



Retrofitting towards climate neutrality

D3.4 Summary Report on Carbon Capture Machine Operation (Public)

Programme: HORIZON EUROPE

Grant agreement number: 101096522

Project acronym: Green Marine

Project title: Retrofitting towards climate neutrality

Prepared by: CCM

Date: 31/07/2026

Report version: v1.0



Funded by the
European Union

Funding acknowledgement

Green Marine is funded by the European Union funding from the European Union's Horizon Europe research and innovation program under grant agreement No. 101096522. UK participants in Horizon Europe Project Green Marine are supported by UKRI grant numbers 10064539 (University of Strathclyde), 10068477 (CalMac Ltd) and 10064666 (CCM).

HISTORY OF CHANGES

Version	Publication Date	Changes
1.0	22/04/2026	First draft

DETAILS	
Grant Agreement No.	101096522
Project acronym	Green Marine
Project full title	Retrofitting towards climate neutrality
Dissemination level	Public
Due date of deliverable	M42
Actual submission date	M42
Deliverable name	Summary Report on Carbon Capture Machine Operation
Type	Report
Status	Draft
WP contributing to the deliverable	WP3
Author(s)	Tomas Ricciardulli, Jennie Morrison, Christine Tambe (CCM)
Other Contributor(s)	
Reviewer(s)	
Keywords	

Nomenclature

Abbreviation	Meaning
BX	BlueXPRT
TEE	Thermoelectric Element
PFD	Process Flow Diagram
P&ID	Piping and Instrumentation Diagram
DWT	Dead-Weight Tonnage
DAQ	Data Acquisition
IoT	Internet of Things
MAP	Manifold Absolute Pressure
CO	Carbon Monoxide
CO₂	Carbon Dioxide
NO	Nitric Oxide
NO₂	Nitrogen Dioxide
NO_x	Nitrogen Oxides
SO₂	Sulphur Dioxide
C_xH_y	Hydrocarbons
STP	Standard Temperature and Pressure
RH	Relative Humidity
GC	Gas Chromatograph
VPN	Virtual Private Network
GUI	Graphical User Interface
CFD	Computational Fluid Dynamics

TEA	Techno-Economic Assessment
LCA	Life Cycle Assessment
KPI	Key Performance Indicator
PPE	Personal Protective Equipment
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
PAT	Portable Appliance Testing

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EXECUTIVE SUMMARY

As part of EU HORIZON Project 101096522, Green Marine, Carbon Capture Machine (CCM) has developed a variation of its technology for marine applications. A prototype demonstration unit was designed fabricated by CCM and tested in Limassol in conjunction with the bypass manifold developed by CMMI and the cooling and compression skid provided by SINTEF. This document comprises D3.4 “Summary Report on Carbon Capture Machine Operation” which pertains to Task 3.4 of the Grant Agreement.

The tailoring of the carbon capture machine for the Green Marine project is described. The system was optimized from an engineering perspective: unit operations, equipment selection, footprint minimization, data acquisition and control were all analysed. The system chemistry was optimized for maximum continuous CO₂ capture and utilization. Additional chemical considerations include contaminant concentrations in flue gas as well as desired properties of the carbon utilization product as different use-cases may have disparate requirements.

1 INTRODUCTION

The Green Marine project is intended to accelerate the path towards net-zero emissions in water-based transportation through the development of multiple technologies for the retrofitting of existing vessels to reach new emissions targets. Within this consortium, the role of Carbon Capture Machine (CCM) is to develop and deploy a solution for maritime decarbonization using chemical absorption and mineralization of carbon dioxide as an approach to emissions mitigation. The mineralized product can be collected and sold to recover operating costs or disseminated for ocean alkalinity enhancement and further carbon dioxide removal.

Since its formation at the University of Aberdeen, CCM has developed a versatile Carbon Capture and Utilization technology which revolves around a mineralization process. The Machine accepts as input a stream containing carbon dioxide (e.g., flue gas), scrubs out the acidic gas using aqueous alkali, releases the cleaned air, precipitates the CO₂ into a usable product, and rejects a decontaminated, depleted, non-hazardous brine.

This technology was demonstrated at the 200 kg/day scale as part of the NRG COSIA Carbon Xprize competition. The primary aim of the XPrize competition was to identify highly scalable solutions to carbon capture and advance them through pilot-scale demonstrations as a proof-of-concept; as part of the competition, a third-party analysis was performed by Southern Research Institute which mapped out key process flows, data streams, operational concerns and verifiable Key Performance Indicators. This analysis validated the ecological benefits of CO₂ capture and utilization using CCM's technology within the aims and context of the XPrize competition. However, the location for these demonstrations was an industrial facility with highly available utilities: electricity, compression, fresh water, ventilation, usable space. In contrast, these resources, especially regarding footprint, become limiting in a marine context.

Deliverable D3.4 "Summary Report on Carbon Capture Machine Operation" presents the outcomes of the development of a Machine intended for deployment to the MV Coriusk comprising a chemical absorption and precipitation process for the capture and utilization of carbon dioxide from flue gas streams. Considerations for the maritime deployment of carbon capture and mineralization technology are outlined with respect to materials of construction, system design, equipment selection and operation. The system is enumerated, beginning with a high level overview and expanding into a process description. The basis of design and assumptions underlying the design calculations for the CCU system are outlined. Chemistry and physics underpinning CO₂ capture and mineralization are explained, and the results most salient to CCM design are emphasized. The intentions and underlying mechanism of ocean deacidification with CCU products are explored.

1.1 PURPOSE OF THE DOCUMENT

This document provides a summary of the tailoring of the Carbon Capture Machine to meet the requirements of the Green Marine project. It comprises the completion of deliverable D3.4.

This document includes a brief history of Carbon Capture Machine as an organisation, an explanation of the Carbon Capture Machine concept, a description of how the engineering and underlying chemistry of the carbon capture machine were re-optimised for a marine application, and description of the available options for utilisation. A chemistry and physics-driven elaboration of the deacidification or ocean alkalinity enhancement application is presented. The deliverable D3.4 also highlights the key operational observations and lessons learned from the tailoring campaign, such as derived engineering requirements, component selection, safety considerations, regulatory compliance.

1.2 DOCUMENT STRUCTURE

Section 2 gives an overview of the Carbon Capture Machine concept as well as an explanation of how the carbon capture machine fits into the integrated Green Marine system and a process description for carbon capture and utilisation. Section 3 presents the tailoring of the carbon capture machine for marine applications with respect to both engineering and chemistry optimization of the system. Section 4 summarises the precipitation and utilisation of carbon capture products. Section 5 discusses the relevant regulatory framework for Carbon capture machine for emissions control, ocean alkalinity enhancement as well as monitoring, reporting and verification.

2 CARBON CAPTURE MACHINE DESCRIPTION

2.1 CARBON CAPTURE MACHINE BACKGROUND

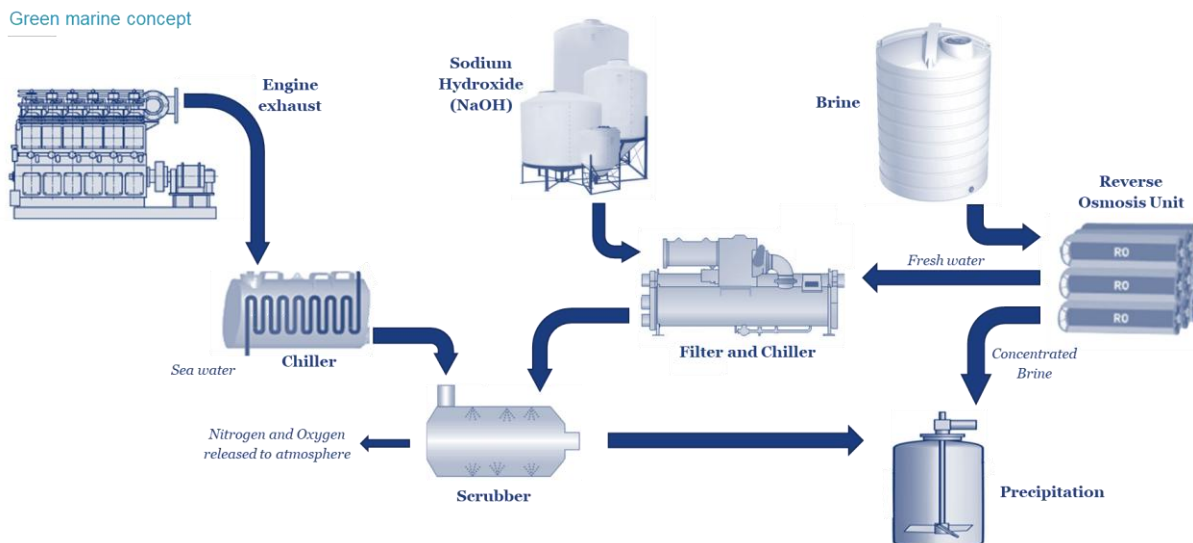


Figure 3.4.1 block flow diagram for the marine application of the Carbon Capture Machine Process.

Figure 3.4.1 shows a block flow diagram which illustrates the marine application of the Carbon Capture Machine Process. Flue gases, containing significant amounts (2-10 v%) of CO₂ and moisture are exhausted at high temperatures (> 200°C) from an internal combustion engine. A heat exchanger is used to remove

heat from this stream to $< 100^{\circ}\text{C}$ such that the CO_2 can be captured. In principle, the heat may be rejected to the ocean, rejected to air, or reused elsewhere within the process. The cooled gas stream is then scrubbed to remove CO_2 and other environmental pollutants present such as NO_x and SO_x before returning to atmosphere.

The CCM can be therefore considered a ‘black box’ which can scrub out all emissions from flue gas – not just CO_2 . The scrubbing is accomplished by a dilute aqueous alkali; heat released from the preparation of alkaline solutions can be rejected prior to scrubbing to increase capture rates, but this is not technically required. Rather than dispose of the spent scrubber liquid, the process seeks to valorise this material through controlled reaction of the scrubber liquid with a concentrated brine to precipitate calcium and magnesium carbonates. The brine may be harvested from a variety of sources such as reverse osmosis rejection streams, which are commonly available aboard oceangoing vessels. CCM adds value in this step by carefully controlling the reaction design to produce high purity nanostructured materials. These carbonates may be either disseminated to support ocean alkalinity enhancement and potentially claim additional credits or recovered and sold to recoup operating costs.

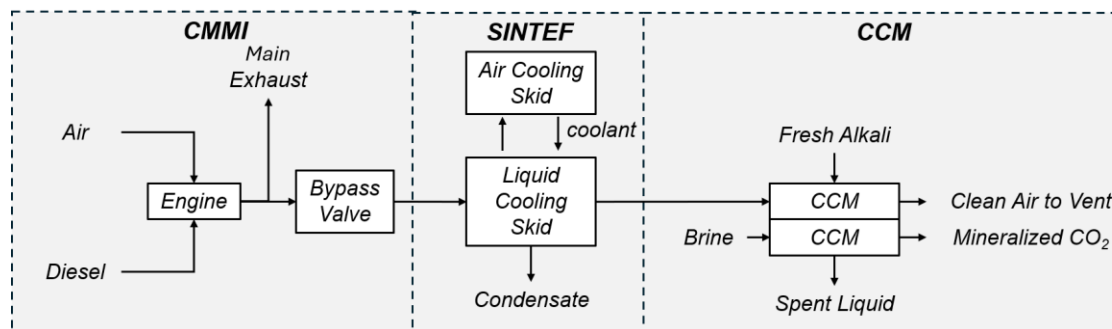


Figure 3.4.2. CCM-containing Green Marine Integrated System as implemented in Limassol for the January 2026 testing campaign

Figure 3.4.2 shows the overall integrated system which was tested and implemented in Limassol. The overall system represents a combination of contributions from two Green Marine consortium members (CMMI, SINTEF) in addition to CCM. The engine used is a marinized Diesel genset (Cummins Stamford) with no emission control equipment installed (e.g., catalytic converter, diesel particulate filter).

While the main exhaust line has no flow restrictions, a CMMI-designed manifold is installed with a valve on the bypass line to control the flow. This layout allows for carbon capture systems to operate with zero net engine backpressure and therefore no impact on engine performance.

Not only are engines designed with a very low maximum allowable backpressure (just 10 kPa), but they are also tuned to their specific installed environment and flow path. Any retrofitting projects therefore cannot change this configuration without also affecting the mapping, therefore the effective backpressure budget for any retrofitting project is zero.

Consequently, the driving force to push the flue gas into the bypass (as opposed to the main exhaust line) cannot come directly from the engine and must be added externally.

The cooling skids are provided by SINTEF and are designed in consideration of the limitations aboard a vessel: rather than a single air/air heat exchanger to cool the engine exhaust gas, two air/liquid heat exchangers are used with constant coolant recirculation. This scheme enables more compact cooling, as it decouples the heat removal from the flue gas from the heat rejection to ambient, allowing for carbon capture

systems to be installed below deck. When heat is removed from the engine exhaust, liquid water condenses and removed by knockout. The cool, dry gas is then compressed with a fan to supply the driving force for gas to flow through the Carbon Capture Machine, which finally captures the CO₂, converts it to a stable mineral and releases clean air.

3 TAILORING OF CARBON CAPTURE MACHINE FOR GREEN MARINE PROJECT

3.1 COMPONENT SELECTION FOR MARITIME CARBON CAPTURE

The Carbon Capture system design shown in Figure 3.4.1, built and delivered to Limassol for the January 2026 testing campaign, represents a major technical advancement for CCM achieved as part of this Green Marine project. The original demonstration system, developed and evaluated in Aberdeen for the XPrize competition, effectively proved the technology's feasibility and was validated by Southern Research Institute. However, it also reflected several design compromises that made it unsuitable for the technical requirements of the Green Marine project. As a result, a clean-sheet redesign was required to adapt the Carbon Capture Machine technology for marine use, beginning with the selection of materials of construction.

The original CCM design used low-cost, readily available plastics such as HDPE and PVC for most process components. However, because of the mobile maritime environment and the potential for UV damage from sunlight exposure, all major process components were redesigned using metal construction. Metals were also preferred because they can operate at higher temperatures than HDPE or PVC, reducing the risk of overheating caused by potential heat transfer from the engine.

Because of corrosion risks from both environmental and process conditions, 316L stainless steel was selected as the primary construction material. Wherever possible, components were specified in 316L stainless steel. For auxiliary components, including gaskets and flexible hoses, fluorinated polymers such as FEP and PTFE were selected. Although these materials are more expensive and have greater environmental impacts than other polymers, their performance benefits justify their use: they tolerate higher temperatures, improve durability, expand the operating window, and are required only in relatively small quantities.

Proper sensor selection and placement are essential for consistent unit operation. In carbon capture retrofit projects, it may seem intuitive to rely on existing upstream measurements of airflow, temperature, pressure, and composition from a vessel's mature propulsion system. However, integrating disparate components introduces complexity that outweighs the potential cost savings. Because each engine room is unique, existing sensors such as thermocouples and tachometers may produce inconsistent results due to subtle differences in device construction. Communications protocols may also be incompatible, and modifying the engine or its subcomponents to accommodate carbon capture equipment could void warranties. Given the relatively low cost of

most sensors, the best approach is to measure process conditions independently within the Carbon Capture subsystem. This enables repeatable operation and consistent data collection across deployments. Upstream measurements are better used for cross-checking unusual readings and confirming calibration accuracy of sensors within the Carbon Capture subsystem, rather than for direct control.

Among the sensors used, flowmeters and gas analysers are the most important instruments for quantifying CO₂ capture and controlling the system as inputs change. Both, however, face specific challenges when applied to carbon dioxide capture from flue gas. Flue gas contains substantial condensable moisture as well as acid gases that dissolve into the condensate. Entrained water droplets can damage flowmeters, causing inaccurate readings and eventual failure. In the Green Marine project, this issue was addressed by placing the flowmeter downstream of a cooling heat exchanger and condensate knockout unit, which proved effective for the project's purposes. A more elegant solution could be a hot-wire anemometer designed for humid environments, which would better tolerate moisture and could potentially eliminate the need for a knockout that must be routinely drained.

Gas analysers measure CO₂ concentration in the inlet and outlet streams. Many CO₂ analysers are designed for specific applications, and they can lose accuracy when used outside those conditions. In addition to the condensation issues that affect flowmeters, analysers may experience reading drift or fouling from contaminants. For example, most commercial sensors used to estimate CO₂ in flue gas do not measure CO₂ directly. Instead, they measure O₂ concentration and infer CO₂ based on oxygen consumption relative to ambient air at 21% O₂. If CO₂ is removed from exhaust gas after combustion without consuming O₂, these sensors will not perform as intended. Electrochemical sensors are also common, but they are highly sensitive to moisture and may be affected by contaminants in engine flue gas. Therefore, the preferred sensor must directly measure CO₂ concentration without directly contacting the gas.

Nondispersive infrared (NDIR) sensors meet these requirements well. Unlike traditional Fourier transform infrared spectrometers (FTIR), NDIR sensors do not monochromatize light before analysis. This greatly reduces cost and complexity, although each sensor is typically limited to one or two gas species, while FTIR can simultaneously measure all IR-active molecules. Gas molecules contain bonds, such as O-H or C=O, with distinct energy levels. When light interacts with these molecules, photons at bond-specific energy levels are absorbed and converted to heat. This is the same fundamental mechanism underlying the greenhouse effect, the primary driver of anthropogenic climate change from CO₂ emissions. As a result, measuring light absorption at specific wavelengths, such as 4.26 µm for CO₂, is a reliable method for determining concentration. Optically transparent windows can also protect sensors and light sources from process gas. The Quantek 906 NDIR CO₂ analyser has proven to be an accurate and economical device and was implemented in the system developed for this project. To ensure consistent measurements, the same analyser model was used at both the inlet and outlet of the CCM.

Although effective and robust, the Quantek 906 analyser has limitations. Most notably, its NDIR analysis chamber is housed within the tabletop unit, so the analyser uses an air pump to draw a gas

sample for analysis before venting it. Physically transporting the gas into the analyser increases response time. However, because the gas flowrate (<1 L/min) and concentrations of toxic species such as NO_x in flue gas are low, this does not present a serious safety risk. The primary risk for the Carbon Capture Machine is a failure mode in which scrubber liquid enters the gas sampling lines and causes a blockage. In-line (in situ) gas analysers address this issue by placing the analysis chamber inside the gas line, eliminating sampling lines entirely. These devices are commercially available, including the Mettler Toledo GPro 500 and Vaisala GMP251, but were not selected for the Green Marine project because of cost and lead time constraints.

Beyond CO₂, understanding other combustion products, including CO, NO_x, SO_x, soot, and hydrocarbons, is critical to advancing marine carbon capture systems. These species can corrode or foul components or cause other unintended process reactions. It is also important to understand how an apparent carbon capture system affects the concentrations of these contaminants to establish a complete emissions profile. Emissions profiles vary by engine; the engine tested in Limassol for this project had no emissions control devices, such as a catalytic converter, diesel particulate filter, or soot oxidation system. Other factors affecting engine emissions include air-fuel ratio, exhaust gas recirculation, and combustion chamber design. Advanced combustion analysers can measure all these components, but they are significantly more expensive and require more overhead than NDIR. To support this objective, an analyser provided by CMMI was installed in the bypass system.

To collect data during the operation of the Carbon Capture Machine, all CCM-incorporated devices were specified to communicate using standard analog 4-20 mA signals and installed into a data acquisition board recording each measurement once per second.

Another key lesson from the Green Marine project is the importance of heat and pressure management in system design. Although engine manufacturers typically specify a maximum backpressure of 100 mbar, effective operation requires a more stringent limit in practice. In a bypass configuration without a throttle, gas must be actively drawn into the carbon capture system by a fan; otherwise, it will follow the lower-resistance bypass path. Higher flow resistance increases the fan power needed for exhaust extraction to compete with the bypass. The original Aberdeen CCM used gases supplied by air compressors and CO₂ cylinders, meaning gas was available under ideal carbon capture conditions: low temperature and high pressure. Refrigeration as low as 5°C was available to support CO₂ capture, and system pressure drop was not a major constraint because the pressure budget exceeded 2 bar. By contrast, flue gas aboard the MV Coriusk is available at low pressure and high temperature. Heat must be rejected before capture, and only outside air is available as a heat sink; refrigeration below ambient temperature is not available. Deploying CCM technology in a marine context therefore requires a system that can operate at higher temperatures with minimal pressure drop. Rather than reuse the existing architecture, a new scrubber was designed from the ground up using process simulation software to meet these stricter requirements. The system's operating conditions were also experimentally reoptimized. Whereas the original Carbon Capture Machine used three to four scrubber units to

remove CO₂ at ambient to sub ambient temperatures, the updated design requires only one unit and can operate up to 60°C with lower overall flow resistance.

Available space and utilities aboard a vessel strongly influence the feasibility of a carbon capture retrofit. The CCM system includes multiple pumps, fans, and sensors, each of which consumes electricity and requires physical space. Although each device must be installed, wired, and configured, these tasks should be distinguished from the retrofit itself. Because each vessel has a unique layout and available utilities, facility requirements should be simplified as much as possible to reduce the risk of incompatibility in electrical supply or footprint. For this reason, instead of assembling and wiring the system on-site, all major CCM process components were packaged into a single 1.0 x 1.5 m skid at CCM's facilities. This also allowed the as-built system to be verified before land-based testing. All power draws were routed to a single 440 V, 32 A, five-pin, three-phase plug selected to match the existing receptacles at the Limassol testing site, so only one electrical connection was needed for setup.

For shipboard carbon capture retrofits, appropriate siting is essential to minimizing cost and complexity. If carbon capture equipment is installed in a hazardous combustible environment, such as a ship's engine room, relevant safety certifications may be required, such as Class 1 Division 2. Neither flue gas nor CCM components are flammable; the risk arises from proximity to fuel-handling equipment in the engine room. Removing carbon capture unit operations from the hazardous area is therefore a more cost-effective safety strategy. The failure mode associated with incomplete engine combustion can be mitigated through engineering controls such as a combustible gas sensor and interlock. Additional safety measures can include larger design margins. For example, although the carbon capture system is intended to operate below 100 mbar and has no mechanism to exceed 300 mbar even under worst-case conditions, the vessel used was rated to 8 bar, which can help build confidence with shipowners. Secondary containment is also an effective mitigation for leaks; appropriately designed systems should be able to contain a leak 10% greater than the maximum possible release from a single point of failure. From this perspective, storing liquids in multiple smaller tanks is safer than using one large tank. Another safeguard to reduce leakage risk is to seal unions by welding rather than by using flanges and gaskets or compression fittings.

3.2 TAILORING OF SCRUBBER FOR MARINE APPLICATIONS

As mentioned above, as a part of this project, the gas scrubber was redesigned from the ground up to accommodate the requirements of the vessel-based testing. In designing a gas scrubber, the first decision to be made is if a staged (discrete) or packed (continuous) column is preferable. Both columns involve counter current flows in which the 'dirty' gas is introduced near the bottom of the column along with a 'clean' liquid at the top. Buoyancy differences force the gas vertically upwards and the liquid downwards; the two streams meet, contact one another and exchange chemical species through absorption/desorption. The manner in which the streams are contacted determines the type of column: staged columns comprise an array of bubble-trays where gas

bubbles contact pooled liquid held up on each level whereas staged columns contain packing media with high surface area which are coated by the liquid to enhance the gas-liquid exchange rates.

Each type of column has its unique advantages and disadvantages. The staged columns are simple to design and capable of achieving very high throughput. Each tray is assumed to reach equilibrium which allows for simple yet accurate modelling. To relax this assumption and further enhance the accuracy of the relatively simple model, a term called the Murphree efficiency defines the approach to equilibrium. However, due to the liquid pooled or ‘held up’ on each tray, there can be a significant pressure drop with this type of column. Additionally, the manufacture of bubble-trays requires a significant amount of machining leading to much higher costs and lead times. Packed columns are much more difficult to model than staged columns but are also significantly less expensive to construct. These columns are physically simpler and contain just a packed bed sandwiched between two distribution plates.

The void space is much higher and the liquid hold up volume much lower with this type of column which helps to reduce the pressure drop significantly at the cost of decreased contact efficiency. However, in theory, it is possible for a ‘packet’ of gas to travel through a poorly designed packed column without ever contacting liquid, effectively bypassing the column, which would adversely impact the performance of the operation. This effect can also occur within the liquid phase and is referred to as maldistribution.

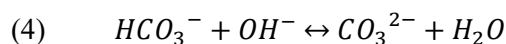
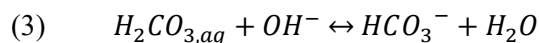
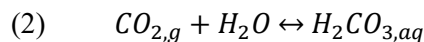
Due to the continuous nature of packed columns, there are no discrete stages which invalidate the simplifying assumptions used for the design of staged columns. Instead, the concept of HETP (“height equivalent to transfer plate”) is intended to bridge the gap between the two schools of column design by allowing for a number of discrete stages to be converted to a required height of packing media within the column. However, HETP must be calculated for each unique case as it depends on the thermodynamic equilibrium, transport rates, column diameter, temperature, gas flowrate, liquid flowrate, surface area, etc.

For the case of CO₂ removal from flue gas, the amount of material exchanged between the liquid and gas phases is <10%, which allows us to use the simplifying assumption that the overall gas and liquid flowrates throughout the column are constant. Because mass is conserved, the required height may be expressed either in terms of the liquid or in terms of the gas:¹

$$(1) \quad h = \frac{G_m}{K_G a P} \int_{y_2}^{y_1} \frac{dy}{y - y_{eq}} = \frac{L_m}{K_L a C} \int_{x_2}^{x_1} \frac{dx}{x_{eq} - x}$$

Where x_i and y_i refer to the fractional concentrations in the scrubber inlets, outlets or at equilibrium; K_G and k_L refer to the gas and liquid phase mass transfer coefficient, G_m and L_m refer to the liquid and gas flowrates; a is the interfacial mass transfer area; P and C are the overall pressure in the gas phase and concentration in the liquid phase. Because the composition of the liquid and gas in the column changes continuously, the integral in (1) must be solved numerically. This expression can also be written as the product of the number of transfer units times the height of each transfer unit, but the underlying mathematical formulation is unchanged.

Though equation (1) is effective for the design of simple absorber columns in which a single mass transfer coefficient can be defined; our system involves the absorption and reaction of CO₂. The reactions are as follows:



Carbon dioxide (CO₂) dissolves in water (reaction 2) to form carbonic acid; reaction with a single free hydroxide ion is sufficient to convert the carbon dioxide to bicarbonate which is sufficient to permanently sequester the CO₂ (reaction 3). However, bicarbonate may undergo an additional reaction with another equivalent of hydroxide to form carbonate ions (reaction 4). This produces a more stable form of sequestered carbon but consumes an additional equivalent of alkalinity.

To derive an expression for the kinetic rate of CO₂ capture, we must calculate the net rate of reaction 2:

$$(5) \quad \frac{d[CO_{2,g}]}{dt} = k_{-2}[H_2CO_{3,aq}] - k_2[CO_{2,g}][H_2O]$$

Where k_x refers to the forward rate constant of reaction x and k_{-x} refers to the backwards rate constant and the brackets refer to the concentration of each species. The spontaneity of a chemical reaction can be determined by calculating the Gibbs Free Energy:

$$(6) \quad \Delta G = \Delta H - T\Delta S$$

Where the enthalpy (ΔH), temperature (T) and entropy (S) change of a reaction can be used to show that a reaction is spontaneous if $\Delta G < 0$.

Carbonic acid (H₂CO₃) is an intermediate within the process; from reference to literature thermodynamic values, we know that this species is short-lived and highly reactive due to the high exothermicity of reaction 3 which is an acid-base reaction. Consequently, the pseudo-steady state hypothesis can be applied by assuming that the rate of change of this intermediate is zero:

$$(7) \quad \frac{d[H_2CO_{3,aq}]}{dt} = 0 = k_2[CO_{2,g}][H_2O] + k_{-3}[HCO_3^-] - k_{-2}[CO_{2,aq}] - k_3[H_2CO_{3,aq}][OH^-]$$

This equation can be rearranged to give an expression for the effective carbonic acid concentration:

$$(8) \quad [H_2CO_{3,aq}] = \frac{k_2[CO_{2,g}][H_2O] + k_{-3}[HCO_3^-]}{k_{-2} + k_3[OH^-]}$$

To obtain a useful expression for the rate of CO₂ capture, we substitute (8) into (5) and assume that reaction 3 is irreversible due to its high degree of exothermicity, giving the overall kinetic expression for the rate of CO₂ capture by alkaline water:

$$(9) \quad \frac{d[CO_{2,g}]}{dt} = - \frac{k_3 k_2 [CO_{2,g}][OH^-][H_2O]}{k_{-2} + k_3[OH^-]}$$

This expression clearly indicates that there exist two regimes for CO₂ capture: in the first regime, when [OH⁻] is high (i.e., high pH or alkaline conditions), the rate of CO₂ capture is limited by the rate at which CO₂ dissolves (reaction 2). Conversely, when [OH⁻] is relatively low, (i.e., relatively low pH or acidic conditions) the reaction is limited by the liquid phase reaction 3 and availability of free [OH⁻] species.

These differences impact the behaviour of the system. For example, reaction 2 is characterized by a large negative entropy change (consumption of a gas phase species) and high degree of reversibility (low solubility) which cause it to be favoured at lower temperatures rather than higher temperatures. In contrast reactions 3 and 4 do not directly consume gas phase species and are known to have kinetic rather than thermodynamic limitations; these are intuitively favoured at higher temperatures. Thus, when pH is very high the column can be expected to perform better at lower temperatures, but when pH is lower the column performance should be enhanced by higher temperatures.

To streamline the fabrication process as much as possible, it was decided to use a packed-type column as opposed to a staged column. However, as mentioned above, this decision increased the complexity of the design stage. The design of the column was heavily informed by its intended application of pilot plant demonstration. For the purpose of conducting a successful pilot test, it is very helpful to have equipment capable of operating across a wide range of conditions. In particular packed columns are known to have relatively narrow windows of operation compared to staged columns. When outside of the design range of flowrates, maldistribution is much more likely to happen. For example, if the gas or liquid flowrates are too high, rather than fall down at the prescribed rate the liquid may become entrained and collect within the column; this effect is known as ‘flooding’ and hampers performance by limiting the available exchange surface area as the packing media becomes soaked rather than wetted by the liquid. Conversely, if the overall flowrates are too low local channels of high flow can form; such nonuniform flow (channelling) causes poor liquid/gas contact and a significant bypass effect.

To effectively operate the column across many conditions, we devised a recycling system which mixes the spent column bottoms with fresh feed prior to introduction to the top of the column. While equation (9) shows that the rate of CO₂ capture is decreased by recycling (and therefore diluting) the scrubbing liquid, our experience is that the enhancement in column performance by overcoming channelling limitations outweighs the kinetic effects. When flowrates are low, the liquid recycling is necessary to keep the liquid flowrates within the range of efficient operation; at high enough flowrates this recycling can be turned down or off. Owing to this scheme, we can effectively turn down the column by more than 50x whereas a turndown ratio of 2-3x is more typical.

Considering the stringent space requirements of this project, the footprint of the scrubber system was minimized to the greatest extent possible. The column was designed to meet the engineering requirements listed in Table 1 while also maintaining appropriate dimensional ratios. Dimensions were chosen following design recommendations in Perry’s Chemical Engineer’s Handbook,² Chapter 14, to mitigate column maldistribution. Random packing was used rather than structured packing due to lead time and cost considerations. Packing media was selected to be the smallest

available size capable of meeting the pressure drop requirement; the column diameter and length were designed to reach a sufficient volume required to contain enough packing media surface area for efficient CO₂ capture at the maximum flowrate while also keeping designs within the recommended proportions. The volume required was calculated using the design equation (1) using estimates for K from literature.³

Figure 3.4.3 shows a computer-aided design image of the final design of the CO₂ capture skid. For ease of transportation and assembly, the column is divided into five more manoeuvrable sections. Each section has chemical resistant sight glasses to aid the operators. Additionally, multiple pumps and sensors are mounted on the mobile skid for compactness. Flexible tubing is used to connect each instrument into the process. The column itself was designed to the specifications given in Table 3.4.2. Though the initial design of the column followed the approach described above, the overall process was additionally verified using process simulator software.

Table 3.4.1. Design Requirements for flue gas CO₂ emissions control device for Green Marine Project

Condition	Requirement
Backpressure	< 10 kPa
Temperature	> 25°C
Footprint	< 2.0 x 2.0 m
Flowrate	< 150 Nm ³ /h
CO ₂ concentration	2-7%
Transportability	High

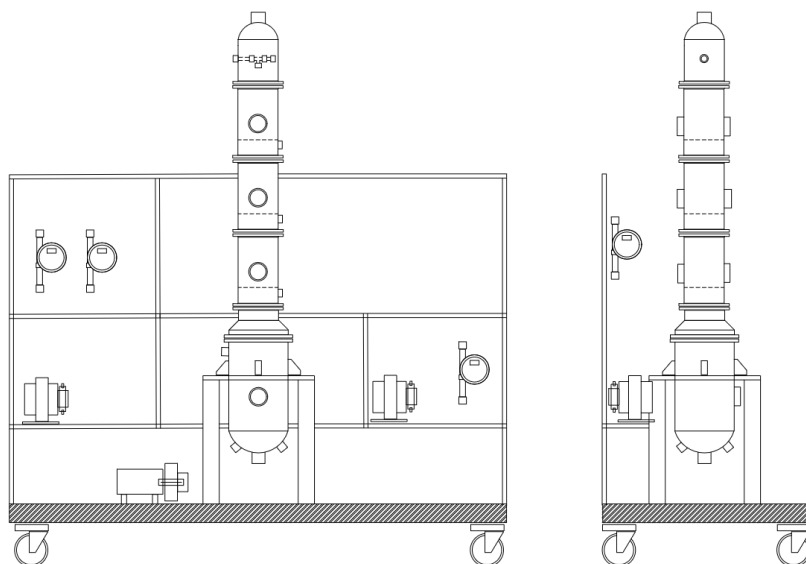


Figure 3.4.3. Renderings to-scale of Carbon Capture Skid showing the column in addition to mounting locations of multiple pumps and sensors

Table 3.4.2 Specification and design of scrubbing column.

Material of Construction	316 Stainless Steel
Maximum Pressure	8 barg
Maximum Temperature	90°C
Type of Column	Packed
Gas Flow	1-150 Nm ³ /h
CO ₂ Concentration	2-7 v%
% CO ₂ Capture	>95%
Number of Scrubbing Units	1

3.3 RESULTS OF SAFETY STUDIES

For a product to be technologically mature, it must also be safe. As part of the Green Marine project, safety and hazard analysis studies of the Carbon Capture Machine were performed both internally within CCM and also with other members of the consortium. The internal safety studies identified two most significant risks being the potential leak of alkaline solution as well as electrical short causing fire or shock to the operator. Alkali solutions may be classified as corrosive, meaning that leakage is highly undesirable. Design-level considerations and safeguards against such risks included the proper selection of materials, connection types, deliberate over-engineering of temperature and pressure limitations, as well as minimisation of risk by limiting the extent to which higher concentrations of alkali are handled. For example, dilution of alkali within the recycle loop would also act as a mitigating factor. Overpressure of the column is prevented by an

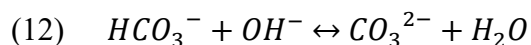
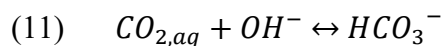
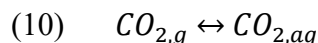
unobstructed exhaust gas flow path as well as a relatively low maximum operating pressure of the fan used to control gas flows.

Procedural safeguards and mitigations also emerged from the safety studies. On-site in Limassol, all available safety measures were taken, including wearing of proper PPE. The system was extensively leak checked using water prior to charging with alkali; these leak checks were performed overnight to identify even a small leak. Out of an abundance of caution, secondary containment was also used as mitigation. An intermediate bulk container with a volume far exceeding the liquid volumes used in testing was used as a waste tank and arrangements were made with a local waste service for disposal. Additionally, all tanks have manual relief valves to allow for easy drainage. Clear evacuation routes and procedures were communicated to all personnel involved in testing. Eyewash as well as shower were made available. An emergency stop was installed onto the system and made available and accessible at all times. Time spent by operators in the vicinity of the equipment was to be limited as much as possible. Additionally, the overall amount of alkali used in the testing was low due to the scale and duration of the test, which also facilitated safe operation. As an engine was to be used in the testing, certified fire-fighting equipment was made available at the test site. All unnecessary flammable materials were removed from the testing site. All equipment was electrically grounded, preventing risk of shock. Prior to final installation and powering on the equipment, a local certified electrician was consulted to verify the setup.

Safety assessments conducted in collaboration with the University of Strathclyde focused more on mitigation of potential consequences of equipment failure. Standard operating procedures were amended to specify maintenance and re-calibration intervals of 12 months. CCM analyser readouts are to be cross-referenced periodically with engine data for verification. Operators are instructed to closely monitor the system for signs of overheating and blockage formation, and multiple high temperature alarms are to be installed in the commercial deployment. Only Normally Closed-type valves are to be used to facilitate safe shutdown in event of emergency. High level sensors on tanks with high alarms to be installed on a commercial deployment, but this was not considered in scope of the Green Marine project because the intended testing procedure only involved outflows from the alkali tank, and the tank filling was to be done manually by skilled operators.

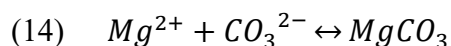
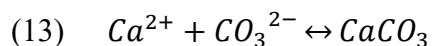
4 CONVERSION AND UTILIZATION OF CAPTURED CO₂

The CO₂ capture system described in earlier sections exploits the acidic properties of carbon dioxide to remove and permanently sequester it from flue gas streams by reaction with alkali to produce HCO₃⁻ and CO₃²⁻ ions:



The origins of CCM are with the capture and utilization of CO₂ to produce ecologically friendly precipitated calcium carbonates (“Eco-PCC”), in addition to precipitated magnesium carbonates (PMC’s) as ‘green’ building materials.^{4,5}

Under carefully controlled conditions, these species can be prepared by reaction of sequestered CO₂ (as CO₃²⁻) with Ca or Mg cations derived from CaCl₂ or MgCl₂ sources such as seawater.⁶



By Hess’s law, all of the above equations ((10) through (14) and (2) through (4)) can be inverted and combined as desired to calculate the propensity for one reaction to occur versus another; this will depend strongly on the concentrations of the various ions, pH and temperature. For example, though the original intention of Carbon Capture Machine was to produce solid MgCO₃ and CaCO₃ species for use as building materials, it is also possible for reactions (13) and (14) to be reversed,⁷⁸ which would generate carbonate ions capable of effecting further CO₂ removal by conversion to bicarbonate upon equilibration with atmospheric CO₂ as shown in reaction (4).⁹

Table 3.4.3. Feasible end products of CO₂ capture and conversion from the CCM

Species Name	Chemical Formula
Sodium Carbonate	Na ₂ CO ₃
Sodium Bicarbonate	NaHCO ₃
Amorphous calcium carbonate	CaCO ₃ ·H ₂ O
Calcite	CaCO ₃
Monohydrocalcite	CaCO ₃ ·H ₂ O
Aragonite	CaCO ₃ ·H ₂ O
Vaterite	CaCO ₃
Ikaite	CaCO ₃ ·6H ₂ O
Dolomite	CaMg(CO ₃) ₂
Amorphous magnesium carbonate	MgCO ₃ ·H ₂ O
Nesquehonite	MgCO ₃ ·3H ₂ O
Magnesite	MgCO ₃
Dypingite	Mg ₅ (CO ₃) ₄ (OH) ₂ ·5H ₂ O
Hydromagnesite	Mg ₅ (CO ₃) ₄ (OH) ₂ ·4H ₂ O
Barringtonite	MgCO ₃ ·2H ₂ O
Landsfordite	MgCO ₃ ·5H ₂ O

Far from theoretical speculation, this approach has been demonstrated to be effective for atmospheric carbon dioxide removal in soil liming under favourable conditions.^{10,11} Further

support for this CDR strategy is provided by simulations of limestone dissemination for OAE indicating high levels of conversion when dissemination occurs in areas with shallow undersaturated waters and high upwelling velocities.¹²

Though calcium carbonate can be inert to the extent that precipitation resulting from ocean alkalinity enhancement is usually considered lost if the precipitates sink to the bottom of the ocean before re-dissolving, a deeper understanding of the alkalinity enhancement process reveals mechanisms by which the state of the art for OAE may be advanced.

This precipitation can occur due to locally high pH (i.e., excessive supersaturation) caused by ineffective mixing upon dissemination of the alkalinity enhancing stream to the ocean.

However, under favourable conditions it is possible for the precipitated alkalinity to re-dissolve and redistribute and therefore become available for marine carbon dioxide removal.¹³

The idea behind ocean alkalinity enhancement is to effectively raise the pH of seawater (typically ~8.1) by disseminating a stream which contains higher pH (e.g., pH 10); as pH is calculated on a logarithmic basis the alkalinity in the OAE stream should be at least 100x higher than in natural seawater.

However, a rather obvious limitation occurs in the attempt to widely implement OAE: the ocean is very large, but alkalinity enhancement is only available from point sources and cannot be easily distributed across the entire surface of the earth. At high rates of OAE, this would naturally create a gradient of alkalinity in the surface waters of the ocean which would decrease its effectiveness. Ships can sail across the ocean, and most corridors of the ocean are regularly traversed by shipping traffic, so dissemination across the entire length of oceangoing voyages can be effective means to more uniformly distribute OAE steams and minimize such alkalinity concentration gradients.

Another means to better improve OAE implementation could be to use a slow-acting source of alkalinity. The fundamental cause of alkalinity loss to precipitation is excessively high local alkalinity; conversely this can be thought of as a mismatch between rates of species transport and reaction.¹⁴ Put into characteristic timescales, such undesired precipitation would indicate conditions where $t_{\text{mix}} \gg t_{\text{rxn}}$ i.e., the mixing is much too slow compared to the rate of alkalinity consumption (reaction). The consequence of undesired precipitation is to generate nearly insoluble species which also become physically inaccessible for OAE, in aggregate this corresponds to a state in which $t_{\text{rxn}} \gg t_{\text{mix}}$ because the alkalinity is unable to react before it is transported away from the surface. Within the context of the CCM system described above, the desired outcome of OAE is the conversion of carbonate (CO_3^{2-}) ions to bicarbonate (HCO_3^-) ions; this would require dissemination conditions where $t_{\text{mix}} \approx t_{\text{rxn}}$ i.e., a careful balance between reactivity and transport. Both timescales can be optimized using the inputs to the CCM. Because the precipitation step within the carbon capture machine can be controlled, the desired morphological and other physical characteristics can be selected and optimized for ocean alkalinity applications. For example, t_{rxn} can be straightforwardly manipulated by pH and temperature effects, in addition to controlling the phase and morphological characteristics of the carbonates (refer to table 3.4.3) which affects solubilities.¹⁵¹⁶

With astute CCM operation, the properties of the product can be tuned to achieve the desired t_{mix} value. Counterintuitively, it is not necessarily guaranteed that the carbonate particles will rapidly sink to the bottom of the ocean where they would be locked away indefinitely. For sufficiently small particles, the surface area/volume ratio is much higher so Brownian motion can overpower the effects of buoyancy to create a stable colloid (also referred to as a sol). Additionally, calcium carbonate is known to dissolve within the ocean¹⁷ and ocean currents serve to distribute the particles along density lamina which appears to also be a more powerful effect than simple buoyancy.¹⁸ Moreover, the carbonate phases (table 3.4.3) show different densities owing to differences in crystal structure and therefore will exhibit differences in buoyancy which will impact t_{mix} . In other words, the intended application of the CCM to OAE is to pre-precipitate carbonates into more soluble and dispersible forms which will slowly redissolve as they are spread out and disseminated, preventing alkalinity loss through uncontrolled precipitation.

5 REGULATORY FRAMEWORK FOR OAE THROUGH CCM

The use of liquid scrubbers for the remediation of emissions is not a new technological development to this project, and an existing set of regulations already governs marine emissions. These regulations are currently implemented and limit the amount of particulate matter as well as acid gases (SO_x and NO_x) which can be emitted (MARPOL).

To address these limits, a myriad of technologies have been developed over the years, including closed-loop scrubbers, open-loop scrubbers and catalytic converters. Catalytic converters allow for particularly hazardous species like unburned hydrocarbons,¹⁹ carbon monoxide,²⁰ nitrogen oxides²¹ and soot²² to be transformed into less immediately hazardous species like CO_2 , H_2O , N_2 gas. Closed-loop scrubbers circulate an alkaline solution which can capture acid gases but not hydrocarbons or carbon monoxide. Open-loop scrubbers use the natural alkalinity of seawater (pH value of 8.1 which is above the neutral pH of 7) to capture NO_x , SO_x and soot from the gaseous emissions stack but are presently banned in many countries because these species also contaminate the discharge water, which becomes acidic and toxic. We do not believe that dissemination of carbonates for OAE would run afoul of these regulations, because the nature of the discharged species from the CCM is radically different from what is banned by the legislation.

The emissions from the engine used in the land-based testing were contaminated with not just CO_2 but also very high levels of particulate matter, acid gases and unburned fuel. The system designed by CCM for the Green Marine project is not intended to capture these other contaminants, though it did prove effective in practice (refer to D2.4 “Summary Report of Results of Land-Based Testing”). These species would pose multiple existential problems for any carbon capture system; for example, the flue gas must be cooled with a heat exchanger in order to capture CO_2 , but over time soot particles would deposit and foul the heat exchanger surfaces eventually causing cascade failures due to overheating. As mentioned above, an elegant yet high-TRL solution to this problem would be to install a catalytic converter and diesel particulate filter assembly containing soot oxidation functions.

The widespread deployment of ocean alkalinity enhancement as a means to combat climate change through marine carbon dioxide removal faces key regulatory hurdles. In addition to the concerns about ‘dumping’ mentioned previously, marine carbon dioxide removal, unlike traditional point-source carbon capture, does not currently have an available funding mechanism in the form of carbon credits.

In OAE the carbon dioxide removal occurs after alkali dissemination;²³ i.e., outside of the control volumes of the OAE facility. Consequently, there is no neat solution to the Monitoring, Reporting and Verification challenge required to motivate investment once the alkaline materials are dispersed. The dissemination itself can be verified easily, but the possibility of uncontrolled precipitation with unfavourable conditions means that it cannot be guaranteed *a priori* that the alkali is fully converted to bicarbonate ions. To address this concern, the deacidification study in subtask 4.4.3 will identify dissemination conditions which allow for the full and efficient conversion of alkali.

6 SUMMARY AND CONCLUSIONS

Deliverable D3.4 (this report) describes the development, tailoring, operation, and broader implications of Carbon Capture Machine technology within the Green Marine project. The project's objective is to support the decarbonisation of waterborne transport by enabling retrofit solutions that can be applied to existing vessels. CCM's contribution focuses on a chemical absorption and mineralisation process capable of removing carbon dioxide from engine exhaust and converting it into stable carbonate-based products. For the Green Marine programme, the technology was redesigned from its previous industrial pilot configuration into a compact marine demonstration system suitable for integration with the CMMI bypass manifold and the SINTEF cooling and compression skid used during land-based testing in Limassol.

The redesigned system reflects the specific constraints of maritime deployment. These include limited footprint, low available pressure, elevated exhaust temperatures, corrosion risks, safety requirements, and the need for robust data acquisition. Major components were specified primarily in 316L stainless steel, with chemically resistant polymer materials used where required. The system was packaged as a transportable skid with independent sensors, pumps, gas analysers, and data logging equipment to reduce reliance on vessel instrumentation and improve repeatability across deployments. Particular attention was given to reliable measurement of gas flow and CO₂ concentration, including the use of corrected flowmeters and NDIR analysers, because accurate inlet and outlet measurements are essential for quantifying capture performance.

A central technical outcome was the redesign of the scrubbing column. The marine system required efficient CO₂ capture at low pressure drop and at temperatures higher than those used in earlier demonstrations. A packed column was selected to reduce footprint, cost, and pressure losses, while a liquid recycle strategy was introduced to maintain effective gas-liquid contact across a wide operating range. The scrubber design was informed by mass transfer theory, reaction kinetics, solubility limits, and process simulation. The analysis of CO₂ absorption in alkaline solution shows that performance depends strongly on ionic strength, hydroxide concentration, pH, temperature, and avoidance of precipitation within the scrubber. The selected operating approach therefore balances capture rate, carbonate formation, and stable hydrodynamics.

The conversion of captured CO₂ into useful or environmentally beneficial carbonate products is explained. Depending on process conditions, the system may a variety of carbonate species and phases. These products may have potential value as construction materials, industrial inputs, or materials for ocean alkalinity enhancement. In the OAE pathway, carbonate products could be disseminated to support additional atmospheric CO₂ uptake, provided that dissolution, mixing, precipitation, and monitoring challenges are properly managed and that regulatory approval for dissemination is achieved.

Overall, Deliverable D3.4 demonstrates that CCM's technology can be adapted from an industrial carbon capture concept into a compact, measurable, and operationally manageable marine retrofit system. The work confirms the importance of integrated engineering, chemistry optimisation,

safety assessment, and regulatory awareness in advancing shipboard carbon capture. It also identifies future priorities, including improved contaminant management, commercial-grade safety systems, validated monitoring and reporting methods, and further optimisation of carbonate product properties for utilisation or marine carbon dioxide removal.

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