2019 T-TRIG Project Report

Decarbonising the Transport System

Evaluation of the Marine Application of Advanced Carbon Capture Technology

PMW Technology

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Executive Summary

1.1 The need for large reductions in carbon emissions to limit climate change is reflected in the Government commitment to net zero by 2050. The DfT has set objectives for sustainable transport including those in the Marine 2050 Decarbonisation Objectives for Shipping, aiming to achieve zero carbon shipping emissions soon after 2050.

1.2 Incremental technical improvements to ship design and operation will reduce carbon emissions, however these will not be sufficient to achieve net zero. In a scenario analysis for the DfT, Frontier Economics examined options for marine decarbonisation. Their key finding was the need for a transition to zero carbon fuels. These were found to have costs of carbon abatement of around £180/te carbon dioxide, adding ca £1.3 billion/y to UK shipping costs.

1.3 An alternative transition to zero carbon shipping is evaluated in this study by process specialists PMW Technology with naval architects Houlder Limited, the University of Chester and Tees Valley Combined Authority. It is proposed to use an advanced process to capture emissions at sea, delivering liquid carbon dioxide for geological sequestration at arrival ports. Impacts are assessed in two case studies, while the necessary port infrastructure is evaluated. The costs are evaluated on a basis consistent with the Frontier Economics study.

1.4 The first case study is an LNG fuelled 10,200 te deadweight pure car and truck carrier, while the second is an 830 te deadweight hybrid diesel electric/ battery ferry. For a series of cases the analysis addresses the physical feasibility of implementation, the impacts on vessel stability and the capital and operational costs.

1.5 The carbon capture process evaluated is the A3C process by PMW Technology which separates the carbon dioxide from the exhaust gases by freezing. Design features reduce process energy consumption while the intensity of the process minimises its size. The separation unit may be safely bypassed if carbon dioxide storage tanks are full, simplifying early operation when fewer ports may be equipped to unload carbon dioxide.

1.6 Incorporation of the process equipment into the vessel designs was found to be feasible with the simplest arrangements, with opportunities for better layouts from more radical redesigns. The stability of the vessels was maintained without requiring other modifications. The size of the additional equipment was dominated by the liquid carbon dioxide storage tanks which only slightly reduced cargo carrying capacity in the more extreme cases.

1.7 The process increased the vessel auxiliary power demand although this could be accommodated. When 90% of vessel carbon emissions were captured the resulting increase in total fuel consumption was less than 17% for LNG and 24% for MGO.

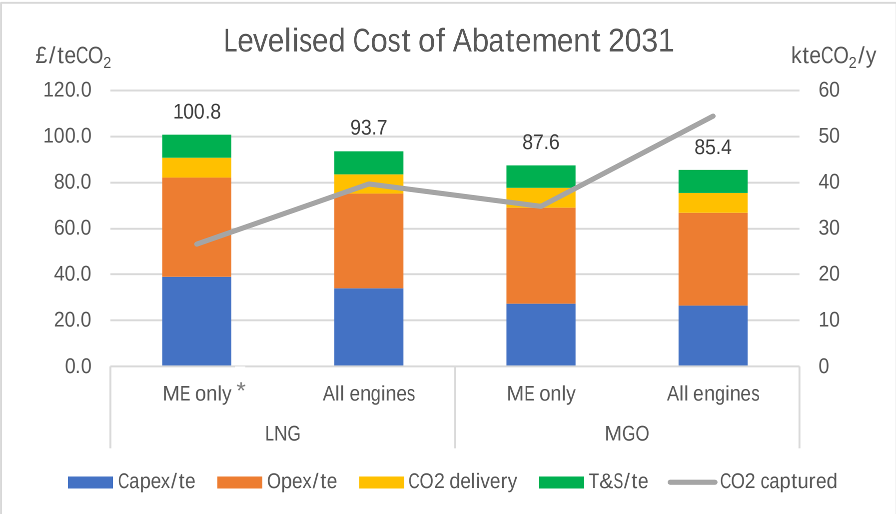
1.8 The capital costs of additional equipment were estimated using process engineering costing tools and budgetary prices from suppliers with appropriate allowances for onboard installation. The total capital cost for implementing carbon capture on the car carrier ranged from £7 - 12 million, according to case, while the ferry was estimated at £3.7 million.

1.9 Comparison of the engine capacity of the two vessels with the global shipping fleet showed that both vessels have larger engines for their deadweight than representative shipping. Hence the findings of this study give a pessimistic view of typical applications.

1.10 Shore infrastructure to support marine carbon capture was found to include additional facilities for liquid carbon dioxide unloading and storage. However a significant proportion of the larger UK ports will form part of industrial carbon capture clusters where such facilities are planned. Other ports would require carbon dioxide handling facilities to unload incoming vessels and tranship to clusters, increasing the costs of carbon abatement by a few percent.

1.11 Marine captured carbon dioxide could significantly increase the throughput of the industrial clusters in the early 2030's. This improved utilisation would enhance the economic case for clusters and support new cluster development around major ports such as Southampton, London Gateway and Milford Haven. The BEIS Industrial Clusters Mission is updating the costs of geological sequestration which are estimated to be around £10/te carbon dioxide.

1.12 The overall cost of carbon abatement for the proposed strategy was calculated using the Frontier Economics economic assumptions. The results are summarised below.



*ME Main Engine

1.13 International application of marine carbon capture will depend on infrastructure at major ports. Industrial carbon capture clusters are being developed around the North Sea with widespread interest elsewhere. Oil exporting regions in the US and Middle East already use carbon dioxide injection for enhanced oil recovery, providing effective carbon dioxide storage. Such early application can be expected to be followed by wider international provision.

1.14 The conclusions of the study are:

- The low temperature carbon capture process is feasible for ship application.
- The overall cost of the proposed alternative carbon abatement strategy for shipping is a decisive 50% lower than for conversion of shipping to zero carbon fuels.
- Marine carbon capture has beneficial synergies with infrastructure already being developed for industrial clusters, minimising the need for additional investment.
- The technical and economic findings of this study strongly support the case for further work to progress the option of marine carbon capture with associated infrastructure at industrial clusters and major ports.

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2. Glossary

A3C carbon capture process	A continuous separation process which freezes carbon dioxide out of a gas stream
Absorber column	A tall vessel in which part of a gas stream is absorbed in a falling liquid
Amine process	A process using an amine solution to extract carbon dioxide from a gas
AspenPlus®	A leading software package for chemical process modelling
Auxiliary engines	Engines used to generate electricity for ship auxiliary systems
Auxiliary power	Electricity supplied for auxiliary systems, services and lighting
BEIS	The Department for Business, Energy and Industrial Strategy
Biofuel	Fuels derived from forestry, agriculture or food wastes, e.g. biodiesel
BOG	Boil-off gas generated by heat leaking into cold liquid gas storage tanks
Bunkering	Loading fuel into a ship
Carbon capture	The separation of carbon dioxide from a gas stream for storage or reuse
Carbon dioxide frost	The solid formed when carbon dioxide is cooled at atmospheric pressure
Classification society	Companies qualified to check compliance of ship design and equipment with international standards for insurance
Conventional carbon capture processes	Carbon capture processes using amine or advanced amine separation
Cryogenic	Temperatures below -150°C
Deadweight	A measure of the size of a ship, the maximum weight of cargo and fuel
Enhanced oil recovery	The injection of carbon dioxide into an oil reservoir to extend its life
Geological sequestration	The storage of carbon dioxide in a porous but sealed underground formation
Industrial carbon capture clusters	Networks of industries capturing carbon emissions for geological sequestration
Industrial strategy grand challenge	A series of government initiatives to tackle specific industrial policy challenges
Levelised costs	A single figure for cost of ownership over an asset's life combining operating costs, discounted capital costs and lifetime throughput
Life cost of carbon abatement	The levelised cost of avoided carbon emissions including all investment and operating costs
LNG	Liquified natural gas - an increasingly important marine fuel
LSMGO	Low sulphur marine gas oil - a low sulphur distillate marine fuel
Main engine	The engine which drives the propeller
MARPOL	The International Convention on Prevention of Pollution from Ships
MDO	Marine diesel oil - a ship fuel including residual oil
MGO	Marine gas oil - a distillate ship fuel
Net zero carbon emissions	When anthropogenic carbon emissions are fully offset by sequestration of biogenic emissions
Nitrogen dioxide	The part of NOx emissions that is the 'brown fume'
Recuperative	An energy saving heat exchange that cools incoming gas using colder gases leaving a process
S(SOx)ECA areas	Sea areas mandating reduced levels of the emission of sulphur oxides
Shore infrastructure	Facilities or services needed onshore (to enable marine carbon capture)
Vessel stability	The ability of a ship to withstand wave and wind forces without capsizing
Zero carbon fuels	Fuels which do not emit carbon dioxide at the point of use (it may however be emitted during manufacture)

3. Introduction

3.1 The commitment by the DfT for sustainable transport is reflected in the Marine 2050 Decarbonisation Objectives for Shipping, which aims to achieve net zero carbon emissions soon after 2050. Frontier Economics undertook a comprehensive scenario analysis to examine options for marine decarbonisation. Their key finding was the need for alternative zero carbon fuels with modifications to ship design and operation.

3.2 The adoption of alternative fuels will necessitate substantial changes to ship design and extensive new infrastructure for fuel manufacture and bunkering. Frontier Economics[1] suggest that these will incur estimated costs of carbon abatement of over £180/tCO_2, substantially higher than comparable costs onshore, such as the £95/tCO_2 estimated for carbon capture and storage for the proposed Teesside industrial cluster[2].

3.3 Recent work by the Global Maritime Forum[3] has shown that global investment of the order of $1 trillion will be required to decarbonise marine shipping.

3.4 Recent developments in carbon capture technology offer an alternative marine decarbonisation option that does not appear to have been considered to date. This disruptive technology uses a compact physical freezing process for carbon capture, avoiding the use of conventional large, energy intensive chemical processes. Feasibility studies[4] for its application in other sectors have shown the process to be up to 70% cheaper than conventional alternatives. The outstanding economy and simplicity of marine application of this energy efficient process could offer a radically lower cost of marine decarbonisation.

3.5 This T-TRIG project has evaluated the marine application of the advanced carbon capture process, considering both the technical and economic impact on vessels and their operation, and on the onshore infrastructure required. The study also assesses the potentially large beneficial synergies from integrating marine carbon dioxide with the Industrial Strategy Grand Challenge carbon capture clusters.

Aims of the project

3.6 The project has four aims:

- Assess the A3C cryogenic carbon capture process in marine application case studies
- Evaluate onshore facilities and their relationship with industrial carbon capture clusters
- Generate life costs of carbon abatement consistent with those by Frontier Economics
- Create an exploitation plan for the concept, prepare reports and disseminate the work

[1] Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution – Scenario Analysis: Take-up of Emission Reduction Options and their Impact on Emissions and Costs – A Report for the Department for Transport, Frontier Economics, UMAS, E4tech and CE Delft, July 2019.
[2] Industrial CCS on Teesside – the Business Case, Pale Blue Dot, 20 June 2015.
[3] https://www.globalmaritimeforum.org/content/2020/01/Aggregate-investment-for-the-decarbonisation-of-the-shipping-industry.pdf downloaded 5 March 2020
[4] P. Willson, G. Lychnos, A. Clements, S. Michailos, C. Font-Palma, M.E. Diego, M. Pourkashanian, J. Howe, Evaluation of the performance and economic viability of a novel low temperature carbon capture process, International Journal of Greenhouse Gas Control 86 (2019) 1-9

Objectives of the project

3.7 The project evaluates the application of the A3C process to two sizes of vessel, using the examples of the 90 m long 830 tonne Victoria of Wight ferry and the 200m long, 10,200 tonne deadweight pure car and truck carrier, the SIEM Confucius.

3.8 The analysis of the applications includes both technical performance and physical implementation into the vessel, taking account of limitations of space, stability and energy consumption.

3.9 The capital and operating costs of the additional plant and equipment are estimated.

3.10 The implications of unloading liquid carbon dioxide at ports have been considered to provide indicative capital and operating costs of onshore facilities.

3.11 The liquid carbon dioxide captured at sea will be unloaded to shore storage to be transferred directly, or via further ship transport, to geological carbon storage facilities. The impact of the additional flows of carbon dioxide on the costs of operation of such facilities has been estimated.

3.12 The final step of the economic analysis has derived a life cost of carbon capture using the A3C process on similar basis to that used in The Frontier Economics Scenario Analysis[1] for comparison with alternative carbon reduction strategies.

4. Innovative Research

4.1 This study evaluates the novel application of carbon capture to shipping. Such application has not been considered feasible to date as conventional carbon capture equipment is large, energy intensive and employs chemical processes unsuitable for installation on board ship.

4.2 The Advanced Cryogenic Carbon Capture process (A3C) uses low temperatures to separate the carbon dioxide physically from a gas stream without process chemicals. The equipment is compact, with an advanced heat exchange and refrigeration design which minimises energy consumption, making it more suitable for marine application.

4.3 The A3C process has been developed primarily for exhaust gas carbon abatement and its application to gas streams containing 1.5% to 40% mol carbon dioxide has already been evaluated[4]. Marine diesel engine exhaust gases typically contain 3.5-6% carbon dioxide. Integration with the exhaust gases and ship systems is therefore the primary area of technical study.

4.4 The feasibility of technical implementation of the A3C process on board ship is only part of the scope; the implications to fuel, bunkering and carbon dioxide transport and storage are also evaluated.

4.5 This section describes the A3C process while the subsequent section reviews the application of the A3C process to two sizes of vessel and addresses its implication to onshore infrastructure and carbon capture and storage clusters. An economic evaluation consistent with that conducted by Frontier Economics in their Scenario Analysis report for the Department is presented to benchmark costs.

Outline of the concept

4.6 The Advanced Cryogenic Carbon Capture (A3C) process was initially conceived in response to the challenge of industrial decarbonisation. It has been found that many potential industrial applications are not suitable for conventional carbon capture processes due to their smaller scale or to the implications of installing an energy intensive chemical process. The potential marine application of the A3C process was identified when wider transport applications for a compact and energy efficient carbon capture process were evaluated.

4.7 The core process was patented by PMW Technology in 2016 and has since been subject to a series of studies supported by experimental work at the University of Chester.

4.8 The A3C process can remove a very high proportion of carbon dioxide in a gas stream, capable of implementation to separate over 99%, but with typical applications expected to remove 90-95%. The process is modular so that part capacity units can be installed progressively to reduce carbon emissions to meet economic or regulatory demands.

4.9 The A3C cryogenic carbon dioxide separation process has two stages, each with a circulating packed bed of metallic beads, as shown in Figure 1. The first step cools and removes all traces of water from the gases, while the second cools the gases further to separate the carbon dioxide as a coating of frost on the moving bed material.

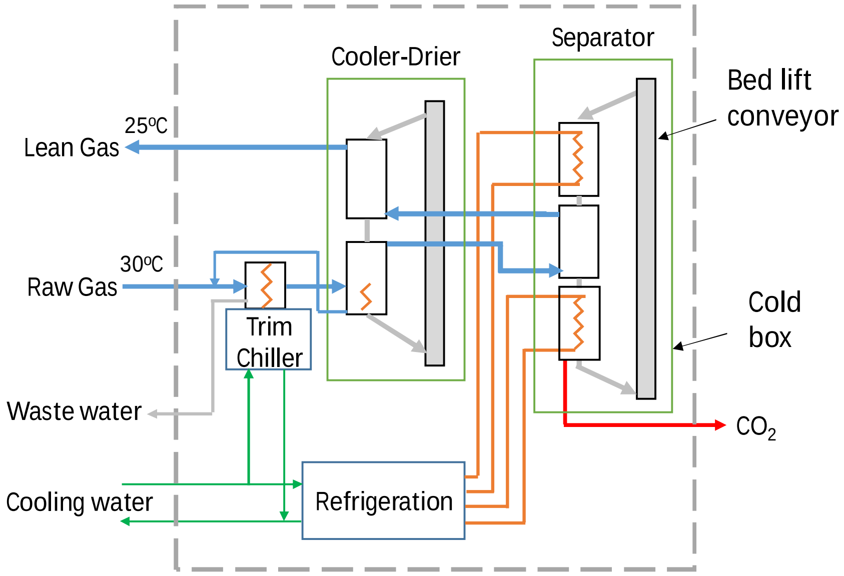

Figure 1 Outline of A3C separation process

4.10 Heat transfer within the moving beds of fine metal beads is very intense, enabling a very compact separation to be achieved, delivering a comparable separation to that in an absorber column 15m high in a bed only 50-100mm deep.

4.11 The advanced recuperative refrigeration cycle exploits the heating required to recover the carbon dioxide from the frosted bed to offer a very low refrigeration energy consumption for a cryogenic system.

4.12 The A3C separation process, currently at TRL3-4, was the subject of a comprehensive techno-economic review by the Universities of Chester and Sheffield, with industrial partners Costain, DNV GL and WSP, completed in December 2018[4]. The 15 month study, funded by Innovate UK, considered onshore industrial and power plant applications, finding that at scales below 10 tCO_2/h, typical of marine application, the cost of capture of the A3C process was estimated to be up to 70% lower than the benchmark amine process.

4.13 The integration of the A3C process with ship systems is illustrated in Figure 2. The stages of the process comprise an inlet cooler which chills and cleans the engine exhaust gases, followed by A3C gas drying with cryogenic separation of the carbon dioxide.

4.14 The inlet cooler removes the sulphur and nitrogen dioxide contaminants in the exhaust gas and washes out any particulate matter. The resulting wash water is treated to remove particulate and other contaminants before discharge to sea.

4.15 The raw gases from the inlet cooler flow into the A3C separation process described above, returning cold lean gases and a separated stream of gaseous carbon dioxide.

4.16 The separated carbon dioxide is liquefied using a simple process developed by SINTEF and Statoil. This compresses the gas to around 30 bar, condenses it by cooling and then flashes the liquid to a lower pressure, typically 10 bar, causing a small part of the flow to flash off, cooling the remainder, while the cold gas is recompressed. The liquid carbon dioxide is stored in insulated tanks at about -40°C.

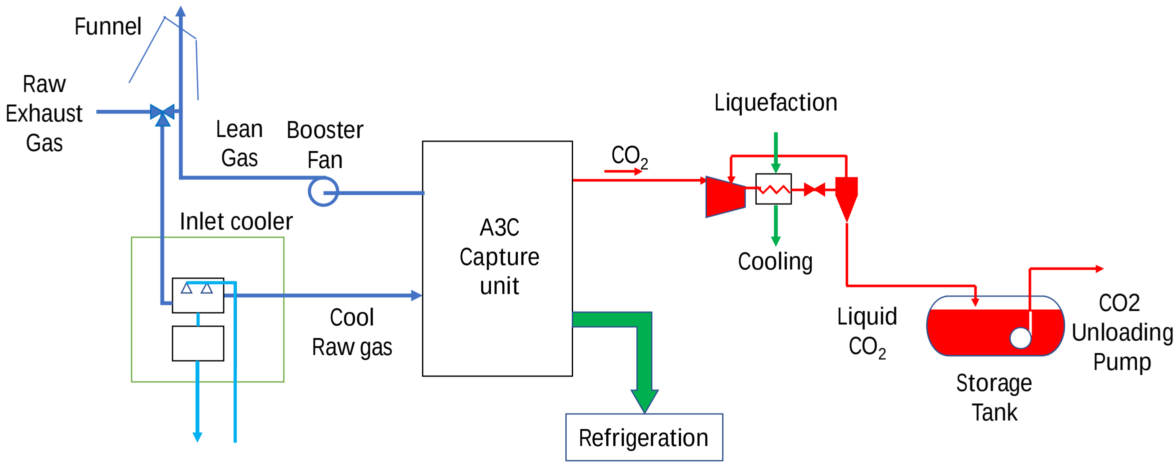

Figure 2 Outline of A3C marine application

4.17 The liquid carbon dioxide would be unloaded at arrival ports to be transferred directly or by onward shipping to industrial cluster systems for sequestration.

4.18 The vessel main engines may be fuelled by fuel oil, distillate (MGO, MDO), a biofuel blend, or LNG. Any biofuel would contribute valuable negative carbon emissions.

4.19 The sulphur and nitrogen oxide emissions are regulated by the MARPOL Annex VI. For emission control the sulphur content of fuel for use without abatement measures such as exhaust gas scrubbing is now limited to 0.5% worldwide and 0.1% in S(SOx)ECA zones. An acceptable alternative is to clean the exhaust gases to reduce sulphur emissions to equivalent levels to these limits.

4.20 The gas cleaning stages of the A3C process inherently remove sulphur oxides to extremely low levels. This would allow vessels incorporating carbon capture to use higher sulphur fuels which may offer economic advantages.

Intellectual Property Rights

4.21 The intellectual property related to the A3C process is held by PMW Technology, including a patent, GB2553277, filed in 2016 and granted in 2020.

Assumptions made

4.22 Technical assumptions about the process and its application to shipping are set out in the sections below.

4.23 Derivation of costs of abatement of carbon dioxide by carbon capture have used the same assumptions as the Frontier Economics Scenario Analysis, as follows:

a. Cost estimate base year – 2018

b. Reference year for evaluation of cost of abatement – 2031

c. BEIS fuel costs in 2031 – LNG £470 /te, LSMGO £440 /te

d. Discount rate – 10%

e. Life of vessel assets – 20 years

f. Life of on shore assets – 40 years

5. Implementation

The work conducted

5.1 The study has been structured around a series of computer models and analyses.

5.2 The AspenPlus® software package was used to model the behaviour of the gas clean-up, carbon dioxide separation and liquefaction processes. These evaluations extended work previously conducted on A3C cryogenic capture process to the treatment of the hot exhaust gases and their contaminants and the liquefaction of the captured carbon dioxide.

5.3 Implementations of the cryogenic carbon capture process were evaluated for two case studies. While these relate to specific vessels, the conceptual implementations were not considered to be retrofits, being treated as developments of new build designs.

5.4 The first case study was the SIEM Confucius, illustrated in Figure 3. This is a pure car and truck carrier with a capacity of 7,500 Car Equivalent Units (CEU), a deadweight of 10,200 te and cruise speed of 19 knots. The ship has a single MAN dual fuel diesel engine burning natural gas (from LNG) injected at high pressure, with a small percentage of MGO as pilot fuel. The LNG is stored in two 1850m^3 low pressure storage tanks. The ship is designed for transport of vehicles between Europe and the US and surrounding countries, with refuelling at one point on each round trip.

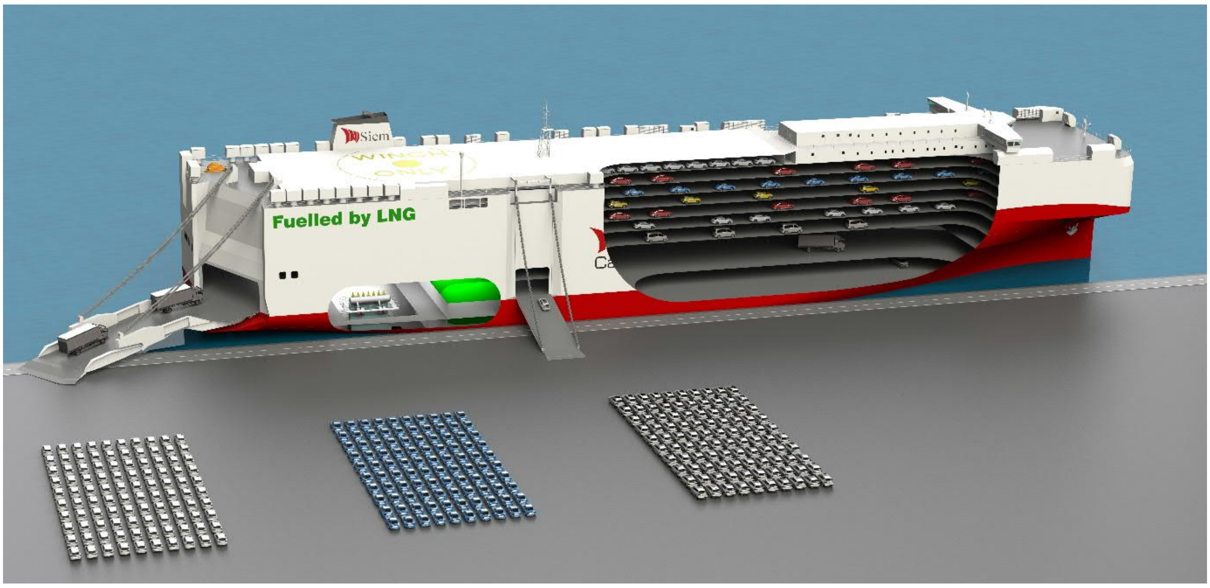

Figure 3. Illustration of the SIEM Confucius, courtesy of SIEM

5.5 The SIEM Confucius design is based on the use of LNG fuel but includes provision for possible future conversion of void spaces to form marine gas oil storage tanks. The main engine is a MAN dual-fuel 7S60ME-C10.5-GI two stroke diesel engine rated at 12,614 kW at 99 rpm. Three dual-fuel four stroke diesel auxiliary engines are installed, two rated at 1,710 kW and one at 1,330 kW.

5.6 The smaller vessel is the Victoria of Wight, a roll-on roll-off passenger ferry in service between Portsmouth and Fishbourne, illustrated in Figure 4. She has a deadweight of 830 te and is 90 m long.

Figure 4. The Victoria of Wight, courtesy of Wightlink

5.7 The Victoria of Wight uses a hybrid diesel electric - battery propulsion system with four 1,200 kW engines burning marine gas oil. The normal running duty is for three of the four engines to be in operation, typically at 60-65% load. The battery allows manoeuvring with minimum change of duty of the engines, reducing emissions and improving fuel consumption.

5.8 The performance of the marine diesel engines in each vessel was analysed to derive the quantity and concentration of carbon dioxide in the exhaust gas streams. The analysis derived the effects on the fuel consumption and the reductions in carbon emissions for the various cases.

5.9 The physical dimensions, weights and power consumptions of the process equipment were based on the process duties derived by the Aspen process modelling.

5.10 The potential location of the main equipment in the reference vessel designs was assessed by naval architects Houlder Limited. The impacts of the additional weights and changed distribution of loads around the vessel was assessed in a stability analysis.

5.11 The application of carbon capture to the various cases is described in the Findings section below.

5.12 The costs of process equipment and its integration with the vessels have been estimated based on a cost estimation tools with supporting budgetary quotations from equipment suppliers for major items. The costs are summarised in the Findings section.

5.13 Levelised (life) costs of carbon capture are derived for the various cases from the capital cost estimates and operating costs calculated from the cost of additional fuel and allowances for equipment maintenance during life.

5.14 The relationship between the case studies and the global fleet is considered to assess the relevance of findings to the wider application of the proposed carbon capture technology.

5.15 The balance of costs of carbon abatement for a carbon capture technology are those related to the unloading and transfer of capture carbon dioxide to geological sequestration or for reinjection for enhanced oil recovery. These costs have been broken down into the costs of unloading facilities, costs of transfer to storage and costs of injection into geological formations.

5.16 The first part of the carbon dioxide transport and storage cost relate to unloading facilities. To allow this be assessed the potential scale of delivery of liquid carbon dioxide from shipping to major UK ports has been estimated. The scale of onward transfer of liquid carbon dioxide from ports remote from industrial carbon capture clusters has been estimated from port traffic data.

5.17 The scale of delivery of marine captured carbon dioxide to the proposed industrial clusters has been used to assess the impacts of increased carbon dioxide delivery on cluster capital and operating costs.

5.18 The final analysis evaluates the range of overall costs of carbon abatement from capture to geological sequestration based on the case studies of the selected vessels using assumptions consistent with the analysis by Frontier Economics for marine decarbonisation[1].

The project findings

5.19 In assessing the impact and feasibility of marine application of cryogenic carbon capture a range of possible implementations were evaluated. The cases are detailed in Table 1 and the corresponding results presented for the SIEM Confucius and Victoria of Wight in turn.

Table 1. Cases evaluated

Reference Vessel	Fuel		Case number		
	LNG	MGO	Unabated	Main Engine only	All Engines
SIEM Confucius	X		1	2	3
		X	4	5	6
Victoria of Wight		X	7		8

5.20 Marine implementation of the carbon capture process involves several elements:

a. Exhaust gas cooling and clean-up

b. Cooling and drying of the gases to separation conditions at around -100ºC

c. Separation of the carbon dioxide

d. Compression and liquefaction of the separated carbon dioxide

e. Refrigeration and chiller systems to support the separation

f. Liquid carbon dioxide storage tanks

5.21 The largest elements among these are the cold box for the cooling and separation units and the carbon dioxide storage tanks.

5.22 The cooling and separation steps use circulating packed beds of fine metallic beads. The high surface area of the beads per unit volume means that intense heat transfer is achieved with separation requiring beds depths of only 50-100mm, resulting in low gas pressure drops through the system.

5.23 The size, detailed arrangement and location of the elements is matched to each vessel and will be described in the following sections.

Process Application

5.24 The carbon dioxide production and its concentration in the exhaust gases was calculated from fuel composition and engine performance data for the various cases. The carbon dioxide capture and residual discharge is summarised in Table 2.

Table 2. Carbon dioxide flows SIEM Confucius

Case		Inlet Carbon dioxide concentration %mol (dry)	Capture at 90% efficiency kg/h CO_2	Remaining Emissions kg/h CO_2	Reduction compared with unabated %
1	LNG unabated	3.65	-	4988	0
2	LNG main engine	3.65	3701	1971	60
3	LNG all engines	3.89	5330	592	88
4	MGO unabated	4.73	-	6510	0
5	MGO main engine	4.73	4843	2796	57
6	MGO all engines	5.04	7375	819	87

5.25 The mixed refrigerant cooling process takes advantage of the heat required at low temperature to sublime the carbon dioxide frost to give a coefficient of performance (COP, which is the ratio of cooling duty to compressor power) of 1.66-1.70. At the separation temperatures conventional refrigeration would achieve a COP of around 0.4. The use of cooling from re-boiling liquid natural gas for the engines can improve performance of the LNG cases further, achieving COPs of over 1.80.

5.26 The cold processes are arranged as a series of columns with screw conveyors circulating the bed material over tubed heat exchangers. An example of the arrangement of one of the two cold boxes considered for Case 2 is shown in figure 5.

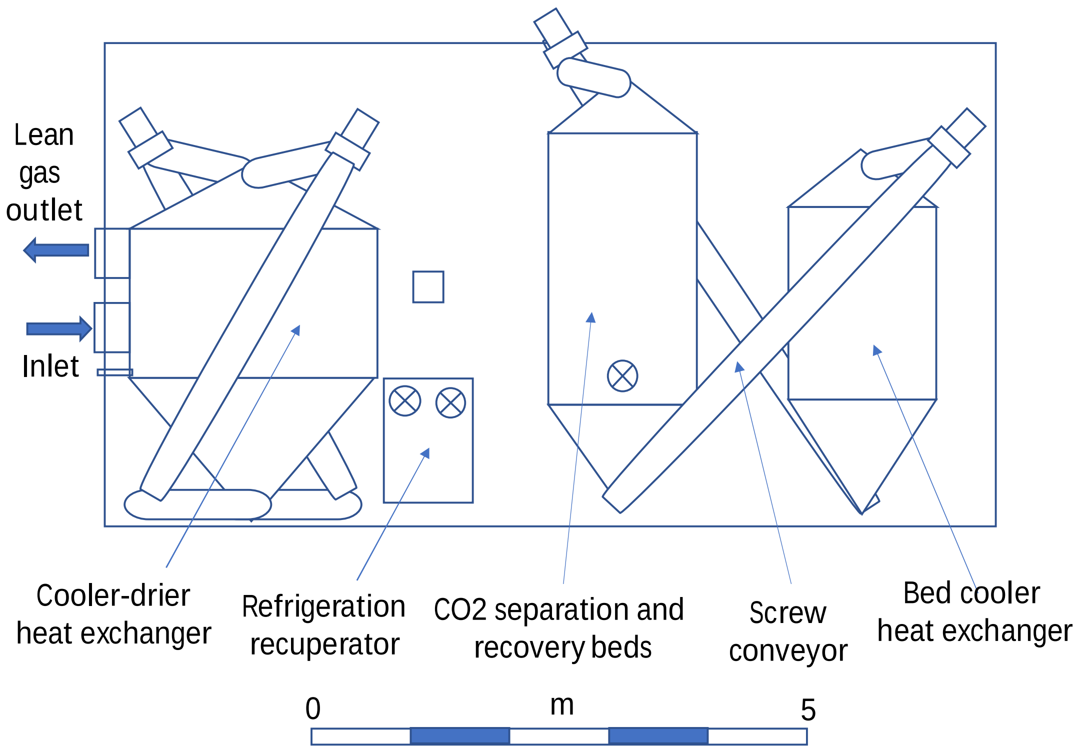

Figure 5. Outline arrangement of separation process units (omitting insulation)

5.27 The dimensions and weight of the separation process unit vary with the case. The units have similar base dimensions of 5m wide by 9m long for all cases but vary slightly in height from 4.5m to 5.2m. Their weights reflect the gas flows, with the cases where only the main engine exhaust is abated having weights of around 100 te, while the all engine cases have weights of 150-170 te.

5.28 The carbon dioxide storage tanks with their content of liquid carbon dioxide are the largest additional load on the vessel. Both the size and weight of the tanks and the weight of their contents depends on the fuel burned and the design maximum range of the vessel.

5.29 The capture of carbon dioxide for longer voyages requires substantial tanks which can reduce the cargo carrying capacity of the vessel. An alternative is a reduced range which limits impacts on the vessel and its cargo capacity. Table 3 summarises the impact of maintaining range while Table 4 shows the impacts at a nominal 50% range.

Table 3. Summary of impacts of carbon dioxide tanks for full range

Case	CO_2 tank capacity te	CO_2 Tank Dia/ Length m	Potential CO_2 tank location	Effect on Cargo space	Increase in arrival weight* te
2	2760	2 x 8.8/ 25.5	Forward of LNG tanks	Reduced by 5%	1100
3	3823	2 x 8.8/ 34.0	Forward of LNG tanks	Reduced by 6%	2300
5	3067	2 x 8.8/ 24.0	In LNG tank space	Increased by 1%	1300
6	4373	2 x 8.8/ 38.4	In LNG tank space	Reduced by 1%	2700

*Compared with departure weight without allowing for any ballast reduction

Table 4. Summary of impacts with reduced range

Case	Fuel capacity %	CO_2 tank capacity te	CO_2 Tank Dia/ Length m	Potential CO_2 tank location	Effect on Cargo space	Increase in arrival weight* te
2	56	1544	8.8/ 28.1	Replaces one LNG tank	Neutral	0
3	50	1911	8.8/ 34.0	Replaces one LNG tank	Neutral	400
5	50	1533	2 x 8.8/ 16.5	In LNG tank space	Increased by 2.5%	0
6	50	2187	2 x 8.8/ 22.4	In LNG tank space	Increased by 2%	630

*Compared with departure weight without allowing for any ballast reduction

5.30 In addition to its impact on weight and utilisation of space within the vessel, the carbon capture process also increases auxiliary power demand, depending on the concentration of carbon dioxide in the exhaust gas stream and the quantity of carbon dioxide captured. The energy consumption of the process is summarised in Table 5.

Table 5. Auxiliary power consumption for the carbon capture cases

Case		Baseline kW	Baseline + capture kW
1	LNG unabated	1854	1854
2	LNG ME only	1854	3543
3	LNG all engines	1854	4278
4	MGO unabated	1854	1854
5	MGO ME only	1854	3918
6	MGO all engines	1854	4973

5.31 The SIEM Confucius design includes three auxiliary engines with a total capacity of 4750 kW. While at sea only two engines would normally be running, providing redundancy in case of breakdown or planned maintenance on one engine.

5.32 All the carbon capture cases would require the three auxiliary engines to be running. Increased auxiliary engine capacity is necessary to provide flexibility for operation and maintenance. A configuration of three or four engines of 1800 to 2600 kW each, according to case, could be accommodated in the engine room. Three could be used if it were acceptable to shut down carbon capture during auxiliary engine maintenance.

5.33 Integration of the additional equipment will require structural reinforcement to support the weight of additional equipment, additional pipework to connect the process equipment and link it to seawater and cooling services. The electrical system will require upgrading, to supply the additional loads and support the extra auxiliary generator capacity. Control, safety and fire systems will also need to be extended.

5.34 The scope of structural reinforcement has been estimated as additional weight considered in the stability assessments.

5.35 The stability studies conducted by Houlder Limited have considered the implications of the changed loading conditions on departure and arrival. These studies assess how the vessel behaves under static and dynamic sea conditions to ensure that adequate margins against capsizing are always maintained. The results show that vessel stability criteria are satisfied in all cases despite the addition of capture process equipment positioned on the top deck and the added weight of captured carbon dioxide on arrival.

5.36 Implementing carbon capture causes a progressive increase in vessel deadweight during voyages since carbon dioxide is heavier than the fuel burned. This results in operation with increasing vessel draught during a voyage which raises the drag and hence fuel consumption for a given speed. The increase in fuel consumption has been estimated to rise to be less than 5% in the worst cases. For most operation it is expected that the increased fuel consumption will be of the order of 1%.

5.37 A minor finding of the stability studies was that the original vessel layout resulted in an asymmetrical equipment arrangement, increasing ballast requirements. A more symmetrical arrangement would minimise this impact, reducing fuel consumption.

Estimation of Cost Impacts

5.38 The addition of carbon capture and storage facilities to the vessel design will have an impact on its capital and operating cost. The capital costs for the additional equipment, its integration into the vessel design and its impact on operating costs have been estimated to enable a levelised cost of carbon abatement to be calculated.

5.39 Capital cost estimation at an early stage in any project is subject to considerable uncertainty. The American Association of Cost Engineers define the uncertainty in estimating conceptual stage designs to be between +50%/-30% and +100%/-50%. Cost estimates presented here are likely to be subject to this level of uncertainty.

5.40 Cost estimates have been derived in several ways:

- Budgetary quotations – e.g. liquid CO_2 tanks, major compressors, inlet gas coolers
- Cost estimation databases – the Aspen costing tool has been used to estimate the cost of process equipment, cross-checked with other costing packages
- Minor items and scope such as cabling that cannot be quantified at this stage, have been estimated as a percentage of the cost of major equipment items

5.41 Equipment costs represent only part of the costs of a complete installation. Costs of installation, interconnection pipework, civil works, electrical and instrumentation equipment and cabling all need to be allowed for. Similarly the costs of engineering, contractors' management costs and profit, integration with external facilities, technology licensing, commissioning and start-up, contingencies and interest during construction need to be included.

5.42 The process industry has established estimates of these additional costs for a conventional land-based chemical plant. Typical contributions from literature are detailed in the first column in Table 6.

Table 6. Total project cost build-up from direct equipment costs

	Conventional chemical plant %	Factory built plant %	Series built plant %
Direct equipment cost	100	100	90
Construction expenses	38	15	10.8
Contractor's fee	19	8	5.4
Inside battery limit	157	123	106.2
Offsites/ interfacing	23.6	18.5	15.9
Process unit investment	180.6	141.5	122.1
Engineering	21.7	17.0	3.7
Paid up royalties	11.0	8.6	3.2
Project contingencies	36.1	14.1	6.1
Fixed capital investment	249.3	181.2	135.1
Start-up	24.9	18.1	6.8
Interest during construction	22.4	8.2	4.1
Total capital requirement	296.7	207.4	145.9

5.43 The additional costs for a ship-board process plant will reflect the very different manufacturing and installation methods. The plant will be factory assembled as a series of modules by the supplier and delivered to the shipyard. The modules will be installed and linked in large sub-sections of the vessel under cover in the dockyard. The sub-sections will in turn be assembled to form the vessel.

5.44 The conventional cost multipliers have been adjusted in the second column of Table 6 for the lower cost of factory assembly rather site erection, the absence of civil and building works, the reduced contractor costs due to the streamlined processes for shipbuilding and the low interest costs due to more rapid construction.

5.45 If the process were to be widely applied to shipping, the production of carbon capture process equipment would benefit from series production. This would reduce equipment costs for multiple purchase, cut costs and duration of construction due to the greater use of jigs and automation, distribute engineering costs across multiple installations and reduce the risks and hence contingencies needed. A typical set of cost contributions for series production is shown in the third column of Table 6.

5.46 The cost reductions achieved from series production represent the benefit of learning from experience. Learning curves for cost reduction are detailed in the Frontier Economics Scenario Analysis, with different rates of learning according to the maturity of the technology. Higher rates of learning are applied for technologies subject to rapid fundamental advances, while more modest rates are applied to processes using more conventional process equipment in a new application. The Frontier Economics learning curves show reductions of 50% and 25% by 2031 for higher and medium rates of learning, respectively. The A3C process falls between these categories.

5.47 Table 6 shows an expected reduction of 30% for the move from the initial factory built plant to series production, consistent with the Frontier Economics medium learning rate curves.

5.48 Table 7 and Table 8 summarise the breakdown of capital cost estimates for the full and half range cases. The upgrade of auxiliary generation capacity is treated separately as it is only a change to existing capacity, requiring minimal additional engineering scope and presenting limited opportunity for cost reduction through learning. Negative costs represent savings against the base design.

Table 7. Summary of capital costs for the SIEM Confucius full range cases

Case	2a	3a	5a	6a
	LNG ME only £k	LNG all engines £k	MGO ME only £k	MGO all engines £k
Inlet cooler	1037	1502	1037	2131
Cold box	1856	2132	1996	2201
Refrigeration	1261	1487	1387	1705
Liquefaction	202	276	250	355
Liquid CO2 Storage	1219	1753	228	910
Direct equipment cost	5575	7150	4898	7303
Total capital requirement	11541	14801	10139	15117
Auxiliary generation upgrade	784	1168	989	1680
Total capital cost	12325	15969	11128	16797
Total capital cost after learning	8863	11529	8086	12262

Table 8 Summary of capital costs for SIEM Confucius reduced range cases

Case	2b	3b	2b	3b
	LNG ME only £k	LNG all engines £k	MGO ME only £k	MGO all engines £k
Inlet cooler	1037	1502	1037	2131
Cold box	1856	2132	1996	2201
Refrigeration	1261	1487	1387	1705
Liquefaction	202	276	250	355
Liquid CO2 Storage	-58	214	-569	-228
Direct equipment cost	4298	5611	4102	6165
Total capital requirement	8897	11614	8491	12762
Auxiliary generation upgrade	784	1168	989	1680
Total capital cost	9681	12782	9479	14442
Total capital cost after learning	7012	9298	6932	10614

5.49 The main operating cost impact is on extra fuel consumption to provide additional auxiliary power for the carbon capture and liquefaction processes. Operation and maintenance costs of the vessel will also be increased for the additional equipment. No increase in crew numbers is anticipated so these costs will primarily be for spare parts. Annual costs in Table 9 use 2031 fuel costs forecast by BEIS, as used for the Frontier Economics study, and assume 7200 hours at sea per annum.

Table 9 Operating costs for the SIEM cases

Case		Additional Fuel te/y		Fuel Cost	Maintenance	Total
		LNG	MGO	£k	£k	£k
2	LNG ME only	1788	232	942	210	1152
3	LNG all engines	2567	334	1353	279	1632
5	MGO ME only	-	2839	1249	208	1457
6	MGO all engines	-	4289	1887	318	2205

Levelised costs of carbon capture

5.50 The capital and operating cost estimates allow the levelised cost of carbon capture in 2031 to be calculated for each case, shown in Table 10, using assumptions for life and discount rate consistent with the Frontier Economics study of 20 years and 10%.

Table 10 Levelised costs of carbon capture

Case/ range		Annualised capex £k	Opex £k	Carbon abated te CO_2/y	Levelised cost of capture £/te CO_2
2a	LNG ME only/ full	1041	1152	26654	82.3
2b	LNG ME only/ half	824	1152	26654	74.1
3a	LNG all engines/ full	1354	1632	39751	75.1
3b	LNG all engines/ half	1092	1632	39751	68.5
5a	MGO ME only/ full	950	1457	34870	69.0
5b	MGO ME only/ half	814	1457	34870	65.1
6a	MGO all engines/ full	1440	2205	54490	66.9
6b	MGO all engines/ half	1247	2205	54490	63.4

5.51 The trend of the levelised costs of carbon capture in Table 10 demonstrates the economies of scale and shows significant savings if reduced range and hence smaller carbon dioxide storage could be adopted. The absolute levelised costs are highly competitive with conventional amine capture applied to emissions at this scale, where levelised costs are typically 100 to 150 £/ te CO_2[2]

5.52 The operational implication of adopting reduced range for a vessel is that bunkering and carbon dioxide unloading would be required more than once in the longest voyage foreseen for the vessel. This might mean bunkering on both sides of the Atlantic rather than only once during a round trip. This could affect costs and would require carbon dioxide receiving facilities at the departure and arrival ports. This may not represent a problem as fuels are widely available and carbon dioxide receiving facilities foreseen in Europe would generally be for sequestration while those already existing in the US are for enhanced oil recovery.

Victoria of Wight

5.53 Analysis of the fuel and exhaust gas flows derived the exhaust gas composition and carbon dioxide production for the cases are summarised in Table 11.

Table 11. Total exhaust gas and carbon dioxide flows Victoria of Wight

Case		Inlet carbon dioxide concentration %mol (dry)	Capture at 90% efficiency kg/h CO_2	Remaining emissions kg/h CO_2
7	MGO unabated	5.8	-	1434
8	MGO all engines	5.8	1565	174

5.54 The duties of the various heat exchangers within the separation process determine the size and weight of the main process equipment. For the Victoria of Wight two separation units would be used. Each engine will have a separate exhaust gas cooler, two engines feeding a separation module. The normal operating regime of three engines in service would mean that one module would operate at full capacity while the other would be at 50% capacity.

5.55 The common refrigeration compressor will deliver high pressure refrigerant to the two separation modules. Its power consumption is estimated to be 390 kW.

5.56 The separation unit for the Victoria of Wight will be as shown in Figure 5, but scaled down to approximately 2.5 m wide by 6 m long, with a height of around 5 m and weight of about 40 te.

5.57 Since the Victoria of Wight makes repeated short crossings between Portsmouth and Fishbourne, storage of the captured carbon dioxide can be simplified. This would allow use of a cryogenic UN T75 ISO tank container, as in Figure 6. The trailer mounted tank would provide storage and simplify unloading and delivery to customers. Location on the open vehicle deck area would minimise any potential safety issues from leakage.

Figure 6. Typical 20’ T75 ISO Tank

5.58 The capacity of such a 20’ T75 ISO tank would be equivalent to approximately 15 hours sailing time, the typical daily duty during high season. This carbon dioxide storage strategy would therefore be simple, requiring the tank container to be unloaded and replaced daily.

5.59 The capture process will incur an additional auxiliary power demand on the vessel. The total additional auxiliary demand is estimated at 571 kW. The electrical system of the Victoria of Wight is supplied by the four main engine/ generators and the battery system power converter to feed the electrically driven thrusters and propulsion units. Vessel auxiliaries are supplied from this common power network. The additional power demand to supply the carbon capture process will therefore result in an increased running load for all engines. This will in turn increase the engine duty, fuel burned, and carbon dioxide produced. The additional demand results in an increase in average engine duty from 64% to 79%.

5.60 Evaluation of vessel arrangement identified the most suitable position for the process equipment to be adjacent to the funnel. The implications of the additional weight on vessel stability were assessed by Houlder Limited finding the stability criteria were again satisfied.

5.61 Table 12 lists capital costs for the Victoria Wight on the same basis as for the SIEM vessel.

Table 12 Capital cost estimates for the Victoria of Wight

Item	Cost £k
Inlet cooler	408
Cold box	1279
Refrigeration	775
Liquefaction	82
Liquid CO_2 Storage	0
Direct equipment cost	2545
Total capital requirement	5268
Auxiliary generation upgrade	0
Total capital cost	5268
Total capital cost after learning	3687

5.62 Operating cost estimates listed in Table 13 show the additional fuel consumption as result of the engines running at a higher load. It has been assumed that the engines are only operating while at sea, i.e. fifteen hours a day, approximately 350 days per year.

Table 13 Operating Costs for the Victoria of Wight

Additional Fuel te/y MGO	Fuel Cost £k	Maintenance £k	Total £k
502	221	111	332

5.63 The levelised cost of carbon capture in 2031, calculated based on the capital and operating costs, is shown in Table 14. Again assumptions for life and discount rate consistent with the Frontier Economics study of 20 years and 10% have been used.

Table 14 Levelised costs of carbon capture

Annualised capex £k	Opex £k	Carbon abated te CO_2/y	Levelised cost of capture £/te CO_2
433.1	332	8316	93.07

Implications of case studies to the global shipping fleet

5.64 The relationship between the selected case study vessels and the global shipping fleet has been evaluated. The largest available dataset for comparison with the global maritime fleet is that assembled by the IMO as part of its Third GHG Report 2014[5]. The relevant data is from 2012. Figure 8 shows the relationship between the installed engine power and deadweight of various classes of shipping.

5.65 The range of scale of engine power installed in vessels in this comprehensive dataset extends from 1,000 to 100,000 kW, while the range of vessel deadweight is from 400 to 300,000 te. This reflects the relationship between hull wetted area and resistance, with propulsion power being a function of deadweight to the power 0.667.

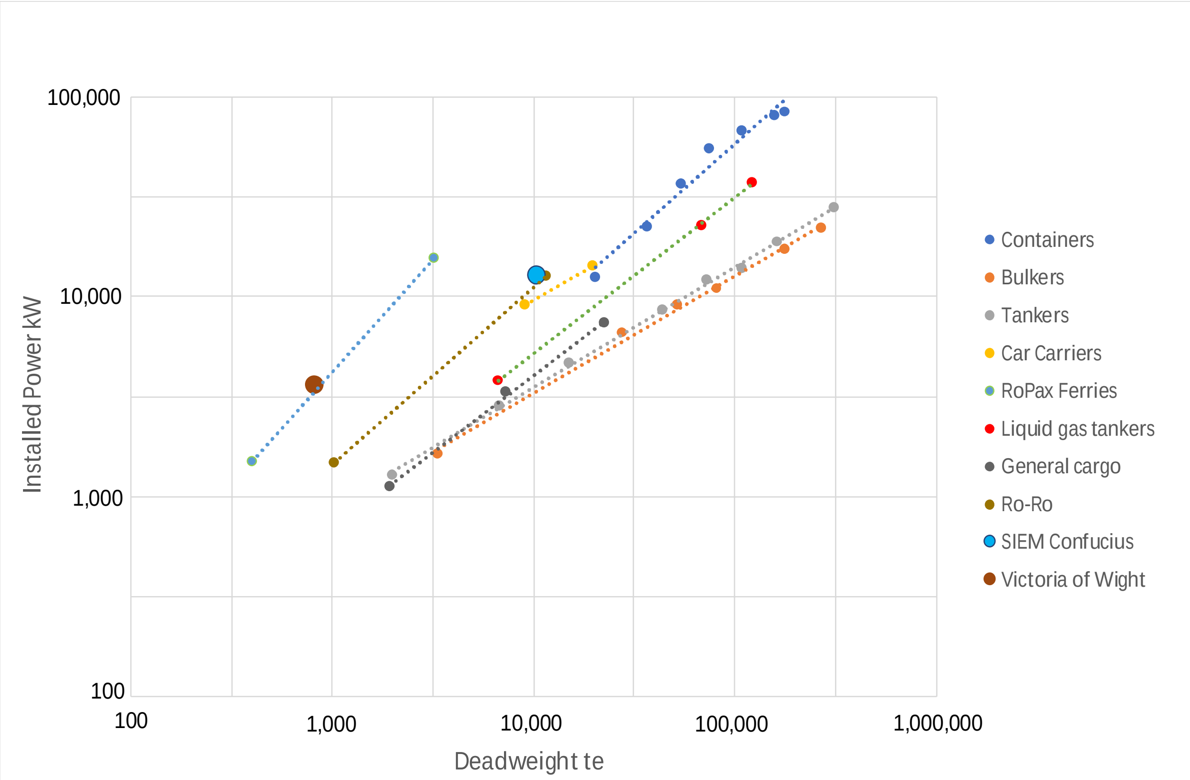

Figure 8. Relationship between selected vessels and IMO global fleet data 2012

5.66 The varying slopes of the trendlines in Figure 8 result from the differing design speeds of the shipping types. Cruise speeds for container ships, for example, are typically 20-25 knots while tankers and bulkers (bulk carriers) are designed for 12-16 knots.

5.67 In Figure 8 the installed engine power for the Victoria of Wight and the SIEM Confucius can be seen to lie close to the trendline for their shipping type but above most shipping by deadweight at their scale. This means that applying this carbon capture technology to representative shipping will be much smaller and cheaper in proportion to the vessel size and cost than for the case studies. Hence the effects on the cargo carrying capacity, stability and draught will also be correspondingly less significant.

[5] IMO Third Greenhouse Gas Report 2014

Shore Infrastructure

5.68 Effective application of marine carbon capture requires appropriate port infrastructure to be in place to receive and transfer liquid carbon dioxide to geological storage or reuse. This infrastructure will include bunkering facilities for unloading, storage tanks to buffer deliveries and either interfaces to a local industrial carbon capture and storage cluster or ship loading facilities to transport the liquid carbon dioxide to a remote cluster port.

5.69 The nature of this infrastructure will depend on the quantity of marine carbon dioxide to be unloaded. Figure 9 shows the 2018 maritime trade at major UK ports[6], highlighting those close to proposed industrial clusters with offshore geological sequestration.

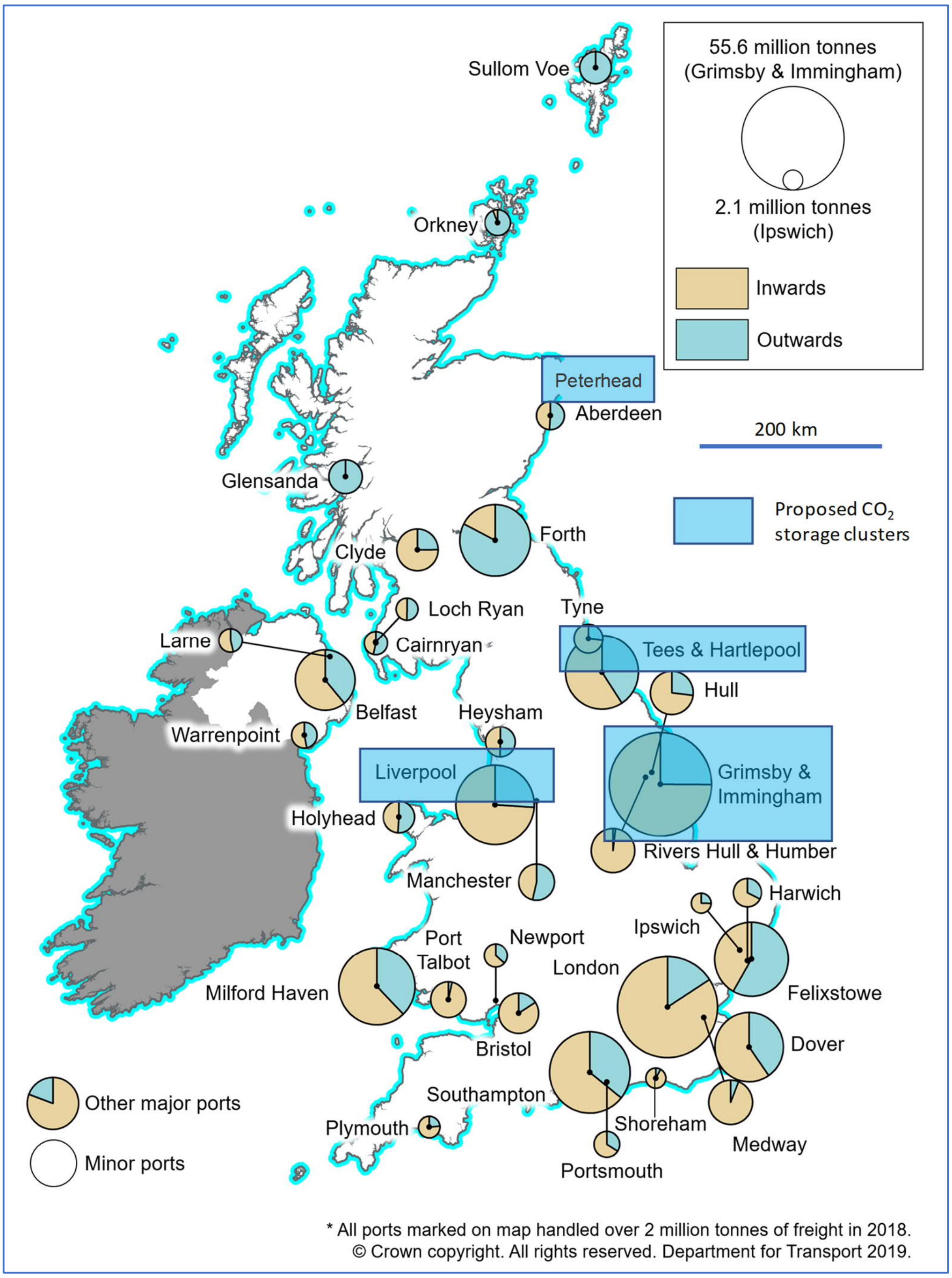

Figure 9. Major UK ports identifying proposed associated geological sequestration clusters

[6]Downloaded 4 May 2020 from https://www.gov.uk/government/collections/maritime-and-shipping-statistics

5.70 Figure 9 shows that while the four major storage clusters represent only a part of UK shipping traffic, all major ports are within 600 km by sea to the nearest storage cluster.

5.71 The report by Element Energy for BEIS[7] derived costs of carbon dioxide liquefaction, loading, unloading and ship transport. The cost of shipping was shown to be £5.90/ te CO_2 for round trips from port to an offshore store 600km away. This indicates that the cost of transhipment will be a small fraction of the carbon dioxide abatement cost so that onward shipment of liquid carbon dioxide to ports with an adjacent cluster with sequestration would be economic.

5.72 Fuel is conventionally delivered to ships from either a bunkering vessel or from a fuelling quay. Fuel oils and LNG are transferred using flexible hoses, with balancing vapour return lines to manage tank pressures being used for LNG. Connections of the hoses may be made manually or, particularly with the low temperature and fire hazards of LNG, by a remotely operated coupling on a loading arm. Arrangements similar to those for LNG handling are foreseen for handling liquid carbon dioxide.

5.73 A flexible bunkering vessel design to load LNG or MGO and unload liquid carbon dioxide has been developed by Houlder Limited. This is illustrated in Figure 7.

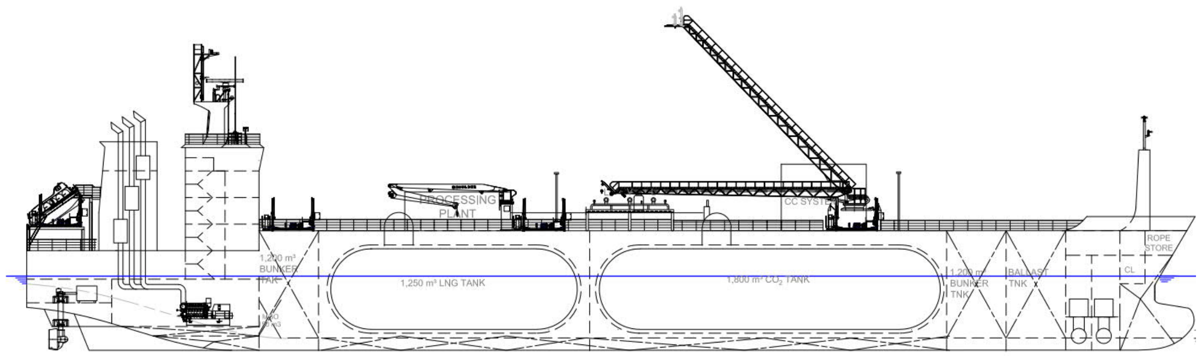

Figure 10. Combined LNG/MGO bunkering and liquid CO_2 unloading vessel

5.74 The relationship between the major ports and the industrial clusters with geological sequestration was analysed. For simplicity it was assumed that carbon dioxide delivery is proportional to freight traffic. The results are summarised in Table 15, showing the potential shares of UK marine carbon captured delivered directly or indirectly to the four major industrial storage clusters.

Table 15. Potential share of UK captured marine CO_2 delivered to each cluster

Cluster	Adjacent Port	Share of UK marine CO_2	Local Port	Transhipped	Potential 2031 $MtCO_2$/y
Humberside	Grimsby & Immingham	51.0%	23.1%	76.9%	2.68
Liverpool/ Manchester	Liverpool	30.5%	22.7%	77.3%	1.60
Teesside	Tees & Hartlepool	7.0%	86.8%	13.2%	0.37
Acorn/ St Fergus	Peterhead	8.6%	2.8%	97.2%	0.45

5.75 The transhipment patterns are likely to be more complex than assumed for this analysis due the economics of scale on different routes, varying harbour fees and the availability of import

[7] Element Energy, Shipping CO_2 – Cost estimation study, Final report for BEIS, November 2018

and export facilities. Despite these limitations Table 15 indicates that the Humberside and Liverpool/ Manchester clusters would be likely to receive significant captured carbon dioxide from UK shipping, with a large proportion of that received by transhipment.

5.76 Several of the UK industrial capture clusters are not in areas with suitable geology for carbon dioxide sequestration. As a result they propose to ship the captured carbon dioxide in bulk as liquid to other clusters for injection into their sequestration facilities. The South Wales cluster is a prime example, planning to ship up to nine million tonnes per year to the Liverpool/ Manchester or Peterhead/ St Fergus cluster for sequestration.

5.77 The planned unloading facilities for carbon dioxide import from remote industrial capture clusters will be extensive. These will include vessel unloading quays and carbon dioxide storage tanks with pumps and regasification heaters to deliver carbon dioxide to the cluster offshore pipeline. This comprehensive infrastructure will reduce the dedicated provision for handling carbon dioxide captured on shipping to smaller scale unloading arrangements.

5.78 At industrial clusters without sequestration, the necessary carbon dioxide export facilities will include substantial storage and ship loading facilities. Only limited additional development to provide alternative piping routes would be required to link unloading of carbon dioxide from marine capture with existing facilities.

5.79 Hence only ports which are not planned to be part of industrial carbon dioxide clusters will need significant development of facilities for unloading and exporting marine carbon dioxide. These would include London, Southampton and Felixstowe, together representing about 25% of UK freight traffic.

5.80 The economic scale for development of unloading and export facilities for marine carbon dioxide will change as carbon capture on shipping becomes more common. Initially only ports with large potential deliveries of carbon dioxide from marine capture would be developed. Felixstowe might be such a case with its regular arrivals of large long-haul container ships. Subsequently smaller ports would be developed in parallel with transhipment capacity, with a likely floor for carbon dioxide export of 30-60,000 te/y representing a sufficient fraction of a cargo of a 5,000 te capacity tanker loading once every two weeks.

5.81 Delivery of carbon dioxide from port bunkering facilities will increase the carbon dioxide throughput of the cluster offshore pipeline and geological storage facilities. Such additional flows will increase operating costs but improve utilisation of the capital investment in pipeline and offshore facilities. Since fixed capital and operating costs generally dominate the costs of transport and storage, the overall impact of the additional flow is likely to be a reduction in costs per tonne stored.

5.82 The magnitude of any cost reductions will depend on the scale of the additional flow contributed by carbon dioxide delivered from marine capture.

5.83 The functions of bunkering at major ports where additional facilities were required to handle carbon dioxide captured at sea would include unloading, transfer to storage, storage tanks, boil off gas re-liquefaction and loading pumps.

5.84 Unloading equipment could either be a suitably equipped bunkering vessel or additional unloading arms on a quay or jetty where other cargos were loaded or unloaded. While a bunkering vessel could deliver liquid carbon dioxide directly to the onshore storage tanks, a pipeline link would otherwise be needed.

5.85 The costs of such a facility with 10,000 te of storage capacity are estimated in Table 16, using costing data from the BEIS carbon dioxide shipping study[7]. Throughput is assumed to be 150,000 tonnes per year, which would represent less than 50% utilisation at Felixstowe.

Table 16. Estimated costs for liquid CO_2 unloading, storage and transfer facilities

Item	Capex £m	Opex £m/y	Levelised cost £/teCO_2
Bunker vessel*	5	0.5	4.40
Unloading arms	1	0.05	1.01
Pipeline to store	1	0.05	1.01
Storage tanks	5.2	0.16	4.60
BOG re-liquefaction	0.2	0.01	0.20
Loading pumps	0.2	0.01	0.20
Total			7.02 – 9.40

*Proportion of costs only for carbon dioxide handling element of services.

5.86 The cost of transhipment was evaluated in the Element Energy study for a ship transporting 10,000 te loads of liquid carbon dioxide between a source and storage facility 600km apart. The levelised costs, inclusive of capital, operating and fuel of the vessel and harbour fees totalled £5.90/te CO_2.

5.87 The cost of transhipment will be largely dependent on distance. The distance between major ports and their nearest storage hubs and estimated shipping costs are shown in Table 17.

Table 17. Distances and estimated costs between major ports and the nearest storage hub

Port	Distance to nearest hub km	Estimated shipping cost £/te	Share of UK freight traffic %
London	422	4.15	11.3
Southampton	600	5.90	7.3
Milford Haven	361	3.55	6.6
Felixstowe	388	3.82	6.0
Freight Weighted average		4.37	

5.88 Aggregating the costs for loading and transfer of liquid carbon dioxide detailed in Tables 16 and 17 gives a total cost of £11.39 – 13.77 /teCO_2 transported. However no such costs apply to carbon dioxide landed directly at ports with an associated carbon storage cluster. Based on freight traffic data summarised in Table 15, the carbon dioxide directly landed at clusters is 25% of the UK total. Hence averaged over the total captured UK marine carbon dioxide the levelised cost for loading and transfer will be £8.54-10.33 /te CO_2.

5.89 Offshore transport and storage costs have been published for a series of proposed geological storage projects, notably for the Hynet Liverpool/ Manchester cluster[8], the Teesside cluster[2] and for the Acorn project[9] at St Fergus. The published work relates to relatively small flows to storage of between 1.5 and 3 $MtCO_2$/y. Table 18 shows their capital and operating cost estimates and the corresponding specific costs of storage calculated consistently with those for the Hynet Project.

Table 18. Published carbon dioxide storage costs for proposed clusters

Cluster location	Storage rate $MteCO_2$/y	Total Capex £m	Total Opex £m/y	Specific cost £/teCO_2
Liverpool/ Manchester	1.59	83	10.0	10.01
Teesside	2.83	420	49.6	14.53†
St Fergus	2.00*	276	19.6	13.90

*Assumes 1.8 $MteCO_2$/y in Phase 2 development †Calculated for installed capacity

5.90 These projects are being developed further under the Industrial Clusters Mission and it is understood that they are all evaluating capacities to 5-15 $MteCO_2$/y. Such an increased capacity will reduce the specific cost of carbon storage significantly, probably to around 80% of the earlier estimates. This would represent a typical cost of offshore transmission and storage of around £10 /teCO_2.

5.91 The impact of additional flows of up to 2.5 $MteCO_2$/y into the clusters will be to reduce the fixed costs per tonne of carbon dioxide chargeable to all users. Since the capital and much of the operating cost are fixed, the reduction in unit cost from the additional flows would be approximately proportional to the percentage increase in throughput. However as the planned capacity of the clusters has not been finalised to date, it is not currently possible to estimate these cost savings.

Aggregating the overall cost of carbon abatement for shipping

5.92 The overall costs for carbon abatement using A3C carbon capture for the larger SIEM Confucius car carrier are presented in Table 19 and illustrated in Figure 11.

Table 19. Overall specific costs of carbon abated for the full range cases

	LNG		MGO	
	ME only	All engines	ME only	All engines
Vessel Capex	39.1	34.1	27.2	26.4
Vessel Opex	43.2	41.1	41.8	40.5
CO_2 delivery to clusters	8.54/10.33	8.54/10.33	8.54/10.33	8.54/10.33
Offshore sequestration	10.0	10.0	10.0	10.0
Total	100.8/102.6	93.7/95.5	87.6/89.4	85.4/87.2

[8] Progressive Energy Limited for Cadent, The Liverpool-Manchester Hydrogen Cluster: A Deliverable, Low cost Project, August 2017

[9] Pale Blue Dot for Acorn Project, D16 Full Chain Development Plan and Budget, 10196ACTC-Rep-19-01, May 2018

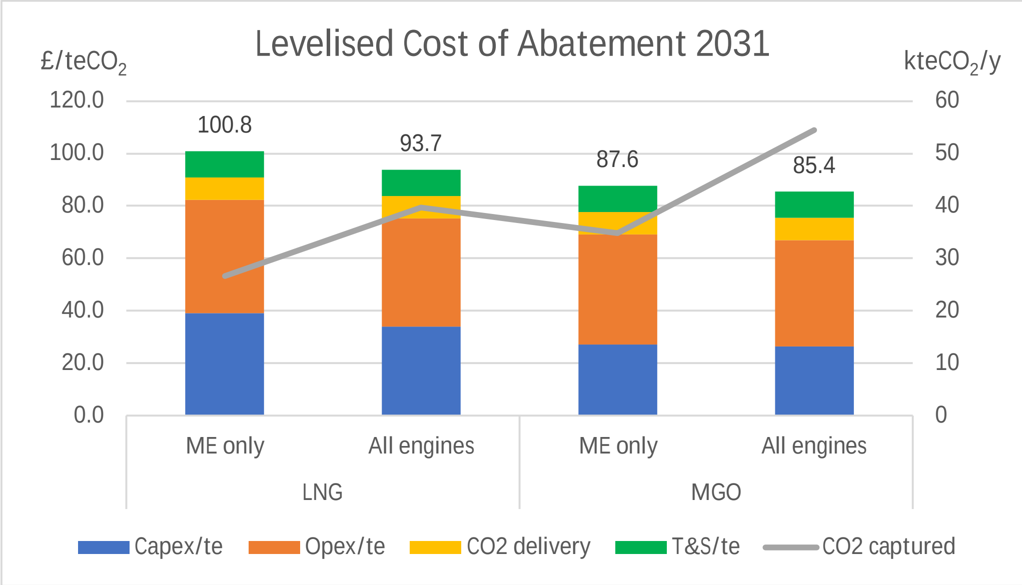

Figure 11. Levelised cost of carbon abatement for various capture options

5.93 The total levelised costs for the Victoria of Wight depend on assumptions about carbon dioxide disposal or sale. If the carbon dioxide is sold to customers within reach of Portsmouth it is likely that the value of sales would cover at least the cost of transport. In that case the total cost of abatement would be the cost of capture, around £93/ te CO_2. Alternatively if a carbon capture cluster were to be established in the region then the total costs would include road transfer to the cluster plus the cluster transport and storage costs. The total costs would be about £120/te CO_2 in that case.

Limitations of the proposed concept

5.94 Decarbonisation of shipping presents challenges from the diversity of scale and function of vessels. A range of solutions are likely to be needed with their adoption determined by economic and practical considerations. The application of carbon capture technology affects both the vessels and the shore infrastructure for carbon dioxide transfer to geological storage. The limitations that these impose will be reviewed in turn.

5.95 The case studies have shown that application of carbon capture to vessels can affect various aspects of vessel design and operation:

- Cargo capacity – limited reduction likely (<5% typically)
- Range – longer ranges result in larger reductions in cargo capacity
- Fuel consumption – increases with capture scope and carbon content of the fuel
- Stability – limited impact provided equipment can be located suitably
- Engine rating – multiple process modules are likely for ratings over 5-10 MW

5.96 The application to vessels will also be determined by economic considerations. For example, at smaller scales or for short range vessels, the added cost of the capture facilities may be less cost effective than the use of more expensive zero carbon fuels.

5.97 Application will also be affected by the availability of port facilities to handle liquid carbon dioxide. Many ports in industrial areas are equipped for carbon dioxide handling for international trade. However this capacity will need to be developed and linked by pipeline or onward transhipment to geological sequestration. This can be combined with the development of industrial carbon capture clusters around ports, as is already being proposed in the UK and in Norway.

5.98 Early international roll-out may be limited by availability of ports equipped for carbon dioxide unloading and transfer to sequestration or EOR. Initial roll-out beyond the likely carbon capture clusters around the North Sea basin and oil-producing regions such as the Gulf of Mexico, North Africa and of the Middle East, may be restricted. The subsequent wider development of industrial carbon capture clusters and shipping of carbon dioxide to sequestration and EOR facilities will remove this restriction.

5.99 The larger scale application of carbon capture to shipping will require government commitment to support for sequestration or EOR facilities. The US government already offers tax incentives for EOR and the Norwegian government has committed to the construction of the Northern Lights sequestration project off Bergen. The implementation of the Industrial Clusters Mission should establish clusters and offshore carbon sequestration facilities for the UK. Adding limited additional facilities for the unloading of carbon dioxide would enable these clusters to act as hubs for the growth of marine carbon capture.

6. Next steps

6.1 Three stages of development are foreseen:

- Build and evaluate a laboratory scale pilot
- Undertake the front end design of a complete demonstrator and qualify the technology for marine application
- Construct the demonstrator and undertake shore trials, followed, subject to approval by a classification society, by sea trials

6.2 Table 20 details the estimated costs, time and resource requirements.

Table 20. Cost, time and resource estimates for development stages

Stage	Equip't cost £k	Staff resource hours			Rig hall Hire £k	External contract £k	Total cost £k	Duration Months
		Tech'n	Academic	PMWT				
Lab pilot	40	400	60	800	6	0	100	6
Demo FEED	0	0	60	800	0	100	146	9
Demo build	250	400	30	1600	6	200	547	12
- Shore trials	10	200	30	400	0	50	87	3
- Sea trials	50	400	30	800	0	130	231	6
Total	350	1400	210	4400	12	480	1,111	36

6.3 We have already applied for support from the University of Chester for a laboratory pilot and are proposing to apply for funding to the ACT3 programme for demo FEED stages of development. We are considering applying for a similar scope to the forthcoming OGCI call.

6.4 We have established non-disclosure agreements with international oil company groups and major shipping companies to explore the application of the technology to their fleets and investigate investment options. We are in discussion with Thyson Technology as process development partner and Houlder Limited to act as application designers and interface with fleet owners, classification societies and vessel charterers.

Dissemination Plan

6.5 We issued a press release on announcement of the award of the T-TRIG grant. We have contributed with Houlder Limited to articles on marine carbon capture in Clean Shipping International[10] and Bunkerspot[11]. We plan to issue further press releases on completion of study. The targets for our dissemination are shipping and oil companies. Our message is that there is a viable alternative to zero carbon fuels for shipping and that it could be radically less costly, could be retrofitted and could be put in place more quickly than alternatives.

6.6 Our press releases and articles have raised considerable interest with major shipping companies e.g. Stena Bulk, and major oil companies. We have received a series of enquiries leading to further discussion. Several such dialogues are on-going under confidentiality agreements.

[10] https://www.csi-newsonline.com/js/plugins/filemanager/files/csi/CSI_Summer_2020_magaine_web.pdf page 38
[11] www.bunkerspot.com/images/mags/flipbook/bs_v17n3_JunJul20/mobile/index.html#p=4 page 83

7. Conclusion

7.1 Case studies analysed in this study have demonstrated the technical and economic feasibility of the application of advanced carbon capture to shipping at scale.

7.2 The cost of abatement of shipping carbon emissions by A3C carbon capture, including both vessel and shore infrastructure costs, is estimated to be between £85 and 120/te CO_2 according to case, substantially below the abatement costs of £180/te CO_2 for ammonia reported in the Frontier Economics Scenario Analysis for the DfT.

7.3 Both carbon capture and storage and large scale ammonia production for shipping will require substantial infrastructure development. However the infrastructure for carbon capture and storage is already being developed for industrial decarbonisation so that costs and savings can be shared. The scale of ammonia production necessary to decarbonise the marine fleet is recognised to be very large, at around 400% of current global production, with investment estimated at over $1 trillion by the Global Maritime Forum[3].

7.4 With the potential of a saving of approximately 50% in the cost of marine decarbonisation and benefit of sharing and promoting facilities for industrial decarbonisation, further work to establish the feasibility and demonstrate practicality of marine carbon capture is strongly justified.

7.5 Publicity following award of the T-TRIG grant has resulted in considerable interest in the technical press leading to the publication of articles and a series of approaches by shipping and oil companies. Several such dialogues are proceeding under non-disclosure agreements.

7.6 Plans for further development of the technology to demonstrate the process at pilot scale and subsequently prepare a high level design for a demonstration unit to be qualified by a classification society have been defined. These will form the basis of funding applications to the ACT3 call and possible OGCI call this summer. The follow-on construction of the demonstration unit and its shore and subsequent sea trials have been outlined. The defined programme of work could result in the process being demonstrated at sea within three years of award of funding.

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