SeaCURE: Phase 1 Public Facing Final Report

This document represents a distilled version of the 131 page SeaCURE project final report produced for BEIS. Commercially sensitive information has been removed to prevent the disclosure of intellectual property to enable future SeaCURE commercialisation. Private investment and commercial CO_2 removal is presently considered to be the only route which will lead to CO_2 removal at the scales required to address climate change. SeaCURE is committed to make as much information publicly available as we can, and will retrospectively publish information which has been removed from this report.

1 Background

SeaCURE has developed and demonstrated the components of a marine-based Negative Emissions Technology (NET), with the potential to be applied at very large scales. The system makes use of the natural behaviour of the carbon cycle, i.e. the 'sucking' of CO_2 out of the atmosphere in response to the atmosphere-ocean difference in CO_2 concentration, generated by rising atmospheric CO_2 concentrations. We accelerate this process by stripping >90% of the CO_2 out of the seawater, so that the CO_2 concentration difference between the air and seawater is enhanced, and the rate and amount of CO_2 removed from the atmosphere is dramatically increased. Importantly, natural concentrations of CO_2 in seawater are much higher than those in air. This means that by processing one cubic meter of seawater and releasing it back into the surface ocean, we can remove as much CO_2 as would be stripped from 150 cubic metres of air, by equivalent direct air capture techniques, delivering huge efficiency benefits. Furthermore, opportunities exist to roll out this approach offshore, facilitating enormous scaling without presenting the land-use challenges that are potential barriers for other methods of CO_2 removal.

The SeaCURE system has the potential to be massively up-scaled. To stay less than 2°C above preindustrial, a middle-of-the-road scenario requires global CO_2 emissions to be below zero (i.e. sucking more CO_2 out of the atmosphere than we are putting in) by around 14 billion ($x10^9$) tonnes of CO_2 per year. Preliminary calculations suggest that this $14x10^9$ tonnes of CO_2 per year could be extracted by SeaCURE by processing 1% of the surface ocean's seawater[1].

[1] . Assumes an average ocean mixed layer depth of 50m, an average seawater dissolved carbon concentration of seawater of 2000 µmol/kg, an equilibration time between ocean and atmospheric CO_2 concentrations of one year, and a conservative SeaCURE seawater stripping efficiency.

SeaCURE seawater CO_2 removal is achieved by acidifying the incoming seawater stream (Figure 1), which converts dissolved carbon into CO_2. This CO_2 is extracted into air (Figure 1) and purified. The CO_2-depleted seawater will then be released back to the ocean, where it will take up $CO_2$from the air. (Figure 2).

Figure 1. SeaCURE process schematic. Removed.

2 Underpinning science and engineering

2.1 Carbon chemistry

The SeaCURE system is designed around the principle that if the pH of seawater is temporarily lowered, all dissolved species of carbon in that seawater will convert to CO_2, facilitating carbon removal (Figure 2). The speciation of the dissolved carbon as a function of pH is presented within Figure 2, in the BEIS facing report.

Figure 2. The use of a seawater pH swing to extract CO_2 from the atmosphere. Removed.

2.2 pH manipulation

Described in BEIS facing report.

2.2.1 Technique 1

Described in BEIS facing report.

2.2.2 Technique 2

Described in BEIS facing report.

2.3 Seawater CO_2 stripping

Current technologies employ membrane-based CO_2 strippers, which present reliability concerns in operational systems (large OPEX costs) and incur substantial pumping and filtration costs associated with ultra-filtration of all seawater for CO_2 stripping. The SeaCURE system is described in the BEIS facing report. Laboratory experiments have also been conducted with a bespoke system to demonstrate the process practically, and to optimise the Phase 2 gas flow rates (in BEIS facing report).

2.4 CO_2 stripping

The concentration of CO_2 in the gas stream leaving the seawater stripper (Figure 1) is massively enriched in CO_2. SeaCURE uses technology described in the BEIS facing report to purity this to >98.1%.

2.5 Chemistry modelling and ion exchange

This section is described in the BEIS facing report.

2.6 SeaCURE energy costs

2.6.1 Present-day, high TRL

The energy source for SeaCURE is renewably generated electricity. Energy will be obtained from the grid in Phase 2, with options explored to upgrade the site with its own microgeneration. Table 111 lays out the energy consumption costs.

Table 11. Full details presented in BEIS facing report.

Process	Subprocess	kWh / tonne CO_2	£ / tonne CO_2 (at £45/MWh)	Assumptions
Total energy:		5731.5	£257.92	

2.6.2 High TRL, neutrally buoyant plant

Following exactly the same assumptions as above, but moving the plant offshore so that the pumping costs are minimised (buoyant system operating at sea level without pumping against low tides), delivers an energy cost of <£200 $tonne^{-1}$ CO_2 (Table 222).

Table 22. Full details presented in BEIS facing report.

Process	Subprocess	kWh / tonne CO_2	£ / tonne CO_2 (at £45/MWh)	Assumptions
Total energy:		4265.0	£191.93	

2.6.3 Lower TRL and energy cost reduction beyond Phase 2

Using the pH manipulation technology (as described in the BEIS facing report), delivers energy costs of £100 $tonne^{-1}$ CO_2 removed (Table 333).

Table 33. Full details presented in BEIS facing report.

Process	Subprocess	kWh / tonne CO_2	£ / tonne CO_2 (at £45/MWh)	Assumptions
Total energy:		2238.3	£100.72	

Note that other options have been explored to substantially reduce the operational costs, but these move outside of the specifications for this call.

2.7 Environmental Impacts

The primary environmental impact of the SeaCURE process is overwhelmingly positive. Projections for the net global CO_2 emissions compatible with a range of globally averaged temperature increases above preindustrial, are presented in Figure 3. Each line represents a scenario from a single integrated assessment model. Lines are colour coded based on the end of the century warming levels they deliver. Single realisations are presented for the two higher end scenarios for clarity, and the full model ensemble is presented for the simulations compatible with 3ºC and below. It is critical to note that almost all scenarios compatible with <1.5ºC or

<2.0ºC require net global negative emissions of the same order of magnitude as today's net positive emissions. The reason why SeaCURE has the opportunity for such a large positive environmental impact is because it has the capacity to scale to the size of this challenge, and because of its ability to scale off-shore, where it would have minimal impact on the planet's land surface and therefore land use (relevant for food production, biodiversity preservation, etc.). Demonstrating the capacity for this level of scalability will be a focus of Phase 2 (details in BEIS facing report).

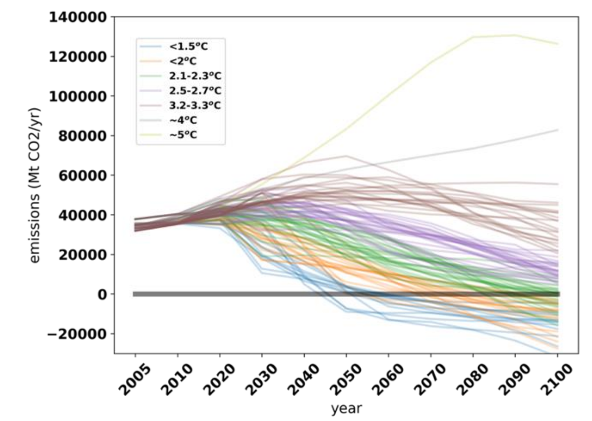

Figure 3. Global anthropogenic CO_2 emissions compatible with a range of global warming 'targets'. Data from the Shared Socioeconomic Pathways Public Database[1].

The area of SeaCURE's operation that will require environmental licencing is the processed seawater inflow and outflow. As illustrated in Figure 1 and explained in Figure 2 (BEIS report), the major chemical difference between the seawater entering the system and that leaving the system is that the seawater leaving the system contains less dissolved carbon. Treated water will continue to contain less dissolved carbon until it has taken up an equivalent amount of CO_2 from the atmosphere to that which was removed within the plant. At this point the seawater is back in equilibrium with the atmosphere. Within this window, water can be considered to have experienced the opposite of ocean acidification. Once the seawater is back in equilibrium with the atmosphere, a process that should take less than one year (Zeebe and Wolf-Gladrow, 2008), it is chemically indistinguishable from the seawater that came in. The post-outflow impact of the processed seawater on the marine environment before it returns to equilibrium with the atmosphere must therefore be understood. At small scales (i.e. equivalent to the Phase 2 pilot plant, <100tCO_2/yr) (details in BEIS facing report), this processed seawater will mix with ambient seawater too quickly to observe any impacts. Phase 2 will however, contain a package of work to understand the tolerances of marine organisms to this low carbon water when the process is performed at scale, and minimally diluted water persists for longer. This step will inform the optimal outflow strategy, plant densities and geographical locations for future SeaCURE plants.

2.7.1 Limitation on photosynthesis

Described in BEIS facing report.

2.7.2 Calcium carbonate production

Calcium carbonate ($CaCO_3$, chalk) is a mineral produced by many marine organisms to provide external structures, e.g. shells. The precipitation of calcium carbonate relies on the presence of calcium (Ca) and carbonate (CO_3). The thermodynamic equilibrium of $CaCO_3$ formation can be calculated as a function of the concentration of Ca, CO_3 and a solubility product (details in BEIS facing report and deliverables). The SeaCURE outflow seawater contains elevated CO_3 concentrations, and these rise on dilution before peaking at a dilution factor of 1.7 before returning towards ambient. Figure 4 (details in BEIS facing report).

Figure 4. Removed. Chemical constituents as a function of dilution from SeaCURE modelling. Details in BEIS facing report.

Key groups of calcifying marine organisms include phytoplankton (coccolithophorids), zooplankton (e.g. foraminifera), molluscs (e.g. bivalves, pteropods) and macroalgae. There has been considerable concern about the impact of low CO_3 concentrations on these groups occurring in response to ocean acidification (e.g. Gruber, 2011). While a logical argument can be made that the opposite of ocean acidification is likely to be good, there is presently not sufficient research to understand the impact of elevated CO_3 concentration on marine organisms. This will be a key component of Phase 2 (details in BEIS facing report). It is interesting to note however, that one of the very few studies that has looked at 'reversing' ocean acidification showed very positive impacts on coral reefs from high CO_3 ion concentrations (Albright *et al.*, 2016).

3 Engineering design

Full engineering plans, design calculations etc. are presented in the BEIS facing report.

3.1 Modelling

Models are described and modelling results presented in the BEIS facing report.

3.2 Data analysis

Data has been generated from experimental work, data analysis, literature review and modelling. This is presented in the BEIS facing report.

4 Costed Project Plan

The proposed Phase 2 project will consist of a set of work packages, each necessary to deliver a Negative Emission Technology which will attract investment by the end of Phase 2 and therefore deliver maximum social value. The largest of these work packages is the build and commissioning of the pilot plant. From an investor's viewpoint there are six items they will need to be confident about before proceeding. These are:

- Does the plant do what we say it can do and is there a short pathway to reliable long-term operation?
- Can we simply demonstrate that the amount of CO_2 extracted from seawater is subsequently removed from the atmosphere?

- To what degree can the approach scale, and hence what is the potential return on investment?
- Will there be any negative environmental impacts when operated at scale which would prohibit regulatory or social licence for rolling out at commercial scales?
- Do the economics justify investment?
- Is there a sound business case?

This project plan demonstrates how the above criteria will be addressed. Full details of this and costings are presented in the BEIS facing report. The project plan consists of 4 stages:

1. Pre-start - finalising design, build and commission, operation and reporting
2. Design and build
3. Strategic projects - 7 strategic work packages, including; commercialisation and social value.
4. Project management

4.1 Pre-start

Pre-start runs from now until the commencement of Phase 2 (April 2022) and includes all work streams. The work involves preparation and submission of the Phase 2 application (design, costing and project planning). All parties are involved in contributing to both tasks before the start of Phase 2.

- **Licensing**: During this phase the relevant site agreements and associated discussions with key regulators will continue to take place.
- **Contracts**: Ahead of application deadline in January ’22 Phase 2 consortium partner contracting will be discussed and agreed. Following the award notification contracts will be signed.
- **Build tender/agreement**: Ahead of the application deadline the party/subcontractors to build the plant will be finalised.
- **Recruitment**: Between award notification and project start, key personnel will be recruited.

4.2 Design and build

4.2.1 Design

Design**:** During this stage we will finalise the preliminary design from Phase 1 using the most up-to-date information available and a site-specific focus. The design will also be informed by scale up work on the seawater CO_2 removal step, CO_2 purification step, and pH manipulation activity. In turn, the preliminary design phase will inform the detailed design phase. Key plant components will start to be assembled. We will test components at a bench or sub assembly scale, and build units on skids. Further details in BEIS facing report.

Specific activities include:

- Health & Safety:
- Procurement:

- Licensing applications:
- Software development:

4.2.2 Build

Following the acquisition of the relevant permits and licenses from the site owner and regulators, the build will begin by carrying out the necessary site preparation and groundworks. This will be followed by plant assembly. Step testing and monitoring will form part of the commissioning phase along with preliminary running trials. Details in BEIS facing report.

4.2.3 Operation

The operational phase spans one year. During this period the plant is to run for extended periods to demonstrate the capacity for successful continuous operation. Successful continuous operation will be defined as running well beyond the time it takes to cycle through all of the processes that operate in a cyclic or periodic way during online operation. The plant will be managed and maintained by all parties (and system engineers as required), including fixing any problems, managing the site and ordering consumables. Details in BEIS facing report.

The preparation, build and operation of the plant will lead to improved understanding, and appreciation of challenges and opportunities. These challenges and opportunities will be focused on within parallel strategic work packages. During the operation stage there will be continuous monitoring of data outputs to verify the plant's success. Wider project activities will deliver the end-to-end verification. Details in BEIS facing report.

4.3 Strategic activities

A number of parallel strategic work packages will be progressed semi-independently from the plant build and operation. These activities summarised here.

- **CO_2 stripper site-specific optimisation.** This package will deliver the site specific optimised design for the seawater CO_2 removal approach. Details in BEIS facing report.
- **Gas-phase CO_2 capture development.** This package will simulate the dynamics of the CO_2 concentration system to inform: (1) how to start up the plant, (2) how to shut it down, and (3) how the plant would respond to sudden and/or gradual variations in a process operating parameters. Details in BEIS facing report.
- **pH manipulation development.** This work package will assess and progress the pH manipulation technology to deliver energy and cost efficiencies beyond Phase 2. Details in BEIS facing report.
- **End-to-end system verification**. This component of the project will undertake the work required to demonstrate that the CO_2 stripped out of the seawater translates to an equal amount of CO_2 being stripped out of the atmosphere, downstream of the plant's outflow. Details in BEIS facing report.
- **Environmental impacts of outflow**. Here we will build the evidence base required to show that the low carbon water produced by the SeaCURE

system has minimal and manageable impacts. This will be important in gaining the regulatory and societal license to operate at scale. Details in BEIS facing report.

- **Scoping 50kt plants, scaleup and system economics.** This package of work will demonstrate the scope of large-scale rollout of SeaCURE plants to inform how and where such plants would be positioned to deliver an effective removal network. This can then be fitted to a present day context and projected carbon prices. Details in BEIS facing report.
- **Lifecycle analysis.** A full life cycle assessment (LCA) following the ISO 14040 standard will be conducted to evaluate the net GHG balance of the pilot system by quantifying the GHG emissions incurred over the life cycle of the system and the GHG captured during its lifetime. Details in BEIS facing report.

4.3.1 System Verification

System verification falls into two components: (1) verification of plant operation, including seawater CO_2 removal and CO_2 stream purity, and (2) wider process (end-to-end) verification to demonstrate plant efficacy in terms of atmospheric CO_2 removal while avoiding net negative environmental impacts. Details in BEIS facing report.

4.3.2 Commercialisation

Commercialisation activities fall in to two categories. (1) Design scenarios for >50ktonne yr^{-1} plants and economic assessment and (2) delivering investment to rapidly accelerate SeaCURE beyond Phase 2. Details in BEIS facing report.

4.3.3 Social Value

Social value activities conducted in Phase 1 included: rapidly progressing a scalable climate change solution, engagement with knowledge exchange events, contributing evidence to central government, media outlets and highly skilled job creation). By generating a pilot and undertaking wider activities beyond design and testing, Phase 2 project will be able to further enhance our social value delivery. Specifically we will be:

- Running a marine CO_2 capture impacts workshop to bring licencing authorities, government departments, politicians, other projects, and the wider interested community up to speed on the technological solutions, potential marine impacts, and findings from our Environmental Impact work. Between PML and Exeter we have world leading expertise and academic reputation in this area.
- Running a marine Negative Emissions Technology monitoring and verification workshop to bring the political, industrial, and academic communities up to speed on marine air capture approaches, and present what we have learnt about MRV. We will facilitate discussion on how to best move this area forward within the UK and internationally. Between Exeter and PML we have world leading expertise and academic reputation in this area.

- Generating highly skilled jobs for the duration of the project, with an increased workforce dedicated to the commercial product moving forwards. Details in BEIS facing report.

4.4 Project management

The aim of the project management is to plan effectively, keep the project on track, manage risks, manage change, and manage the budget. The project management will also oversee the legal and compliance activities planned for Phase 2. A high level project plan is shown in Figure 7.

4.4.1 Reporting

During the final reporting stage the Phase 2 output requirements will be collated and produced in the appropriate formats as specified by BEIS.

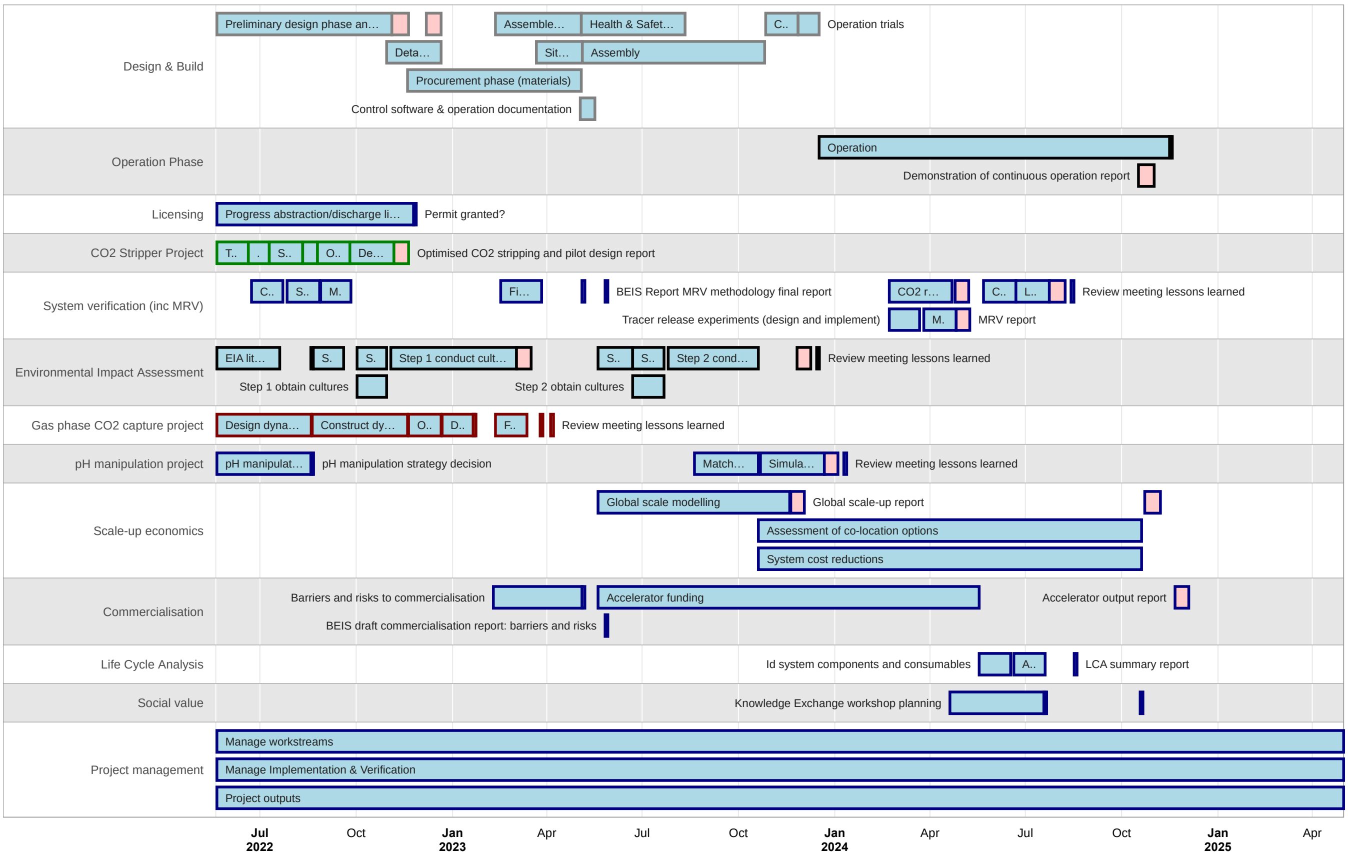

Figure 75. Phase 2 project Gantt chart. Full sized version and interactive version available through the BEIS facing report. Blue represents a process, light red a deliverable or report, and light green an external workshop. The outline colour of the box defines who is leading on that work; Exeter = Blue, PML = Green, Brunel = Red and Eliquo Hydrok = Grey.

4.4.2 Cost savings compared with exclusive development contracts

The Phase 1 and Phase 2 project activities are conducted by all partners without profit. Phase 2 will use and develop the monitoring system constructed in Phase 1, and will rely heavily on existing resource/expertise at PML and Exeter for environmental impact assessment and monitoring and verification work. Phase 2 is highly ambitious and simply could not be delivered as an exclusive development contract. The SeaCURE project has made use of appropriate expertise across all organisations ‘on demand’, which represents significant saving and productivity gain compared to short-term recruitment of individuals.

4.5 Site

This section is available in the BEIS facing report.

4.6 Programme and business plan beyond Phase 2

Four alternative markets and product solutions have so far been identified, ranging from land-based units which are collocated with facilities such as desalinisation plants, through to neutrally buoyant systems collocated with floating offshore wind. Conversations have begun in these areas. Details in BEIS facing report.

Strategic decisions in the business plan will be made in the run up to the Phase 2 application, and throughout Phase 2. At present the SeaCURE consortium is represented by; two university partners, a marine research organisation and a SME. The expertise within this consortium has been perfectly placed to address the challenges set in Phase 1. The success of Phase 1 however, has demonstrated two things. Firstly, that the fundamental and theoretical design is solid, and secondly, that the approach could be rolled out soon, and at very large scales to address the fundamental challenge of decarbonisation and committed global warming. This leads to prioritisation in two focussed areas moving forward.

1) Practical build experience should be prioritised over theoretical design experience in Phase 2. The theory is solidly understood now, so we want a partner embedded in this project who can undertake the fabrication and plant build in a way that involves the whole consortium to allow quick feedback and solving of build challenges, as well as exploitation of new ideas.
2) While the size of the Phase 2 activity is unlikely to be appropriate for involvement of a partner with the capacity to scale this solution, we need to be engaging with such scaling partners, and bringing them on in advisory capacities to allow us to rapidly step to the large scale.

None of the Phase 1 partners are positioned to undertake the fabrication and build piece, or to scale this technology. Phase 2 will therefore bring in new expertise formally and informally in this area.

It is critical to society that SeaCURE rapidly moves beyond SME scale. Two potential routes are thus being actively considered:

- During or shortly following Phase 2 we licence the IP to a new industrial partner who has the size, customer base, resources, and expertise to scale the solution within their day-to-day business.
- We form a spinout company within Phase 2 into which the IP is licenced, and bring in investment through Series A to Series E funding rounds to grow a company that can scale this itself.

4.7 Intellectual Property (IP)

Fundamental to the options explored above, is that the IP generated within Phase 1 and Phase 2 are packaged in an investable or sellable form. The project has an IP register into which all partners have clarified their IP position and are supported by Exeter's technology transfer team.

4.8 Carbon market and investment opportunities

Placing SeaCURE's pilot scale project through to future projected operational costs in the context of historical to present day carbon prices from the World Bank[2] and UK government future valuation of carbon emissions (shadow price)[3], we see that the SeaCURE carbon removal costs can not only meet the BEIS target of £200/tonne CO_2 removed, but also come in to line with historical carbon prices (Figure 6). For much of December 2021 the European Union Emission Trading Scheme carbon price has been above €80/tonne-CO_2 (Figure 7). The rapidly increasing price of traded carbon reflects the present energy challenges. When gas price increases, coal use is substituted with an associated increase in demand for emissions allowances). Investors take a longer term view that the carbon prices will continue to rise, and companies hedge against climate risk[4]. The move to see the EU ETS as an investment opportunity reflects the confidence that governments are increasingly taking climate policy seriously, but more concretely, the confidence that the EU 'Fit for 55' package of proposed legislation will pass[5]. Fit for 55 would see changes to the EU ETS that drive emissions reductions in the covered sectors by 61% (relative to 2005) by 2030. A key aspect of this plan is an acceleration of the rate at which available carbon allocations are annually reduced (from 2.2% to 4.2%[6]). How high EU ETS prices will rise is impossible to predict, but

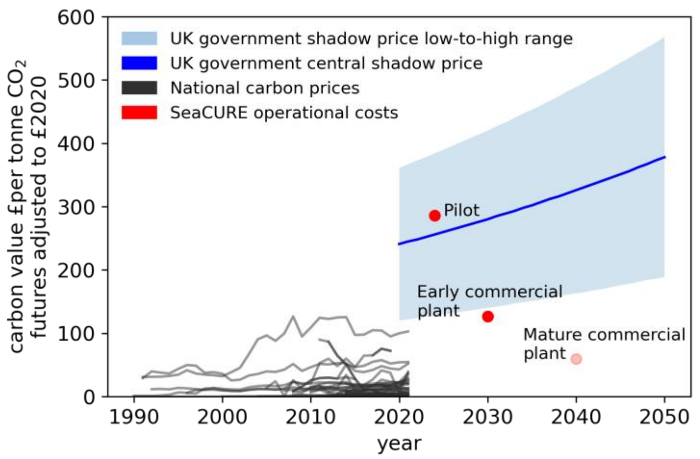

Figure 6. Calculated and projected SeaCURE operational costs compared to present nationally/block determined carbon price (black lines) and UK government shadow carbon price.

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[2] https://carbonpricingdashboard.worldbank.org
[3] https://www.gov.uk/government/publications/valuing-greenhouse-gas-emissions-in-policy-appraisal/valuation-of-greenhouse-gas-emissions-for-policy-appraisal-and-evaluation
[4] https://www.energymonitor.ai/policy/carbon-markets/why-european-carbon-prices-could-be-higher-for-good
[5] https://www.consilium.europa.eu/en/policies/green-deal/eu-plan-for-a-green-transition/
[6] https://www.cleanenergywire.org/factsheets/understanding-european-unions-emissions-trading-system

it will not take much of an increase before it is higher than the projected 2030 SeaCURE operational costs.

We have presented to government our ideas about how carbon markets needs to develop to allow the industry to mature at the required pace[7]. Here our proposition is to stimulate the UK negative emissions market by making use of a 'feed-in-tariff' like approach, as applied during the early days wind power generation. Activities like SeaCURE could then bid into this with certainty. The government would act as a "carbon bank", reselling the negative emissions credits to polluters at a price driven by the regulatory environment the government decides to create. Providers of NETs need to be insulated from carbon market uncertainties as they go through scale-up, to make it easier to secure funding (if revenue is known, investors can focus attention only on costs and delivery risks). The renewables example was highly successful, providing a market which encouraged investment and innovation, leading to very rapid reductions in cost. This model is also flexible, in that 'feed-in-tariff's' can be scaled up or down depending on the volume of unabated emissions the government decides to accept over time. Government can always ensure that it can dispose of the acquired NET credits by tightening carbon rules to drive up carbon credit prices and/or by reducing 'feed-in-tariff' allocations going forward.

An important part of our business plan has been to understand the final customer and the priorities of investors. These conversations have strongly influenced the focus of activities within Phase 2. From these conversations we have established a network of mentors, supporters, 'critical friends' and potential investors and customers who are all keen to be involved informally in Phase 2.

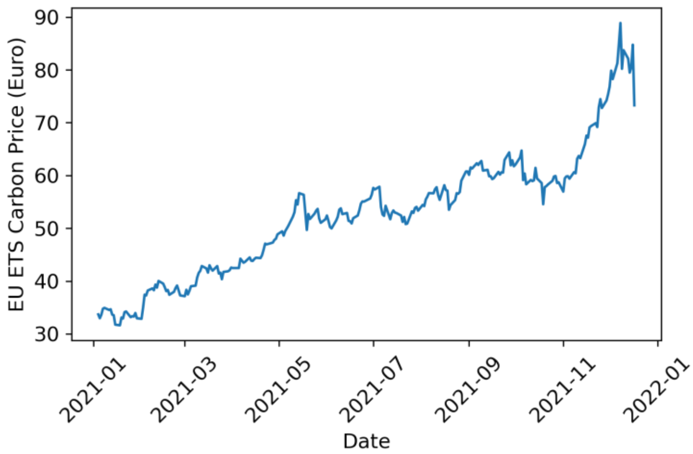

Figure 7. European Union Emission Trading Scheme carbon price (Euro). From ember-climate.org.

5 Summary/conclusions

From a standing start the SeaCURE Phase 1 project has worked through, tested the underlying concepts behind and delivered underpinning data to allow the successful delivery of high-quality designs for a first of its kind marine-based Negative Emission Technology. It demonstrates a clear pathway to <£200 per tonne of CO_2 and a pilot plant capacity of 100 tonnes of CO_2 per year. SeaCURE has delivered the context and justification for the value of marine based solutions to the climate change

[7] https://committees.parliament.uk/writtenevidence/40459/html/

problem. Finally the SeaCURE Phase 1 project has developed a detailed, costed plan for the delivery of the pilot plant, and has developed a full plan of work to deliver a commercially viable solution and meet or exceed all of the requirements within Phase 2.

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