SeaCURE Phase 2 Public Facing Final Report

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This public facing version of the SeaCURE Phase 2 project final report is an abridged version of the full final project report prepared for the project funders: the Department for Energy Security and Net Zero (DESNZ). The report brings together work done and reported on through over 60 deliverables within the SeaCURE project by the four project partners, the University of Exeter, Plymouth Marine Laboratory, Brunel University of London and ELIQUO HYDROK. This condensed version of the report removes data, modelling, evidence and methodology appendices, and briefly summarises the sections that are intended for peer reviewed publication, or which may be of a commercially sensitive nature to the project, partners or contractors. Some sections included in the full report primarily to meet the funder's evidencing requirements have also been removed, and sections reordered to improve the document's accessibility.

The DESNZ Phase 2 Greenhouse Gas Removal (GGR) projects, of which SeaCURE was one, were tasked with delivering:

- The construction of a GGR pilot in a real-world environment.
- Operation/trial of the GGR pilot in a real-world environment.
- Evaluation and Intellectual Property Requirements.
- Contribution to knowledge dissemination activities.
- An evidence-based interim report detailing the methodology for measuring/calculating the greenhouse gas capture rate for Monitoring, Reporting and Verification (MRV).
- An evidence-based interim report detailing the barriers and risks to commercialisation.
- An evidence-based final project report detailing the design and development of the pilot system, demonstration and trials results, key successes, lessons learned, remaining uncertainties and next steps.

These objectives were successfully delivered by the project between May 2022 and June 2025 with just under £3M funding from the Department for Energy Security and Net Zero.

Glossary

Term or acronym	Brief definition (detailed explanation in main text as required)
Alkalinity	Ocean's ability to neutralise acid
BEIS	Department for Business, Energy & Industrial Strategy (no longer exists)
BPMED	Bipolar Membrane ElectroDialysis
Ca	Calcium
$CaCO_3$	Calcium Carbonate
CapEx	Capital Expense
CDR	CO_2 Removal
CO_2	Carbon dioxide
CO_3	Carbonate
CREPE	Carbon Removal: Efficient Pre-treatment for Electrochemistry
DACC	Direct Air Carbon Capture
DESNZ	Department for Energy Security and Net Zero (Since 2023)
DIC	Dissolved Inorganic Carbon
DOCC	Direct Ocean Carbon Capture
DSEAR	Dangerous Substances and Explosive Atmospheres Regulation
EA	Environment Agency
GAC	Granular Activated Carbon
GGR	Greenhouse Gas Removal
GHG	GreenHouse Gas
Gt	Gigatonnes
HCl	Hydrochloric acid
HCO_3	Bicarbonate
HSE	Health and Safety Executive
LC/LP	London Convention and Protocol
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LPM	Litres per minute
m^3	Cubic metre
mCDR	marine CO_2 Removal
Mg	Magnesium
$Mg(OH)_2$	Magnesium Hydroxide
mg/l	Milligrams per litre
MRV	Monitoring, Reporting, Verification
MWh	Mega Watts per hour
N_2	Nitrogen

NaOH	Sodium hydroxide
NOx	Nitrogen oxides
O_2	Oxygen
OAE	ocean alkalinity enhancement
OH	Hydroxide
OpEx	Operating Expense
P&ID	Piping and Instrumentation Diagram
PVSA	Pressure Vacuum Swing Adsorption
R&D	Research and Development
SCADA	Supervisory control and data acquisition
SeaCURE	Sea Carbon Unlocking and REmoval
SOx	Sulphur oxides
TRL	Technology Readiness Level
t	Tonnes
TSA	Temperature Swing Adsorption
µatm	Micro-atmosphere
µeq	Micro equivalents
µmol	Micromole

1 Introduction

Minimising the impacts of climate change requires not only very deep and rapid emissions reductions but also active removal of carbon dioxide (CO_2) from the atmosphere. Even with ambitious decarbonisation efforts, residual emissions from many sectors such as aviation, agriculture, and heavy industry will persist, necessitating negative emissions strategies to meet net-zero. Then, to meet the Paris Agreement goals we must go further and deliver net-negative emissions. The ocean, which already absorbs around a quarter of anthropogenic CO_2, presents a promising avenue for large-scale CO_2 Removal (CDR) through techniques such as Direct Ocean Carbon Capture (DOCC) and Ocean Alkalinity Enhancement (OAE).

Natural concentrations of CO_2 in seawater are much higher than those in air, so processing 1 m^3 of seawater is approximately equivalent to processing 100 to 150 m^3 of air. The SeaCURE project has developed and tested a novel DOCC technology that extracts dissolved inorganic carbon (DIC) from seawater before returning the treated water to the marine environment with a lower DIC concentration but unchanged alkalinity. The released water naturally reabsorbs CO_2 from the atmosphere over the following weeks to months. To our knowledge, we have built and operated the second DOCC pilot plant to exist anywhere in the world, and developed the first DOCC MRV protocols and DOCC marine impact data.

This report presents the key findings from the SeaCURE project, including the technological development, pilot-scale build and testing, MRV development and environmental impact research. The report then presents data derived from the plant design and build that inform Life Cycle Assessment (LCA) and costs, and underpinning sections examining the route to commercial scale operation. A critical component of the SeaCURE work, has been to evaluate the implications of releasing chemically modified seawater back into the marine environment. High pH and low DIC conditions alter carbonate chemistry, influence biological processes, and affect marine organisms, particularly in areas of limited mixing. To address these concerns, SeaCURE has combined laboratory experiments with hydrodynamic modelling to assess potential ecological impacts under real-world conditions.

2 SeaCURE Plant Science, Design and build

2.1 Overview of process

The SeaCURE process is designed to efficiently remove CO_2 from seawater while ensuring that the treated water can fully reabsorb CO_2 from the atmosphere downstream of the plant. The process is built around electrochemical pH manipulation, CO_2 stripping and purification, with interdependencies between stages to improve energy efficiency and minimise consumable requirements (Figure 1).

Seawater enters the system through an intake and flow splitting stage, ensuring that the required volume - fully optimised this is around 2-3% - is delivered for pre-treatment, and the remainder passes to the seawater CO_2 removal step. Calcium (Ca) and magnesium (Mg) must be removed from the seawater prior to the electrochemical step to avoid scaling. Magnesium hydroxide ($Mg(OH)_2$) and calcium carbonate ($CaCO_3$) are selectively precipitated to remove Ca and Mg ions that would otherwise lead to precipitate formation on, and damage of, the electrodialysis membranes.

Following pre-treatment, the seawater is used for electrochemical acid and base generation. A bipolar membrane electrodialysis (BPMED) system is used to generate the acid and base streams, eliminating the need for bulk chemical dosing. The acidified stream is sent forward to enable CO_2 extraction, while the alkaline stream is used to elevate the pH in the pre-treatment step and to restore the treated seawater's alkalinity before discharge.

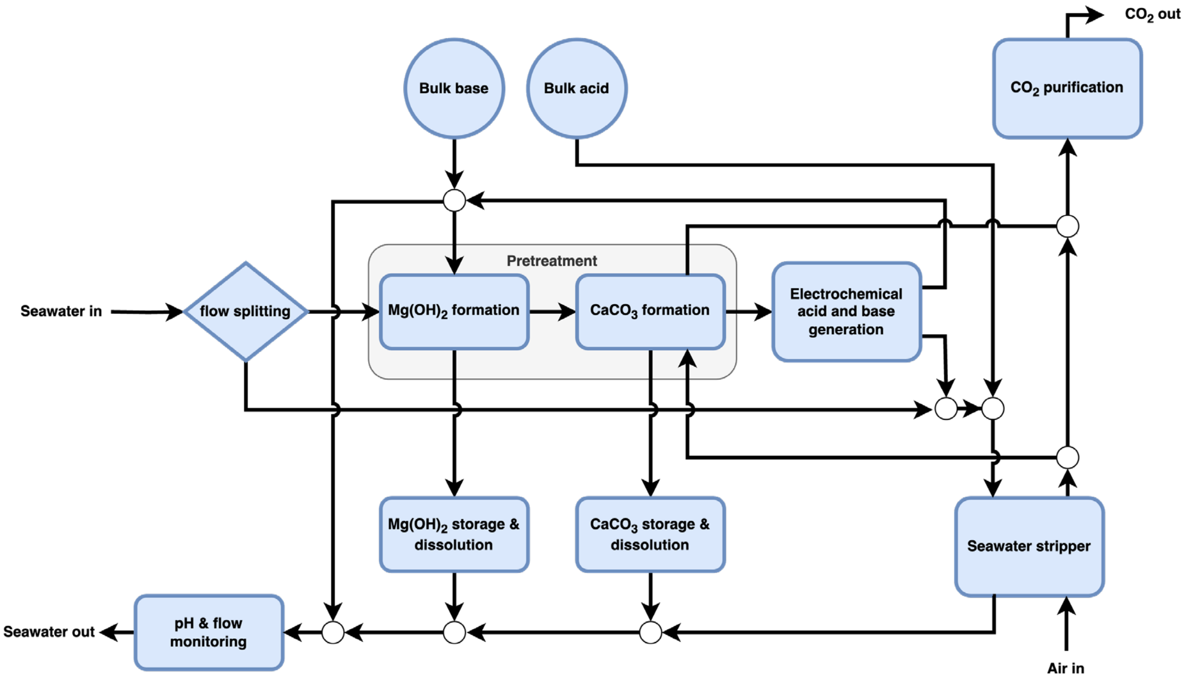

Figure 1. Schematic of final SeaCURE process.

In the CO_2 stripping stage, acidified seawater enters a gas-liquid separation column where CO_2 is liberated from solution and extracted as a gas (see Box 1 for an explanation of the underpinning seawater chemistry behind this). The stripping process maximises the removal of dissolved inorganic carbon (DIC) by exploiting the lower pH, which converts bicarbonate and carbonate species (non-volatile) into dissolved CO_2 gas (volatile). Through efficient gas-exchange mechanisms, the CO_2 is separated and transported for further processing.

Once separated, CO_2 enriched gas is directed into the purification system, which employs a granular activated carbon (GAC) pressure-vacuum swing adsorption (PVSA) process. This step ensures high-purity CO_2 output, suitable for permanent storage or industrial applications. The PVSA system selectively separates any remaining atmospheric gases, delivering CO_2 at high purity.

To complete the cycle, the CO_2-depleted seawater undergoes alkalinity restoration before being returned to the ocean. The previously precipitated magnesium hydroxide and calcium carbonate are reintroduced, restoring the chemical balance of the water. This ensures that the discharged seawater remains undersaturated with respect to atmospheric CO_2, allowing it to naturally reabsorb CO_2 from the air over time.

Box 1. Overview of seawater carbonate chemistry.

Seawater's high dissolved carbon concentration exists because high alkalinity in the water converts CO_2 absorbed from the atmosphere into dissolved carbonate and bicarbonate. This buffering of the CO_2 concentration maintains the air-sea CO_2 gradient, allowing further CO_2 to be taken up (Zeebe and Wolf-Gladrow, 2008). Dissolved carbon is removed from seawater in the SeaCURE system by acidifying the seawater to convert dissolved carbonate and bicarbonate into CO_2 (Figure 2); the CO_2 is then extracted into a stripping gas from which it is purified to >98% purity for transportation and storage or utilisation. The seawater's alkalinity is then restored before release to the ocean.

By lowering the pH to around 4, essentially all of the dissolved inorganic carbon in seawater is converted to CO_2. In this form, the carbon can exchange with gas in contact with the water and be removed. The addition of H^+ to reduce the pH results in a decrease in alkalinity (Equation 1). After CO_2 stripping, the pH is increased by OH^- addition to the water to restore it to ambient seawater alkalinity, allowing the water to buffer new CO_2 uptake from the atmosphere, absorbing an amount of CO_2 from the atmosphere equal to that removed within the plant, and returning the seawater chemistry to that of ambient seawater.

Equation 1. Total alkalinity as defined by (Dickson, 1981) and updated in (Wolf-Gladrow *et al.*, 2007). Ellipsis stand for potential unidentified species.

$$Total\ Alkalinity\ (TA) = [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [OH^-] + [HPO_4^{2-}] + 2[PO_4^{3-}] + [H_3SiO_4^-] + [NH_3] + [HS^-] + \cdots - [H^+] - [HSO_4^-] + [HF] - [H_3PO_3] - [HNO_2] + \cdots$$

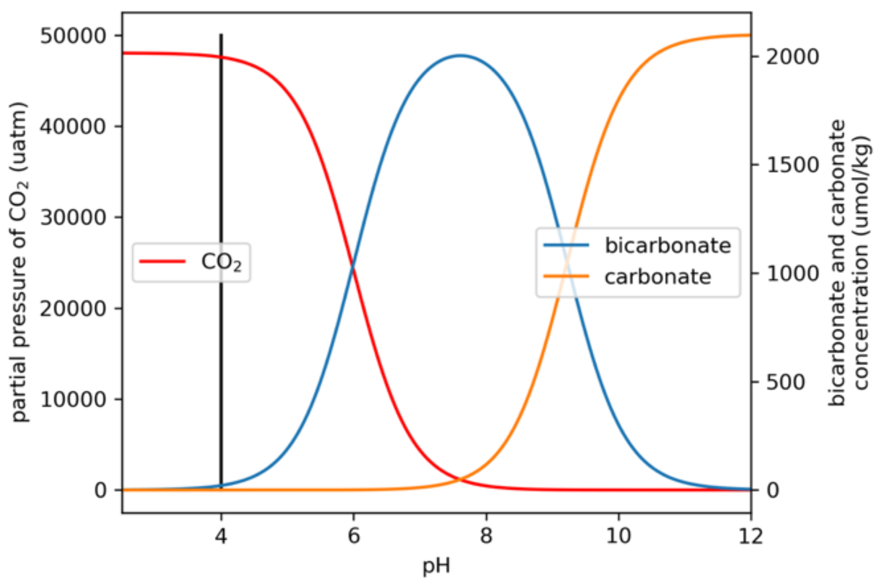

Figure 2. Partial pressure of CO_2 and concentration of non-CO_2/carbonic acid components of seawater dissolved inorganic carbon (carbonate and bicarbonate) in response to a range of pH values for standard seawater conditions of 2100 µmol/kg total dissolved carbon, 10.0 ºC and a salinity of 35 psu. pH 4, where essentially all dissolved carbon is CO_2, is marked with a vertical black line.

2.2 Design considerations

2.2.1 Permitting

Operation of the SeaCURE pilot plant required a bespoke Environment Agency (EA) discharge permit because its effluent composition lay outside standard regulatory limits. The process and timeline for developing and obtaining this permit is illustrated in Figure 3.

Details of the permit application development have been removed for brevity.

A permit was granted for a maximum daily discharge of 14,200 m^3 in the pH range 7-10. Effluent sampling and monitoring as well as monitoring upstream and downstream of the discharge outflow were a requirement of this permit.

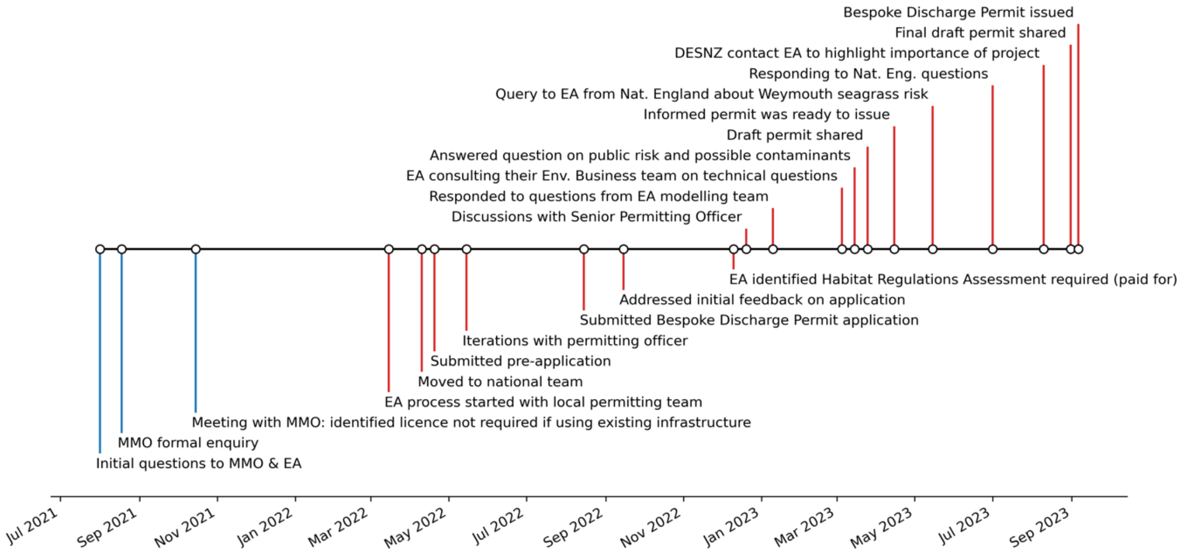

Figure 3. SeaCURE's Environment Agency bespoke discharge permit journey.

2.2.2 Seawater abstraction

2.2.2.1 Site selection

The SeaCURE pilot plant required a continuous and reliable seawater supply to sustain its CO_2 removal process. Work during the SeaCURE Phase 1 project, the nine-month project that preceded the project being reported on here, identified that the permitting timescales and permitting risks associated with installation of bespoke seawater abstraction infrastructure were not compatible with the Phase 2 time constraints. A site in Weymouth UK was therefore identified as an appropriate site and agreements put in place for lease and use of infrastructure that guaranteed SeaCURE continuous access to seawater. In Phase 2, an assessment was conducted of the seawater abstraction system at Weymouth site. This evaluation included CCTV examination of existing pipework and modelling of the expected seawater abstraction to understand seawater flow rates, and to inform design of the seawater abstraction skid. The conclusion of this work was that the site had the potential to support up to ~100 m^3 of seawater per hour at high tide - close to 134 m^3/h, the absolute minimum requirement for 100 tonnes of CO_2 per year removal, assuming a capture efficiency of 90% and continuous operation (calculations provided in full report).

2.2.2.2 Existing infrastructure

The existing seawater abstraction and discharge infrastructure at the site is analysed and described in the full final report but omitted here.

Time constraints and limited alternative locations, balanced with the positives of the initially selected site, meant that it was decided to proceed despite lower water abstraction than desired, acknowledging that full testing of the abstraction would not be possible ahead of committing to much of the pilot design.

2.2.2.3 Design and operation implications, and lessons leant

The SeaCURE plant design needed to align with the calculated achievable water flow, which required a scaling down of the CO_2 removal target to a maximum of ~ 60 tCO_2/yr.

Testing of the SeaCURE installed extraction skid was only possible in late 2024, where it was identified that maximum seawater extraction rates were unlikely to exceed 10 and 20 $m^3/hour$ from the site's older and newer extraction lines respectively. A key lesson learnt is that this should have been captured in the site specific designs and requirements activity delivered early in the project. The wider lessons learnt is that there is risk associated with 'piggybacking' on existing infrastructure, particularly where the original user's requirements are lower than the new plant requirements. Future sites would ideally include dedicated abstraction infrastructure, and would be designed to extract water under positive pressure rather than suction.

2.2.3 Seawater pre-treatment

As described above with reference to Figure 1, a sub-stream of seawater needs to be pretreated to remove Ca and Mg before it enters the electrodialysis cell to avoid scaling. The presence of divalent cations such as calcium (Ca^{2+}) and magnesium (Mg^{2+}) poses a significant challenge because these cations precipitate as minerals on and within membranes, leading to increased resistance, reduced system efficiency, and potential operational failures.

Existing softening approaches involve trade-offs between consumable-intensive chemical precipitation methods and energy-intensive physical separation techniques. Chemical-based approaches, such as reagent-induced precipitation and use of ion-exchange resins, require frequent 'topping up' or regeneration, leading to high operation costs and waste disposal challenges. Physical separation methods, including nanofiltration and reverse osmosis can, in the case of reverse osmosis, effectively remove divalent cations but at the cost of substantial energy demands due to high-pressure operation.

With funding from UKRI's CO_2RE (CREPE project) we developed an innovative low-energy pre-treatment method that precipitated the Ca and Mg without the need for any additional feedstocks, and fully utilised the produced precipitate in the system. Results from this lab based study were immediately fed into the pilot design, and incorporated into the pilot build.

The full description of this development has been removed from this report so that it can be published in the peer reviewed literature.

2.2.4 Generation of seawater alkalinity swing

2.2.4.1 Alkalinity Swing Process in the SeaCURE CO_2 Removal System

SeaCURE employs an alkalinity swing process as a fundamental mechanism to liberate CO_2 from seawater and facilitate its subsequent uptake from the atmosphere downstream of the plant. This process involves lowering the pH to approximately 4 (the point where all of the alkalinity has been consumed by acid), and converting nearly all dissolved inorganic carbon in seawater into CO_2 (Figure 2 and Box 1) so that it can then be extracted. Following CO_2 stripping, the alkalinity is elevated back to ambient seawater levels, ensuring atmospheric CO_2 uptake downstream of the plant. The selection of an optimal pH manipulation strategy for the pilot plant had to balance several key criteria, including operational reliability, economic feasibility, scalability, energy efficiency, and supply chain availability.

All available technologies that we could identify to produce the alkalinity swing were reviewed and in reports to DESNZ. Two primary approaches were identified in the design phase and considered with respect to their suitability for commercial-scale SeaCURE-like plants: the chloralkali process and bipolar membrane electrodialysis (BPMED). At the pilot scale, we also needed to consider direct acid/base dosing using commercially available hydrochloric acid (HCl) and sodium hydroxide (NaOH). This option was included to reduce risk due to its operational simplicity and known supply chain, and to minimise interdependencies during commissioning.

2.2.4.2 Direct Acid/Base Dosing Approach

The SeaCURE system has the option to function with imported HCl and NaOH to achieve the required pH shifts. While this method reduces operational risk, enables rapid deployment and relatively straightforward operational control, it presents significant logistical and economic challenges for commercial-scale implementation. The primary limitation of this approach is its dependence on large volumes of chemicals, which introduces supply chain vulnerabilities, cost uncertainties, life-cycle challenges, and may limit the overall cost reduction potential.

For the removal of one tonne of CO_2, approximately 1.3×10^7 kg of seawater must be processed. This requires 1.24 tonnes of NaOH and 1.1 tonnes of HCl, equating to approximately 0.79 m^3 of 32% NaOH and 0.7 m^3 of 37% HCl per day in a facility designed to remove 100 tonnes of CO_2 per year. The high demand for these chemicals underscores the need for a transition to more sustainable pH manipulation strategies at commercial scales.

Several further challenges arise from the use of direct acid/base dosing in large-scale CO_2 removal applications, including chemical supply and logistics present a major hurdle.

The environmental footprint of producing these chemicals is also significant, with the manufacturing process contributing to carbon emissions. At present the global warming potential of typical 32% NaOH is 0.54 kg CO_2 per kg, while 37% HCl contributes 1.07 kg CO_2 per kg, undermining the net-negative carbon removal objective of the SeaCURE project.

2.2.4.3 Alternative Strategies for Commercial Deployment

Given the limitations of direct acid/base dosing from bulk product, alternative pH manipulation strategies are required for commercial-scale implementation. Two promising methods are the chloralkali process and bipolar membrane electrodialysis (BPMED), both of which offer substantial benefits in terms of sustainability and cost efficiency. BPMED was implemented in the SeaCURE pilot plant.

2.2.4.3.1 Chloralkali Process

The chloralkali process is an electrochemical method widely used for producing NaOH and HCl precursors from sodium chloride brine. Integrating this process into the SeaCURE system would eliminate the need for external acid and base supplies, significantly reducing logistical constraints and lifecycle emissions. This method operates with an energy requirement of approximately 1.66 MWh per tonne of CO_2 removed. Additionally, the exothermic nature of HCl production from the chloralkali generates hydrogen and chlorine gases and offers a potential energy recovery opportunity, further improving process efficiency. However, the method requires pre-concentrated brine, and pre-treatment of seawater to remove impurities that could degrade membranes.

2.2.4.3.2 Bipolar Membrane Electrodialysis (BPMED)

BPMED is an energy-efficient alternative for acid/base generation from seawater with literature suggesting operation in the range 0.98–1.6 MWh per tonne of CO_2 removed. These published energetic costs make it one of the most promising approaches for long-term scalability. However, they are not necessarily representative of the real world direct ocean carbon removal use case. Potential for future improvements in energy consumption are discussed in section 4.3.

As applied within the SeaCURE project, BPMED operates an electrochemical cell comprised of a series of anion-exchange membranes (AEM), cation-exchange membranes (CEM), and bipolar membranes (BPM) arranged between the cathode and the anode (Figure 4). When an electric field is applied, cations migrate towards the anode through the cation exchange membranes, and anions move towards the cathode through the anion-exchange membranes, removing salts from the central compartments. The bipolar membranes comprise two layers, an anion-permeable side and a cation-permeable side where water dissociates into H^+ and OH^-. The H^+ ions flow toward the acidic compartment on the BPM side facing the anion-selective layer, while the OH^- ions travel into the basic compartment on the side facing the cation-selective layer, ultimately producing streams enriched in acid and base. The changes generated by the dissociation of the water are balanced by the negative and positive changes of Cl and Na respectively. The dashed lines in Figure 4 indicate the minor leakage of ions that inevitably occurs through these membranes.

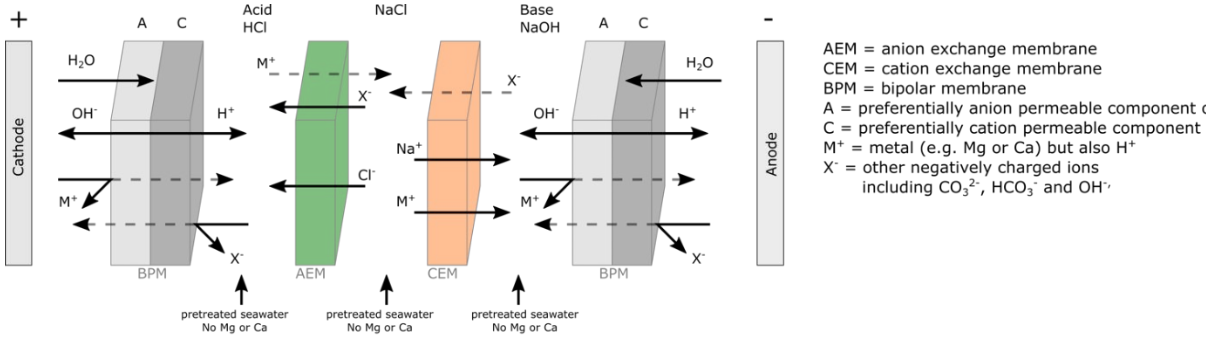

Figure 4. Schematic of BPMED system for seawater acid and base generation. AEM = anion exchange membrane, CEM = cation exchange membrane, BPM = bipolar membrane, A = preferentially anion permeable component of BPM, C = preferentially cation permeable component of BPM, M^+ = metal (e.g. Mg or Ca), X- = other negatively charged ions including OH^-. Solid lines indicate intended transfer, dashed lines indicate leakage.

The primary benefits of BPMED include its ability to generate acid and base on-site, thereby eliminating supply chain dependencies, and its seamless integration into the SeaCURE process. However, BPMED systems require careful pre-treatment to mitigate membrane scaling and fouling risks.

2.2.4.4 Lab testing to inform pilot design

Laboratory testing was conducted both at Exeter and with a BPMED manufacturer, but results are omitted here because of commercial sensitivities.

2.2.5 Seawater CO_2 stripping

The work on seawater CO_2 removal focused on optimising CO_2 stripping efficiency to inform the design and build of the pilot plant. Through a series of experiments during Phases 1 and 2 of the SeaCURE project, the team developed and refined a stripper design in the lab that could achieve ≥90% CO_2 removal efficiency, while simultaneously considering energy efficiency, CO_2 concentration in the gas leaving the stripper (relevant to the subsequent purification step), and ease of scalability up to the seawater flows anticipated in the pilot plant.

2.2.5.1 Principles of Seawater CO_2 Removal

The CO_2 removal process takes advantage of Le Chatelier's principle and Henry's Law. Increasing the hydrogen ion (H^+) concentration in seawater adjusts the equilibrium position of the inorganic carbonate system (see Box 1) such that the carbonate species (carbonate, CO_3^{2-}, and bicarbonate, HCO_3^- ions) are converted to CO_2 (Le Chatelier's principle). Once seawater is acidified to pH <4, nearly all of the carbonates are converted into dissolved CO_2 and it reaches a concentration of ~50,000 ppm, significantly higher than ambient air (~425 ppm). Henry's Law describes gas-liquid equilibrium of ideal gases. Ensuring a large concentration gradient between the liquid phase (seawater) and the stripping gas stream favours CO_2 mass transfer (degassing) of CO_2. The efficiency of the process is then controlled by the surface area that facilitates contact between liquid and gas phases, and the time in which they are in contact. This was the focus of the Phase 1 and 2 experiments, the findings of which are summarised below.

2.2.5.2 Experimental Setup & Key Findings

The general lab setup was consistent for all experiments, consisting of two tanks - a header tank (~1 m³) and a buffer tank (~2.5 m³). Seawater was acidified in the header tank and then transferred into the buffer tank via a single pass through the stripper. CO_2 loss from the header tank was minimised and shown to be <10% per working day, confirming efficient containment during experiments. CO_2-rich air was extracted from the stripper using compressed nitrogen as a stripping gas. pH and CO_2 concentrations were continuously monitored, and water samples routinely collected from before and after the stripper for subsequent analysis of DIC.

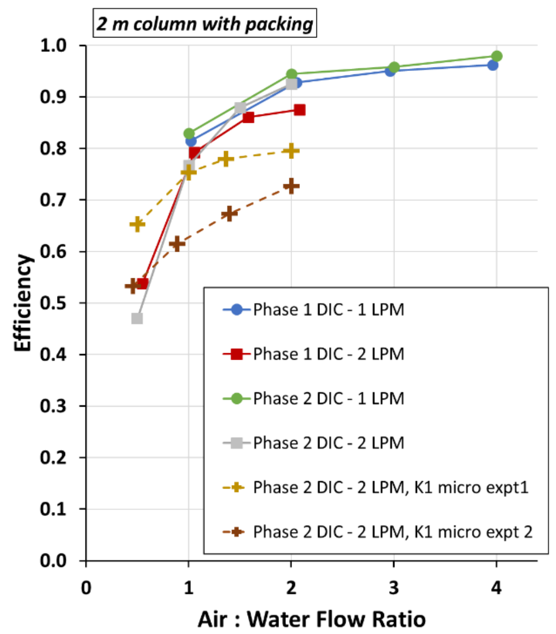

Figure 5. Stripping efficiency versus air:water flow rate ratio for K1 micro packing material (orange and red plusses) compared with Phase 1 (blue and red) and Phase 2 (green and grey) experiments using 16 mm Pall Rings. The K1 micro packing material resulted in lower efficiencies and inconsistent experimental data.

Initial work during Phase 1 developed a packed stripper column containing material to facilitate a large seawater surface area per column volume. Acidified seawater was introduced via a spray nozzle. Additional experiments showed that increasing column height from 1 m to 2 m helped improve stripping efficiency while minimising the air:water flow rate ratio. Using a 2 m column packed with 16 mm Pall Rings (320 m² per m³ surface area) coupled with a 2:1 air:water flow rate ratio enabled >90% stripping efficiency (whereas a 1 m column required a 3:1 air:water flow rate ratio to achieve the same stripping efficiency). Gas phase CO_2 concentrations in the stripper outflow were 1.5-2.0%.

Phase 2 focussed on identifying any substantive impacts on stripping efficiency either due to a) modifications to the general design principles developed during Phase 1, or b) upscaling by a factor of ~10. The lessons learnt would then inform the design of the pilot plant stripping unit. The upscaled design was achieved by maintaining a constant ratio between column cross-sectional area to the seawater flow rate through the stripper. Building an upscaled stripping column for flow rates a factor of 10 greater than Phase 1 resulted in very similar stripping results. A 2:1 air:water flow rate ratio achieved ~90% stripping efficiency and 2% CO_2 concentration in the stripper outflow.

The major design change tested in Phase 2 was the use of alternative packing material. K1 Micro packing material was trialled. The benefit of K1 Micro was its extremely high surface area per volume ratio (1400 m² per m³), with the hypothesis that this would improve stripping efficiency. However, the low void fraction of K1 Micro meant that this created excessive back pressures and made flow control difficult. As a result, Pall Rings remained the preferred packing material due to their operational stability.

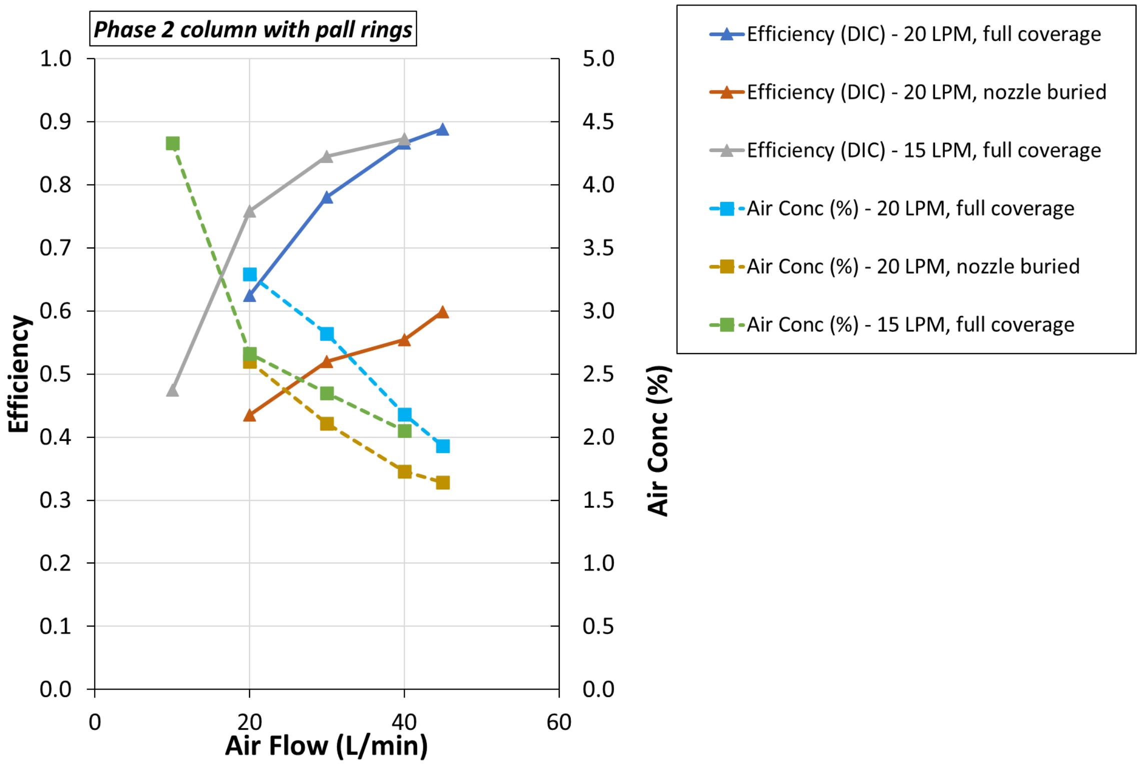

Figure 6. Air flow rate versus CO_2 stripping efficiency using the Phase 2 upscaled CO_2 stripping column. Three experimental runs were conducted: One at 15 LPM seawater flow rate; one at 20 LPM seawater flow rate; and one (also at 20 LPM seawater flow rate) with the nozzle buried in the packing material.

2.2.5.3 Pilot Plant Design Recommendations

Based on the Phase 2 lab experiments, design and operating parameters were identified for the pilot plant. It was recommended that:

- Each column should be at least 1.5 m tall, packed with 16 mm Pall Rings.
- A sump system should be used to stabilise pressures and prevent air siphoning out with the seawater leaving the stripper.
- Even coverage of Pall Rings by seawater is essential and a redistribution tray placed midway in the column was recommended.
- Air flow rates needed to have the flexibility to achieve from 1:1 to 3:1 air:water flow rate ratios so that stripping efficiency and CO_2 concentrations could be optimised and achieve results equivalent to or better than the lab experiments.

- Any increase in stripping column height above 1.5 m (if design allows) could improve stripping efficiencies, but the final configuration should take into account the energy costs (e.g. increased pumping head for seawater) required to achieve this.
- Consider upscaling via multiple stripping columns that could be used in a modular fashion to give the pilot plant maximum flexibility.

2.2.5.4 Conclusions & Future Work

The optimised CO_2 stripping process provided a scalable and efficient approach for CO_2 removal from seawater, which informed the pilot plant design and build. Future work at the pilot plant should focus on testing the longer-term continuous performance, system stability, and CO_2 extraction efficiency. In addition, alternative packing geometries could be investigated to see if stripping kinetics could be further enhanced.

2.2.6 Pressure Vacuum Swing Adsorption (PVSA)

The CO_2 removal and purification (i.e. CO_2 capture) step of the SeaCURE pilot plant modelling and design originally relied on amine-based scrubbing (absorption-based) for CO_2 capture and purification. Amine-based CO_2 scrubbing is efficient and commercially scalable, however this method was reconsidered and replaced with adsorption-based techniques because of environmental and safety concerns associated with amines and associated challenges and limitations at the construction site. Amines are toxic, corrosive and highly flammable, creating significant risks for both human health and the surrounding environment. The presence of oxygen in the mixed gas removed from seawater poses a challenge for amine-based scrubbing, since oxygen can degrade amines and reduce their effectiveness over time. Adsorption, on the other hand, employs solid materials to capture CO_2, presenting a safer and more sustainable alternative. A lot of these solid materials have been sourced from waste materials, making them a potentially cost-effective alternative for CO_2 capture.

As part of the transition from amine-based CO_2 capture to adsorption-based capture**,** Brunel University of London comprehensively evaluated the use of granular activated carbon (GAC) as the adsorbent material for the SeaCURE project. The outcomes from this work are presented below, and data and figures from the deliverable are summarised in the non-public facing version of the report.

2.2.6.1 Selection of GAC Adsorbents

Prior to selecting GAC, alternative adsorbents such as metal-organic frameworks (MOFs) and aluminosilicate-based materials (e.g. zeolites, mesoporous silica) were considered. However, GAC was chosen due to its relatively high affinity towards CO_2 coupled with its cost-effectiveness, availability, mechanical stability and superior tolerance to oxygen and moisture (which are part of the off-gas from the CO_2 stripping unit). After substantial investigations, four major GAC suppliers were identified and shortlisted based on cost, lead time, and performance characteristics. These companies were selected because they offer adsorbents with pore sizes (i.e. ultra microporous adsorbents) that are most favourable for CO_2 adsorption.

2.2.6.2 Experimental Evaluation of GAC Performance

Gravimetric Adsorption Screening (Step 1). Gravimetric tests were the first step of the screening process. The procedure involved loading a particular sample mass into a temperature-controlled thermogravimetric analyser (TGA) with continuous weight measurement. The samples were then exposed to high temperatures (150 °C) and a flow of an inert gas (nitrogen, N_2) to purge any existing/trapped species off the surface of the GAC. Then the temperature was brought down to a pre-selected point (namely, 50 °C and 30 °C, the in-house standard temperatures for CO_2 adsorption measurements on this apparatus), where a pure flow of CO_2 was introduced. The subsequent increase in sample mass indicated the CO_2 molecules were being adsorbed on the GAC's surface. Based on the mass change relative to sample weight, CO_2 uptake was calculated and used as an indication of CO_2 adsorption capacity. Two of the nine samples; *Chemviron SRD24004* and *CPL FY5 3x6*, were selected as the best performing adsorbents with CO_2 adsorption capacities of 1.88 and 1.96 mmol/g respectively at 30°C. Interestingly, the best performers in terms of gravimetric estimations of CO_2 adsorption were the most cost-effective options and provided the shortest lead times for their products. Therefore, these materials were selected for further screening, whilst the other candidates were discarded.

Volumetric Adsorption Screening (Step 2). The two selected samples then underwent volumetric tests where harsher conditions (higher desorption temperatures (250 °C) and under vacuum) were utilised to purge the adsorbent. These conditions allowed for more effective purging of any pre-adsorbed (trapped) species off the sample's porous surface. The adsorption step, however, involved the supply of a pre-determined small volume of pure CO_2 to mimic the estimated partial pressure conditions of the expected mixed gas stream. Then, based on the total pressure change in the gas-phase (i.e. supplied total pressure versus the measured total pressure), the volume of adsorbed gas was determined. These values were then used to determine the working capacity by subtracting the adsorbed amount at a given low pressure from the adsorbed amount at a given high pressure. For these tests, the upper CO_2 partial pressure values were 200 and/or 100 mbar, whilst the lower was 40 mbar (corresponding to the proposed conditions of the designed pressure-vacuum swing capture unit).

The CO_2 adsorption step was conducted at 0°C with CO_2 partial pressures indicated earlier. The calculated working capacity from these tests confirmed that *CPL FY5 3x6* was better than *Chemviron SRD24004*. The results at both adsorption-desorption partial pressure ranges (i.e. 200 mbar – 40 mbar and 100 mbar – 4 mbar) was 1.07 and 1.02 mmol/g for *CPL FY5 3x6*. This sample not only had the highest working capacity but also recorded the lowest pressure drop**,** making it the optimal choice for the SeaCURE pilot plant**.**

2.2.6.3 Dynamic Adsorption Performance

To simulate real-world process conditions, dynamic adsorption tests were conducted using a lab-scale temperature swing adsorption (TSA) rig, which mimicked the planned PVSA unit at Weymouth.

The selected GAC (*CPL FY5 3x6*) was tested at 1% and 2% CO_2 concentrations (the estimated concentration to be received from the seawater stripper) with flow rates of 5.28 L/min and 9.05 L/min - which represents the in-house standard and the maximum possible value for the lab-scale TSA column.

The study demonstrated that optimising CO_2 adsorption is achievable by increasing the CO_2 concentration and reducing gas flow rates, which together extend breakthrough times and reduce unused bed length. By splitting the inlet gas across four columns, the superficial gas velocity is reduced, further enhancing adsorption efficiency. The proposed operational strategy employs discontinuous adsorption cycles to maximise capture performance.

2.2.6.4 Key Recommendations for Pilot Plant Implementation

Based on experimental results, it was recommended that the SeaCURE PVSA used *CPL FY5 3x6* GAC as the adsorbent due to its high CO_2 uptake, favourable pressure drop, and excellent performance in dynamic tests. It was decided that the system should be configured with four parallel adsorption columns operating in a pressure-vacuum swing adsorption mode offering the opportunity for sequential adsorption/desorption cycles to ensure continuous operation.

2.3 SeaCURE plant design

Following the scientific and fundamental design work presented in the above sections, the objectives for the design were defined, the mass and material/chemical flows modelled and chemical reaction and separation steps agreed. Table 1 summarises the key sources of data, including outcomes from the Research and Development (R&D) described above, that fed into the pilot plant design.

Table 1. Key data informing the design.

Description	**Data Source**	**Impact on /relevance for design**
Available seawater flow rate from existing infrastructure	Early measurements & infrastructure survey and modelling	Existing sub-sea filtration avoided pre-filtering. Reduction in plant capacity
Space constraints	Site survey	Covered space for work, building height restriction impacting stripping column designs, switch to PVSA & PVSA column design
Seawater chemistry	English channel seawater (Kitidis *et al.*, 2012)	Pumping requirement, plant size
Environmental constraints including permitting	Environment Agency requirements Environmental Quality Standards (EQS),	pH of discharge impacting design. Position of discharge. Modelling to understand dilution.

	nearby protected habitats	
Safety	(DSEAR) & HSE	Move from Monoethanolamine to GAC based PVSA
Cost constraints	DESNZ budget	Procurement decisions. Stripping column design. Dosing decisions. BPMED lease rather than purchase.
Stripping column lab test	SeaCURE lab experiments	Stripping column dimensions, media and air:water requirements. Concentration of removed CO_2 impacting PVSA and mass flow modelling.
Pre treatment experiments (inc. resins)	SeaCURE lab testing and NERC CREPE project experiments	Pre-treatment designs and mass flow requirements.
BPMED	Manufacturer contract to assess operation conditions	Mass flow, pre-treatment capacity, electrical supply
PVSA GAC testing	SeaCURE lab experiments	Media choice and column dimensions.
Mass balance modelling	SeaCURE modelling	Component sizing, consumable requirements.
Supply chain	Supplier input	Component and supplier selection, impact on timescales.
DESNZ purity and removal targets	Phase 1 and 2 guidance documents	Plant sizing, process design.

In addition to the R&D-informed design constraints, the following were considered:

- Discharge had to be sited at the far end of the site to allow ‘clean’ monitoring of the conditions upstream and downstream of the outflow.
- Hazardous chemicals are involved in the plant commissioning and operation, requiring bunding of both tanks and lines.
- Other site specific constraints discussed in the full report.

The design work progressed in four phases. A critical site assessment,
including evaluation of environmental impact considerations, infrastructure feasibility, and logistics for plant installation
detailed design, which included the process knowledge developed in Phase 1 and the first stage of Phase 2 (summarised in Section 2.2, Table 1 and above). This helped formalise the technical specifications, process flow diagrams (PFDs), and piping and instrumentation diagrams (P&IDs, Figure 7 and Figure 8) for the SeaCURE pilot plant. Based on the detailed design, schedules were drawn up, and iterated upon, and a 3D model of the plant was developed to plan the physical layout.

2.3.1 Changes to design

During build and commissioning a number of necessary design changes were identified. This resulted in changes to the hydraulics, sensor positioning, and mixing of acid and base into the seawater stream. *These are described in the full version of this report.*

Figure 7. SeaCURE plant P&IDs have been removed from this version of the report.

Figure 8. SeaCURE plant P&IDs have been removed from this version of the report.

2.4 Build of the SeaCURE plant

The plant construction was broken down into three major phases:

1. Build Phase 1 focused on the seawater abstraction infrastructure, initial pipework, and installation of the CO_2 stripping system.
2. Build Phase 2 saw the arrival and assembly of BPMED and associated ancillaries, bulk chemical dosing, and air handling systems.
3. Build Phase 3 involved the final integration of mechanical, electrical, and control systems, including SCADA implementation and pressure testing.

The build is fully evidenced in detail in the full version of the report but summarised in Figure 9 to Figure 14).

2.4.1 SeaCURE plant in numbers

- 7 process vessels/tanks
- 3 kilometres of pipework
- 8 kilometres of cable
- instruments/sensors (>150)
- 15 pumps
- 5 tank mixers
- >10 tonnes of stainless steel (Seawater stripper & PVSA),
- 5 tonnes of galvanised steel (Pipework & cabling supports)
- 10 chemical dosing packages
- 6 air blowers/compressors
- 100 valves with one third being motorised

2.4.2 Seawater intake and distribution

Figure 9. Seawater extraction skid, intake and outflow pipework crossing Site & intake and outflow entering plant.

2.4.3 Pre-treatment

Figure 10. Seawater pre-treatment precipitation and settling tanks, BPMED unit and cell.

2.4.4 Seawater CO_2 stripping and monitoring

Figure 11. Blowers and air intake (and outflow) pipework, Seawater CO_2 stripper and break tank & CO_2 monitoring system.

2.4.5 Chemical dosing

Figure 12. Two of the bunded bulk chemical tanks and a dosing station, BPMED acid, base and desalinated water product tanks, BPMED product dosing pumps.

2.4.6 Pressure Vacuum Swing Adsorption (PVSA)

Figure 13. Compressor, receivers and dryers.

2.4.7 Electrical, instrumentation & control

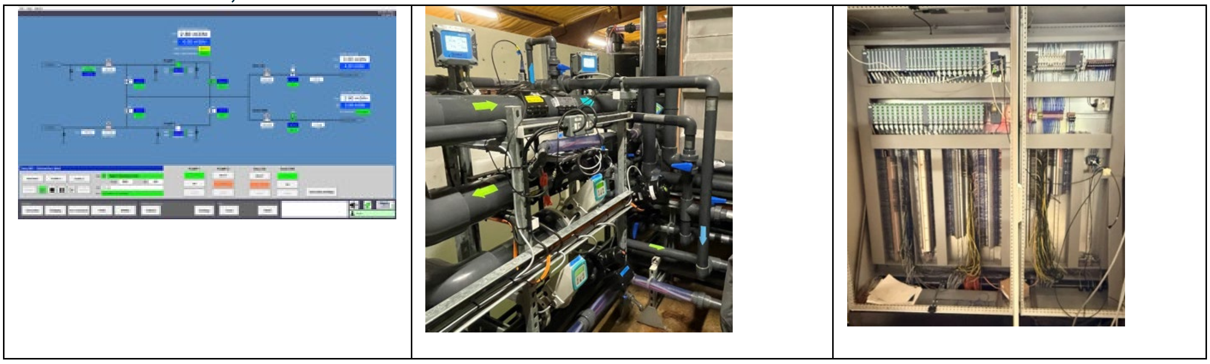

Figure 14. Example screen from SCADA interface

A description of the build preparation has been removed here to enhance readability.

2.4.8 Final system costs

A breakdown of the plant enabling and materials costs, including some subcontracted costs, are presented in Table 2.

Table 2. Pilot plant enabling materials costs. Full cost breakdown provided in the full version of the report

	Inc. equip. associated labour	Excl. labour
Controls/Electrical	£382,950.29	£188,384.58
Vessels/Tanks	£103,256.40	£103,256.40
Pumps/Drives	£274,588.68	£271,804.68
Instrumentation	£121,911.33	£121,911.33
Valves	£26,517.35	£26,517.35
Pipework/Support/Fixings	£186,423.35	£133,175.02
Site	£51,718.27	£42,177.53
Fabrication	£13,630.72	£13,630.72
BPMED Hire	£(redacted to protect supplier)	£(redacted to protect supplier)
Hire	£46,006.27	£46,006.27
Total	£1,207,002.66 + BPMED hire	£946,863.87 + BPMED hire

2.5 Commissioning

The commissioning process and results have been removed from this version of the report to enhance readability as they are highly project-specific, but the lessons learnt are shared below as they are valuable to wider audiences.

2.5.1 Commissioning conclusions

Overcoming a range of technical challenges primarily related to reduced seawater flow rates and the complex hydraulics of the seawater loop the commissioning process met all defined success criteria other than for PVSA and seawater stripping, where further data and small changes to operation were required. Adjustments such as pipework modifications, air relief additions, and P&ID tuning enabled stable system performance, though some flow instability remained in later stages of the plant. The stripping column performed reliably with higher air:water flow ratios than initially planned, achieving high stripping efficiency. The BPMED pretreatment and acid/base production systems were successfully commissioned in collaboration with suppliers, despite some operational constraints like flow rate limitations and the need for operator presence.

2.6 Demonstration trials and results

Here we present data from the operation phase and identify challenges faced and solutions implemented or proposed.

The original project plan involved the operation of the plant continuously for three months. Delays to the design and build phase and an underestimation of the length of time required for commissioning meant that this was reduced to 9 weeks. Staffing constraints and the H&S requirements at the site meant that continuous operation did not equate to 24/7 operation as originally envisioned. A decision to move into the operation phase once the basic plant processes had been commissioned meant that the operation phase involved periods of plant downtime to implement modifications, as well as running the plant in a variety of configurations throughout the operational phase. The hours of operation accrued for each component on the plant are presented in Table 3.

Table 3. Accrued hours of operation of each plant subprocess during the formal operational phase.

System Component	Operational hours accrued	Notes
Seawater extraction and discharge	396	
Pretreatment	83	Operating as required to pretreat water for BPMED (in recirculation & continuous flow into BPMED)

BPMED	15	Batch operation of oversized unit produces a large volume of product in a short period of operation. Includes operation just ahead of operation phase which generated product that was used during the 1st part of the operation phase.
Seawater CO_2 stripping	204	Operating with both BPMED product and bulk chemical
PVSA	147	Combination of running with seawater derived and cylinder derived CO_2

2.6.1.1 Operation phase data

2.6.1.1.1 CO_2 removal

Total CO_2 removal from seawater is calculated from the total flow rate of seawater through the stripper during the operational phase, the carbon concentration in seawater and the efficiency of the CO_2 removal.

The total processed seawater during the operational phase was 1405 m^3.

The mean seawater dissolved CO_2 concentration, measured on nine occasions across the operation period is 2.36 mol/m^3.

The efficiency of seawater CO_2 stripping during typical operation was 0.7, reflecting the need to balance low air flow to minimise dilution of CO_2 being passed to the PVSA unit with efficiency of CO_2 removal. At higher air flow rates, it is possible to remove almost all of the CO_2.

Molar mass of CO_2 = 0.04401 kg/mol

Total CO_2 removed during the operation phase = The total processed seawater * mean seawater dissolved CO_2 concentration * seawater CO_2 stripping efficiency = 102 kg

This level of removal reflects the amount of water that we were able to process in the available timeframe with available seawater flow. Scaling this value, if the plant were running 24 hours a day 365 days a year, would deliver 6.4 tonnes of CO_2 removal per year, with the low value reflecting the low seawater flow rate available at the site.

2.6.1.1.2 CO_2 purity

A key challenge identified during the operation phase has been demonstration of high CO_2 purity at the end of the process. During the vacuum step of the process, we measure a CO_2 concentration of between 55 and 90% purity, but were unable to measure flow rates during this interval because the amount of gas being moved was too low. The lower concentration than anticipated (based on lab and theory was ~100%) is hypothesised to be from (a) an inability to accurately measure the CO_2 from vacuum pump exhaust because such a small mass of gas is removed it cannot fully flush the tubing and CO_2 sensor, (b) dilution of the extracted gas from leaks in the pipework, including sucking air into the system through pCO_2 sensors when the system is under negative pressure, or (c) a combination of (a) and (b).

2.6.1.1.3 Energy requirements

The pilot plant was designed, built and operated to demonstrate and understand processes rather than to optimise energy consumption. The numbers generated and presented in the full report are therefore not reflective of the real costs of running a DOCC plant.

2.6.2 Extraction pumps

The extraction pumps used for the SeaCURE plant are operating against a large suction head due to the limited water availability at the site, and pumps were used to supply water to both the main site user and to SeaCURE.

2.6.3 BPMED

The Bipolar Membrane ElectroDialysis (BPMED) process was benchmarked in the lab at between 3 and 6 MWh/tonne of CO_2 removal (depending on concentration of supplied product). The concentration we have been producing on site (0.25 mol/L) sits between these two benchmarking concentration (0.15 and 0.5 mol/L), yet the energy consumption per batch has been much higher. Further work is required to understand why this difference arises.

2.6.4 PVSA

The PVSA process energy consumption is based on compressor duty only, as the small period of time for which the vacuum pump is operating can't be separated within our data. However, the compressor is running for around 20 hours in a cycle and the vacuum pump only for a few minutes, so the error this introduces is negligible. The compressor is significantly oversized for the final plant CO_2 removal leading to inefficiencies.

2.6.5 Balance of plant

The balance of plant energy consumption is high. This energy is used to operate blowers, pumps, valves, instruments and control. The blowers are the highest power items included in 'balance of plant', and as they are oversized for the final plant, they have had to run very low on their curves (often ~5%), which is highly inefficient. In addition, the balance of plant energy consumption was calculated from the weekly energy metering of the plant room items. This includes significant background energy draw when nothing was operating.

2.7 Key successes, lessons learned, and remaining questions (*abbreviated in this public facing version of the report*)

Key project development and implementation steps				
Category	**Key Successes**	**Lessons Learned**	**Remaining Questions**	**Next steps to answer outstanding questions**
Oceanographic complexity	Weymouth Bay discharge modelling and MRV fieldwork achieved.	It is important to factor in the complexity of the local oceanography into timelines for model development and budgeting for observational campaigns.		
Monitoring, Reporting, and Verification (MRV)	SeaCURE developed the 1st MRV protocol for DOCC, and shared information about this through workshop. MRV framework developed combining field measurements and ocean modelling.	Current sensors limit what can be achieved economically in terms of downstream MRV, Modelling for MRV is still highly bespoke, so presents an economic challenge.		
Seawater Abstraction	Successfully integrated existing seawater intake infrastructure at the site in Weymouth, demonstrating feasibility of site adaptation, and accelerating timescales.	Flow rate variability impacted process stability; modifications required to improve intake control. Use pumps under positive pressure.		
Seawater Pre-Treatment	Developed low-energy Mg $(OH)_2$ and $CaCO_3$ precipitation method for removing divalent ions before BPMED.	Settlement of Mg $(OH)_2$ is slow in cool water, CO_2 absorption for $CaCO_3$ precipitation appears to be a bottleneck.		
Electrochemical pH Manipulation	BPMED successfully produced acid/base streams, eliminating need for bulk chemical addition.	Enhanced interlocks, refined physical design and automation are required to run the plant unmanned		
CO_2 Stripping and Capture	Stripping columns achieved >90% CO_2 removal efficiency with optimised air-to-water flow ratios.	Packing material and column design can significantly affect stripping efficiency.		
CO_2 Purification	Granular activated carbon (GAC) adsorption successfully used in PVSA system to sorb CO_2. Standard s-shaped breakthrough curve was observed.	Optimal flow rates and adsorption cycle are critical for efficiency. Desiccant dryer can remove CO_2 prior to intended removal and concentration step.		
Automation & Control	Control system implemented with real-time process monitoring enabling operation.	Allow more time for control development, commissioning and testing		
Environmental Impact	Detailed (in depth and robust) trials on 3 key indicator species to inform marine impacts research for mCDR technology development Dilution modelling and initial biological exposure tests confirm potential for impact on marine ecosystems if not done responsibly.	Dilution is crucial in relation to potential marine impacts Continuous flow design is required for experiments to avoid chemistry evolving during culture experiments.		
Permitting	We obtained the 1st permit for this kind of activity issued by the Environment Agency,	There is risk and uncertainty associated with timescale and outcomes of abstraction permitting & installation. Importance of permitting to critical path in moving to commercial scales.		
Regulatory & Stakeholder Engagement	SeaCURE organised and hosted a strategically important workshop bringing together key regulators and stakeholders to highlight and discuss pathways for future permitting and deployment of mCDR technology. A network has been created to address the key barriers and risks and their work will continue beyond the end of the project	Current marine permitting frameworks are not designed for novel CDR technologies, requiring case-by-case assessment and permitting in accordance with the precautionary principle, presenting a Catch 22 for application of novel discharges.	How can regulatory processes be streamlined to support responsible scale-up of marine CDR? Can a UK strategy to speed up the feedback loop arising from the Catch 22 situation be developed and implemented?	Meet with regulators to develop strategy.

Societal Impact & Economic Viability	Funding secured for follow-on study to investigate societal acceptance and economic feasibility.	Public perception and policy support remain largely unexamined, requiring targeted engagement.	What are the key economic and social drivers for widespread adoption of SeaCURE type technologies?	Desk and survey-based study with social science expertise .
Commercialisation	Engagement with two accelerators and a global management consultancy firm, leading to significantly enhanced insights into how to reach scale.	The project would have benefited from a dedicated commercialisation lead.	Can DOCC compete with DACC or find appropriate niches through co-location or site selection?	Costing analysis based on process-based engineering modelling and use of expertise in CapEx and scaling assessment.
Expertise	We have developed a team that was more than the sum of its parts to deliver a global first of its kind CDR plant. Developed world leading expertise in MRV and marine impacts of marine CDR.	We would have benefited from an experienced engineer within the lead organisation to oversee the work and keep design and build work on track. However, unlikely that there would have been sufficient budget to cover this. Team leadership is vital to securing a positive outcome		For large complex projects, recruit someone into the lead partner organisation who has previously done the most similar thing to what you are trying to do.

Table 4. Modelled energy (core OpEx) costs of pilot through to commercial plants. Price is based on £45/MWh wind energy derived from DESNZ guidance documentation and explores a range of future scenarios.

	Generation 1 *(Optimised Pilot plant design in optimal location)*		**Generation 2** *(on-shore/ near-shore units)*		**Generation 3** *(Offshore)*		**Generation X** *(Theoretical electrochemistry)*	
	£/ tonne	**Notes**	**£/ tonne**	**Notes**	**£/ tonne**	**Notes**	**£/ tonne**	**Notes**
Seawater extraction & pumping	12	Based on 90% stripping efficiency and no dilution	9	Assumes reduced height/distance	3	Assumes plant at sea level so minimal lift head	3	No change
Pre-treatment	3		3	No change	3	No change	3	No change
Electrodialysis	352	Based on Supplier's current estimate for the pilot.	299	15% reduction based on industry's 10-20% expectations for membrane improvements	194	Based on industry expectations for where ED should be in 10 years: 45% improvement.	11	Thermodynamic calculations on theoretical system
CO_2 extraction	28	Including hydraulic head associated with moving water though plant and discharge	13	Based on requirements of vacuum degassing with 80% efficient pumps	12	Minor improvement in pressure drop across system	9	Assuming highly efficient vacuum pumping and minor improvement in pressure drop across system.

CO_2 purification	45	Based on modelling for amine unit	-	This is removed by a double degassing stage	-	No change	-	No change
Total energy cost	440		325		211		26	

3 Benefits, challenges, constraints and opportunities of the solution

3.1 Plant costs

3.1.1 Operating Expenditure (OpEx)

Energy-based OpEx costs are provided in Table 4. Energy is anticipated to be the dominant OpEx cost. Commissioning the pilot plant provides critical additional data in this area. Four generations of plant are considered, and the changes between each are described. Conversion between electricity consumption and costs is based on £45/MWh for wind energy derived from the project's guidance documentation. The underpinning calculations behind these OpEx costs are shared in the full version of the report.

The four scenarios presented in Table 4, Generation 1-3 and Generation X represent:

Generation 1: Pilot plant design using pilot plant technology but performing as we expect them to operate from modelling and lab-based BPMED experiments, and assuming the plant was located such that the intake had a minimal pressure drop (8 m hydraulic head is assumed).

Generation 2: 2nd generation plant that has a reduced hydraulic head associated with better plant location, a 15% increase in efficiency of the electrodialysis step (industry indication of what their new generation of membranes should allow) and a move from a percolating CO_2 stripper and PVSA CO_2 purification to two-step degassing. In the two step degassing, the 1st step at ambient pH degasses the <1% dissolved carbon that is in the form of CO_2 and all of the O_2 and N_2, then a second degassing after acidification only degasses CO_2, as all of the O_2 and N_2 has already been removed. What has not been considered in this scenario is the energy requirement associated with condensing the removed water vapour. Note that there may be a challenge in operating a plant with this two phase degassing as at significant flow rates, it is unlikely that deoxygenated water discharge would be permitted.

Generation 3: Assumes that the hydraulic head is minimised by moving to a neutrally buoyant plant or a plant on the coast that had been excavated to sit at sea level, that a 45% improvement in efficiency can be achieved within the BPMED acid and base production (based on industry projections of what could be achieved within a decade, and informed by improvements in other membrane technologies in response to demand), and minor improvements in the pressure drop across the system.

Generation X: Generation X takes a different approach. For the non-standard components (i.e. BPMED and degassing), the thermodynamic limit of operation is calculated and used.

Non-energy OpEx will be primarily people, as no significant additional feedstocks beyond seawater, electricity and replacement membranes, together with acid, base and RO water for membrane cleaning are required for the process. As an analogy, a wastewater or small desalination plant requires a plausible staffing of 6-10 FTEs, made up of 2-3 FTE plant operators, 1-2 FTE maintenance, 1 FTE laboratory/QC/MRV, 1-2 FTE administration/support, 1-2 FTE managerial & H&S. Assuming an average salary including contributions of £50k, this adds £6-10 per tonne of CO_2 removal.

3.1.2 Capital Expenditure (CapEx)

The bill of materials for the pilot plant and a projected 10 kilotonnes of CO_2 per year (kt/yr) plant are summarised in the full version of the report. CapEx for plant material and enabling work for a 50 kt/yr plant have been projected based on a review of those components required for a large plant following the same process approach; scaling the elements/materials required, an estimated cost reduction tied to the scaling factor and type of item (e.g. bespoke or off the shelf), and an assumption of 15 years of operation. Results of the cost modelling are presented in Table 5 (calculations behind this are broken down in the full version of the report). This cost modelling does not assume any changes in the technology employed, as we don't currently have CapEx estimates for the next stages of technological development. A next step will be to consider technological development in the context of CapEx reduction.

The cost modelling assumptions are:

1. Items are assumed to last the full lifetime of the plant, other than BPMED membranes which assume an annual replacement cycle
2. We are taking the pilot as a 100 tonne a year plant (based on design scope), meaning:
    - A scaling factor of 500 is applied to any item that would either have to be replicated, or would increase linearly in size.
    - A scaling factor of 250 is conservatively applied to items of the plant that relate to water or air movement based on pipe cross sectional area being multiplied by 4 for a doubling of diameter.
    - A scaling factor of 5 is applied where at larger scale the same number and size of items is fundamentally required (e.g. pressure sensors), but acknowledging that there may be some parallelisation or need for redundancy.
3. Cost reduction factors are tied to the scaling factor and type of item as follows:
    - A cost reduction factor of 1 is applied where items would be purchased at the same order of magnitude to that required in the pilot plant.
    - A cost reduction factor of 0.75 is applied to off the shelf items that can be ordered in significant bulk.
    - A cost reduction factor of 0.5 is applied to bespoke items where scaling offers a significant cost saving, and where supply chain is unlikely to be limiting.

Table 5. Pilot and 50 kt/yr plant (estimate) CapEx.. This table is made up of a combination of estimated costs at the design stage, and actuals with some element of equipment associated labour included. The final equipment/materials only cost in brackets.

	Pilot plant	50 kt/yr plant estimate
Site Preparation and enabling	**£236,475.72**	**£26,605,340.50**
Seawater extraction	**£81,581.42**	**£18,127,094.81**
Main seawater stream	**£393,513.37**	**£46,950,779.13**
Acid and base generation	**£345,094.58**	**£214,296,574.75**
Dosing	**£62,600.95**	**£996,804.65**
CO_2 purification	**£137,641.54**	**£ 16,202,340.85**
Total	**£1,256,907.58.(1,079,463.87)**	**£323,178,934.68**

Total costs per tonne of CO_2 removal for a 50 kt/yr plant, based on the above considerations and a 15 year lifetime comes to £431 for CapEx, <£10 staff and £325 (assuming Gen 2) energy OpEx. CO_2 transportation and storage is estimated as an additional £10 per tonne (Royal Society). Site lease/purchase costs have not been included in CapEx estimates as these will be highly variable, but if we assume a range from £50-£100 per m^2 per year, and assume a significant footprint reduction (see Section 4: Plant scaling & assessment of) and consider the plant to be similar in size to a large desalination complex (~100,000 m^2), this could add £100-200 per tonne. The total cost for a 50 kt/yr plant is therefore estimated to be in the order of £800-900 per tonne of removed and stored CO_2. Costs for design work, project management or labour for plant build are not included in this estimate as scaling these numbers from the pilot plant construction was deemed to be too uncertain.

3.2 Life Cycle Assessment (LCA)

The Life Cycle Assessment (LCA) of the SeaCURE pilot plant evaluates its cradle to grave carbon emissions, from raw material extraction to eventual decommissioning. Conducted in accordance with ISO 14040/44 standards, the assessment quantifies resource consumption, emissions, and energy use to determine the net sustainability impact of the technology. The LCA is then extended through electricity consumption to the proposed future generations of plant discussed in the non-public facing version of the report.

LCA provides a robust framework to assess the overall environmental impacts such as greenhouse gas (GHG) emissions of any system, by comprehensively accounting for all environmental inputs and outputs along their whole life cycle and evaluating the associated impacts in a wide range of environmental dimensions (G. International Organization for Standardization, Geneva, 2006; International Organization for Standardization, 2022). The standardised framework for LCA includes four phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation (International Organization for Standardization, Geneva, 2006, no date). This framework has been extensively applied to relatively mature carbon capture technologies or facilities such as post-combustion capture (Yang *et al.*, 2019; Young *et al.*, 2019; Zang *et al.*, 2020), pre-combustion capture (Piewkhaow *et al.*, 2014; Zhou *et al.*, 2014) and direct air capture (de Jonge *et al.*, 2019; Terlouw *et al.*, 2021) to understand their net emissions or environmental impacts. However, to our knowledge, this is the first full LCA assessment of a Direct Ocean Carbon Capture system.

This study seeks to systematically evaluate the potential GHG emissions of the SeaCURE seawater carbon capture plant from a full LCA perspective, providing critical insights into real-world carbon removal performance of this emerging technology. The findings from this LCA will enable design improvements to minimise the carbon footprint of the plant and support broader adoption of seawater capture solutions.

Within this analysis, each future plant generation is assumed to have the same embedded GHG emissions as the pilot plant, as detailed engineering designs for later phases are not yet available. In practice, future designs would aim for net carbon negativity with a stronger focus on reducing embedded carbon. Additionally, a five-year plant lifetime is used across scenarios to enable direct comparisons back to the pilot plant. In reality, commercial installations would be designed for much longer operational lifetimes.

3.2.1 GHG emissions of pilot plant construction

The results from this part of the report have been omitted so they can be published in the peer reviewed literature, with a qualitative summary provided below.

The main seawater stream is the largest contributor, driven primarily by the extensive use of metal-based fittings and pipe supports—which account for nearly 54% of its emissions. Other significant contributors include the BPMED unit and ancillaries, where the chiller alone contributes over 37%, followed by tanks (30%) and pipe fittings/support (19%). The PVSA system under ¼ of the embedded carbon, with 53% coming from the steel PVSA columns vessels, 14.4% from fittings/support, and 13% from vacuum pump racks. Dosing Packages contribute around 5% of the embedded carbon, largely due to water tanks (58%), with electric mixers (6.3%), pressure sensors (6.2%), and pipe fittings/support (3.5%) also playing roles, while Seawater Extraction is responsible for <5% tCO_2e, with 60% from pipe fittings/support and 14% from the pump's power supply.
In summary, while the pilot plant was not designed to give net carbon removal – not least because it was not storing the removed CO_2 – this work has highlighted the need for both minimising plant materials and careful selection of materials for future plant generations.

3.3 Process risk

Process risks are presented in the full version of the report.

3.4 Monitoring, Reporting and Verification (MRV)

Monitoring, Reporting, and Verification (MRV) should be a fundamental component of any CO_2 Removal (CDR) activity. A plant performing the SeaCURE process will pump seawater, process it to remove the inorganic carbon, and release the low carbon water where it is subsequently expected to take up atmospheric CO_2. It is necessary to ensure that all carbon fluxes are accurately quantified, reported transparently, and verified with scientific rigor. At the core of the MRV strategy for SeaCURE is the quantification of carbon fluxes at three stages: 1) Build materials and energy use; 2) Direct monitoring of CO_2 removal from seawater inside the plant; and 3) The long-term uptake of atmospheric CO_2 by processed low-carbon water once it is discharged back into the ocean. SeaCURE MRV thus requires a robust combination of different assessment techniques, models and observations. Within a commercial context, to retain the trust of the high quality carbon markets it would be necessary for this to be as independent a process as possible, or transparent and externally auditable.

3.4.1 Key components of an MRV framework

The SeaCURE MRV methodology follows a multi-tiered approach, incorporating direct monitoring of plant build, operation, and assessments of the marine environment to understand discharge dilution/mixing with ambient seawater and the uptake of atmospheric CO_2 by surface waters. There are three primary verification steps:

1. *Life Cycle Assessment (LCA) of materials and energy usage*
   This involves assessing the carbon footprint of the entire system, considering the embodied carbon in plant materials, electricity consumption, and supply chain logistics. A LCA methodology, aligned with international standards (ISO 14040), ensures that the calculation of net carbon removal efficiency accounts for the carbon costs embedded in plant construction, operation, and decommissioning. LCA also includes the energy sources used for plant operation and the carbon intensity of material transportation, which will ultimately allow a full assessment of true net CO_2 removal efficiency.
2. *Direct monitoring of CO_2 removal within the SeaCURE plant*
   Plant operation can be monitored through in situ instrumentation for pH, salinity, flow rates and the mass and purity of CO_2 removed. All data are continuously monitored and logged for consistency. Empirical linear relationships can be identified between salinity and Total Alkalinity (TA), facilitating the estimation of TA from continuous salinity observations. Unprocessed seawater TA and pH observations are then combined with existing knowledge to model the carbonate system and estimate total inorganic carbon content (referred to as dissolved inorganic carbon, DIC). Comparison of DIC in unprocessed seawater with the total CO_2 extracted in the stripper enables a calculation of CO_2 removal and is the primary metric of in-plant carbon removal efficiency.
3. *Verification of downstream CO_2 uptake by the ocean*
   Once treated seawater is released back into the marine environment, it begins re-equilibrating with (taking up) atmospheric CO_2. The challenge is to quantify the rate and completeness of this uptake, which depends on local ocean conditions, hydrodynamics, and air-sea gas exchange processes. This verification step is particularly complex, as seawater discharged into high-energy coastal environments will typically undergo rapid mixing and dilution. The challenge is to understand the changes in seawater CO_2 levels due to atmospheric uptake versus those due to dilution by ambient seawater that has a higher carbon content. Furthermore, any changes in carbon chemistry must be contrasted against the changes that would have

occurred due to the complex natural variations in marine biogeochemistry and CO_2 transfer from air-to-sea. The combination of oceanic complexity combined with the (practically impossible) challenge of directly quantifying atmospheric CO_2 uptake in all places at all times necessitates a robust MRV framework. The MRV framework requires the integration of computational modelling and field observations.

Step 1 is discussed in detail in Section 3.2 *Life Cycle Assessment*. Step 2 is a relatively straightforward aspect of MRV due to the controlled conditions in the plant. As a result, Steps 1 and 2 will not be considered further and the rest of Section 3.4 focuses on detailing the activities and findings associated with Step 3.

3.4.2 Modelling as a key MRV tool

Due to the scale and complexity of ocean dynamics, MRV cannot rely solely on field measurements. A high-resolution hydrodynamic ocean model was developed for Weymouth Bay to be used as a "digital twin" of the marine environment. The model was used to predict how discharged seawater would mix, which would influence pH variations and seawater CO_2 levels in Weymouth Bay and resultant atmospheric CO_2 uptake. The Finite Volume Coastal Ocean Model (FVCOM) was coupled with the European Regional Seas Ecosystem Model (ERSEM) to track water mass transport and the evolution of seawater chemistry due to biogeochemical interactions and air-sea CO_2 exchange. The model integrates tidal and atmospheric conditions, and shows good agreement with observed sea surface elevation data. The model was subsequently run multiple times for a range of different discharge scenarios. Each model run assessed the CO_2 uptake within a limited region downstream of the discharge point. Model runs from different seasons were used to assess variations due to environmental changes (e.g. air and water temperature, seawater chemistry, etc.).

3.4.3 Field observations and data collection for MRV

Model validation using field observations is necessary to gain confidence in the hydrodynamic model outputs and understand the degree of uncertainty in atmospheric CO_2 removal estimates. To support the SeaCURE MRV framework, a two-week field campaign in Weymouth Bay was conducted in Sep./Oct. 2023. The campaign used an extensive combination of observations, including fixed sensor moorings, mobile drifters, and boat surveys. The primary objective was to evaluate the model's ability to reproduce ocean currents and mixing processes using observations of seawater physical properties (temperature, salinity) via horizontal and vertical surveys, and ocean currents using Acoustic Doppler Current Profilers on two moorings and multiple releases of Lagrangian surface drifters.

Vertical profiles demonstrated that water in the Bay was not stratified and any discharged seawater would mix from the bottom to the surface and be available to take up CO_2 from the atmosphere. Horizontal gradients in temperature and salinity were minimal although the variability was greater than seen in vertical profiles. Drifter releases and Acoustic Doppler Current Profilers data confirmed that water disperses in response to tidal flows, with retention in sheltered areas.

Seawater pH was also surveyed and a novel CO_2 sensor successfully tested and deployed (towed behind the boat) for high frequency in situ measurements. These data were useful for understanding the variability in seawater carbonate chemistry in the region. pH variability within the bay was moderate (~0.1 pH units), with evidence of a East-West-gradient that corresponded to variations of ~100 µatm in seawater CO_2 (Figure 15).

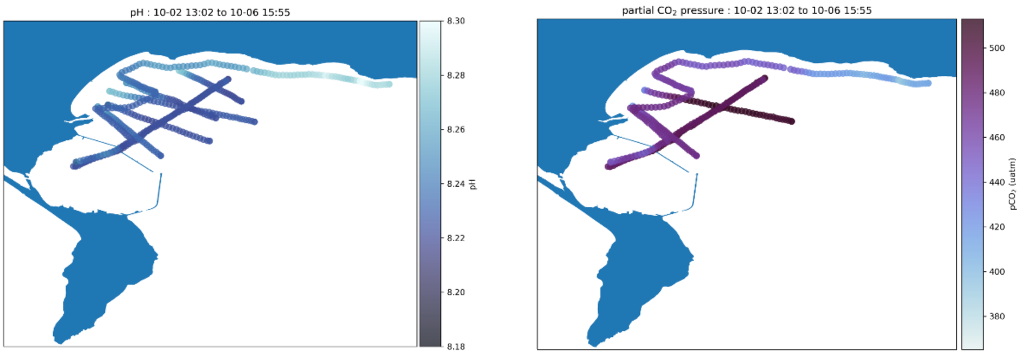

Figure 15: Distribution of pH and seawater CO_2 partial pressure during 5 days of horizontal surveys in Weymouth Bay.

3.4.4 Model assessment: Combining observations and simulations

Field observations were compared with coincident model runs used to simulate CO_2 uptake over time. Model runs were evaluated for their ability to predict the movement of discharged water. The data and model output align well, giving confidence to model predictions. The results also demonstrate that tidal dynamics are the dominant factor (more than wind- or wave-driven forcing) influencing discharge water mixing and transport.

A high-resolution model makes it possible to accurately track a discharge plume and estimate its uptake of atmospheric carbon (Figure 17). However, due to computational constraints, a high-resolution model requires compromises in model domain size and run duration, which results in the inability to track low carbon water long enough to observe the complete re-equilibration (ocean uptake from the atmosphere) of CO_2. Incomplete atmospheric CO_2 uptake captured by the model occurs mainly because the low carbon water leaves the model domain relatively quickly. Despite this limitation, model runs suggest that the discharge water would already have achieved up to 23% of the possible atmospheric CO_2 uptake within 2 months, with the uptake happening outside of the model domain being additional to this. Model runs during different seasons suggest that CDR efficiency will vary due to changes in wind speed and temperature (key drivers of air-sea CO_2 flux magnitude).

3.4.5 Implications and challenges for MRV strategy

The MRV lessons learnt are equally as applicable to the pilot plant as they are to a commercial plant operating at a much larger scale. The primary challenge for MRV is quantifying the uncertainties in CO_2 removal estimates, which are likely to be influenced by some factors that could not easily be assessed by the SeaCURE MRV work to date. This MRV work specifically addressed the dynamics in mixing due to variations in wind, waves, and currents. Model runs suggest that different conditions will influence atmospheric CO_2 removal, but only one field campaign was conducted. As a result, it was not possible to quantify the consistency of model performance between seasons. No validation could be made of discharge water dynamics as the plant was not operational when the MRV fieldwork was conducted. Also, no comparison was made between natural seawater carbonate system observations and the equivalent model estimate. Each estimate of atmospheric CO_2 uptake is made by comparing model runs with and without SeaCURE discharge turned on (removing the baseline natural signal).

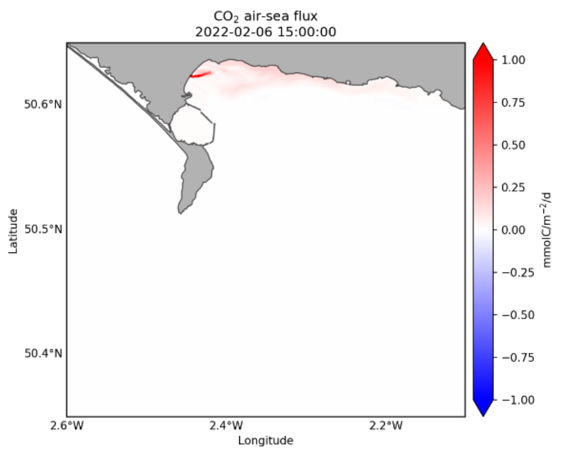

Figure 16: The distribution of the air-sea CO_2 flux difference between low-DIC seawater discharge and its corresponding baseline run during a model run in February 2022.

Future observational campaigns are needed to deliver the necessary site-specific data to ensure that model output can be relied upon going forwards. However, future observations will need to be cost-effective and should leverage autonomous platforms as much as possible in order to reduce reliance on costly field campaigns. Autonomous platforms and monitoring will ultimately help to reduce costs while increasing the necessary spatial and temporal coverage to test the models.

3.4.6 Knowledge exchange and stakeholder engagement in MRV

A key aspect of MRV is the necessary stakeholder confidence and regulatory alignment. MRV is important for industry because it plays a significant role in securing carbon credits and gaining regulatory approval. The long-term success of any mCDR industry depends on how MRV is viewed by all stakeholders, including the public, how it is integrated into policy, and the cost-effectiveness of the monitoring solutions. To this end, we organised an international knowledge exchange workshop and presented insights acquired during the MRV field and modelling work to representatives from government agencies, academia, and industry. See Section 3.6: Social value.

3.4.7 Conclusions

The MRV methodology developed within this project represents a comprehensive, science-driven approach that is rigorous, transparent, and verifiable. Atmospheric CO_2 removal due to SeaCURE discharge waters can be quantified, and the limitations understood. Extensive field observations have been successfully integrated with advanced numerical modelling. In addition, lessons were learnt that can be applied to future MRV activities, and the nature and scope of future field observations have been identified that are necessary to improve model performance and reduce uncertainty. These include direct observations of the seawater carbonate system within the discharge plume using autonomous monitoring platforms. All observations should be integrated into a model validation framework acting as a true 'digital twin'. The MRV workshop was a resounding success, starting a dialogue with, and creating a network of diverse stakeholders. Continued engagement with regulatory bodies is necessary to establish best practices for mCDR MRV and to ensure that this develops as the technologies mature. This will be essential in building public trust, and for ensuring meaningful climate impact as systems are scaled up. Workshop findings were published in Halloran et al. (2025a).

3.5 Environmental impacts

This section synthesises key findings from SeaCURE's novel experimental studies and hydrodynamic modelling, with a focus on the chemical perturbations to seawater introduced by the carbon removal process, developing an early understanding of biological responses and an examination of how local mixing mitigates environmental risks.

The removal of DIC from seawater though the SeaCURE process strips out carbonic acid and therefore drives a pH increase. With the pH change, a large fraction of the remaining DIC shifts from CO_2 and bicarbonate (HCO_3^-) toward carbonate (CO_3^{2-}). This shift is illustrated in Box 1. If there are no further interventions, this low-DIC, high-pH water will naturally return to ambient conditions as CO_2 is re-absorbed from the atmosphere and/or as water mixes with ambient seawater. A modest discharge volume in a vigorously mixed coastal system rapidly becomes indistinguishable from untreated seawater within a relatively short distance. If, however, outflow volumes are scaled up substantially, or local mixing is weak, the patch of elevated pH and reduced DIC will persist longer and/or over a larger area, with greater potential to influence local marine life.

From an ecological perspective, the chemical shift resulting from DIC removal introduces several potential stressors for marine life. High pH can interfere with physiological processes happening within organisms, or impact fluxes between cells and the external environment. The impacts can be directly due to carbon removal from seawater, and/or indirect, due to shifts in the relative proportion of carbon species (Box 1) and resultant availability of CO_2 and the bicarbonate ions that are essential for photosynthetic organisms. In extreme cases, the availability of carbonate and bicarbonate for calcium carbonate formation may also be impacted. Furthermore, extreme cases of elevated pH may promote mineral precipitation, removing magnesium and calcium, which could, disrupt seawater chemistry and cause turbidity changes that potentially impact filter-feeding organisms.

A report was produced at the beginning of SeaCURE Phase 2 which presented an extensive review of existing literature on the potential impacts of low DIC, high pH seawater[1]. Indications of possible changes could be extracted from the literature, but there are no directly-relevant experiments to draw on to determine the impact of Direct Ocean Carbon Capture. SeaCURE's environment impact work has focused on developing the methodologies and delivering early impact studies to begin to understand and deliver evidence of the potential impacts of at-scale Direct Ocean Carbon Capture.

Results from experiments on bivalves and phytoplankton are omitted from this version of the report so that they can be published in peer reviewed literature.

While marine impacts work has only been a small component of the SeaCURE project, delivered through a single PhD studentship, this has generated the first data on the potential impacts of DOCC discharge on marine organisms. From this data it is clear that there is potential for undiluted DOCC discharge to be harmful to marine life, with implications for discharge location siting with respect to sensitive ecosystems, as well as outflow mixing and plant operation. At the time of writing, experiments had only been conducted on bivalves and two species of phytoplankton, but an initial interpretation of these results suggests that at least 1:1 dilution will be necessary after seawater is decarbonised and before waters come into contact with sensitive ecosystems. Further research into this area should be a key priority.

3.6 Social value

The SeaCURE Phase 2 project placed a strong emphasis on generating social value alongside our technical and scientific work. To this end, two knowledge exchange workshops were delivered. The first workshop focused on Monitoring, Reporting, and Verification (MRV) for engineered abiotic marine CO_2 removal, while the second examined the potential marine impacts of abiotic engineered marine CDR, explored the fitness of existing regulation and licensing, and looked towards pathways for effective regulation and licensing.

The MRV workshop brought together experts from government, industry, and academia to address one of the most critical and challenging components of marine CDR deployment, establishing a robust and transparent MRV framework. Participants examined current best practices and the challenges inherent in monitoring the efficiency and efficacy of CO_2 uptake from the atmosphere downstream of a DOCC plant following DIC removal. Discussions centred on how to accurately track changes in key parameters such as pH, dissolved inorganic carbon, and total alkalinity, and how to combine in-plant data with downstream environmental observations. The workshop underscored the importance of combining life cycle assessment with continuous field monitoring, while recognising the uncertainties posed by natural variability in marine carbonate chemistry. The workshop resulted in a peer reviewed paper "Seawater carbonate chemistry based CO_2 Removal: Towards commonly agreed principles for carbon Monitoring, Reporting and Verification" (Halloran *et al.*, 2025), which included the diverse stakeholders attending the workshop as authors. We found that stakeholders could agree on a common set of principles for abiotic

[1] Hooper et al, Removal of dissolved inorganic carbon from seawater for climate change mitigation – understanding the potential marine ecosystem impacts, Front. Clim. Accepted.

marine CDR MRV that were achievable today, but identified that delivering this MRV with today's technology and know-how is unlikely to be economically viable in a mature commercial market. Achieving economic viability would involve driving down uncertainties (which will push up obtainable credit prices) and driving down operational costs. To reduce costs, the community will need to focus on the development of higher quality autonomous instrumentation and platforms, more computationally-efficient modelling tools with lower barriers to use, a skilled workforce able to deliver marine MRV activities outside of the research sector, and clarity from a (yet-to-be established) regulator of MRV requirements.

The second workshop focused on the potential marine impacts of engineered marine CDR and the regulatory frameworks necessary to address these impacts. The gathered experts presented on and discussed the environmental risks associated with the discharge of high-pH, low-DIC and high alkalinity water (covering both DOCC and Ocean Alkalinity Enhancement) into the marine environment. The workshop explored how mCDR driven changes in seawater chemistry could affect local ecosystems. Participants considered case studies from similar environmental perturbations and discussed mitigation strategies that could be implemented to minimise adverse outcomes. Regulatory challenges were also discussed, and explored how to establish clear, science-based guidelines that ensure both the safe deployment of CDR technologies and the protection of marine biodiversity, while avoiding the unnecessary holding back of promising mCDR technologies. Recommendations from this session stressed the importance of ongoing environmental monitoring, adaptive management approaches, and the need for regulatory frameworks that are both flexible and robust enough to accommodate new scientific findings as the technology evolves.

Overall, the two workshops significantly advanced the project's objectives by bridging the gaps between research and at-scale implementation. The workshops provided a forum for interdisciplinary dialogue, ensuring that both the MRV protocols and the environmental risk assessments developed within the SeaCURE project were informed by a diverse range of perspectives.

3.7 Governance and regulatory challenges and opportunities associated with scaling

The regulatory and governance landscape presents a significant challenge to scaling.

3.7.1 International governance

The international regulatory landscape for marine CO_2 removal (mCDR) is still evolving, creating uncertainty around the long-term viability of commercial-scale deployment. The recent London Convention and Protocol (LC/LP) LC 46/LP 19 meeting underscored the lack of regulatory clarity around Ocean Alkalinity Enhancement (OAE) and other marine geoengineering techniques, raising questions about whether such activities should be restricted to research or allowed to be undertaken commercially. The precautionary stance taken by the London Convention and Protocol reflects legitimate concerns about potential environmental risks. The SeaCURE approach (DOCC) differs from OAE, but both share similar risks with potential, and as yet largely unquantified, marine impacts. Both OAE and

DOCC are likely to face similar scrutiny. The absence of clear regulatory pathways undermines the case for long-term investment in DOCC.

It is likely that the restrictions being proposed within the LC/LP would only apply to activity offshore, meaning that shore-based plants with pipes going offshore could continue commercially (unless countries adopted the regulations to cover on shore activity as well). In the short term, this regulatory ambiguity may undermine investment in SeaCURE-like activity. However, to scale to megatonne or gigatonne levels, operations will likely need to move offshore, where access to large volumes of seawater is more feasible. If future LC/LP restrictions are extended to include DOCC alongside OAE, they could create a regulatory barrier that prevents the necessary transition to offshore deployment, limiting SeaCURE's ability to scale effectively.

3.7.2 Permitting and regulation

SeaCURE's path to commercial-scale deployment can only happen with rigorous environmental stewardship to underpin regulatory and societal approval. UK marine environmental regulation operates under the precautionary principle, meaning that scaling up marine CO_2 removal requires an iterative, evidence-driven approach, allowing each expansion to first demonstrate safety to secure permits. This creates a Catch-22, where large-scale deployment is delayed by the lack of real-world impact data, stalling investment and slowing progress. Section 4 describes work towards a structured pathway to accelerate toward commercial deployment in a way that is scientifically robust and environmentally sustainable while aligned with development of processes and expertise amongst the regulators.

4 Plant scaling & assessment of pathway to commercial scale operation

4.1 Scaling

SeaCURE technology has the theoretical potential to operate at gigatonnes of CO_2 per year ($GtCO_2$/yr) scales. As a thought experiment we can explore what amount of seawater would be required and what this would look like to deliver 12 Gt of CO_2 removal per year - sufficient to meet 1.5°C-aligned carbon removal targets when coupled with deep and rapid decarbonisation (Smith *et al.*, 2023). This calculation makes the following assumptions:

- All seawater is full equilibrated with the atmosphere over a timescale of one year (Zeebe and Wolf-Gladrow, 2008).
- A typical surface ocean mixed layer depth of 45 m within which the water is regularly in contact with the atmosphere.
- Seawater has a homogenous dissolved inorganic carbon concentration such that processing 12500 m^3 of seawater delivers one tonne of CO_2 removal.
- The upper 45 m of the ocean has a total volume of 1.63×10^{16} m^3.

Calculation using these assumptions suggests that less than 1% of the world's surface ocean water would need to be processed annually through a SeaCURE-like system to remove 12 Gt of CO_2 from the atmosphere each year. Based on the highly simplified assumption that the shallower water is the easiest to access, we can visualise what the most accessible 1% of the surface ocean looks like (Figure 18).

The above demonstrates that there is theoretical potential to operate at $GtCO_2$/yr scales, but practical implementation requires several critical barriers to be addressed. The rest of this section explores the feasibility of large-scale deployment and the key technical challenges associated with scaling.

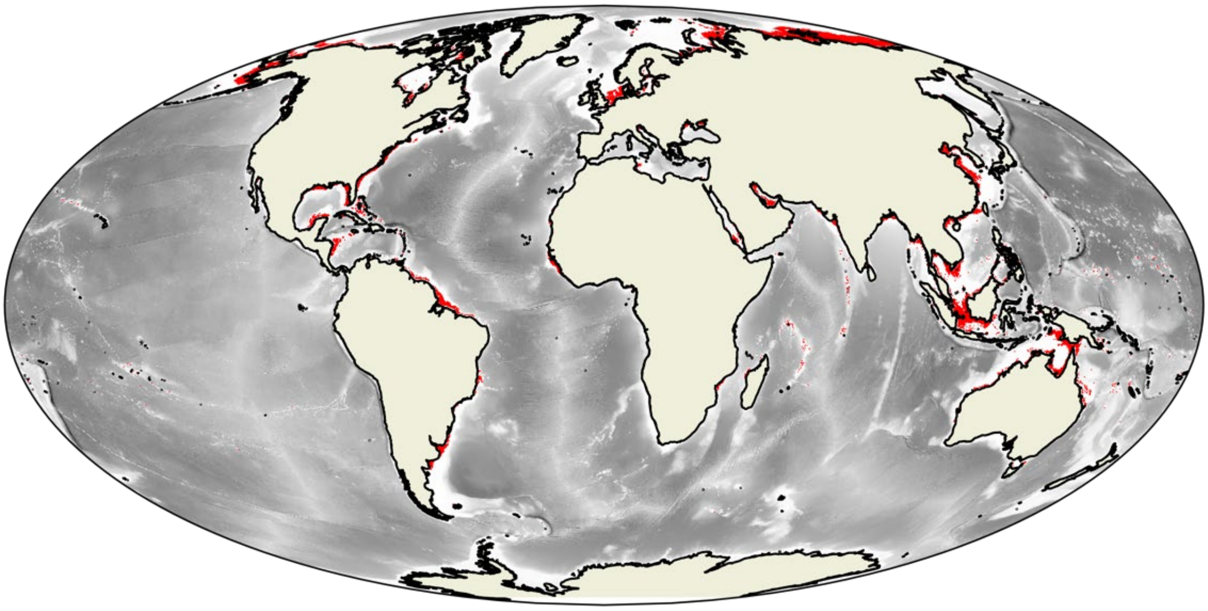

Figure 17. Shallowest 1% of the surface ocean (i.e. water shallower than 45m water depth). Halloran et al., 2025.

4.1.1 Scaling potential and global feasibility

Key location-based constraints include:

- Sufficient atmospheric contact time – low carbon seawater must remain in contact with the surface long enough to re-equilibrate with atmospheric CO_2 (i.e. no subduction to deeper ocean layers.
- Sufficient supply of 'not yet decarbonised' (untreated) seawater.
- Accessibility and infrastructure availability – SeaCURE plants require proximity to existing industrial infrastructure, renewable energy sources, and CO_2 transport and storage options to minimise operational costs.
- Energy availability – The viability of large-scale deployment of SeaCURE technology is strongly tied to renewable energy access, as electricity consumption represents a significant portion of operating costs. Operation without low carbon inputs pushes up the cost of negative emissions credits, or could even make the operation net carbon emitting.

We assess the first of these constraints - the duration of seawater contact with the atmosphere, by running a Lagrangian (passive, current following) particle tracking experiments in 3D velocity fields from NEMO ocean hydrodynamical models (Gurvan *et* *al.*, 2022). Tracking particle depth through time enabled the determination of particle release locations that correspond to discharge seawater expected to stay in the mixed layer for up to a year (and therefore take up CO_2 from the atmosphere), and determination of locations where water would be subducted. Results from Global and North West European Shelf Sea model runs are presented in Figure 18 and Figure 19, and a full description of the modelling work is presented in the full version of the report.

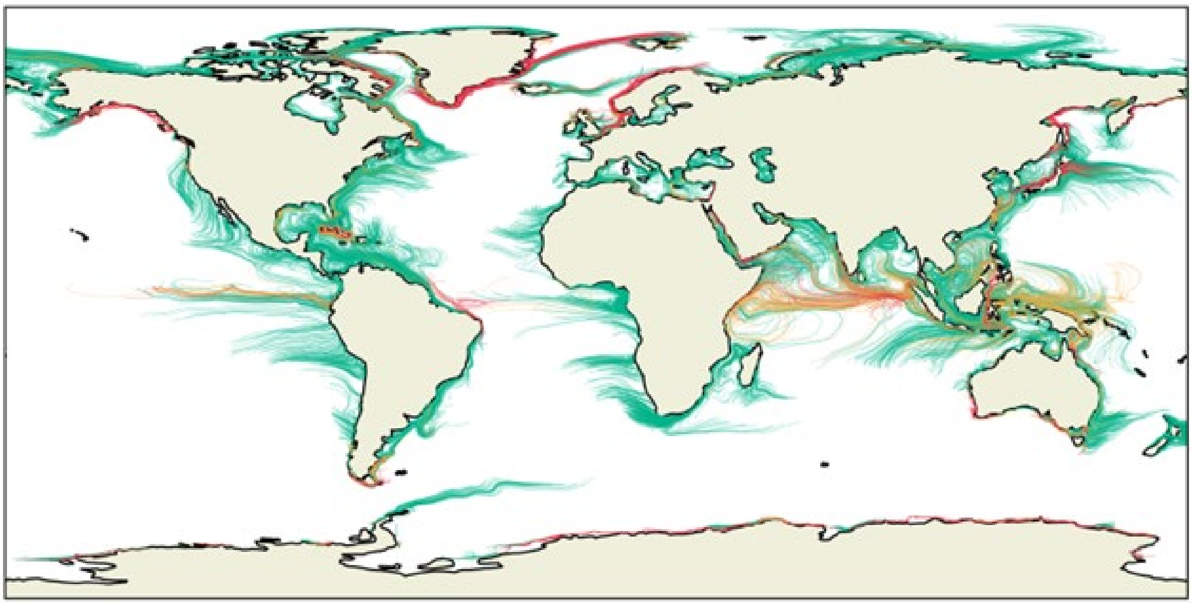

Figure 18. Trajectories of Lagrangian particle releases that stay above 50m (green), between 50 and 100 m (amber) and below 100 m (red) for a year after release. Simulation using global 1 degree NEMO velocity fields. Note global model results should be interpreted only as indicative as the underlying modelling lacks the fidelity to represent the detail of the coastal ocean circulation (Halloran et al., 2025b).

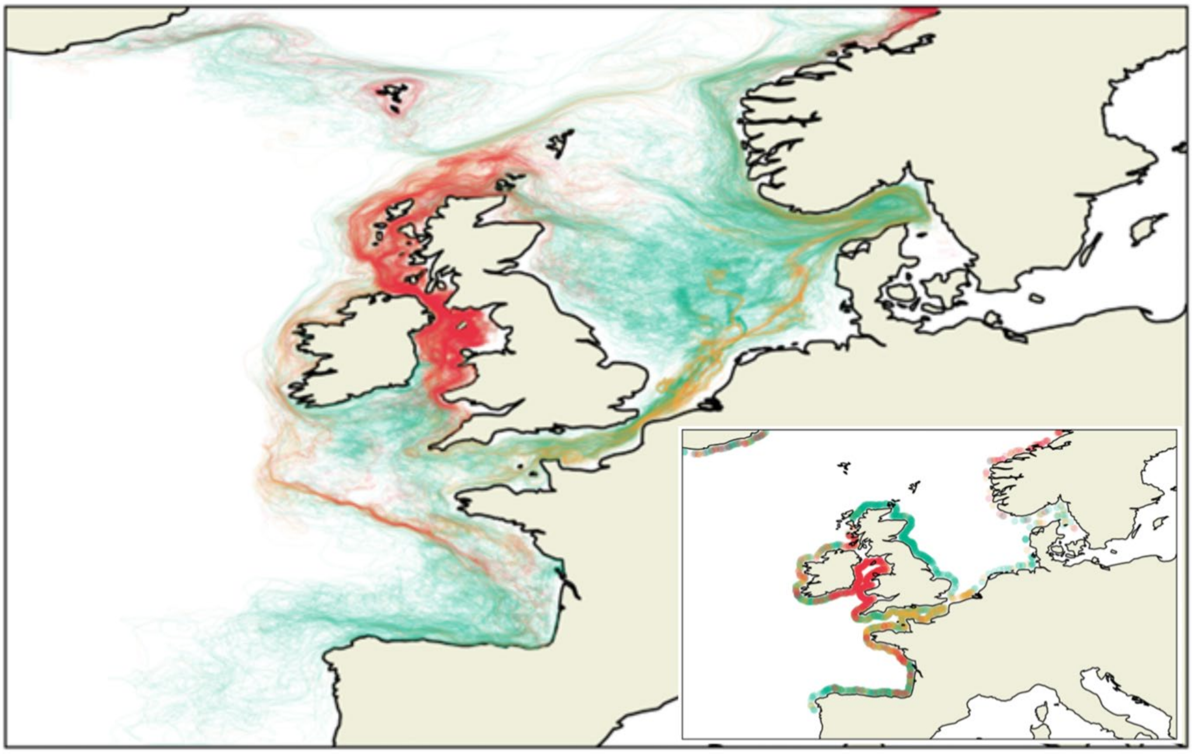

*Figure 19. **Main figure**: Trajectories of Lagrangian particle releases that stay above 50m (green), between 50 and 100 m (amber) and below 100 m (red) for a year after release. **Inset**: Initial release location of Lagrangian particle releases that stay above 50m (green), between 50 and 100 m (amber) and below 100 m (red) for a year after release. Note that*

there is a lower density of 'successful' releases along the Nordic coast because most particles left the model boundary before the analysis period was up.

A second oceanographic constraint is provided by the velocity of the seawater in the region of the plant. To illustrate, a plant sitting at a location where water was static would deplete the carbon in that pool of water and become ineffective. In practice therefore, the flow rate of water due to ocean currents is a useful constraint on plant size.

Seawater velocity is highly variable but approximately 0 – 1 m s^{-1} (Lumpkin and Johnson, 2013). Fast currents can be found locally in coastal locations, particularly during phases of changing tide, however, stable ocean currents also exist in certain regions and these can exceed 1 m s^{-1}. The fastest stable currents are the Western Boundary Currents moving away from the equator on the western boundary of each ocean basin. Due to bathymetric constraints these develop most strongly in the west Pacific and west Atlantic - the Kuroshio current and Gulf Stream current, respectively.

The volume of seawater required to be discharged by a plant (per tonne of CO_2 removal) will depend on the efficiency of the plant, and the allowable pH of discharge. As an upper limit, we would not anticipate discharge at a pH higher than ~10.3 because above this level $Mg(OH)_2$ will spontaneously precipitate from seawater – in practice the limit would likely be significantly lower, particularly at large scale. Assuming starting seawater DIC of 2095.78 µmol/kg (Kitidis et al., 2012) and 90% stripping efficiency, a dilution ratio of at least 0.3 is required to keep seawater pH below 10.3. This necessitates approximately 17500 m^3 of seawater to be accessible per tonne of CO_2 removed.

To understand the bounds imposed by this on plant size, a 1 megatonne CO_2 per year (Mt/yr) plant would need to process 550 m^3 of water per second. A megatonne plant processing all of the seawater in a 25 m deep mixed layer where the water was flowing past at 1 m s^{-1}, would need to process all of the water passing through an area 22 m wide. In a region with more typical seawater flow (e.g. 0.2 m s^{-1}), this becomes a 110 m wide area. It can be seen from these highly simplified calculations that seawater current speed provides an important constraint on plant location and size. It is likely that this constraint pushes development in the direction of a number of discrete plants across an area with common CO_2 offtake, similar to the approach taken by offshore wind energy.

4.1.2 Technical challenges and opportunities in scaling

Expanding SeaCURE from pilot-scale to megatonne- or gigatonne scale presents a number of key engineering challenges.

4.1.2.1 Plant footprint

The current pre-treatment system—raising seawater pH, settling precipitate in two 2.5 m^3 tanks, further alkalinizing to precipitate calcium carbonate, then settling again—works reliably at around one cubic meter per hour, but occupies substantial space. Scaling calculations are presented in the full report to envision a 50 kilotonne per year CO_2 removal plant.

4.1.2.2 Energy Efficiency

High pH requirements for calcium and magnesium removal increase the energy load on the bipolar membrane electrodialysis (BPMED) system (see Section 4.3.2 for a more complete analysis). The purification using pressure-vacuum swing adsorption (PVSA) also adds energy costs. Shifting to membrane-based CO_2 separation or other adsorption materials could offer efficiencies. Process intensification opportunities include switching to temperature swing adsorption (TSA) with waste heat regeneration, optimizing adsorbent properties and developing moisture-tolerant materials to reduce pre-processing steps (see Section 4.3.4 for a more complete analysis). Additionally, synthesising mechanically-stable adsorbents with minimum capacity loss for long-term performance is critical for the at-scale deployment of SeaCURE technology.

4.1.2.3 BPMED supply chain

Bipolar membrane electrodialysis (BPMED) remains a specialised area with relatively niche application. Like many emerging electrochemical technologies, BPMED must source high-performance membranes from a small number of producers, resulting in both cost and availability uncertainties.

In discussion with electrolyser experts as part of a commercialisation assessment, it was identified that electrolyser size could be increased and efficiencies gained by aligning with the hydrogen industry, where electrolysers are currently in the range of around 600 Euro per kW. This price is largely invariant with scale until electrolyser requirements reach around 5MW, where costs are projected to come down to around 400 Euro/kW by 2030, and ultimately to around 300 Euro/kW. It is the membrane rather than the electrolyser that is likely to be the supply chain bottle neck. Certain manufacturers could make km^2 of the base membranes if the economics justified them switching their activity to these membrane requirements. However, what remains is the capacity of the membrane industry to produce the required coating and the specialised sandwiched bipolar membranes. Unless the larger membrane producers have cause to switch facilities to bipolar membrane production, there will likely be a supply chain bottle neck, and limited cost reduction on bipolar membranes.

4.2 Co-location opportunities and challenges

We examined co-location opportunities, building on work done recently with Mott MacDonald through the NZIP accelerator and others. These co-location options present some opportunities on the route to scale as well as opening up routes to cost reduction. As SeaCURE progresses from pilot-scale, through demonstration to full-scale commercial deployment, one of the key challenges is reducing capital and operational costs while ensuring an efficient and scalable system design. The vast volumes of seawater required for megatonne-level CO_2 removal demand infrastructure capable of handling large flows while maintaining energy efficiency and minimising environmental impact. Co-location with existing industrial facilities offers a potential solution, allowing SeaCURE to leverage shared infrastructure, reduce duplication of systems, and streamline regulatory approvals.

4.2.1 Integrating with desalination facilities

One possible co-location strategy involves integrating SeaCURE like processes with desalination plants. There are approximately 16,000 operational desalination plants across 177 countries, producing an estimated 95x10^6 m^3/day of fresh water[2].These facilities already process significant volumes of seawater and operate large intake and discharge systems that could be shared, reducing the need for additional infrastructure. Desalination plants also have extensive pre-treatment processes that could be adapted for SeaCURE-like technology, potentially simplifying operations and cutting costs. However, even the world's largest desalination plants process less seawater than is needed for large-scale carbon removal. Co-location may provide a useful stepping stone for early deployments, but it is unlikely to be a viable long-term solution at gigatonne-scale removal unless high-volume desalination infrastructure expands significantly.

4.2.2 Deeper integration between SeaCURE technology and desalination

In addition to sharing the water stream, potential economies of scale, and some detailed process integration, SeaCURE technology could be integrated even more completely with desalination. Figure 20 presents a schematic of a typical BPMED membrane configuration. The process works to produce the acid and base streams required by SeaCURE by dissociation of water (H_2O) at the bipolar membranes (BPM), and balancing the charge generated by this by moving anions and cations out of a third water stream across anion exchange and cation exchange membranes respectively. In seawater, the dominant cations and anions are Na^+ and Cl^-. The third seawater stream is thus being desalinated as part of the normal production of acid and base. At present this water stream is mixed back into the process flow together with the acid stream, which is effectively wasting a valuable desalinated water product.

[2] https://en.wikipedia.org/wiki/Desalination_by_country

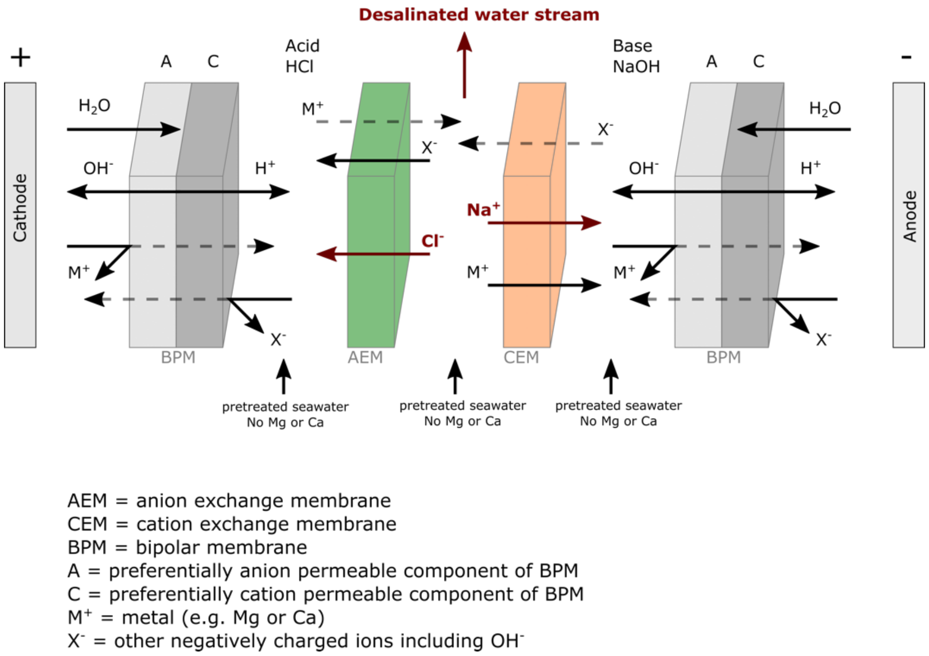

Figure 20. Bipolar Membrane Electrodialysis membrane configuration highlighting production of a desalinated water stream.

A review of electrodialysis for water desalination is presented in Campione et al. (2018). This paper highlights how advances in ion exchange membranes are improving permoselectivity, lowering the electrical resistance, and - through pulsed electric fields or electrodialysis reversal (EDR) operation - mitigating fouling, making it a more serious contender for desalination. The authors highlight that further reductions in membrane cost and improvements in fouling resistance are critical to bringing electrodialysis to a broader market. If SeaCURE could provide desalinated water in parallel to CDR, the cost of both would be significantly reduced. A key consideration for the integration with desalination is whether discharging combined enriched brine and decarbonised water would compromise downstream atmospheric CO_2 uptake due the increased density and reduced buoyancy of the discharge water.

4.2.3 Utilising power station cooling water

Another promising route is integrating SeaCURE with power stations that use single pass cooling water systems. Importantly, all of the power station water could be used. This is in contrast to desalination, where around 40% of the water is unavailable for SeaCURE, and an even smaller fraction is needed for the electrodialysis stream alone. Power stations can handle substantial seawater flows, and their intake systems are designed to limit ecological impact, providing an existing platform for SeaCURE-like technology to build upon.

The elevated temperature of cooling water may also enhance some aspects of pre-treatment, such as improving precipitation kinetics. However, as the energy sector transitions towards closed-loop cooling systems and moves away from fossil fuel power generation, the availability of suitable opportunities is not clear, as is the likely future magnitude of low-carbon thermal power generation.

4.2.4 Offshore co-location: Renewables and repurposed infrastructure

Beyond coastal facilities, offshore deployment could play a crucial role in SeaCURE's long-term scalability. Integrating with offshore renewable energy infrastructure could provide a reliable, low-carbon power source while reducing transmission losses. However, offshore installation presents engineering challenges, including high maintenance costs and exposure to harsh environmental conditions. Similarly, repurposing decommissioned oil and gas platforms offers a potential route for integrating CO_2 capture with offshore storage. Existing pipeline infrastructure could facilitate direct CO_2 sequestration.

4.2.5 The role of co-location in scaling up

As SeaCURE-like technologies move towards commercial viability, co-location strategies offer a means of reducing costs, optimising infrastructure use, and accelerating deployment. In the near term, integration with desalination plants and power station cooling systems could provide cost-effective early deployment opportunities. However, as the scale of operation increases, standalone or offshore solutions may become necessary to achieve climatically-impactful carbon removal targets.

4.3 Future developments of SeaCURE technology, informed by Phase 2

Plant scale and technical aspects of the commercialisation journey for SeaCURE-like technology have been introduced in Section 4.1.

The SeaCURE pilot plant has demonstrated the ability to remove carbon from seawater effectively, but the design, build and commissioning process has highlighted critical challenges, particularly around energy efficiency and system footprint. The current process is energy-intensive, requiring substantial improvements to reduce operational costs and enhance feasibility at commercial scales. The physical footprint of the pilot system is also a major challenge, impacting deployment options and scalability. Addressing these issues will be key to advancing SeaCURE-like technology towards commercial viability in a mature market.

4.3.1 Reducing footprint and overall energy required for pre-treatment

This section has been omitted from the public facing version of this report.

4.3.2 Reducing energy demand in electrodialysis (BPMED)

This section has been omitted from the public facing version of this report.

4.3.3 Reducing footprint and overall energy required for CO_2 stripping

This section has been omitted from the public facing version of this report.

4.3.4 Reducing energy demand in CO_2 purification

This section has been omitted from the public facing version of this report.

4.3.5 Automation and process control optimisation

The commissioning phase has revealed that manual operation is currently necessary. An important next step should focus on a further level of automation to optimise process efficiency in real time. Machine learning control algorithms could improve system responsiveness to variable seawater conditions, reducing energy demand while maintaining consistent CO_2 removal performance, or given inertia in the system could optimise based on predicted changes in requirements. Fully automated operation is critical for large-scale deployment, particularly in offshore or remote locations.

4.3.6 Implications for commercialisation and location of future activity

Addressing the areas identified above will be crucial to making SeaCURE-like technology commercially viable in a mature market while maintaining environmental integrity. Further funding and partnerships will be needed to explore these pathways and accelerate the transition from pilot-scale demonstration to commercial-scale deployment.

The Weymouth plant is a valuable resource in terms of testing technology and collecting data. The plant could also be used to generate new data and test technological developments, as well as develop improved understanding of the processes downstream of the plant. A key lesson learnt from the Phase 2 project has been the importance of site selection. This becomes even more critical with any increase in plant size.

4.4 Route to market assessment, including barriers, risks and opportunities

SeaCURE is a first of its kind pilot plant, designed to validate the technology's core functionality. The journey to commercial-scale deployment of this kind of technology encompasses technical development and optimisation, site selection, environmental studies, and stakeholder engagement. The journey also involves careful navigation of regulatory pathways, market forces, and community perspectives. The ocean is a complex environment, and the ability of SeaCURE-like technology to reach its potential depends not only on technological progression, but also on holistic considerations such as marine stewardship, MRV, and social licence. The wider journey to commercial-scale operation is presented graphically in Figure 21. This process is not linear as upscaling to commercial scale needs to be done iteratively, to fit with the precautionary principle applied within environmental permitting.

According to the precautionary principle, new marine discharge activity cannot be undertaken until it is proven to be safe. Marine CO_2 removal is a new process, and the resulting seawater changes are not seen elsewhere in nature or from existing activity. Plants therefore, need to be operated to generate the data required for similar or larger sized plants to receive permits to operate. This could lead to a Catch-22 scenario that inhibits rapid scale up. The marine stewardship/permitting/build cycle is therefore a critical path (highlighted in Figure 21).

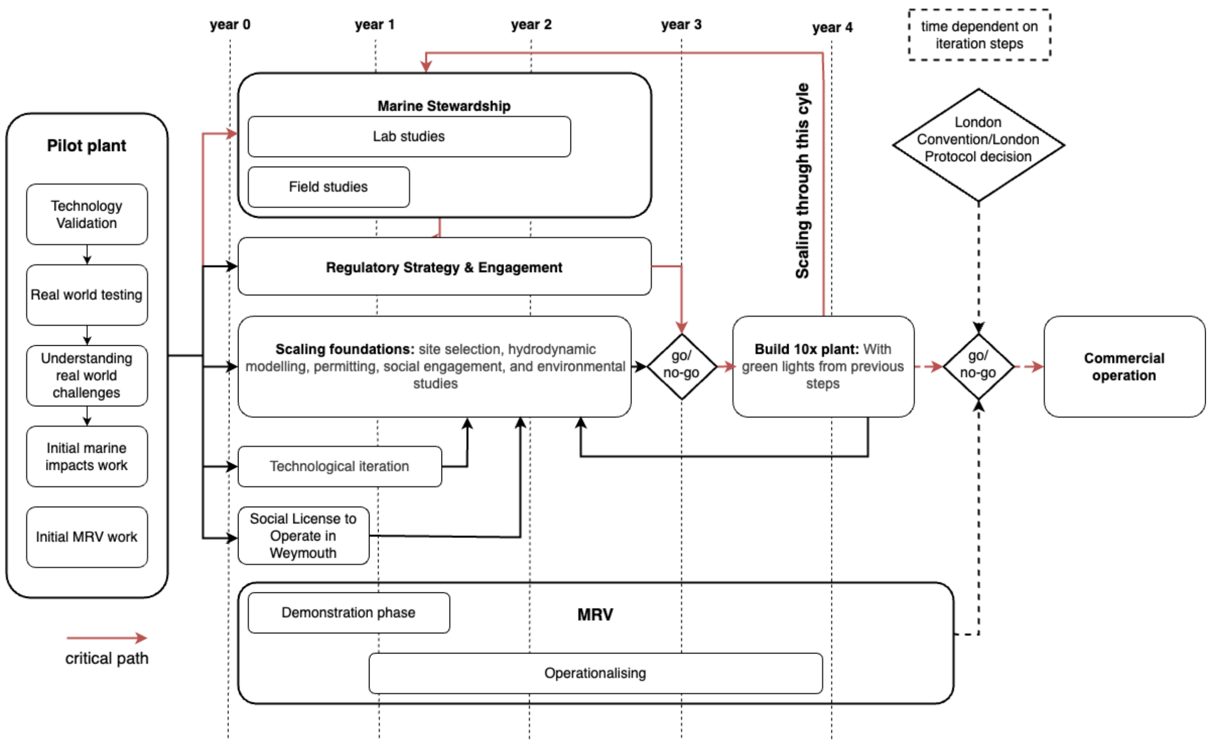

Figure 21. SeaCURE's route to market.

4.4.1 Marine stewardship, societal and governance considerations

While an important aspect of marine stewardship, the application of the precautionary principle to marine permitting has the potential to stall investment, prolong uncertainty, and prevent the creation of robust datasets needed to unlock meaningful commercial deployment. To resolve this fast enough to help deliver a safe climate, we identify a model that addressed a similar problem in the marine aggregates industry - a cycle of sequential scale-up and evidence generation at designated test sites with industry and regulators working hand-in-hand[3].

The core of this approach lies in a structured sequence of permitted trials, starting with small-scale, highly monitored deployments, incrementally expanding in size and complexity. Establishing test sites where data can be systematically gathered, analysed, and shared, enables safety to be demonstrated. Test sites also mean that operating processes can be refined without delaying necessary progress. At each stage, developers will need to implement rigorous environmental monitoring, reporting, and verification (eMRV) protocols to ensure environmental integrity. Regulators will have access to real-world evidence, allowing them to make informed decisions about the risks and benefits of scaling up, rather than relying solely on theoretical models or laboratory-scale experiments.

[3] https://bmapa.org/issues/aggregates_levy.php, https://marine-aggregate-rea.info/

A phased permitting framework would provide the flexibility needed to adapt to new findings while maintaining clear oversight. Initial trials would focus on assessing key environmental indicators, such as changes in local carbonate chemistry, wider seawater chemistry, seawater turbidity and biodiversity impact. The results of these studies would inform subsequent regulatory decisions, ensuring that each scale-up step is backed by empirical data. Over time, this process would lead to a set of standardised permitting conditions for larger installations, removing the current uncertainty that could make investors hesitant to support the sector.

By aligning the regulatory process with iterative technological and scientific advancements, this model allows responsible innovation while safeguarding marine ecosystems. It also ensures that permitting authorities develop the experience and frameworks necessary to evaluate mCDR projects effectively, accelerating their deployment.

Ultimately, resolving the permitting impasse is not just about enabling a single technology—it is about creating a pathway for responsible mCDR at scale. Developing a clear regulatory strategy enables both precaution and progress, and will give the UK the opportunity to lead this potentially huge but currently nascent sector and play a critical role in meeting climate targets responsibly. By leveraging lessons from the marine aggregates industry and adopting a stepwise, evidence-driven approach, it is possible to break the cycle of uncertainty and accelerate deployment in a way that is both environmentally responsible and commercially viable.

4.4.2 Marine stewardship and environmental concerns

A pivotal aspect of commercial readiness is the demonstrable safety of the SeaCURE process for local marine ecosystems. Ensuring that extraction and discharge streams do not cause harm to keystone species or disrupt important habitats, requires robust marine impact assessments. In early-stage laboratory work, we have explored potential changes in carbonate chemistry and pH caused by adjusting seawater carbon content. Building on these studies, detailed laboratory experiments focused on keystone species and acute exposures would be required alongside a concerted field research program. The field program should measure environmental indicators such as keystone species' stress, biodiversity levels, nutrient concentrations, turbidity, and the health of local fisheries at demonstration sites. Repeated measurements over time will be required to assess any chronic or periodic impacts on seasonal-interannual timescales. If early tests show negligible or manageable impacts, marine stewardship concerns become less of a barrier to eventual commercial-scale deployment. The need to produce this data presents a commercial challenge, as the results need to be in the public domain, ideally peer reviewed or independently validated to be used as required for permitting. It would not be in the interest of a commercial entity to do this with private capital as it would be using its resources to produce a public good, and disadvantaging itself relative to its competitors. SeaCURE sees this as needing to be progressed prior to any commercial activity, and is proactively seeking public and philanthropic funding to do this.

4.4.3 Social licence

A significant benefit of the cyclic permitting/build approach is that it provides evidence and a framework that helps secure the necessary social license to operate. Public concerns about unintended consequences are legitimate, and transparency is key to maintaining trust. By engaging local communities, conservation groups, and other stakeholders from the outset, and by making environmental monitoring data publicly available, potential opposition can be taken on board, understood and discussed with open, evidence-based dialogue. If impacts are found to be minimal or manageable, public confidence in mCDR technologies will grow, making broader adoption more feasible.

Securing social licence is complex. mCDR technologies are unfamiliar, and the sea is often considered by the public as an untouched wilderness that deserves a higher level of protection than the land. Concerns are more readily-raised about ecological risks and community disruption, especially in public or ecologically sensitive areas. Without proactive engagement, resistance, either from legitimate concerns or misinformation, could delay activity that is of a strong net benefit to the environment. To address this, SeaCURE has been developing a plan to encourage an inclusive, two-way dialogue with stakeholders (working/planning with Sense About Science). Early engagement in this plan identifies key stakeholders, historical context, and community perspectives, informing tailored communication and consultation strategies. Instead of passive outreach, this approach ensures public input directly influences research, and that deployment plans follow the concept of a “public led, research fed” discourse.

By embedding social licence activity early in the journey we hope that we can co-create with stakeholders a direction for future research and development where the benefits are understood, risks mitigated, and that local communities can feel part of. Publicly-supported deployment is a key part of making mCDR a scalable and responsible climate solution.

4.4.3.1 London Convention / London Protocol

See Section 3.7. The absence of clear regulatory pathways makes long-term investment in DOCC uncertain. This uncertainty may mean that progress towards understanding the ultimate feasibility of this technology may be faster in the near-term when working as a non-commercial entity (as SeaCURE is set up to do) compared to startup companies working in this field.

4.4.4 Monitoring, Reporting, and Verification (MRV)

As identified in Figure 21, the development of reliable MRV protocols to confirm net CO_2 removal is important. The ocean’s dynamic nature, with varying currents, temperatures, and biological interactions, can complicate assessments. We have developed and done initial work towards delivering mCDR MRV throughout the Phase 2 project, but further work is required. We plan to develop an approach that integrates direct tracer studies, advanced hydrodynamic modelling, and in situ measurements of carbonate chemistry and air-sea CO_2 fluxes. During a comprehensive demonstration phase, these methods would be deployed across multiple seasons to capture a full spectrum of oceanic variability, then expanded to different oceanographic regimes. Over time, the aim would be to transition to autonomous sensing networks and data-assimilating models that can operate with minimal human intervention at commercial sites. Achieving this level of robust MRV is critical for securing carbon credits and investor confidence, because any uncertainty in atmospheric CO_2 removal levels will undermine the commercial value proposition.

4.4.5 Social justice and global capacity building

For marine CO_2 removal to scale effectively, it must be deployed in a socially just and globally inclusive way. Without equitable access to knowledge, infrastructure, and governance frameworks, deployment will be slow, fragmented, and risk reinforcing global inequalities, meaning its geographical scope is limited. The Global South, despite being highly vulnerable to climate change, often lacks the resources to engage in emerging (climate) technologies. If mCDR technology remains concentrated in wealthier nations, resistance could grow, slowing international adoption and limiting the required climate impact. This has been identified as a key barrier to the necessary global scaling of renewable energy infrastructure and we have the opportunity to avoid making similar mistakes in the mCDR domain.

SeaCURE's commercialisation strategy explores open-source technology development and sharing, regional partnerships, and governance support to enable broad, responsible adoption. Open-access engineering designs and process models could lower technical barriers, while regional mCDR hubs could provide hands-on training, site-specific data, and locally driven research. These hubs would foster expertise, strengthen supply chains, and support pilot projects in diverse marine environments, rapidly generating the necessary data required to plan the journey to climatically meaningful scales.

Beyond ethics, social justice in mCDR has practical benefits. A globally distributed approach enhances resilience, reduces dependency on specific regions, and supports economic diversification in coastal communities. By embedding equity into future plans, we hope to enable SeaCURE like technology to develop faster, be more widely accepted and more widely assessed, tested and developed, ultimately maximising the climate impact.

4.4.6 Market opportunity and external factors

The global demand for high-quality carbon removal solutions is expected to reach multiple gigatonnes of CO_2 removed per year by 2050. This projection stems from stringent decarbonisation pathways identified by international bodies and national governments, which increasingly recognise negative emissions as a key component of net-zero targets. While a considerable share of these negative emissions may come from nature-based solutions, market assessments show that engineered carbon removal options, including technology such as DOCC, will be pivotal to bridging the remaining gap. , and their share of removals is on, and is likely to continue on, a rapidly-increasing upward trend.

Within this context, DOCC technologies are noteworthy for their scalability and ability to work with storage that locks away carbon over long timescales (i.e., high permanence). As industries worldwide pivot to net-zero commitments, the demand for carbon removal credits, particularly those verified through rigorous MRV standards, has begun to climb steadily. Analysis of current supply-and-demand forecasts suggests a significant shortfall in carbon removal availability (Smith *et al.*, 2023). Against this backdrop, innovative solutions like SeaCURE present a timely solution.

National and international policy drivers, ranging from carbon pricing to procurement commitments by large corporations, reinforce this demand. Government programs in regions such as North America and Europe are beginning to incentivise the rapid scaling of new technologies that can help achieve mid-century decarbonisation goals. SeaCURE-like technology has the potential to contribute significantly here, but it first needs to demonstrate that a pathway to be cost competitive with Direct Air Carbon Capture (DACC).

4.4.6.1 Direct Ocean Carbon Capture (DOCC) vs. Direct Air Carbon Capture (DACC)

It is important to compare DOCC with DACC, as DACC is effectively the incumbent and essentially the competitor to DOCC. DACC is already receiving substantial government and private support, particularly in the U.S. with tax credits of $180 per ton of atmospheric CO_2 removed and permanently stored. DACC is at higher Technology Readiness Level (TRL), has more flexibility about where it is located, requires simpler MRV and offers a 'cleaner' approach that presents less environmental risk. DOCC therefore needs to either identify niches where it may be favourable to DACC, or needs to meaningfully undercut DACC in cost. The promise of lower costs comes from: (1) the ocean providing the CO_2 absorption, avoiding the big DACC-related challenge of contact between CO_2 and the sorption media and the associated pressure drop with this; and (2) the higher CO_2 concentration in the feedstock (water versus air).

SeaCURE technology presents possible advantages over DACC. First, material consumable requirements are likely to be lower than that of several DACC processes reliant on proprietary sorbents that need regular replacement. Second, by leveraging existing infrastructure, SeaCURE can potentially co-locate key process steps (see Section 4.2), minimising transport and inefficiencies in operation, build and regulation. Third, the required intake volume for seawater based removal is two orders of magnitude smaller than for air-based removal. A smaller intake is significant if it can be translated into a two-order of magnitude smaller plant with associated two-order of magnitude reduction in CapEx, because DACC CapEx estimates are thought to be about 80% of the total costs at present. Favourable CapEx would make for a highly compelling reason for DOCC investment. Additionally, the possibility of harnessing offshore wind or other renewable power sources aligns well with the technology's overall footprint, further reducing the lifecycle carbon intensity, although it is less clear whether this represents a benefit over DACC.

Finally, the fundamental premise of DOCC - removing CO_2 directly from the ocean - could garner heightened policy support as governments seek to counteract ocean acidification. However, it is yet to be demonstrated that this is a scientifically meaningful selling point, as the marine impact evidence does not exist to determine if pH changes due to large scale deployment presents a net positive or negative for the marine environment. Capitalising on the different aspects of DOCC versus DACC will require effective stakeholder engagement coupled with a robust demonstration of cost competitiveness plus any other co-benefits.

4.4.6.2 SeaCURE versus other Direct Ocean Carbon Capture (DOCC) technology

This section has been omitted from the public facing version of the report.

4.4.6.3 Investment trends in carbon removal

Emerging data shows that early-stage venture capital and private equity investors account for almost two thirds of deals in the carbon removal sector. These investors typically look for projects with demonstrable technical potential, strong management teams, and a clear pathway to scale. Given the projected shortfall in removal capacity by 2030, there is considerable appetite for new approaches that promise lower costs and higher volumes.

SeaCURE's early economic modelling and route to market assessment indicates that reaching commercial viability for a technology like this would require £10s millions in early-stage funding and positive developments in the marine regulatory space. Beyond these immediate capitalisation needs, success for this kind of technology would hinge on forging long-term offtake agreements with buyers looking to manage their residual emissions. Advanced market commitments could provide SeaCURE like technology with the necessary revenue certainty to unlock larger capital pools, although purchases at present do not appear to be meeting fundamental capitalisation needs, rather providing market and success signals.

4.5 Dependencies and uncertainties

Bridging the gap from demonstration to commercial deployment requires a supportive policy environment, consistent funding, and local community acceptance, as well as all of the technology and scientific development. Commercialisation of SeaCURE like technology would therefore depend on securing adequate public and/or private investment to cover capital and operational expenditures, but also moving rapidly forward along the critical path defined by environmental impact and regulation (see Figure 21). Policy support for greenhouse gas removal (GGR) and stable carbon pricing mechanisms are important, although initially as a signal to provide confidence in investment rather than as a direct source of funding.

Beyond financial and policy factors, a key dependency lies in the broader supply chain for equipment, membranes and sorbents, as well as the availability of skilled labour in engineering, data analysis, and marine science. Further key uncertainties arise from legitimate permitting and potential public concerns about marine impacts, a key part of the answer to which is an acceleration of the production of the marine impact evidence base.

4.6 Non-climate benefits

Scaling SeaCURE-like technology in the UK could deliver significant national benefits beyond carbon removal. Many of the benefits stem from the UK's longstanding expertise in maritime industries, its extensive coastal resources and world leading marine science. First, substantial job creation could arise as the technology moves from pilot to commercial scale. Engineering and manufacturing firms would be engaged and new supply chains could be developed. Coastal communities stand to benefit from the employment opportunities associated with plant operations, vessel support, and marine monitoring. These roles will likely extend into research and development, as universities and private labs help develop and then operationalise the Monitoring Reporting and Verification (MRV) data collection, modelling and analytics for real-time carbon removal assessment and reporting.

SeaCURE-like technology also has the potential to spur industrial growth by fostering synergies with existing offshore infrastructure. Oil and gas platforms in decline, for instance, might be repurposed to house modular units for CO_2 extraction and storage. Meanwhile, integrating SeaCURE technology with offshore wind farms could lower costs through shared grid connections, maintenance crews, and supply chains. Similar value could be created in the co-development and location with the expected increase in UK desalination facilities. Co-location activities would occur for reasons of cost saving, but would also stimulate broader innovation across industry boundaries.

Beyond these direct economic gains, SeaCURE has reinforced the UK's position as a global leader in marine science and CDR. Monitoring programs designed to track the potential environmental impacts of CO_2 extraction will deepen understanding of ocean biogeochemistry and biodiversity, producing data that can inform conservation strategies and the wider mCDR space. Any breakthrough developments in membrane technology, water treatment processes, and CO_2 capture may also find applications in desalination, wastewater management, resource-recovery and the wider CDR sectors, amplifying the carbon savings.

4.7 Conclusion on commercialisation

Transitioning SeaCURE technology from its current pilot to a fully commercial system in the UK would demand a carefully staged approach. The journey would depend on stable funding, policy support, and robust local and international engagement. The technology's route to market requires demonstration plants that can confirm high carbon capture efficiency, minimal environmental impact, predictable and competitive operating costs, confidence in permitting support, as well as the removal of international governance risks. The route to market could then open up through partnerships with marine industries, climate finance initiatives, and carbon trading schemes. In parallel, the technology's broader benefits could include new engineering and operational roles, stimulating coastal economies and generating export opportunities for technology expertise and carbon removal services. By integrating environmental stewardship, social justice and transparency with technological development and demonstration, SeaCURE aims to further position itself as a key player in the evolving Greenhouse Gas Removal landscape.

5 Summary

Given the importance and urgency of the climate-change challenge, the SeaCURE project has rightly been extremely ambitious. SeaCURE was a £3M project, asked to "pilot part or parts of a GGR process" with the option to go further. The project ambitiously proposed then built and trialled an "end-to-end" solution. The Phase 1 project was the genesis and first lab tests of a novel technological approach. The Phase 2 project, reported on here, built a pilot plant based on this in a real operating environment, scaling up the design capacity from lab-tested components to pilot plant components by up to 100,000 times in a single step, as well as undertaking work on MRV development, marine impact assessment, social value and commercialisation. The project has resulted in a huge amount of learning, which we have been taking forward through spin out projects and bids, and has been communicating with partners and the wider CDR community through workshops, reports and peer reviewed publications. We are very grateful for the support provided by DESNZ, both financially and in terms of the ambitious goals, timescales and structure that have been set for the project. We now look forward to addressing the key barriers identified in this report. In doing so, we aim to accelerate marine CDR technology to reach its potential – playing a valuable role in helping to deliver a safe and stable climate.

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