SOUTHAMPTON MARINE & MARITIME INSTITUTE

University of Southampton

Open call for evidence

Carbon capture, usage and storage (CCUS): non-pipeline transport and cross-border CO2 networks

July 2024

Questions

1. Who are you responding on behalf of, and what is your interest in this call for evidence?

This response is prepared by members of the Southampton Marine and Maritime Institute (SMMI) at the University of Southampton. The SMMI is a large multidisciplinary community of more than 400 ocean-facing researchers investigating a spectrum of topics including marine science, climate change, maritime and offshore engineering, energy systems and maritime law. This specific response involves researchers engaged in the UKRI-EPSRC Industrial Decarbonisation Research and Innovation Centre (IDRIC) Project #50, CO_2 – Ports to Pipelines (CO2P2P) that investigated, from energy, cost, feasibility, regulatory and public acceptance points of view, the shipping of CO_2 from industrial regions without local permanent geostorage to ports where offshore CO_2 geostorage was being developed.

The CO_2P2P study produced three major reports lodged with IDRIC. These reports are currently in review or being prepared for publication in the peer-reviewed academic literature. These reports are also being complemented by knowledge exchange syntheses for a range of stakeholders including local and national government, industry and the public.

Vakili, S., Manias, P., Topic, T., Dbouk, W., Armstrong, L.-M., Turnock, S.R., & Teagle, D.A.H., (2023) *CO_2 energy flows from capture, maritime transport to offshore geostorage*. IDRIC Project 50 – CO_2 from Port to Pipeline (CO_2P2P), 51p.

Dbouk, W., Teagle, D.A.H., Ntovas, A., Armstrong, L.-M., Turnock, S.R., (2024). *Review of the Legal and Regulatory Framework for CO_2 Shipping as part of Carbon Capture and Storage in the United Kingdom*, IDRIC Project 50 – CO_2 from Port to Pipeline (CO_2P2P), 137p.

Feetham, P., Carlisle, D., Wright, M.J., Teagle, D.A.H., (2023). *Public perceptions of shipping and storing Carbon Dioxide*. IDRIC Project 50 – CO_2 from Port to Pipeline (CO_2P2P), 59p.

We note that Vakili et al., 2024 "*Optimising Life Cycle Costs of Carbon Capture and Storage: Insights for Shipping CO_2 from the Solent Region*" was recently awarded the "Best Paper on the Green Maritime Ecosystem" at International Association of Maritime Economists IAME 2024, Valencia, June 2024.

Vakili, S., Armstrong, L.-M., Teagle, D.A.H., Turnock, S.R., Manias, P., (2024) *Optimising Life Cycle Costs of Carbon Capture and Storage: Insights for Shipping CO_2 from the Solent Region*, IAME 2024, Valencia, June 2024, IAME2024-2137.

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2. If you consent to members of the team reaching out for clarifications on responses provided, please provide contact details.

The **Southampton Marine and Maritime Institute**
Boldrewood Innovation Campus, University of Southampton, Southampton SO16 7QF, UK
e: smmi@southampton.ac.uk t: +44 (0)23 8059 2291 w: www.southampton.ac.uk/smmi

Professor **Damon A.H. Teagle**, Director – SMMI, damon.teagle@southampton.ac.uk

Professor **Stephen Turnock**, Head of School of Engineering, S.R.Turnock@soton.ac.uk

Dr **Lindsay-Marie Armstrong**, Assoc. Prof. Energy Technologies Group, L.Armstrong@soton.ac.uk

Dr **Seyedvahid Vakili**, SMMI Research Fellow, maritime decarbonisation, S.Vakili@soton.ac.uk

Dr **Wassim Dbouk**, SMMI Policy Research Fellow, W.Dbouk@soton.ac.uk

Mr Panos Manias, SMMI Research Associate, maritime decarbonisation, p.manias@soton.ac.uk

Professor Malcolm J. Wright, Visiting Professor SMMI and MSA Charitable Trust Chair in Marketing, Massey University, New Zealand.

3. Do you give permission for your anonymised evidence to be shared with external advisors for the purpose of technical analysis? View on the potential vision for the NPT sector

Yes

4. Please provide views on the potential long-term vision for the NPT sector.

Non-pipeline transport (NPT) of CO_2, including shipping, road, rail and barge, will be an essential component of the UK's Carbon Capture, Utilisation and Storage ambitions. Shipping is essential for the regular movement of large volumes of CO_2 from major industrial sources (>1Mtpa) that are distant (>300-400 km; e.g., Solent, South Wales, London/Thames Gateway) from available long term geostorage (e.g., Irish and North Seas). Compared to long-distant pipelines, CO_2 shipping should have lower establishment and implementation costs for moving CO_2 from point sources to receiving ports for geostorage. Hence shipping may be important for CO_2 transfer over shorter distances during the early ramp-up stages of the CCUS economy. NPT offers the opportunity to implement the technology in clusters without pipelines that are at an early stage of CCUS implementation. The initial systems to integrate into a CCUS shipping network are large point source CO_2 industrial emitters (e.g., power plants, petrochemical complexes and refineries, and cement such as Fawley Refinery, Solent, Milford Haven Refinery and Tata Steel in South Wales) that have large, continuous emissions and located in ports where CO_2 storage and transfer facilities can be built. Power generation from gas, waste combustion or bioenergy would benefit from NPT if the generation sites are not closely located to pipeline routes or geostorage. NPT could enable the bioenergy with carbon capture and storage (BECSS) industry. Although many major and moderate scale CO_2 emitters are not located in ports, once major anchor facilities are established, one can imagine interconnected regional networks of rail, road, barge and short, local pipelines that transfer CO_2 from other point sources to a collection port for transfer via ship to the receiving port for the offshore geostorage. Pipelines are best suited for short (<300-400 km) transferral of CO_2 from industrial sources where there is a large and continuous supply of CO_2. NPT including shipping provides greater flexibility compared to pipeline solutions and resilience as CO_2 cargoes can be directed to a range of available geostorage options. CO_2 shipping may eventually involve both major direct routes from source to storage as well as more local "milk-run" operations that collect containerised CO_2 from a variety of small ports for transfer to geostorage hubs. Shipping and related port facilities will also enable the growth of a new foreign/imported CO_2 storage industry that can take advantage of the UK's range of offshore geostorage options exceeding likely UK demand. Shipboard carbon capture (SCC) involves potential new approaches to reduce carbon emissions from ships but because of the large storage volumes required (CO_2 to be stored ~3x mass of fuel burnt) will require offloading at ports probably after every voyage. If port CO_2 handling facilities are widely available this may allow the implementation of SCC.

It will be essential to standardise or at the very least clarify the required state (p, T, phase) and purity (%CO_2, %H_2O, other contaminates) requirements of each receiving geostorage facility (temporary dockside storage, offshore pipelines, geostorage reservoirs). Minimizing the energy required to pressurize and chill CO_2 cargoes during their journey from capture at source, transfer to export port storage, to ship to receiving port storage will be essential to ensure the NPT-CCS system is as cost-effective as possible. Known purity and phase standards, will enable CO_2 polluters to optimise capture and cleaning processes to ensure efficiency and acceptance of CO_2 cargoes into the transport network and geostorage reservoirs.

5. A) Which regions and sectors of the economy will benefit most from NPT solutions unlocking CCUS?

All regions stand to benefit from effective NPT solutions as many CO_2 polluters are not immediately juxtaposed to on-store geostorage pipeline nodes. However, the sectors and regions that will benefit most are those with no available regional long term geological storage reservoirs (e.g., Solent, South Wales, Thames, London). Heavy, energy intensive industries such as oil refineries, petrochemical complexes, and steel and cement manufacture that are major CO_2 polluters with near continuous CO_2 waste streams will be the most efficient to link to NPT networks particularly ports and shipping. Power generation from gas, waste combustion or bioenergy would benefit from NPT if the generation sites are not closely located to pipeline routes or geostorage. NPT could enable the bioenergy with carbon capture and storage (BECSS) industry and could eventually provide negative emissions. Similarly, the Direct Air Capture with CCS (DACCS) industry would benefit from NPT although DACCS will require an absolute excess of renewable energy following the full electrification of the economy. High concentration and high volume CO_2 emissions need to be reduced, curtailed or captured, and there needs to be an over-abundance of renewable energy, before major investments in energy intensive systems to pull CO_2 from atmosphere or oceans.

Other locations that are near abundant geostorage will benefit from new CO_2 import industries where cargoes are most likely to come via ships. These facilities will benefit through economies of scale from co-established UK CO_2 supply chains.

In some regions, the CO_2 supply may be significant but not continuous and would not warrant the high cost and operational demands of a pipeline link. Such sources would benefit from milk-run or on-demand shipping or other non-pipeline (rail-road-barges) distribution services.

B) Which regions and sectors of the economy will continue to struggle to deploy CCUS?

Based on the University of Southampton's study (Vakili et al., 2023), transportation and liquification contribute the greatest highest cost in CCUS value chain (with respect to both energy and financial cost). Consequently, clusters that are far from pipeline options and geostorage sites (a significant minority of major industrial emitters) will be affected by (additional?) costs for CCUS due to higher transportation and logistic costs for NPT. Regions in which industrial activities are less concentrated than the major industrial clusters, may struggle with the economic justification of CCS without the aid of effective NPT options.

All sectors faces challenges in utilizing CCUS technology, though the types and severity of these challenges varies. Small and Medium Enterprises (SMEs) often lack the financial and technical resources needed for implementation. Heavy industries, such as cement and steel production or power generation, emit large amounts of CO_2 but face high costs and technical complexities associated with CCUS adoption. Similarly, the agriculture and waste management sectors struggle with the lack of centralized capture points. The transportation industry also encounters significant challenges due to high costs and the absence of sustainable onshore infrastructure. However, efficient NPT infrastructure based around major continuous emitters should allow smaller (but in aggregate significant) polluters to adopt CCS at reasonable cost.

C) Should the government look to prioritise any particular regions or sectors of the economy for NPT?

REGIONS: It is imperative that through substitutions, efficiencies and improved processes that carbon emissions are reduced as significantly and quickly as possible. For CO_2 emissions that can't be further reduced, then carbon capture must be implemented as soon as possible. Government should nudge and incentivise the development of CCS and requisite pipeline and NPT networks for the major (top 50?) point source CO_2 emitters in the UK. Such an approach would help stimulate an efficient CO_2 distribution network and processes, and once established this will enable smaller emitters to confidently invest in carbon capture technologies.

One of the most significant challenges in expanding the use of CCUS is the lack of regulation. The government needs to design, develop, and implement an appropriate policy framework to promote CCUS adoption. Additionally, the government can accelerate the transition to CCUS by introducing policy measures such as GHG pricing mechanisms and incentive schemes. It is crucial that these proposed policies are tailored to regional characteristics and that the type and level of support are adapted accordingly.

An effective approach might be to tackle the largest emitters, most conveniently located to long-term geostorage, to get effective systems established (e.g. the Track approach). However, it is imperative that there is follow up investment and incentives to fulfil short- to medium term ambitions to include all major industrial polluters, many of which are in locations that will need effective NPT solutions.

6. Please provide details of your potential NPT or cross-border solution. Please provide any information on the timing of the project through the initial phase and into the future, and the minimum viable project.

The SMMI has made a detailed study of the shipping of CO_2 captured from industrial (mostly Fawley refinery), power generation and other industrial sources from the Solent Industrial Cluster to the East Coast Cluster for permanent geostorage in the North Sea (Valili et al., 2023). Our full report has been provided but here we provide a condensed version of the Executive Summary of the Report. We note that Vakili et al., 2024 "Optimising Life Cycle Costs of Carbon Capture and Storage: Insights for Shipping CO_2 from the Solent Region" was recently awarded the "Best Paper on the Green Maritime Ecosystem" at International Association of Maritime Economists IAME 2024, Valencia, June 2024. A manuscript is currently in revision for publication in the peer-reviewed academic literature.

Adapted Executive Summary from Vakili et al., 2023.

The United Kingdom (UK) has set forth a resolute commitment to attain net-zero emissions by 2050. This will require the deployment of CCUS technology by 2050, with a particular emphasis on curbing emissions across a spectrum of industries and power generation sectors. Although the UK possesses abundant reservoirs for permanent CO_2 geostorage, the geographical distribution of these sites presents inherent challenges. Notably, although industrial clusters concentrated in the southern and central regions of the North Sea and eastern Irish Sea lend themselves to efficient pipeline-based transportation solutions for captured CO_2., other industrial regions such as the Solent or South Wales do not have readily available CO_2 storage options. Consequently, these regions must rely on either long pipelines or coastal shipping of CO_2 as UK geostorage options to become available.

The Southampton/Solent industrial cluster, emits more than 2.7 Mt CO_2 annually, ranking sixth in emissions intensity. Yet, when combined with other emitters in the wider Solent cluster, emissions are more than 6.2 Mt CO_2 per year. To reduce CO_2 emissions in the Solent in the short term, shipping becomes an essential solution to transport CO_2 captured within the cluster to permanent geostorage. CO_2 shipping may play a pivotal role in advancing CCUS by driving competition among storage sites and developing a global CO_2 storage market. However, large scale shipping of liquid CO_2 (LCO_2) brings challenges to ship design and optimal solutions still need to be identified.

During the preliminary stages of this investigation, the practice of emissions budgeting played a fundamental role in quantifying the necessary carbon transportation capacity originating from the Solent region. This rigorous evaluation, harmoniously integrated with the design considerations for LCO_2 carriers of varying sizes, guided the identification of optimal vessel dimensions, ultimately endorsing a capacity of 32,000 m^3 of CO_2. Furthermore, to attain a comprehensive vantage point, an exhaustive analysis involving 7,500 m^3 vessels was also conducted, yielding invaluable insights into the dynamics of a fleet. The outcomes derived from this examination, encompass both techno-economic and environmental facets, actively facilitating informed and discerning decision-making processes.

Subsequent analysis of fleet requirements unveiled a noteworthy contrast – whereas 32,000 m^3 vessels necessitated a mere quartet for the carriage of 5.9 Mt CO_2, their 7,500 m^3 counterparts demanded a fleet of seventeen. Somewhat counterintuitively, despite the cost-effectiveness demonstrated by the standalone viability of the 7,500 m^3 vessel, a holistic economic evaluation favoured the larger 32,000 m^3 fleet, given the evident benefits stemming from reduced capital and operational costs facilitated by fewer vessels.

Further economic scrutiny disclosed that the combined capital and annual operational costs of the 7,500 m^3 vessel significantly undercut those of the 32,000 m^3 vessel. However, an intrinsic fleet perspective presented a divergent scenario, where the 32,000 m^3 fleet demonstrated superior economic feasibility, attributed to the significantly lower vessel count and, consequently, mitigated capital and operational expenditures.

Analysis of transportation expenses reveal that the cost per ton of transported CO_2 for vessels with a 32,000 m^3 capacity stood at £19.50, a figure that notably reduces to £13.23 upon the elimination of stringent penalties associated with chemical discharges at ports. Conversely, the analogous metric for the 7,500 m^3 vessel registered at a higher £46.82/ t_{CO2}.

Consequently, the presented scenarios were subjected to assessment, wherein the capital and operational costs of a 32,000 m^3 vessel fleet constituted a minor proportion of the "10 Mt CO_2" scenario, contrasting starkly with the 7,500 m^3 fleet, where this metric was significantly more pronounced. This disparity is intrinsically linked to the divergent vessel counts within each respective fleet.

Drawing attention to propulsion systems employing dual-fuel engines (LNG/MDO), the analysis indicated that fuel consumption was beneficial factor for the 32,000 m^3 vessel, contributing 22% (£7.28 million annually), whereas the 7,500 m^3 vessel incurred a comparable 26% cost (£5.65 million). This empirical assessment consistently underscored the superior efficiency of the 32,000 m^3 vessel across all scenarios. This pattern was mirrored in both Well-to-Well (WTW) and Tank-to-Well (TTW) analyses, thereby affirming the need for enhanced efficiency through the integration of energy-saving measures.

Moreover, the adoption of CO_2 storage at higher pressure and medium temperature conditions (e.g., liquified at -20°C & 25 bar) provided heightened efficiencies, yielding energy savings of 225 TJ on the Southampton to Immingham route.

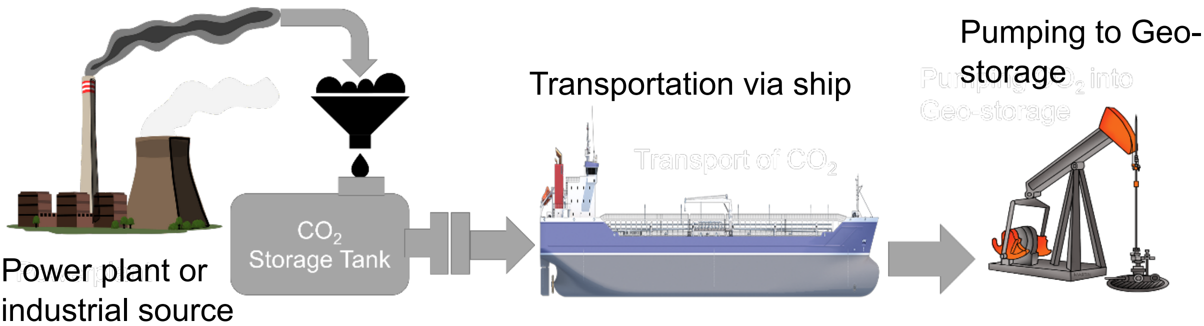
Incorporating an encompassing Life-Cycle Cost (LCC) analysis further accentuated the intricate interplay of financial, societal, and policy-driven factors, which collectively underpin the feasibility and sustainability of large-scale carbon capture initiatives within the Solent region. Remarkably, the 32,000 m^3 fleet consistently emerged as the more cost-effective option per ton of CO_2 transported, compared to the 7,500 m^3 fleet, regardless of the evaluated scenarios. A benchmark analysis yielded a LCC of £53.60 per ton of CO_2 for the 32,000 m^3 fleet in contrast to £76.34 /t_{CO2} for the 7,500 m^3 vessel fleet. Inclusion of supplementary benefits such as vessel scrapping and societal advantages led to marginal cost reductions, resulting in LCC values of £53.19 and £52.18 for the 32,000 m^3 and 7,500 m^3 fleets respectively. Most notably, the integration of the Emission Trading Scheme (ETS) yielded a substantial decrease in the LCC, highlighting the potential of policy-induced interventions in effecting substantial reductions in carbon transportation costs. Specifically, the LCC per ton of CO_2 was markedly reduced to £15.64 and £37.81 for the 32,000 m^3 and 7,500 m^3 fleets respectively. Examining the LCC per ton of CO_2, liquefaction stands out as the largest contributor at £20.09, followed by transport costs at £19.35. CCS infrastructure, distributed across the project's lifespan, ranks third with £13.15. Notably, the exclusive focus on port equipment in the 25-year evaluation makes it the least influential factor.

In summation, the study furnishes invaluable insights into the intricate dynamics of carbon capture and transportation within the Solent region. These findings transcend mere technical evaluations and underscore the paramount role of CO_2 supply, vessel size and fleet composition in shaping the economic feasibility and efficiency of large-scale carbon capture initiatives. The study proffers a comprehensive understanding of the intricate interplay between societal benefits, policy interventions, and financial dimensions, emphasizing their collective role in shaping the landscape of carbon capture projects. The results, collectively underscore the potential of well-crafted policy frameworks in galvanizing meaningful climate change mitigation efforts. Furthermore, the study acts as a clear call to enhance energy efficiency and net-zero emission strategies within the carbon capture value chain. We propose pathways including the incorporation of a smart grid, utilization of renewable energy, adoption of alternative fuels, integration of hydrogen fuel cells, implementation of battery technology, incorporation of onboard carbon capture, and the integration of energy-saving mechanisms. The ports and shipyards are undeniably significant and demand the implementation of sustainable infrastructure advancements to accelerate the shift towards emission-free shipping, in line with the UK's formidable environmental goals. Moreover, the establishment of LCO_2 carriers and the facilitation of vessels, coupled with the integration of autonomous maritime technology and eco-friendly innovations, holds the potential to not only amplify employment opportunities but also invigorate the economy on both regional and national scales within the UK. Thus, the study echoes the imperative of all stakeholders – policymakers, industrial entities, and researchers – to converge their efforts in the pursuit of sustainable solutions to the formidable challenge of global carbon emissions reduction.

7. Please provide the technical and operational considerations for the major pieces of infrastructure, equipment, and transportation. Considerations may include information on the sizes and numbers of the above, CO_2 temperature and pressure conditions, loading/un-loading times and NPT journey lengths and duration. Please also provide the rationale for the technical and operational decisions.

To make NPT feasible, the full value chain for CCUS must be taken into consideration. Ship design, storage pressures (low vs high pressure), type of material, and optimization of the size and number of the fleet within the value chain are crucial factors. The Vakili et al, (2023) report from the University of Southampton provides examples for the optimization of ship design, vessel size, and fleet, as well as operational features (including taxes and incentives) that can reduce the associated costs for NPT, in particular CO_2 shipping.

The diagram below provides an example of the expected lifecycle of carbon emissions. The idea is to capture emissions from a point source, convert them to state that is easily transported via ship and then store the same emissions in a geo-storage location.



These processes require the development of carbon capturing infrastructure, which will be part of emission sources, such as powerplants, and will increase their energy needs, by at least 20%. If Direct Atmospheric air capture is to be used instead, the amount of energy required to capture a unit mass of CO_2 will greatly exceed that of flue gas sources, as the concentration is significantly higher in the later example. As such, Direct air capturing infrastructure will require equivalent investments in renewable energy sources, for it to be carbon negative.

The state at which carbon will be transported is of great importance. With the aim to store it permanently underground, requiring high pressure (200 bar), no excess energy should be wasted to cool CO_2. Instead, more energy should be spent pressurising it, yet the current limit on type C tanks is 20 bar. This type of pressure will be at least 10 times less than the final geo-storage pressure, requiring pressurisation of the cargo when pumping it into the geo-location. Higher pressure and temperature (20 bar and -25°C instead of 10 bar and -55°C) yields significant energy savings during the transportation of CO_2, although there remains the requirement for further pressurising for injection into geostorage.

8. For the above NPT chain, please provide information on the expected ownership/operatorship (e.g. leasing, owned, shared ownership, etc) and expected commercial/contractual arrangements. Please include when equipment is to be shared between multiple entities or for sole use.

There remain on-going questions about the ownership and responsibilities of CO_2 cargoes and if ownership is to be transferred, at what stages of the processes should ownership and liabilities be transferred. The adoption of CO_2 purity and phase standards will help the transfer of cargo ownership and avoid dirty cargoes contaminating vessels, storage tanks, pipelines and/or geostorage. Cargos will need to be measured and verified at each stage of the transfer process (e.g., at capture, transfer to outboard port storage, transfer to ship, transfer to receiving port storage, transfer to pipeline to geostorage). For NPT, the transfer (and accounting) of ownership from polluter/shipper to geostorage operator could be at the transfer of cargo from vessel to receiving port aggregated storage (prior to pumping into pipeline for offshore geostorage). Due to purity, phase, pressure and temperature changes, mols of CO_2 is probably the best measure for accounting purposes (equivalent to volume at defined T, p). Although there may be some good practice to import from cyrogenic substances such as LNG or LPG, this may be limited because CO_2 is not a fuel (with calorific value) and generally not a chemical feedstock.

In the initial stages of establishing a CO_2 transport network, joint-ventures between CO_2 polluters–CO_2-transporters (NPT and pipelines) and–CO_2 storage operators, with shared ownership of the cargo and liabilities would be advantageous. This will also enable the parallel, rather than sequential, development of essential infrastructure.

9. Please provide information on the elements in the NPT chain with the longest lead times which could be rate determining in the deployment of the NPT chain. Please provide any information that you have on timelines for delivery of your NPT chain (e.g., project delivery Gantt charts).

The full development of a CO_2 non-pipeline transport system requires significant infrastructure development. Government clarity and a stable direction of decarbonisation travel are essential to enable investment in major infrastructure, and these infrastructural components need to be developed/constructed in parallel rather than sequentially. For regions without nearby geostorage, it is difficult to invest in carbon capture technologies until there is a stable, efficient route to transport CO_2 to permanent geostorage. Similarly, a stable, large continuous supply of CO_2 is imperative to develop and optimise the vessel, storage and transfer infrastructure to move captured CO_2 to permanent geostorage.

Major infrastructure requirements:

1) Carbon capture facilities at major CO_2 polluters (e.g., refining, petrochemical, steel, cement, electricity generation via BECSS)

(also Direct Air Capture facilities, discussed later)

2) CO_2 conditioning plants to remove contaminants (e.g., H_2O, hydrocarbons, sulphur) and increase purity to required industrial geostorage standards.

3) Local pipeline or NPT transfer of CO_2 from industrial sources to out-going (export) port storage

4) Dockside export port storage, transfer and wharf facilities to provide temporary storage and enable aggregation of CO_2 from a range of point sources (including from smaller polluters). This

temporary storage must be at least 1.5 to 2 times the capacity of the vessels employed to transfer CO_2 to receiving port to allow for (minor) delays and disruptions in schedules.

5) A fleet of specialist ships for port-to-port CO_2 transport. In the Vakili et al. (2023) we considered in detail two vessel sizes (7500 m^3 and 35,000 m^3 CO_2) but the optimisation of vessel size principally depends on the size of the major continuous CO_2 polluter/capturer. Vessel fleet size will also depend on the full round-trip duration of each voyage. Early agreement of clusters of major emitters would enable the optimisation of vessel size and port infrastructure.

6) Receiving port storage (many multiples of vessel capacities?) for integration with pipeline and other vessel imports and aggregation of CO_2 cargoes before pipeline and injection into geostorage.

Each infrastructural element will have major lead-times of years out to a decade. Planning permission for dockside infrastructure may be difficult especially in confines of ports, many of which have limited space. Global ship building capacity has greatly reduced in the past 20 years and there is limited capacity to construct specialist ships (3-4 years each), although there would be major savings in building fleets of similar vessels. The supply of specialist materials for high pressure and cyrogenic storage of CO_2 as well as pipework, values and monitoring devices will impact the construction of dockside and vessel facilities.

However, the construction of large scale (>1 Mt_{CO2}pa) carbon capture and purification/conditioning facilities is likely to be the time-dependent step and decadal in scale. Such facilities typically require ~25% or additional energy and up to 50% of industrial footprint compared to the plant from which the carbon dioxide is to be captured. With planning and a long-term commitment to CCS, the NPT elements of the CCS system can be designed and implemented while the carbon capture plant is being designed and built.

10. What are the expected transport emissions and fugitive emissions expected within the NPT value chain? Please provide any information on how these emissions can be minimised.

It is crucial to consider zero emissions throughout the value chain of the CCUS process. In the context of ship transportation, emissions types and size of emissions heavily depend on the type of fuel used to power the vessels and size of vessel. Depending on the fuel type, air pollutants such as SOx, NOx, CO, PM, and black carbon, as well as GHG emissions like CO_2, CH_4, and N_2O, may be released. There are no "silver bullet" or "one size fits all" solutions for mitigating emissions from the shipping industry. However, measures such as improving logistics and energy efficiency, and utilizing carbon-neutral fuels and energy sources like hydrogen, ammonia, biofuels, batteries, and fuel cells may significantly reduce emissions. Additionally, ports can play a vital role in mitigating air emissions from the shipping industry by providing sustainable fuel bunkering stations and shore-power systems. (Please refer to Vakili et al., 2023).

There are on-going debates about strategies to decarbonise national and global shipping that is responsible for ~3% of global CO_2 emissions, albeit whilst carried a large proportion (>80%) of international trade. One approach, is the re-powering of ships using green e- or syn-fuels generated from crops or synthesised from green hydrogen and captured CO_2. The “green-ness” of such fuels greatly depends on the origin of both the H_2 AND the Carbon. It is important to note that all these proposed substitute fuels (H_2, NH_3, CH_3OH) require more energy to produce that they contain – this is a very distinct change from fuel oil or marine diesel where ~90% of the energy embedded over geological time is available for combustion. However, many of the fuels proposed are not ideal substitutes for the current hydrocarbon fuels used in shipboard internal combustion engines.

Moreover, due to the high safety and reliability standards and the tight financial margins in shipping, it is important that any new fuels developed have similar combustion characteristics to current options. It is also imperative that green fuel emissions are offset at early stages in their production lifecycles (i.e., they are truly "green") rather than during their utilisation point onboard ships (where upon shipboard CC is then the only option).

Developing e-fuels, such as e-methanol, may give value to captured carbon dioxide, as maritime demand may spark new manufacturing industries. However, it is essential that the carbon used for manufacture is from waste, biological or direct air capture sources. Carbon credits (or other subsidies) could be a way of ensuring a price for carbon while also offsetting the expense of e-fuels, considering that future fuels will be significantly more expensive than current fossil fuels. Synfuels produced by re-processing of CO_2 from industrial processes such as oil refining, petrochemicals or cement, will only briefly delay the passage of geological carbon (from oil, gas, coal, limestone) to the atmosphere, whilst consuming significant amounts of valuable renewable energy.

Onboard carbon capturing will require a significant amount of additional energy to be available on ships. Even though cargo capacity will not be significantly affected by its installation, there will be increased energy consumption to support the capturing and storage energy required. Increased consumption as well as the installation of the entire system will lead to increased costs for shipowners and managers (both OPEX and CAPEX). The on-board storage of captured CO_2 will be significant (~3x the volume of the fuel combusted) and will impact the cargo capacity of the vessel depending on its fuel consumption and length of journey. Shipboard carbon capture will require NPT transport of CO_2 from many ports to regions with geostorage facilities.

Additional revenue streams will be required to compensate for the increased costs of shipboard carbon capture. CO_2 should therefore be treated as an asset, setting a price per ton of CO_2 which will include the capture and storage. From a carbon-systems point of view, it may make more sense to offset carbon on shore, through for example the large-scale renewable energy powdered production of e-fuels from bio- or air-captured CO_2 rather than capturing using small on-board systems.

In Vakili et al. (2023) we model LNG-powered ships. However, a bold move could be to stimulate the development of clean mid-21st Century technologies through the design and development of say green hydrogen powered ships, to develop the concept of national green corridors and the Zero-carbon coastal highway (UoS-BMT-MarRI-UK Plan to DfT, 2020). The relatively short duration of source to storage voyages (<400 nm) and likely availability of blue and/or green H_2 at both origin and receiving ports, should assuage concerns about the low volumetric energy density of H_2, especially if employed in combination with more energy efficient fuel cell/battery hybrid electric systems.

11. Could the costs associated with the full NPT value chain prevent investment and deployment of NPT solutions? If so, why?

Yes, cost is a significant barrier to implementing NPT. One of the primary challenges in accelerating CCUS adoption is the associated expenses. To make this technology competitive with other options, it is essential to reduce costs. (Please refer to the university report as supporting evidence). However, although cost is important, the stability of decision making and long-term government commitments to potential climate solutions are imperative to enable and release private sector investments.

12. If available, please provide any assessments that have been carried out to show an NPT solution is more economically viable than a piped solution for your NPT value chain, or that a piped solution is not technically viable.

See Valiki et al., 2023; Also elementenergy (2018) Shipping CO2 – UK cost estimation study (for BEIS)

13. Please provide evidence on the costs associated with NPT. Where possible disaggregated to the nodes delivered by NPT service providers (e.g. after capture plant and before delivery to the T&S network). Where possible, please provide information in relation to the devex, capex and opex of the operation. Please include the stage and Association for the Advancement of Cost Engineering (AACE) Cost Class at which this cost data has been generated, and please share the methodologies and assumptions that have been utilised to generate this data.

Please refer to the details in Vakili et al., 2023. We note that Vakili et al., (2024) that summarised our report, was awarded as the best paper on this topic at International Association Maritime Economist (IAME) 2024 Conference, Valencia, Spain. An associated manuscript is in revision for publication in a peer-reviewed academic journal.

14. What are the main financing risks with a disaggregated chain, and how do these differ to the full chain piped approach?

The NPT-CCS chain is only as strong as the weakest links and needs to be complete to provide the services desired. Hence, we propose (at least initially) that joint-ventures with co-ownership of cargoes (with or without HMG investment/subsidy or underwriting) are the most effective mechanism for initiating efficient NPT via shipping, enabling investments by current polluters in expensive and energy intensive carbon-capture technologies.

~~**15. What are the main financing risks associated with operational flexibility, and how do these differ to the full chain piped approach?**~~

SMMI will not provide answers to Q15 through Q29 although some of our answers to other questions and the attached reports may have some relevance to these questions.

~~**16. Which archetype do you think would be most attractive to investors? Why?**~~

~~**17. What types of financing are best placed to deliver NPT value chains?**~~

~~**18. Do you agree the rationale for economically licensing NPT service providers does not exist? Or do you believe that some elements in the NPT value chain may still require some kind of economic licencing?**~~

~~**19. Considering the expected deployment timelines for potential NPT projects within the CCUS programme, can the risks associated with the deployment of an NPT value chain be effectively managed commercially between the different actors within the NPT value chain? If not, please provide evidence and rationale why these risks cannot be managed commercially.**~~

~~**20. Please provide details on how you believe that the CCS Network Code[footnote 24] would need to be updated to facilitate NPT.**~~

~~**21. What changes to the Track-1 capture BMs do you envisage being required to make the capture BMs work for NPT solutions? What considerations would be required for power-BECCS and GGR BMs when developing for NPT? Please flag in your response which of the capture BMs you are answering in reference to.**~~

doi:10.5258/SOTON/PP0064

~~**22. How important should consistency in approach between capture BMs be? How important is consistency between NPT users and piped users within a specific BM (e.g. ICC via pipeline and ICC via NPT)?**~~

~~**23. If NPT solutions are assessed against pipeline solutions, would this raise any concerns?**~~

~~**24. If government is to allow all archetypes of NPT, how should an assessment of an NPT value chain be considered to allow comparisons?**~~

~~**25. Please provide views on the potential vision for cross-border CO_2 T&S networks in the UK.**~~

~~**26. With regard to Questions 18 and 19 and in the context of establishing cross-border CO_2 T&S networks, do you have a view on:**~~

~~i) whether an economic licensing framework for CO_2 T&S might need to evolve to accommodate cross-border T&S networks?~~
~~ii) how cross-border CO_2 volumes should be viewed within a commercial landscape currently designed for domestically captured CO_2 volumes?~~
~~iii) how service providers could manage the risks on a commercial basis that would allow for a merchant delivery model?~~
~~iv) whether there are any specific changes needed to the current suite of capture business models if CO_2 cross-border T&S networks are established?~~

~~For each answer please provide further explanation.~~

~~**27. With regard to Question 20 do you think any changes will be required to the CCS Network Code to ensure cross-border CO_2 T&S networks can be established?**~~

~~**28. To what extent would enabling NPT users and cross-border users incentivise storage exploration and appraisal activity? If not, why doesn't it?**~~

~~**29. Could a store which is solely reliant on NPT users be viable? What are the technical challenges to operating a store solely reliant on NPT users? How would this operating model impact the risk profile of the project?**~~

30. Please provide evidence for the potential viability of shipping CO_2 straight to the wellhead for CO_2 injection. Please expand on the risks/barriers and benefits of straight to wellhead shipping.

SMMI has only briefly considered direct wellhead injection from ships and prefer the initial concept of transport to a receiving port before pumping into an offshore pipeline and injection into permanent geostorage. On-shore pressurisation and pumping can be powered by renewable energy. Direct injection from ships into geostorage will require high pressures (200 bar) and although technically feasible, it will require either specialist high pressure pumps to be mounted on every vessel (and likely powered by marine diesel) or some form of floating pumping facility (also likely powered by diesel). Such systems are very likely suspectable to harsh weather and storms that may interrupt and disrupt optimised transport schedules. Multiple operators of vessels may challenge the safe operation of offshore facilities. These technologies might be possible in the future when offshore carbon geostorage become routine but wouldn't be a good place to start.

31. What regulations need to be considered or amended for NPT value chains to deploy (excluding those regulations which are covered in the CCUS policy landscape section)?

Please refer to our report Dbouk, W., Teagle, D.A.H., Ntovas, A., Armstrong, L.-M., Turnock, S.R., (2024). *Review of the Legal and Regulatory Framework for CO_2 Shipping as part of Carbon Capture and Storage in the United Kingdom*, IDRIC Project 50 – CO_2 from Port to Pipeline (CO_2P2P), 137p.

The Dbouk et al., (2024) report provides in depth interrogation the current public law aspects of the regulatory and liability regimes governing the transport of CO_2 from port to port, taking the Solent Industrial Decarbonisation Cluster as an example. Here we summarise some of the major findings of that report.

The following recommendations are made to support HMG with ensuring the *safe* deployment of NPT value chain, for people and for the environment. They relate to shipping CO_2 and the temporary storage of CO_2 in UK ports as part of CCUS. In relation to in-port storage, the recommendations are concerned with regulations governing the duties of operators to manage the risk of major accidents due to storage of dangerous substances - the Control of Major Accident Hazards Regulations 2015 (COMAH). In relation to shipping CO_2, they are concerned with regulations aiming at preventing pollution of the marine environment by the discharge of harmful substances - the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) as transposed into UK law via the Merchant Shipping (Prevention of Pollution from Noxious Liquid Substances in Bulk) Regulations 2018 (Merchant Shipping Regulations).

- Ports regulations – COMAH

Existing regulations governing the health and safety and environmental protection aspects of port-based activities do not neatly apply to the temporary storage of CO_2 in UK ports as part of CCUS. This creates considerable uncertainty for those involved in this important element of the value chain with regards to identifying the applicable regulations and understanding their duties thereunder. HMG should ensure that the regulations in place govern CO_2 storage activities in UK ports to ensure the health and safety of the port workforce and surrounding populations, and to protect and preserve the environment.

Where applicable, the COMAH impose a duty on operators of establishments where dangerous substances are present in certain quantities to take all measures necessary to prevent major accidents and to limit their consequences for human health and the environment. Despite this clearly applying to flammable and oxidising gases and to Hydrogen, the regulations do not neatly apply to liquified CO_2 due to it not being included in any form in Schedule 1 of the regulations. However, the regulations apply to substances not included in Schedule 1 should they present "equivalent properties [to those listed in the Schedule] in terms of major accident potential", in which case they must be provisionally assigned to the most analogous category or named dangerous substance falling within the scope of these regulations. **Given that CO_2 poses some risks to health and to the environment and that it is expected to be stored in larger quantities in ports to upscale CCUS in the UK, it is recommended for CO_2 to be added as a new substance in Schedule 1 of the COMAH to ensure that the regulation govern CO_2 storage activities in UK ports.**

- CO_2 shipping - MARPOL 73/78 and the Merchant Shipping Regulations

Annex II of the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) regulates the prevention of pollution by noxious liquid substances in bulk. It has been transposed into UK law via the Merchant Shipping (Prevention of Pollution from Noxious Liquid Substances in Bulk) Regulations 2018. With an aim to "minimize the accidental discharge into the sea of [noxious liquid] substances", Annex II provides for specific requirements with regards to the design, construction, equipment and operation of ships certified to these substances in bulk when they are identified in

Chapter 17 and/or 18 of the International Maritime Organization (IMO)'s International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code). Liquified CO_2 is currently not included in Chapter 17/18 of the IGC Code. However, it arguably still falls under the broader definition of "harmful substances" set out in the Article 2(2) of MARPOL 73/78 due to the health and safety and environmental pollution risk posed by its potential release into the marine environment.

Given the anticipated increase in the carriage of liquified CO_2 by sea in support of CCUS activities globally, **it is recommended that liquified CO_2 is added to the list of substances in Chapter 17 and/or 18 of IGC Code.** This will result in the specific requirements under Annex II of MARPOL 73/78 and the Merchant Shipping Regulations to become applicable to the carriage of liquified CO_2 by sea globally. It would also settle any potential confusion around the application of the broader obligation to prevent pollution of the marine environment by the discharge of harmful substances or effluents containing such substances set out in Article 1(1) of MARPOL 73/78.

32. Do the current processes to comply with existing health and safety or environmental regulations or controls create barriers to NPT deployment when transporting CO_2 via road, rail, barge, ship, or processing CO_2 at intermodal facilities? If so, what are those barriers, and what would you suggest as an alternative?

Environmental protection from various risk-creating activities and industries in the UK is achieved in part through an established regulatory regime for environmental permitting. However, the application of existing environmental permitting regulations to CO_2 storage activities as part of CCUS within UK ports is dubious. Under certain conditions, several regimes under the Environmental Permitting (England and Wales) Regulations 2016 (EPR) and the Pollution Prevention and Control (England and Wales) Regulations 2000 (PPC) can govern activities constituting different components of the CCUS process (*i.e.* CO_2 capture, liquefaction, and temporary storage). This creates a complex regulatory landscape for port stakeholders to navigate to ensure they are consistently fulfilling the legal requirements incumbent upon them by virtue of several regimes when they operate CCUS activities. It also ultimately leads to applying varying environmental protection standards with regards to the processing and handling of CO_2 as it passes through the CCUS stages and undergoes phase changes. Without official guidance from the competent authorities, there is a significant risk of misinterpreting the regulations or not applying them at all. This could result in their inconsistent application by various stakeholders and, potentially, an underestimation of the health and environmental risks associated with large-scale CO_2 storage activities in UK ports.

Expressly including CO_2 capture, liquefaction and storage activities in the list of activities which bring installations where they are performed within the scope of the regulations is recommended to avoid confusion about whether they govern different components of the CCUS process in UK ports. This can be achieved through expanding the provision under section 6.10, Part 2, Schedule 1, of the EPR (which in its current form only applies to the capture of CO_2 from an installation for the purposes of geological storage) **to CO_2 liquefaction and temporary storage activities.** It would also simultaneously ensure that the same conditions for triggering the regulatory requirements incumbent upon port operators, including environmental protection duties, would apply in respect of *any* of those activities.

~~**33. Are there any specific changes to UK legislation, existing regulations or permitting processes which are necessary to support the development of cross-border CO_2 T&S networks?**~~

SMMI will not provide answers to Q33 through Q37 although some of our answers to other questions and the attached reports may have some relevance to these questions.

~~34. What do you see as the biggest regulatory barriers to the growth of cross-border CO_2 T&S networks?~~

~~35. What are your views on the best approach to creating interoperable CCUS networks?~~

~~36. How should the UK design the standards and specifications for CO_2 T&S which offers network users sufficient flexibility in store choice but also provide sufficient protection to core T&S infrastructure? How can the UK ensure that its T&S network design does not impede access to an interconnected and interoperable European system?~~

~~37. Are there any technical or operational limitations that may exist that could be a barrier to domestic NPT or cross-border T&S network deployment? Please explain.~~

38. Is there any specific foundational infrastructure that must be operational in the UK before UK stores can offer storage to domestic NPT or international customers? If so, what should the UK prioritise?

Similar infrastructure and standards will be required for CO_2 imported from foreign countries. UK government investments (including subsidies and incentives) should be used primarily to store UK-sourced CO_2 and to establish the UK market. Imported CO_2 should be transferred and stored at cost(+) but there should be economy of scale advantages from this CO_2 import industry. **The UK, having a significant proportion of European offshore geostorage, should ensure that it leads the establishment of standard protocols and processes so they are optimised for UK industries.** Superior profit-making CO_2-imports should not be allowed to distort the CO_2-storage market in ways that are detrimental to UK CO_2 polluters attempting to permanent store waste CO_2.

39. Do you foresee any infrastructure innovations which could speed up the deployment of NPT and cross-border T&S networks and/or reduce associated costs? Please provide any supporting evidence.

^{13}C-labelled (and ^{17,18}O) isotopic spiking of CO_2 consignments could be used to uniquely identify specific CO_2 sources and cargoes. This may assist with the accounting, monitoring and verification of imported and national CO_2 consignments.

40. What are your views on other flexible users of CCUS networks, e.g. flexible use of technologies such as DACCS? Do you foresee that NPT and buffer storage could be complimentary to operate alongside a flexible piped user (e.g. projects that could ramp up or ramp down CO_2 output, potentially including technologies such as DACCS).

Ships and pipelines are currently both used to transport natural gas. Hence, the same approaches can be applied to CO_2 transport. Pipelines are best suited for short distance transfers whereas shipping is more appropriate for long distances (>300-400 km) or for imports from other countries. DACCS powered by excess renewable energy could potentially be allowed to sell more credits per ton of CO_2 stored as (following full life-cycle accounting) these should be true atmospheric CO_2 reductions – so-called "negative emissions". However, DACSS supplied CO_2 is likely to be available in only small volumes and would require the major industrial CCS network including NPT to be established and working efficiently. At present time, DACSS is not be an efficacious use of renewable energy, and the energy requirements of such systems are large (per t_{CO2}) compared to the extraction of high concentration CO_2 from industrial waste streams (40% vs 400 ppm CO_2). Additionally, the impact of Air Capture on the oceans is poorly quantified for accounting purposes. Reductions in atmospheric CO_2 concentrations may result in CO_2 degassing from the oceans (~30% of reduction) – making the precise amount of CO_2 captured by DACSS difficult to measure or validate.

41. Does the UK have the relevant skills and capability to deliver NPT? Does the UK have a competitive advantage to deliver certain elements of the NPT value chain?

The UK holds a significant proportion of European offshore geostorage in its territorial waters. HMG must ensure that this geological advantage leads the establishment of standard protocols and processes that are optimised for UK industries and provide design, manufacturing and export opportunites for UK business. Regarding ship transportation, the UK possesses relevant expertise across the value chain for design of appropriate L_{CO2} ships. However, in the realm of ship building UK shipyards need to enhance their capabilities and expand their capacities for manufacturing liquid CO_2 shipping vessels. Currently, due to cost considerations, the bulk of orders for L_{CO2} shipping vessels are placed with East Asian shipyards. Considering market trends and the UK's commitment to achieving zero emissions by 2050 through CCUS technology, along with the critical role of CO_2 shipping in the value chain, it is imperative for UK shipyards to enhance their skills and capacities to build various types and sizes of CO_2 shipping vessels. There are opportunities to trial world-leading clean propulsion technologies (e.g., green-H_2 powered fuel-cell batteries hybrid ships) on new specialist routes from major industrial CO_2 sources to regions with permanent geostorage through the establishment of zero-carbon coastal CO_2 shipping routes.

42. What other areas should government be considering for successful deployment of NPT?

This survey has not considered the public understanding or acceptance to the transfer of CO_2 by pipeline nor the storage of large volumes of CO_2 in ports and its transfer by ships. In IDRIC Report Feetham, P., Carlisle, D., Wright, M.J., Teagle, D.A.H., (2023). *Public perceptions of shipping and storing Carbon Dioxide*. IDRIC Project 50 – CO_2 from Port to Pipeline (CO_2P2P), 59p, we conducted a large (n = 1070) representative survey of the UK population to elicit perceptions of CCS and CO_2 transport as well as preferences for different CCS capture, storage, transport, and regulation options. Compared to the three other industrial substances (hydrogen, ammonia and LNG), perceptions of transport and storage of carbon dioxide were somewhat favourable, indicating public reaction towards carbon dioxide shipping and temporary storage at ports is unlikely to cause major controversy. When considering preferences for alternative CCS and transport options, the most important factors of those evaluated were Regulation and Transport. The most preferred combination includes international or government regulation, rather than industry self-regulation, and transportation by pipeline, although the responses to CO_2-shipping were relatively mild. These findings suggest the use of pipelines and either international or government regulation are likely to increase the chances of public acceptance of CCS.

A refined version of this research is currently in review in the peer-reviewed academic literature.

43. Please respond with any other comments that are not contained in the above questions.

no further comments