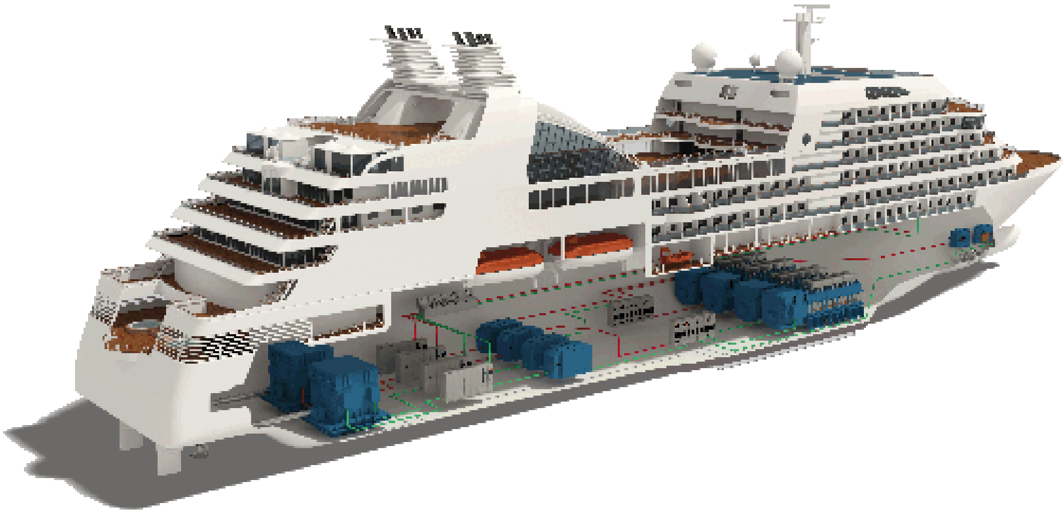
I.1.1 Technology description

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. In vehicle terms they can be compared with series hybrids. Diesel-electric drive systems have been used for many years (e.g. QE2 or Canberra from the 1960s) offering improved redundancy and manoeuvrability. Parallel drives also exist (e.g. Type 26 frigates), combining direct engine drive or electric drive, though they have higher complexity. Typical large electric motors are poly-phase induction (asynchronous) machines, (e.g. Type 45 and QE class aircraft carriers) or permanent magnet synchronous machines (Skjong et al., 2016).[114]

For the purpose of this assessment the focus is on the UK's competitiveness in electric motors, drives and related controls, but not the engines or gas turbines (for example) that may supply them since these fall outside the scope of 'electrical' systems.

[114] https://brage.bibsys.no/xmlui/bitstream/handle/11250/2386846/IEEE_TTE_2016_Skjong.pdf?sequence=3

Figure 33 Electric propulsion example



Source: Wartsila[115]

I.1.2 Justification for inclusion in technology shortlist

The use of integrated electric propulsion has numerous benefits, which are increasingly relevant (Marine Insight, 2017):[116]

- simplification of the propulsion system, including easier manoeuvring without latency or mechanical wear;
- reduced maintenance costs as engines operate at constant speed (meaning that they can operate at their more efficient operating points) and electric motors essentially have only one moving part and are more controllable;
- more flexibility in siting engines, including shorter exhaust paths;
- reduced noise and vibration as the engine need not be directly connected to the hull via drive-shafts and allows the use of resilient-mountings;
- ability to serve high ancillary and transient electrical loads (e.g. cruise ships, warships) in an integrated way rather than complex, separate mechanical and electrical systems; and
- potential for higher efficiency as engines can be operated more constantly, hull forms can be optimised, and overall propulsion system efficiency increased (in particular where multiple propulsors[117] are needed for manoeuvring).

Disadvantages include:

- higher initial cost as more sub-systems are involved; and
- overall less efficient than 2-stroke engine driven vessels which suit long constant operation (2-stroke engines are much less efficient for manoeuvring and need to have compromised controllable pitch propellers for port access – that is why very few ferries have 2-stroke engines, for example).

[115] www.wartsila.com/products/marine-oil-gas/power-systems/electric-propulsion/electric-propulsion-systems

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

[117] A marine mechanical propulsion system.

Examples of vessels that currently use integrated electric propulsion include: cruise ships, warships, tugs and trawlers, dredgers, drill-ships, dynamic positioning vessels, cable laying ships, ice breakers, research ships, floating cranes and support vessels for offshore industries.

I.2 Further detail on supply chain

Electric propulsion is adjacent in the vessel energy system to the energy store and conversion device and may be part of a large vessel-wide electric architecture. In the case of hybrid electric drives, it includes the generator to convert engine power to electricity.

Electric propulsion has its own component supply chain, which mainly comprises electric motor components (steels, windings, casings), propellers, motor controls and power electronics.

Expert opinion was used to identify key actors in important parts of the related component supply chains in order to identify significant strengths and weaknesses for the UK, where appropriate.

I.3 UK economic footprint and share of global export proxy market

This section presents evidence on the estimated market shares of the UK for relevant sub-technologies using data from the United Nations International Trade Statistics Database (Comtrade). This provides information on the value of imports and exports by country-pair and product (UN, 2019). These results are presented below and described in the Summary Report. This section also discusses the key actors in the UK.

I.3.1 Global export market size and UK share

Figure 34 shows the export market for electric propulsion technologies using the proxy of the HS6 codes 850162, 850163, 850164 and 850300 (see Annex A). While the value of the global export market for electric propulsion technologies has varied between $20bn and $26bn over the last 10 years, the UK share of this export market has declined fairly steadily from around 5% to below 3%.

Figure 34 International trade: electric propulsion

Source: Comtrade, Frontier analysis

I.3.2 Key UK actors

Key actors in electric propulsion technologies are outlined below. The relevance of these companies to the UK economy and the technology is described. Also, the current activity or, in the absence of current activity, the readiness for activity in the technology is outlined.

Figure 35 Electric propulsion technologies UK actors

Actor	Parent company	Relevance	Activity or readiness
Advanced Electric Machines Ltd (AEM)		UK SME with specialisms in high-performance tractions motors.	AEM traction motors are relevant to heavy duty applications, and therefore possibly applicable for marine. However, it is a small player.
ATB Morley Ltd	ATB AG	ATB Morley is globally recognised and specialises in robust and reliable drives for mining, power generation, marine, defence and many other heavy duty industrial applications. Subsidiary of ATB Austria Antriebstechnik AG. £17m revenue, all relevant to electric machines.	Focusing on electric machines for industrial applications, notably the oil and gas industry.
ATB Laurence Scott Ltd (ATB LS)	ATB AG	ATB LS is considered a centre of excellence for manufacturing mid and high voltage induction motors. Subsidiary of ATB Austria Antriebstechnik AG.	ATB LS offers single-source supply and design of high and low voltage AC/DC electric motors, and associated components.

Actor	Parent company	Relevance	Activity or readiness
Alstom UK Limited		With a presence in the UK, Alstom transport focuses on rail and rolling stock. Part of a group with revenues of €7bn, the UK transport sectors reports £300m revenue due to high investment of the UK government in the rail infrastructure.	Alstom recognises the shift away from diesel technology and has developed a hydrogen powered train that uses electric motors. The high power required for rail applications is relevant to marine applications.
BAE Systems plc		BAE Systems plc is a British multinational defence, security, and aerospace company with 39% of its revenue directly attributed to marine and naval defence projects.	BAE delivers marine solutions called HybriGen, for hotel loads, and hybrid power assistance depending on the applications. BAE is also producing a system called HybriDrive for bus and light duty applications.
Cummins UK	Cummins	A US corporate with distribution links in the UK. Cummins designs and manufactures medium to large diesel and alternative fuel engines, electrical gensets, and related components. Now expanding into the electrified power markets.	Cummins is targeting the role of leading provider of electrified power in commercial and industrial markets. Its Battery Electric Vehicle system for buses launches in 2019, followed by its Range Extended Electric Vehicle for Buses system in 2020. With a large engine focus, a shift to marine applications is possible.
Rolls-Royce plc (RR)		A large engineering and technology firm with over 100 years' experience. Centred in the UK with a global reach, RR works on clean innovation projects. RR has a major presence in the marine industry at the forefront of innovation. 22,300 employed in the UK (27% on marine projects), with £12.2bn UK revenue, £1bn related to the marine sector.	Producing both reciprocating engines and electric machines and power systems, RR also produces propulsion systems, i.e. integrated propeller systems mainly for defence applications e.g. submarines.

Actor	Parent company	Relevance	Activity or readiness
Quartzelec Ltd		UK leading electrical contractors in both low voltage and high voltage , particularly with experience in rotating machines. Turnover of £68m of which the majority is in the UK. Employs 650 people.	Quartzelec offers design, modification, repair and maintenance of machines up to 600MW. These are industrial scale for power generation, and relevant experience for large electric machines.
Leonardo DRS	Leonardo S.p.A	Leonardo DRS, operates in the UK, with head office in the US. A leading supplier of integrated electric drive products, primarily for defence. Leonardo DRS has capabilities in electronics and electric machines.	Leonardo DRS's permanent magnet machines are optimised for their application, whether electrical power generation or vehicle propulsion.
Magtec		Magtec is a UK-based company that designs and manufactures electric drive systems up to 1MW and components for multiple vehicle types. Magtec is the UK's largest manufacture of drive systems for commercial vehicles.	Magtec has demonstrated products in buses and other OEM products worldwide. Producing and selling electric machine products for trucks up to 26 tonnes.
Magnomatics Limited		Magnomatics is an SME developer of electric machines and magnetic gears in the UK.	Innovative but currently small relative to the needs of most marine applications.
Nidec SR Drives Ltd	Nidec Group	Wholly owned subsidiary of Japanese Nidec Corporation. Nidec SR drives and Nidec SR Drives Manufacturing are electric machine producers in the UK. £10m revenue and 80 staff.	Nidec SR drives focus on electric machines with switched reluctance (SR) technology. Marine systems may require very high torque at low speeds and a constant power output capability over a wide speed range, where SR technology is beneficial.
Tevva Motors Limited (TM)		TM is a low-volume producer of electric machines and light duty electric vehicles.	TM produces its own electric machines for a low-volume light duty transport application. Scale-up will not be immediate.

Actor	Parent company	Relevance	Activity or readiness
Turbo Power Systems Limited	TAO Sustainable Power Solutions (UK) Limited	Turbo Power Systems specialises in the design and manufacture of a wide range of electrical machines and power electronic products for multiple applications in energy, industrial, transport and defence markets. 50% of revenue is from sales in the UK.	Specifically designing generators for coupling to gas turbine applications.
Winder Power Limited (WP)	Winder Power Group Limited	WP, operational for over 100 years, is a leading UK manufacturer of power and distribution transformers and generator equipment, specialising in design, build and deployment of power transformers and distribution transformers up to 60MVA.	WP is a supplier of exciter machines to the world's major manufacturers of large synchronous generators and motors.

Source: Expert knowledge, company websites, company financial statements, UK Companies House

I.4 UK competitiveness

I.4.1 Technology advantages

The UK large-scale (1MW+) electric machine sector has declined in recent years, with three significant players left after several moved operations to Europe. One (Advanced Electrical Machines) is a novel technology developer. The UK nevertheless is recognised as having a strong research base in the relevant science and technology areas (physics, electrical engineering, materials). For example, Siemens Wind power based its wind turbine R&D centre at Sheffield University, recognising its capabilities in the development of large electrical machines as relevant for its generators. Adjacent areas such as power generators and electronic controls remain active in the UK. The UK has significant expertise in materials development that will be essential to tomorrow's electrical machines, including advanced insulation systems, specialist steels (e.g. silicon steels, permanent magnets and lightweight alloys).[118]

Importantly, the integration of electrical drives into vessel power systems remains a UK strength. The UK is also home to several other industries that are likely adopters of small- and large-scale electric machines, such as automotive, rail, wind and marine energy, and aerospace where there is a need for innovation and an opportunity for local supply chains. Together these factors have led to the establishment of the Stephenson Challenge under the Industrial Strategy Challenge Fund, with £78m of initial funding announced in 2018.[119]

[118] Private communication with former designer of integrated electric drives for, inter alia, Type 23 frigates.

[119] Budget statement 2018 https://ktn-uk.co.uk/news/key-points-from-budget-2018

I.4.2 Factor advantages

Large e-machine manufacture is, in principle, an area where the UK's ability to manufacture high-value specialist machinery (such as aero engines) remains a relevant strength. However, skills are being lost as the sector shrinks, so the UK marine sector's pockets of strength in marine integrated electric drive system design are a valuable pull factor (UK Marine Industries Alliance, 2014).[120]

I.4.3 Market advantages

UK activities in vessel design are very relevant, and electrification activities in road, rail and – soon – aviation provide a pull factor. UK policy is providing a strong push, especially in road and rail at present (House of Commons, 2018).[121]

I.4.4 International competitors

The UK undeniably faces tough competition in large electric machine design and manufacture, notably from leading exporters in France, Sweden, Germany, China and the USA (note that the USA is also experiencing loss of its manufacturing base to low-cost economies, such as Mexico, Vietnam and Malaysia).[122] However, the UK's innovation strengths are a platform that the Stephenson Challenge intends to build upon.

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 very relevant strengths in design of electric propulsion systems for vessels. However, manufacture of more standard e-machine designs is harder for the UK to compete in.

[120] https://www.maritimeindustries.org/CoreCode/Admin/ContentManagement/MediaHub/Assets/FileDownload.ashx?fid=121380&pid=12853&loc=en-GB&fd=False

[121] https://publications.parliament.uk/pa/cm201719/cmselect/cmbeis/383/383.pdf

[122] Private communication, ibid.

ANNEX J AIR LUBRICATION

J.1 Introduction

This Annex applies the analysis framework set out in the Summary Report to air lubrication technologies. Firstly, a brief description of air lubrication technologies is provided, and the technology is then assessed against the criteria for selection.

The subsequent sections present the supply chain for air lubrication technologies, explore relevant firms' current contribution to the UK economy and present current levels of global deployment. UK competitiveness is then assessed and future opportunities within the global market for air lubrication technologies are considered.

Wherever possible, throughout this Annex, references to supporting evidence have been made. In some cases no references are available because the points raised are based on expert knowledge and/or engagement with stakeholders.

J.1.1 Technology description

The Wärtsilä Encyclopaedia of Marine Technology (2015) [123] 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.[124]

The precise mechanism used to create the bubbles varies according to the specific air lubrication system. In some cases, bubbles are mechanically generated via an air injection nozzle, while in other systems air is pulled into the boundary layer in micro bubble form when water passes across a small cavity in the front of the hull.[125]

Previously, cavity systems were also explored as a means of air lubrication. These involved the installation of large cavities across the entire hull bottom. However, this type of technology was difficult to implement and expensive to operate as significant quantities of air were pulled from the cavity when the ship was operating at speed.

Manufacturers of the air lubrication technologies acknowledge that the air lubrication systems are more suited to vessels with a relatively large flat bottom.[126] This is because these vessels will experience larger efficiency gains. Creating a bubble carpet that adheres to the ship sides rather than the bottom is significantly more difficult, which means that the technology is less applicable to vessels with a v-shaped hull.

Air lubrication systems can either be incorporated as part of a new build or retrofitted onto an existing vessel.

[123] https://www.wartsila.com/encyclopedia/term/air-lubrication

[124] https://glomeep.imo.org/

[125] https://www.wartsila.com/encyclopedia/term/air-lubrication

[126] https://www.silverstream-tech.com/faq/

J.1.2 Justification for inclusion in technology shortlist

Contribution to emissions reduction

Air lubrication 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.[127] Manufacturers claim that actual fuel savings of 5-10% can be achieved.[128] The upper end of this range may, however, only be possible for certain ship types.

Where notable energy reductions are achieved, this would in turn lead to material reductions in emissions. Air lubrication performance has been independently verified by Lloyds Register, HSVA, Shell and Southampton University.[129]

Importantly, air lubrication technology can be deployed regardless of the propulsion mechanism used. This is not the case for some other abatement options where some technologies are interdependent or mutually exclusive. Therefore, in theory at least, air lubrication could become standard on all newly built vessels.

Cost effectiveness

Purchasing air lubrication equipment may cost between £1 million and £2 million. Additional installation costs could be approximately an additional 50% of the technology cost.[130]

Air lubrication systems could become cost effective for some ships over a medium time horizon. The expected payback period for certain types of ship can be less than five years. This depends on a number of factors, such as fuel prices, vessel fuel consumption, vessel operational profile and actual installation costs. The payback period may shorten over time if alternative fuels, which are likely to have a higher cost initially than current fuel sources, are increasingly used. This will also occur if the cost of traditional fuel rises due to the imposition of carbon pricing, for example.

Data availability

Information on the deployment of air lubrication technologies is publicly available from a number of outlets. These include:

- air lubrication patent data;[131]
- technology providers' websites;[132]
- trade press;[133]

[127] https://www.sciencedirect.com/science/article/pii/S2092678216303594

[128] https://www.silverstream-tech.com/the-technology/

[129] https://conferences.ncl.ac.uk/media/sites/conferencewebsites/scc2016/1.3.2.pdf

[130] Installation would typically cover modification of the hull, integration of the air release units/nozzles, installation of the compressors, electrical connections to the ship's power and relocation of displaced equipment.

[131] https://worldwide.espacenet.com/help?locale=en_EP&method=handleHelpTopic&topic=coverageww

[132] For example https://www.silverstream-tech.com/ or https://www.mhi.com/news/story/1210031580.html

[133] https://www.marineinsight.com/green-shipping/how-air-lubrication-system-for-ships-work/

- academic articles; and[134]
- international shipping organisations.[135]

These sources along with the results of qualitative engagement with sector exports are reflected in the assessment presented below.

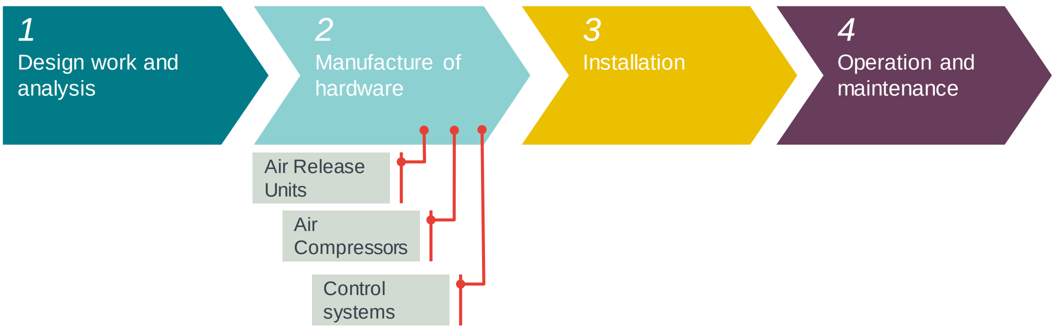
J.2 Further detail on supply chain

There are several stages involved in the development of an air lubrication system:

1. The first stage consists of upfront design work and modelling. This will include analysis to estimate performance via computational fluid dynamics and structural analysis to make sure that modifications are suitable. Depending on the ship to be fitted and the design of the air lubrication system, all of this work may have to be carried out every time a new system is sold because it has to be bespoke to the specifications of the ship. In this case, the system would then have to be designed.
2. Secondly the hardware must be manufactured. This consists of three core components:
    a. The steelwork required for the air release units/nozzles.
    b. The compressors which provide air for the entire system. The air compressors used in air lubrication systems are typically high volume and low pressure, which are most similar to compressors used in water treatment.
    c. The control systems that operate the system and manage the airflow.
3. The air lubrication technology then needs to be installed at a shipyard either as part of a new build or via a retrofit.
4. Finally the completed system will require ongoing maintenance work at regular intervals post installation.

This process is illustrated below in Figure 36.

Figure 36 Air lubrication supply chain



Source: Frontier / UMAS

[134] https://www.sciencedirect.com/science/article/pii/S2092678216303594

[135] https://glomeep.imo.org/

J.3 UK economic footprint

J.3.1 Contribution to UK economy

It should be noted that the current market for air lubrication systems is very small, with only a handful in active service across the world.

Firm size and activity

In the UK, the only company active in this area is Silverstream.[136] This is a UK-based firm, and air lubrication is currently 100% of its activity. In relation to the supply chain described above, Silverstream carries out Stage 1 activities in-house.

The air release units 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.[137] 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 which Silverstream is aware of.[138] Likewise, currently the air control systems are manufactured in the EU but there are other UK providers.

Figure 37 Silverstream sales locations

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

[137] 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/

[138] https://lontra.co.uk/blade-compressor-lontra/

Silverstream's first system was retrofitted in 2014 on a tanker owned by Danish shipping company Dannebrog Rederi, with net efficiency savings of more than 5% from multiple sea trials.[139] More recently, the Silverstream system was installed on a Norwegian Cruise Lines vessel in 2016,[140] and in 2017 a Silverstream air lubrication system was successfully retrofitted onto a Carnival cruise ship. Silverstream claimed net efficiency improvements of over 5%.[141] Both cruise ship companies are headquartered in the USA. In 2018, it was announced that a Silverstream Technologies system will be installed on 12 new Grimaldi Group[142] ro-ro vessels. Grimaldi is headquartered in Italy. The CEO of Grimaldi expects fuel savings of between 6-10%.[143]

Silverstream currently has 12 UK-based employees.[144] According to standard UK classifications, that would place Silverstream in the 'small' firm category (10-49 employees). The average annual turnover of 'small' businesses in the UK in 2016 was £2.8 million (House of Commons Library, 2018).[145]

J.4 UK competitiveness

There are a number of international firms that are also focused on developing and deploying their own air lubrication technologies. In this section a small number of international competitors are listed and briefly described. The competitiveness of the UK relative to these international competitors is then considered. Some of the points raised in this section will affect UK competitiveness across multiple abatement options rather than being limited purely to air lubrication.

In summary, there appears to be a significant opportunity for the UK in this sector, specifically in carrying out the upfront modelling and analysis 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. However, the lack of shipbuilding in the UK relative to key competitors could pose a challenge.

J.4.1 International players

There are a small number of other major international players involved in air lubrication technology. For example:[146]

1. Mitsubishi Heavy Industries' (MHI) Air Lubrication System;[147]
2. Samsung Heavy Industries' (SHI) Air Lubrication System (SAVER Air);[148] and

[139] https://www.wartsila.com/encyclopedia/term/air-lubrication

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

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

[142] https://www.grimaldi.co.uk/AgencyUK/

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

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

[145] https://researchbriefings.parliament.uk/ResearchBriefing/Summary/SN06152

[146] This list is not intended to be exhaustive.

[147] https://www.mhi.com/news/story/1210031580.html

[148] https://www.marineinsight.com/shipping-news/shi-applies-its-air-lubrication-system-to-super-large-container-ships-for-the-first-time/

3. Finnish marine design and engineering company Foreship.[149]

MHI installed its air lubrication system on a ferry for the first time in 2012 and reported fuel efficiency improvements of 5%.[150]

SHI announced that it will apply its air lubrication system to a super-large container ship for the first time in 2018. This will be the first time that air lubrication will be applied to a large high-speed container ship.[151] Also in 2018, SHI secured a contract to build two LNG carriers, both of which will feature its air lubrication system.

Foreship's air lubrication system was installed on a Royal Caribbean cruise ship in 2015.[152]

J.4.2 Technology

Innovation

A key advantage of the UK for firms active in this area is the domestic tradition of innovation. The Global Innovation Index ranks the UK as the fourth most-innovative country in the world.[153] London is one of the UK's innovation hubs. Maritime UK refers to a culture of innovation embedded within the sector, which drives participants to innovate, challenge existing norms and create new technologies.[154]

In this specific context, Silverstream was able to engage with Shell initially when developing and refining its system because Shell's centre for shipping R&D and innovation is based in London.[155] All firms active in this space will be constantly undertaking R&D activity to improve existing technology. For example, firms may be updating software that optimises the flow of bubbles over the hull so there are ongoing opportunities in this fast-developing space of shipping innovation.

Existing intellectual property

Both Silverstream and the international competitors have patented their systems. The unique aspect of Silverstream's system is that it utilises what is known as the shearing effect between water and air to create bubbles rather than producing them mechanically. The international patent system means that potential entrants to the market cannot precisely replicate this system. Patents are therefore crucial to encouraging innovation and mean that existing players, such as Silverstream in the UK, have an opportunity to gain market traction with their innovation.

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[149] https://www.foreship.com/en

[150] https://www.mhi.com/news/story/1210031580.html

[151] https://www.marineinsight.com/shipping-news/shi-applies-its-air-lubrication-system-to-super-large-container-ships-for-the-first-time/

[152] https://www.passengership.info/news/view,foreship-launches-fuelsaving-air-lubrication-system-to-ferries_38184.htm

[153] https://www.globalinnovationindex.org/analysis-indicator

[154] https://www.maritimeuk.org/media-centre/publications/annual-review-2018/

[155] https://www.shell.com/business-customers/trading-and-supply/trading/news-and-media-releases/silverstream-air-lubrication-technology.html

The strength of innovation activity by Silverstream alone is demonstrated in European Patent Office data[156] which indicates that Silverstream currently has six patents in effect, all of which are related to air lubrication.

It is possible that existing UK firms in adjacent technology areas could enter the air lubrication market. Possible candidate firms could be large engineering firms that may have expertise in high efficiency pumps, air distribution systems or that have worked in the area of fluid dynamics previously. This could include BAE Systems, BMG Research or Babcock. However, in order to compete effectively they would have to offer something unique to the market, which may be very challenging.

J.4.3 Policy

Policy and regulation would not be expected to hinder the uptake of these technologies in the UK or internationally. Policies such as the International Maritime Organization's Energy Efficiency Design Index (2001)[157] will encourage uptake of air lubrication technology across all jurisdictions. Air lubrication systems are explicitly listed in the EEDI as a technology which can aid with emissions reduction.

The UK policy direction on shipping emissions is ambitious, as demonstrated by initiatives such as the Clean Maritime Council.[158] This will help to ensure that the UK remains an attractive location for firms active in this area. In addition, Silverstream has received direct support from the Department for International Trade (DIT) in the UK.[159] Specifically, DIT arranged meetings between Silverstream and large shipbuilding firms in China to explore business opportunities.

In addition, Innovate UK (IUK) has provided funding in a number of different forms to encourage the development of systems that can reduce emissions and improve the efficiency of marine vessels. For example, IUK opened a marine vessel efficiency competition in January 2014 which aimed to build collaboration across the maritime sector and create opportunities for smaller businesses. The total amount of funding available was £5 million.[160] This type of R&D funding will help to ensure that the UK remains an attractive environment for technology suppliers to locate to.

J.4.4 Skills

Academic capability

The UK's marine R&D base is extensive, with a significant amount of R&D conducted by UK universities, research institutes and businesses (House of

[156] https://worldwide.espacenet.com/advancedSearch?locale=en_EP

[157] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/COP%2017/Submissions/Final%20SBSTA%20EEDI%20SEEMP%20COP17.pdf

[158] https://www.gov.uk/government/news/clean-maritime-revolution-starts-voyage

[159] https://www.silverstream-tech.com/special-recognition-for-innovation/dit-award-2017/

[160] https://interact.innovateuk.org/competition-display-page/-/asset_publisher/RqEt2AKmEBhi/content/vessel-efficiency-ii-better-systems-at-sea

Commons Committee on Existing the European Union, 2017).[161] Development of air lubrication technologies rely on two primary fields of expertise:

1. fluid dynamics; and
2. naval architecture and systems integration.

The UK would be considered a world leader in these fields and has a strong base in terms of academics and industry practitioners. Using the British Library’s online thesis database[162] it is possible to examine the number of completed PhDs covering specific topics from UK institutions in each year. In 2018 alone, four PhD theses, from three institutions, referred directly to naval architecture in their abstract. Over the same period, 138 PhD thesis abstracts, from 43 awarding institutions, included a mention of fluid dynamics. While all these doctorates will not be directly relevant to the current context of improving energy efficiency of marine vessels, they provide an indication of the current strong academic base of the UK in these important areas.

UK companies active in this space in the UK would be able to access these key skills. For example, Silverstream has good links to UCL’s shipping research group[163] and the University of Southampton’s Marine and Maritime Institute.[164] Major international competitors, such as Korea, would also be well placed in this regard.

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.[165] 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.

J.4.5 Market access

Links to potential customers

Silverstream is currently focusing on shipping market segments which consume large amounts of fuel. This will include cruise ships, ro-ro vessels and container ships. To market its product, Silverstream is focusing its engagement on key players in those segments including owners, operators and shipyards. Often, once a big player installs a new technology and proves its effectiveness, others may be more likely to follow.

The UK offers valuable market access potential due to the substantial maritime presence in place domestically. Maritime UK commissioned the Centre for Economics and Business Research to estimate the value of the UK maritime sector as a whole in 2017. The research concluded that the sector directly supported just

[161] https://www.parliament.uk/documents/commons-committees/Exiting-the-European-Union/17-19/Sectoral%20Analyses/22-Maritime-and-Ports-Report.pdf

[162] https://ethos.bl.uk/Home.do;jsessionid=84E777224735B8BE22C2917C2F9F7595

[163] https://www.ucl.ac.uk/bartlett/energy/research/themes/transport/shipping

[164] https://www.southampton.ac.uk/smmi/index.page

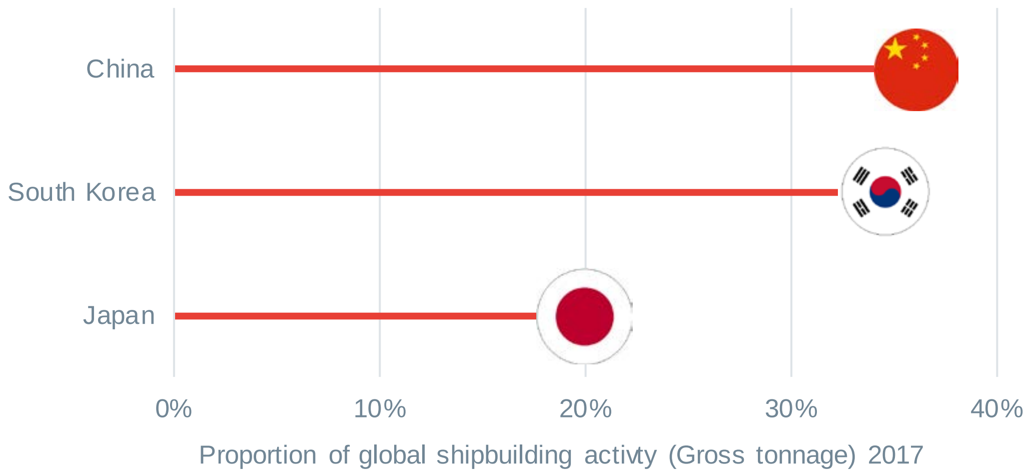
[165] https://www.maritimeuk.org/media-centre/publications/annual-review-2018/

over £40 billion in business turnover, £14.5 billion in gross value added (GVA) and 185,700 jobs for UK employees in 2015. The marine and shipping industries are the largest constituent industries in terms of economic activity, contributing £6.5 billion and £4.3 billion in GVA respectively, and directly supporting around 99,500 jobs and 50,800 jobs respectively in 2015.[166] This indigenous UK shipping activity is likely to increase the attractiveness of the UK as a place to locate for a technology provider.

Japan and South Korea, where two of the major air lubrication international players are based, are also well placed. Both countries are major shipbuilding locations (see Figure 38 below). One of the main challenges for UK-based firms in this sector is that some of the major international competitors are either shipbuilders themselves or have close tie-ins with shipyards. This provides them with an advantage. This is because when a shipyard has its own air lubrication system available for installation, it can be difficult for other providers to access users of that shipyard, even if those potential customers would prefer to install a different system.

In 2017, when measured by gross tonnage, South Korea was responsible for 34% of global shipbuilding output. The equivalent figure for Japan was 20%. Outside of these two countries and China, no single country had a market share of over 3%. This could mean that Silverstream finds it relatively more difficult to break into Korean shipyards, for example. However, there may be opportunities to deploy elsewhere in Asia, such as Chinese yards.

Figure 38 Proportion of global shipbuilding activity in 2017



Source: UNCTAD Stat, Frontier calculations

Support services

The UK is also the global leader in maritime professional services, with extensive expertise in finance, vessel chartering, insurance, legal and educational

[166] https://www.maritimeuk.org/value/

services.[167] An Oxera report produced for DfT concluded that the UK has a market-leading 26% of global maritime insurance premia.[168]

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 US.[169] This is an important advantage for the UK, as air lubrication providers will have enhanced access to finance options for the development of a new system and customers may be better placed to access local finance for the installation of the new technology.

[167] https://www.maritimeuk.org/media-centre/publications/annual-review-2018/

[168] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/445133/international-competitiveness-of-UK-maritime-sector.pdf

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

ANNEX K WIND PROPULSION

K.1 Introduction

This Annex applies the analysis framework set out in the Summary Report to wind propulsion technologies. Firstly, a brief description of wind propulsion technologies is provided, before the technology is assessed against the criteria for selection (Step 1 of the framework).

The subsequent sections present the supply chain for wind propulsion technologies, explore relevant firms' current contribution to the UK economy and present current levels of deployment. UK competitiveness is then considered and future opportunities for the UK within the global market for wind propulsion technologies are considered.

Wherever possible, throughout this Annex references to supporting evidence have been made. In some cases no references are available because the points raised are based on expert knowledge and/or engagement with stakeholders.

K.1.1 Technology description

The use of wind propulsion in modern commercial shipping covers a variety of specific technologies.[170] These technologies reduce the energy required from traditional motors and therefore reduce associated emissions by using wind as an auxiliary primary energy source. It should be noted that given the magnitude of propulsion energy required to power a ship, wind may not be always used without other energy sources; it is, however, a valuable zero emission complement to other means of propulsion.

This Annex considers three wind propulsion abatement options:

- Sails: these can be installed on commercial vessels to harness wind power. There are several other different types of sail currently in operation or under development. Wingsails, for example, supplement traditional propulsion via a fixed curved surface area that is fitted to marine vessels and is analogous to airplane wings.[171]
- Flettner rotors: these are vertical cylinders that are mounted on the deck of a vessel. The rotors spin mechanically and develop thrust as the wind blows across them.[172] This thrust can contribute to the propulsive needs of the ship.[173] The thrust is generated in a direction perpendicular to the wind's direction due to a pressure differential which occurs as wind blows past the rotating cylinders.[174] Given the contribution to the ship's propulsion, they reduce the need for other energy sources and, in the current fleet, therefore save emissions.

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[170] http://wind-ship.org/wind-propulsion-wp-wind-assist-shipping-projects-wasp/

[171] https://waset.org/publications/245/revival-of-the-modern-wing-sails-for-the-propulsion-of-commercial-ships

[172] https://glomeep.imo.org/technology/flettner-rotors/

[173] http://www.bmtdsl.co.uk/media/5045823/BMTDSL%20The%20Use%20Of%20Flettner%20Rotors%20In%20Efficient%20Ship%20Design%20Conference%20paper%20%28RINA%202014%29.pdf

[174] https://www.wartsila.com/encyclopedia/term/flettner-rotor

- High altitude kites: these can be connected to the forward part of the ship to partially tow the ship and save engine power, and hence emissions. In general the higher the kite, the greater and smoother the windspeed (Sanderson, 2008).[175] The kites can be brought down to allow passage under bridges or through other navigational constraints.

Wind propulsion is naturally suited to voyages on seas with high wind speeds. Its viability can also be influenced by wind direction relative to the route taken. It can also be very difficult to integrate the equipment (sails/rotors) on certain ships either because of lack of deck space (such as on some offshore vessels) or because these technologies can get in the way of cranes and equipment during loading/unloading operations (some dry bulk carriers).

K.1.2 Justification for inclusion in technology shortlist

Contribution to emissions reduction

Wind propulsion technologies have the potential to make a material contribution to emissions abatement. The International Windship Association claims that these systems offer fuel savings in the 10-30% range.[176]

These options could be applied to large sectors of the global fleet, in particular slow speed dry or wet bulk vessels and ro-ros. Deployment of wind propulsion technologies which require a lot of deck space (such as Flettner rotors) will not be suited to container ships or cruise ships, as deck space is at a premium.

Cost effectiveness

The cost of these technologies will vary according to the specific technology employed, ship type and ship size. Installation of Flettner rotors on the largest category of bulker costs $2.7 million, whereas the deployment of kites on the largest category of container ship costs $3.4 million.[177] Wind assistance technologies can have payback periods of less than five years. The precise payback period will depend on realised fuel savings and the future cost of fuel.

Data availability

Information on the development and deployment of wind propulsion technologies is available from a number of sources. These include:

- wind propulsion patent data;[178]
- technology providers' websites;[179]
- media coverage;[180]

[175] https://www.nature.com/news/2008/080208/full/news.2008.564.html

[176] http://wind-ship.org/does-wind-help/

[177] Frontier et al., (2019b)

[178] https://worldwide.espacenet.com/searchResults?ST=singleline&locale=en_EP&submitted=true&DB=&query=flettner+rotor

[179] For example http://magnuss.com/ or https://www.norsepower.com/

[180] https://www.bbc.co.uk/news/av/stories-46540862/smart-ships-using-the-wind-and-air-bubbles-to-save-fuel

- academic articles; and[181]
- international shipping organisations.[182]

These sources, along with the results of qualitative engagement with sector experts, are reflected in the assessment presented below.

K.2 Further detail on supply chain

There are several stages involved in the development of wind propulsion technologies:

1. Companies involved in the R&D stage of the supply chain for wind propulsion technology would firstly undertake analysis to determine the design of their specific technology and assess potential fuel consumption savings. This would be based on fluid dynamics and voyage performance modelling and would allow a customer to develop their internal business case for investment. An initial prototype may be developed at this stage, which would lead to further testing.
2. If the customer makes the decision to install the specific wind propulsion technology, sails, kites or rotors would then need to be manufactured.
3. The next step would be to supply the operating software, which would optimise the position of the technology and monitor fuel and emissions savings.
4. The completed system would be installed on a newly built boat or retrofitted to an existing vessel. This work would be carried out by shipyards.
5. Finally, the finished wind propulsion technology would require ongoing maintenance at regular intervals.

This process is illustrated below in Figure 39.

Figure 39 Wind propulsion supply chain

Source: Frontier / UMAS

[181] https://waset.org/publications/245/revival-of-the-modern-wing-sails-for-the-propulsion-of-commercial-ships

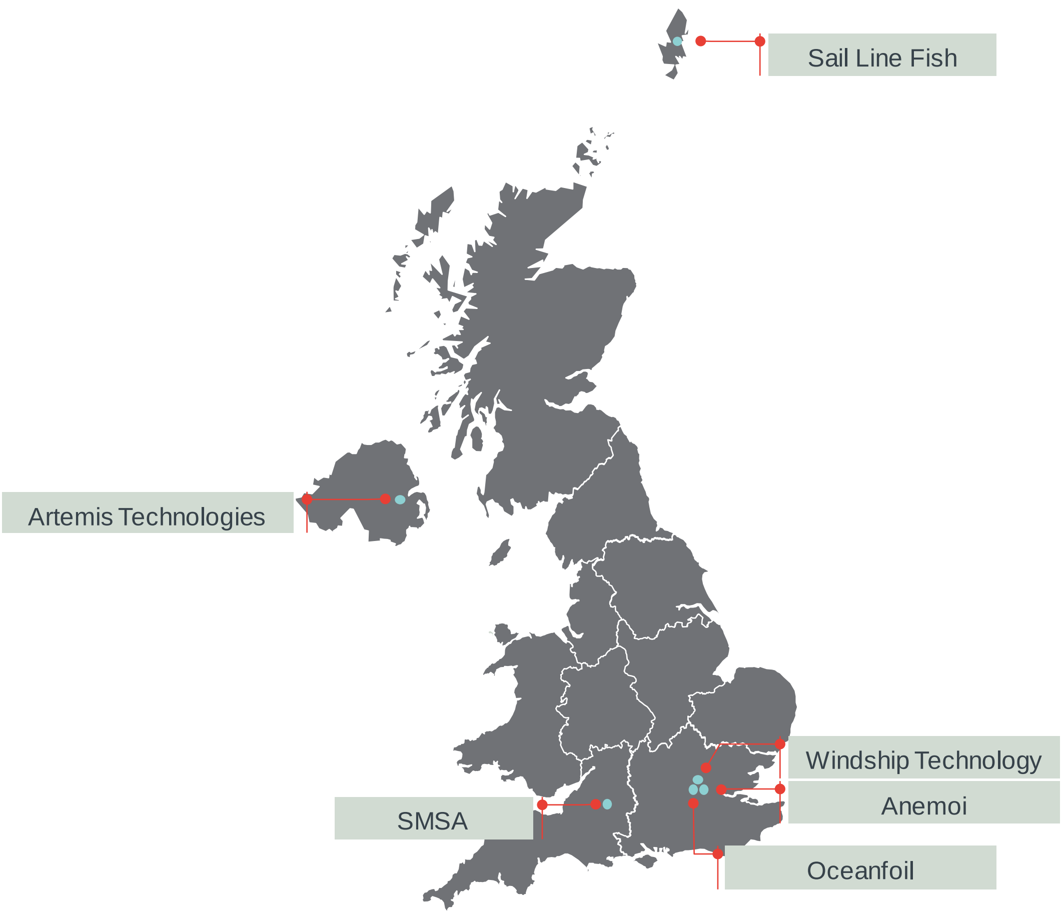
[182] https://glomeep.imo.org/technology/flettner-rotors/

K.3 UK economic footprint

K.3.1 Current contribution to UK economy

Firm locations

Figure 40 Location of some of the main UK firms involved in the wind propulsion sector (registered HQ)



Firm size and activity

There are a small number of UK firms active across the supply chain above. In general, these firms would be classified as either micro or small.[183] Currently, direct UK employment in this area is likely to consist of fewer than 50 jobs. However, as described below, there is significant potential for growth and there are established links with other larger sectors such as academic research organisations, naval architects and engineering companies. Therefore, wind propulsion technologies would be expected to support other jobs indirectly. Some of the main market players are:

- Oceanfoil offers wind solutions for the global commercial shipping fleet. Its specific technology is a wingsail. Working in partnership with ship designers

[183] https://researchbriefings.parliament.uk/ResearchBriefing/Summary/SN06152

BMT, Oceanfoil claims that its technology can achieve significant fuel consumption and emissions savings. Based on these results a ship owner would achieve payback in less than five years.[184]

Oceanfoil works in partnership with Owen Clarke Design, which is a UK Naval Architecture firm.[185]

- Smart Green Shipping Alliance (SGSA) is a multi-disciplinary partnership committed to building shipping system solutions. The SGSA's system combines soft sail technologies with an engine powered by liquid biomethane. Up to 50% of the propulsion comes from wind.[186]

  In 2018 it was announced that the SGSA was partnering with Drax (operator of the UK's largest power station) and Ultrabulk (cargo transporter). A £100,000 12-month feasibility study funded by Innovate UK will examine the potential of fitting an innovative sail onto ships importing biomass into the UK.[187]

  SGSA is supported by the Institution of Mechanical Engineers at international shipyards. [188]

- Anemoi is focused on Flettner rotor technology. Following prototyping, a Flettner rotor system was installed by Anemoi onboard a bulk carrier vessel. Verifying fuel savings at sea is advancing with a structured test plan and data acquisition.[189] Its Flettner rotors are designed and manufactured in the UK.[190]

  According to the most recent company accounts available Anemoi employed nine people throughout 2018.[191]

- Artemis Technologies develops green-powered/solar-powered, zero emission commercial vessels as well as fast ocean racing boats.[192] Artemis is currently developing an autonomous sailing vessel which relies on sustainable energy sources such as wind.[193]

  According to the most recent company accounts available, Artemis employed three people throughout 2017.[194]

- Sail Line Fish develops sail-system technology for emissions reductions and fuel efficiency in the shipping and fishing industries. Sail Line Fish received Scottish Government funding in 2010 to carry out a feasibility study into the potential of sail-assisted fishing. During the 18-month sail-assisted fishing trials, it recorded a 17.6% reduction in fuel.[195]

- Windship Technology uses a sail system which has the ability to reduce fuel costs significantly and cut resulting CO_2 emissions significantly. It utilises three

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184 http://wind-ship.org/en/oceanfoil-iwsa-member/

185 http://oceanfoil.com/about-us/

186 http://wind-ship.org/smart-green-shipping-alliance-iwsa-member/

187 https://www.drax.com/press_release/smart-green-shipping-alliance-partners-drax-ultrabulk-cut-shipping-supply-chain-emissions/

188 https://www.smartgreenshippingalliance.com/people/

189 http://wind-ship.org/en/anemoi-marine-technologies-iwsa-member/

190 https://www.anemoimarine.com/flettner-rotors/

191 https://beta.companieshouse.gov.uk/company/09821734/filing-history

192 http://www.artemisracing.com/en/technologies/what-artemis-technologies-does.html

193 http://www.artemisracing.com/en/technologies/what-artemis-technologies-does/autonomous-sailing-vessels

194 https://beta.companieshouse.gov.uk/company/09412785/filing-history

195 http://wind-ship.org/saillinefis/

35-metre masts, each housing three aerodynamic wings to harness wind power.[196]

The firms listed above constitute the vast majority of UK activity in this area.

K.4 UK competitiveness

There are a number of international firms that are also focused on developing and deploying their own wind propulsion technologies. In this section a small number of international competitors are listed and briefly described. The competitiveness of the UK relative to these international competitors is then considered.

Overall, these technologies offer an opportunity for the UK to be a major global player. 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.

K.4.1 International players

There are 56 members of the International Windship Association – the trade association. Not all of these organisations will be technology providers, as membership is open to companies, organisations and individuals active in the marine wind propulsion sector. Two international competitors are listed below:

- The most prominent international technology provide is Norsepower which is based in Finland. Norsepower is a leading marine engineering company specialising in clean tech solutions within maritime. Its Flettner rotor system is called the Norsepower Rotor Sail Solution, which is the first practical auxiliary wind propulsion solution that is commercially available.

  In 2017, it was announced that the Norsepower Rotor Sail Solution would be installed on board a Viking Line Cruise Ferry vessel in 2018.[197] In addition, Norsepower planned to install rotor sails on a long-range tanker ship operated by Maersk in the first half of 2018. This was subsequently delayed.[198] However, the vessel had two 30m-by-5m diameter rotors installed on the vessel in August 2018.[199] The project is the first installation of wind-powered energy technology on a product tanker vessel.

- Magnuss is a US-based maritime technology firm that produces a suite of fuel efficiency technologies for the global shipping fleet. Specifically, it developed the Magnuss VOSS (Vertically variable Ocean Sail System), which uses mechanical sails to achieve fuel savings. The sail is a 100-foot tall spinning, hollow, metal cylinder that propels a ship. The cylinders are retractable and can be stored below deck when loading or unloading, if required. Magnuss claims savings of up to 50%.[200] Currently its technology has yet to be fully deployed commercially.

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[196] http://www.windshiptechnology.com/

[197] https://www.vikingline.com/globalassets/documents/market_specific/corporate/press/pressrelease-eng/2017/20170125_norsepower_grace-eng.pdf

[198] https://worldmaritimenews.com/archives/257742/maersk-tankers-rotor-sail-project-delayed/

[199] https://worldmaritimenews.com/archives/259777/rotor-sails-fitted-on-board-maersks-tanker-in-a-worlds-1st/

[200] http://wind-ship.org/magnuss/

K.4.2 Technology

Innovation

As described above in relation to air lubrication, a key advantage of the UK for firms active in this area is the domestic tradition of maritime innovation. London is an innovation hub. This culture of innovation is embedded within the sector and drives participants to innovate, challenge existing norms and create new technologies.[201]

For example, Anemoi refers to ongoing continuous development, which is refining its innovative production and assembly methods.[202]

Existing intellectual property

Each firm in the UK and internationally will be seeking to develop its own niche in terms of design and deployment of wind technologies. Figure 41 illustrates the number of current patents held by UK-based firms and the specific technology area they relate to.

Figure 41 UK wind propulsion firms patents

Firm	Number of patents	Specific technology area
Oceanfoil	4	Aerofoils/sails
SGSA	-	-
Anemoi	2	Rotors
Sail Line Fish	1	Masts
Windship Technology	1	Aerofoils/sails

Source: Frontier analysis of European Patent Office Data (2019)

International firms will be in a similar position (for example Magnuss's VOSS design is protected by patent[203]) and all firms will be undertaking further R&D activity to improve their technologies. The UK has a strong existing research and knowledge base to support R&D activity.

K.4.3 Policy

Policy and regulation are not likely to hinder the uptake of these technologies in either the UK or internationally. Policies such as the IMO's EEDI[204] are designed to encourage the uptake of wind propulsion technology (along with other emissions abatement options) across all jurisdictions. Wind propulsion systems are explicitly listed as a technology that can aid emissions reduction.

UK policy is fully committed to reducing shipping emissions as evidenced by the establishment of the Clean Maritime Council.[205]The UK's Energy Technologies

[201] https://www.maritimeuk.org/media-centre/publications/annual-review-2018/

[202] https://www.anemoimarine.com/flettner-rotors/

[203] http://magnuss.com/

[204] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/COP%2017/Submissions/Final%20SBSTA%20EEDI%20SEEMP%20COP17.pdf

[205] https://www.gov.uk/government/news/clean-maritime-revolution-starts-voyage

Institute (ETI)[206] is also active in this specific area. The ETI provided funding for Norsepower's installation of rotors on a long-range tanker.[207] This could help signal a UK policy interest in this specific sector.

K.4.4 Skills

Academic capability

As discussed in relation to air lubrication technologies, the UK has an extensive marine R&D base composed of universities, research institutes and businesses.[208] This expertise will benefit UK-based companies involved in wind propulsion.

Individual UK-based wind propulsion firms have established links to academics. For example, the SGSA includes UCL, Southampton University's Wolfson Unit and the Tyndall centre for climate change research.[209] In addition, both Southampton University's Wolfson's Unit and Lloyd's Register's Technical Investigation Department have carried out independent tests of Windship Technology's system to verify the reductions in consumption.[210]

Skill clusters

Manufacture of bespoke wind propulsion technologies such as Flettner rotors requires the application of cutting-edge technical knowledge. Supplier firms may encounter technical issues during the fabrication phase. Manufacturing currently represents an important contribution to the UK economy (11% of UK GVA and 54% of UK exports).[211] High-value manufacturing which applies innovative processes and expertise to the creation of products has been identified by Innovate UK as an opportunity for economic growth for the UK.[212] In this context specifically, the UK offers high-quality and bespoke maritime design and manufacturing.[213] The UK's marine manufacturing sector is recognised globally for its skills and expertise in marine systems, equipment, design, manufacturing, engineering and architecture.[214]

However, the UK's manufacturing base may be higher cost than other countries due to higher labour costs, for example.[215] This may limit the attractiveness of constructing these technologies in the UK at a large scale. Also, if manufactured in the UK, the fabricated technology may need to be transported to shipyards

[206] The ETI is a public-private partnership between global energy and engineering companies and the UK Government. https://www.eti.co.uk/about

[207] https://www.eti.co.uk/news/norsepowers-fuel-efficient-technology-expected-to-save-approximately-10-in-fuel-consumption-and-associated-emissions-on-109-647-dwt-product-tanker-vessel

[208] https://www.parliament.uk/documents/commons-committees/Exiting-the-European-Union/17-19/Sectoral%20Analyses/22-Maritime-and-Ports-Report.pdf

[209] https://www.maritimeuk.org/media-centre/blog-posts/uk-maritime-tech-interview-1-smart-green-shipping-alliance/

[210] http://www.windshiptechnology.com/

[211] https://hvm.catapult.org.uk/about-us/why-hvm-catapult/

[212] https://hvm.catapult.org.uk/about-us/why-hvm-catapult/

[213] https://www.maritimeuk.org/media-centre/publications/annual-review-2018/

[214] https://www.parliament.uk/documents/commons-committees/Exiting-the-European-Union/17-19/Sectoral%20Analyses/22-Maritime-and-Ports-Report.pdf

[215] Steel structures can generally be fabricated cheaper in east Europe, Singapore or Far East relative to the UK.

(primarily in Asia) before they can be installed on ships. Flettner rotors, in particular, are very large and the shipping of completed rotors is therefore very expensive. One potential model which UK firms could follow would be to take advantage of the domestic skills base in high-value manufacturing by basing their centre of R&D here. The actual manufacture of the wind propulsion technology hardware could also be located here or could take place closer to the shipyards.

It is also encouraging that the UK has had success in manufacturing and exporting turbines used to convert wind energy to electrical energy.[216] The offshore renewable energy industry presents huge opportunities for UK economic benefit and jobs growth.[217] Some of the skills which feature prominently in this sector may be applicable to the application of wind to shipping, which would advantage the UK further.

K.4.5 Market access

Links to potential customers

As described above in relation to air lubrication, the UK offers strong market access potential due to the substantial maritime presence in place domestically. The considerable indigenous UK shipping activity will mean that the UK is a natural place to locate for a technology provider.

Support services

The UK is also the global leader in maritime professional services, with extensive expertise in finance, vessel chartering, insurance, legal and educational services.[218]

The high cost associated with wind propulsion technologies[219] means that financing is essential. London is seen as the market leader in maritime financing.[220] This is an important advantage for the UK.

In addition, the International Windship Association which facilitates and promotes wind propulsion for commercial shipping worldwide and brings together all relevant parties is based in London. [221] This is a further strength of the UK.

216 https://www.renewableuk.com/page/WindEnergy

217 https://ore.catapult.org.uk/

218 https://www.maritimeuk.org/media-centre/publications/annual-review-2018/

219 Installation costs for Flettner rotors on certain ship types can be over $2.5 million.

220 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/445133/international-competitiveness-of-UK-maritime-sector.pdf

221 http://wind-ship.org/en/grid-homepage/

ANNEX L EGR AND SCR ENGINE EXHAUST TECHNOLOGIES

L.1 Introduction

This Annex applies the analysis framework set out in the Summary Report to exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) engine exhaust technologies. Firstly, a brief description of EGR and SCR engine exhaust technologies is provided, and the technologies are then assessed against the criteria for selection.

The subsequent sections present the supply chain for EGR and SCR engine exhaust technologies, explore relevant firms' current contribution to the UK economy and present current levels of global deployment. UK competitiveness is then assessed and future opportunities within the global market for EGR and SCR are considered.

This Annex has been prepared using a combination of desk research, expert knowledge and discussions with industry, which have been referenced within the text where appropriate.

L.1.1 Technology description

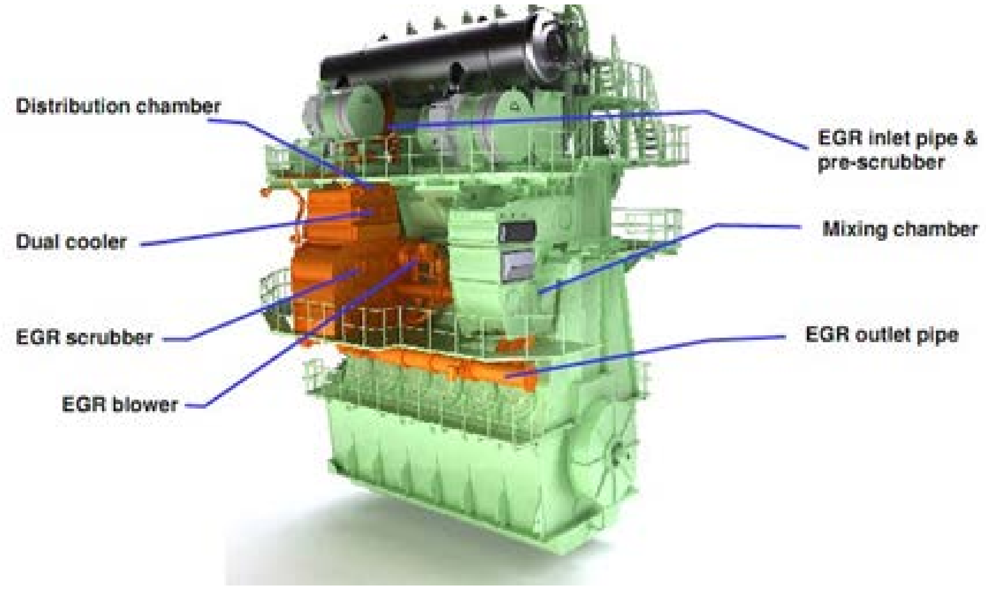
EGR and SCR are different technologies with a common purpose – to reduce the nitrogen oxides (NO_x) in the exhausts of vessels with internal combustion engines, which can react in the marine environment to form nitric acid or low level ozone. The technologies are alternatives but can also be employed in tandem to achieve greater reduction. They have very different technical characteristics.

EGR

NO_x is formed at high temperatures in the cylinders of an engine. EGR takes a proportion of the exhaust gas from the main engine exhaust receiver and recirculates it to the scavenge air via a dedicated closed loop scrubber which removes damaging contaminants. This has the effect of reducing the oxygen level and therefore the combustion temperature and therefore NO_x formation.[222] The main systems are shown below.

[222] Wartsila Encyclopedia of Marine Technology https://www.wartsila.com/encyclopedia/term/exhaust-gas-emissions-from-ships

Figure 42 EGR example

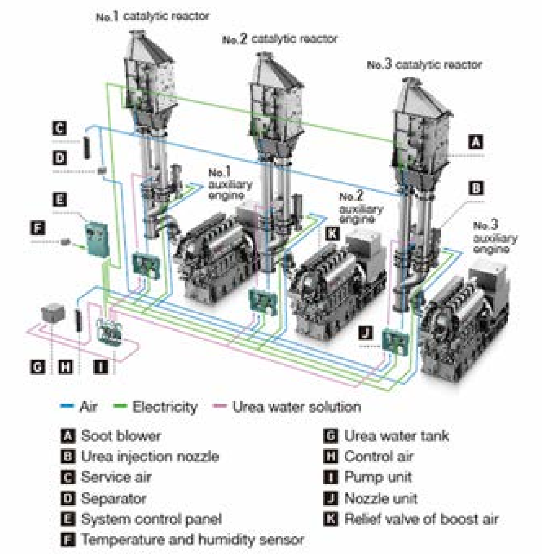


Source: MAN[223]

SCR

Whereas EGR avoids NO_x formation, SCR is an after-treatment system that chemically reduces the NO_x back to nitrogen by adding a chemical (urea). It involves injecting urea water into the exhaust gas and using the exhaust gas heat to produce ammonia (NH_3). This is then reacted with the NO_x on a catalyst to break the NO_x down into nitrogen and water.[224]

Figure 43 SCR example



Source: Yanmar[225]

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[223] www.egcsa.com/exhaust-gas-recirculation-explained/

[224] Wartsila Encyclopedia of Marine Technology https://www.wartsila.com/encyclopedia/term/selective-catalytic-reduction-(scr)

[225] www.yanmar.com/sg/technology/technical_review/2018/0413_2.html

L.1.2 Justification for inclusion in technology shortlist

EGR and/or SCR are essential technologies for vessels operating in NO_x Emission Control Areas designated by the IMO. The most stringent regulations already apply in the coastal waters of the USA and Canada, with the North Sea and Baltic Sea to be added from 2021. Although many of the other fuel and propulsion options outlined in this work avoid the formation of NO_x, such options may not be available to large ocean-going vessels and/or may not be available in the timeframe of these regulations. EGR and SCR therefore enable the continued use of conventional marine fuels, especially for larger vessels.

The relative merits of each technology are complex, though key considerations are engine size, importance of first cost versus operational costs and engine room size. SCR tends to be lower cost than EGR below engines of size 35MW.

Economic opportunities are judged to derive from the UK's potential to develop and export technologies related to EGR and SCR, which is the focus of this assessment.

L.2 UK economic footprint and share of global export proxy market

This section presents evidence on the estimated market shares of the UK for relevant sub-technologies using data from the United Nations International Trade Statistics Database (Comtrade). This provides information on the value of imports and exports by country-pair and product (UN, 2019). These results are presented below and described in the Summary Report. This section also discusses the key actors in the UK.

L.2.1 Global export market size and UK share

Figure 44 shows the export market for EGR & SCR technologies using the proxy of the HS6 codes 841950, 841350, 841459 and 848180 (see Annex A). The value of the global export market for EGR and SCR technologies has risen, with some discontinuities, over the last 10 years. In this period, the UK's share has remained fairly constant at 2-3%.

Figure 44 International trade: EGR/SCR

Source: Comtrade, Frontier analysis

L.2.2 Key UK actors

Selected key actors in EGR- and SCR-related technologies are outlined below. The relevance of these companies to the UK economy and the technology is described. Also, the current activity or, in the absence of current activity, the readiness for activity in the technology is outlined.

Figure 45 EGR and SCE UK actors

Actor	Parent company	Relevance	Activity or readiness
BorgWarner Turbo Systems	BorgWarner	Borg Warner Turbo Systems is a UK division of the US global company. The parent company, Borg Warner Turbo systems is split into two divisions, engine and drivetrain. The engine segment develops and manufactures products to improve fuel economy, reduce emissions and enhance performance. $10bn global revenue, of which 60% is for engines and a smaller percentage for EGR systems.	While BorgWarner Turbo Systems does not produce EGR specifically, the parent company has the capability and offers complete systems and components, primarily for the vehicle market.
BM Catalysts Limited (BM)		BM is a large independent manufacturer of aftermarket catalytic converters and other emissions-related components for exhaust systems in Europe.	BM manufactures the largest range of catalytic converters for the automotive market. ,Further the company specialises in performance catalysts for exhaust systems.

Actor	Parent company	Relevance	Activity or readiness
Calsonic Kansei United Kingdon (CK)	Calsonic Kansei	The UK is the home to CK's European head office, technical centre and vehicle and system test facilities. CK produces exhaust systems for the automotive markets. The UK hosts nearly 800 employees (~40%) of the company's workforce.	CK in the UK completes a range of exhaust system product design, test and manufacture. Exhaust systems are specifically for the automotive markets and operations would need to adapt to larger engines.
Cummins UK	Cummins	A US corporate with distribution links in the UK. Cummins designs and manufactures medium to large diesel and alternative fuel engines, electrical gensets, and related components.	Industry leading after-treatment (SCR) for light, medium, heavy duty, and high horsepower commercial vehicles, on or off road. Cummins also has significant experience in turbo technology and EGR for large diesel engines.
Delphi technologies	Aptiv PLC	Tier 1 supplier[226] for global powertrain systems design and development in the automotive sector with 100 years' experience. £700m revenue, of which 15% is from the UK.	Involved in product design and development for catalytic converters and emissions reduction for automotive applications.
Doosan Babcock (DB)	Doosan	Under the parent organisation, Doosan Group, DB is an R&D specialist, focusing on smart energy products for the power and oil and gas industries. DB is also involved in marine applications for steam-related components, e.g. DB is nominated and approved maintenance and aftermarket service provider for all Kawasaki Heavy Industries marine boiler designs.	DB offers both non-catalytic and catalytic selective reduction systems for NO_x control, for post combustion. DB has the first full SCR retrofit in the UK, although this is for industrial applications. However, the combustion profile could be similar to marine engine exhausts, meaning DB is a company with the potential capability to advise and design maritime systems.
Eberspächer UK Limited	Eberspächer Group	UK arm of the Eberspächer group, specifically operating in the UK for supply of catalytic converters and exhaust systems to the BMW Mini facility. £20m revenue for exhaust supply to BMW Mini.	Supplier of exhaust systems to the automotive industry, specifically small passenger cars. Demonstrated production capability and volume.

[226] Tier 1 suppliers are those that supply directly to OEMs.

Actor	Parent company	Relevance	Activity or readiness
Eminox Limited	Hexadex Limited	Eminox Limited is a UK company which designs and manufactures high-performance, stainless steel exhaust and emission control systems for bus, truck, rail and off-highway vehicles. Parent organisation employs 430 people in the UK.	Eminox can supply OEM parts, retrofit, aftermarket, or custom designs. Eminox works with partners to design the systems. Less focused on new technology design.
Johnson Matthey plc (JM)		Large global science and technology firm with a vision for sustainable energy. JM is one of the world's leading catalyst providers, based on more than 80 years' experience with Imperial Chemical Industries (ICI) and 100 years' experience with BASF. £14bn revenue, with £680m EBITDA, across all sectors.	JM offers a range of catalyst solutions for multiple applications from mobile or stationary emissions control and across the transport sector, although not explicitly marine engines, engine sizes from 500kW to 20MW are catered for.
MAHLE Powertrain Ltd.	MAHLE GmbH	Global engineering company focused on powertrains and electronics with UK engineering businesses. MAHLE works with manufacturers on whole engine design. 70,000 employees worldwide. 6/170 office locations are in the UK.	Not directly involved in marine applications, but with experience in engine design, and emissions control, they could be a relevant development partner.
Perkins Engines	Caterpillar Inc.	Perkins, part of the US Caterpillar Group, designs and manufacture engines in the UK, and has a marine sector for smaller engines. £1.4bn revenue, which includes applications for all engines, EGR/SCR is a small portion of this.	Perkins sells, among others, diesel oxidation catalysts, SCR, EGR and ammonia oxidation catalysts to give high-end performance with reduced engine emissions across a range of 75-750HP engines.
Tenneco Automotive Ltd	Tenneco Inc.	Tenneco Automotive is a UK subsidiary of a larger US and European group, which has product lines for clean air (SCR) for automotive and heavy duty, as well as marine operations.	Delivering whole clean air products (XNO_x SCR) and exhaust manifolds for multiple applications within marine and automotive, including commercial vehicles, and large engines.

Actor	Parent company	Relevance	Activity or readiness
Wärtsilä UK Ltd.	Wärtsilä Oyj Abp	Although not UK-based, Wärtsilä has a UK presence, and has acquired several UK marine sector players, e.g. Hamworthy. Wärtsilä is a global leader in smart technologies and complete lifecycle solutions for the marine and energy markets.	Wärtsilä offers a NO_x reduction (NOR) SCR technology specifically for marine and Wärtsilä engine applications.

Source: Expert knowledge, company websites, company financial statements, UK Companies House

L.3 UK competitiveness

L.3.1 Technology advantages

EGR is an engine technology, so is more likely to be integrated by the engine maker; SCR is to a large extent a separate system, so can be provided by a different supplier from the engine. The UK has a strong presence in engine design and manufacture including large diesels, though not at ship scale. Many of the relevant firms are expert in applying 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.[227]

L.3.2 Factor advantages

The UK benefits from an automotive supply chain that is partly focused on diesel engines. There is also a UK ammonia supply industry which is relevant for urea. UK vessel builders are mostly focused on specialist vessels which do not feature the largest engines, though the UK's design capability is broad (UK Marine Industries Alliance, 2014).[228]

L.3.3 Market advantages

The UK's policy support for NO_x reduction from land-based transport as well as impending Tier 3 regulations creates a strong push for the technologies. However, the UK's lack of large ship engine builders is a challenge for EGR in particular.

L.3.4 International competitors

Marine EGR leaders are those countries with large ship engine industries such as Germany (MAN) and Japan (Mitsubishi). SCR systems are offered by some of the engine companies (Wärtsilä), but also by urea companies (such as Norway's

[227] UK Research Excellence Framework 2014. https://www.ref.ac.uk/2014/

[228] https://www.maritimeindustries.org/CoreCode/Admin/ContentManagement/MediaHub/Assets/FileDownload.ashx?fid=121380&pid=12853&loc=en-GB&fd=False

Yara). UK catalyst providers (Johnson Matthey) compete strongly within the SCR supply chain with others such as Belgium's Umicore.

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 but is less well positioned for full system supply.

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