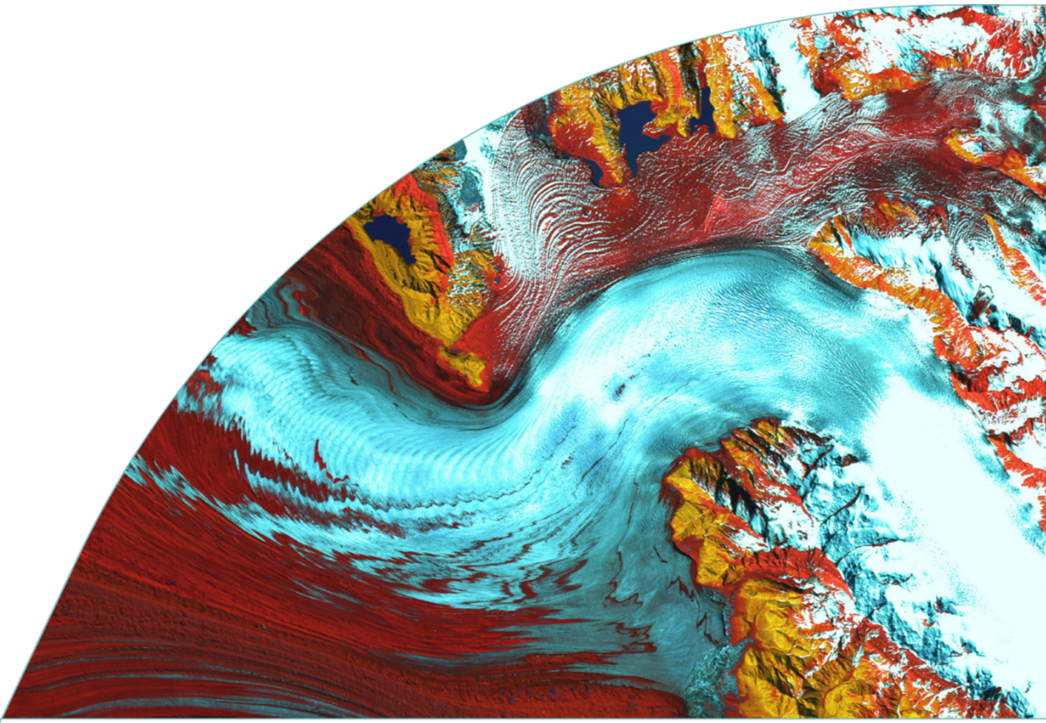
May 2024

Methodology for Measurement, Reporting, and Verification of Electrolytic Oceanic Carbon Dioxide Removal



–

ecoengineers.us

+1 515.985.1260

Sponsored by: Equatic

Table of Contents

List of Figures

List of Tables

Section 1: Legal Note

This document outlines the general requirements for projects that utilize Equatic's methodology for carbon dioxide removal (CDR) through seawater electrolysis to comply with ISO 14064-2:2019, *Specification with Guidance at the Project Level for Quantification, Monitoring, and Reporting of Greenhouse Gas Emission Reductions or Removal Enhancements*.

It does not prescribe criteria and procedures specific to a project. A specific project should minimally follow the requirements contained in this document, but a registry managing CDR credits or other governing or monitoring authority may impose additional/other requirements in relation to additionality, specific methodologies, project baselines, and other metrics, in which case, the project may also need to meet those requirements to be eligible to generate CDR credits or other credits, certifications, or other designations.

ISO 14064-2:2019 provides a framework for quantifying, monitoring, reporting, and validating or verifying greenhouse gas (GHG) emissions and removals. It specifies principles and requirements and provides guidance for project-level quantification, monitoring, and reporting of activities intended to cause GHG emission reductions or removals. It includes requirements for planning a project, identifying and selecting GHG sources, sinks, and reservoirs (SSRs) relevant to the project and the baseline scenario, monitoring, quantifying, documenting, and reporting GHG project performance, and managing data quality.

While preparing this document, EcoEngineers advised Equatic on how to apply the principles of ISO 14064-2:2019 for quantification, monitoring, and reporting of GHG projects to its seawater electrolysis methodology. This document proposes possible guidelines for establishing measurement, reporting, and validation (MRV) protocols for projects implementing seawater electrolysis.

This document refers to third-party data, assumptions, and analytical methods to evaluate the potential for carbon removal from seawater electrolysis. The data sources, assumptions, and analytical methods, among other things, address specific issues related to the behavior of ocean water, ocean water chemistry, electrolysis, and associated emissions. These data sources were generally provided by the Equatic team.

While choosing to include a data source, assumption, or an analytical method as a basis for setting MRV requirements, EcoEngineers employed diligence to follow the principles of completeness, consistency, accuracy, transparency, and conservativeness as required by the ISO 14064-2:2019 standard. The authenticity, accuracy, and completeness of third-party research, data, and analytics, however, cannot be guaranteed by EcoEngineers.

To EcoEngineers' knowledge at the time of this document's issuance, all third-party data used in this document were obtained from reliable sources. Should any such third-party source be erroneous, misleading, or incomplete, in whole or in part, the same may impact any conclusions outlined in this document. It was not within the scope of producing this document to confirm or validate the authenticity, accuracy, and completeness of all third-party data, assumptions, or analytical methods incorporated within it.

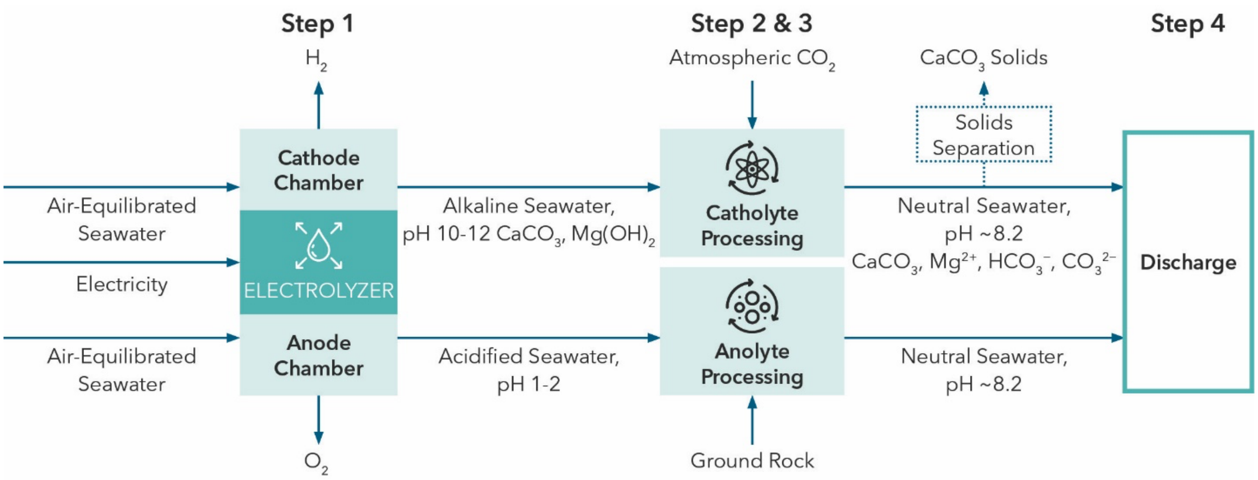
Section 2: The Equatic Process Description

Equatic's process is detailed below in Figure 1.[1] It works by flowing seawater through electrode surfaces, applying a current at the cathode, and growing carbonate and hydroxide mineral precipitates. Carbonation and equilibration draw CO_2 from the atmosphere into the seawater, storing CO_2 in the form of carbonate and bicarbonate ions and solid carbonates that may then be stored on land or discharged into the ocean.

Seawater is processed at a facility with access to the ocean and an abundant supply of low-emission power, rock, and atmospheric CO_2. The composition of the seawater is changed between input and output by an increase in bicarbonate and carbonate ion concentrations and total suspended solids. Carbonates and bicarbonates are stable over geological periods and permanently sequester carbon.[2] CDR amounts are calculated by converting the carbon removed to a CO_2 equivalent and subtracting emissions generated by the project's activities.

In addition, the co-products hydrogen (H_2) and oxygen (O_2) are created. Equatic's process of electrolytic oceanic CDR consists of the following steps:

Figure 1: Process Block Diagram



– Equatic

---

[1] References Equatic's process from https://www.equatic.tech/technology.

[2] See Appendix B for a fuller explanation of Equatic's scientific basis for claiming removal permanence and relevant research publications.

Step 1) Electrolysis of seawater or a feed having elevated ionic strength, causing increased pH at the cathode, and the subsequent precipitation of divalent cations as minerals, namely, $Mg(OH)_2$ and $CaCO_3$. The use of oxygen evolution reaction (OER)-selective anodes substantially mitigates the production of chlorine gas.

Step 2) Catholyte processing can take two forms, using either atmospheric CO_2 or introducing a pure form of CO_2 from a biogenic source, causing the dissolution of precipitated $Mg(OH)_2$ by introducing atmospheric CO_2 (pCO_2 = ~420 ppm) or elevated CO_2 gas into the process stream. The process stream, a) having an elevated CO_2 activity, causes further carbonate precipitation, and b) having an elevated pH causes increased dissolved inorganic carbon species (bicarbonate and carbonate ions).

Step 3) Anolyte processing (co-occurs in time with Step 2) alkalinization of the anolyte stream to replenish the divalent cations and restore pH to seawater levels using rock or other alkali materials.

Step 4) Discharge of processed anolyte and catholyte streams into the ocean. Where applicable, calcium carbonate solids in the processed catholyte stream may be removed before discharge.

Section 3: Definitions

CO_2	Carbon dioxide
°C	Degrees Celsius
BOL	Bill of lading
Book-and-Claim	Book-and-claim accounting of low-CI electricity is where a reporting entity uses indirect accounting to claim environmental attributes produced remotely
$CaCO_3$	Calcium carbonate
CDR	Carbon dioxide removal - the net quantity of carbon dioxide (CO_2) removed because of project activities
CI	Carbon intensity
Cl_2	Chlorine gas
CO_2e	Carbon dioxide equivalent
CO_3^{2-}	Carbonate ion
COD	Chemical oxygen demand
CWA	Clean Water Act
DIC	Dissolved inorganic carbon – includes carbonate ion, bicarbonate ion, carbonic acid, and dissolved CO_2
EIA	Environmental impact assessment
EPMA	Environmental Protection and Management Act
FAC	Free available chlorine
GAC	Granular activated carbon
GF	Grid emissions factor
GHG	Greenhouse gas
Gt	Gigatonne
H_2	Hydrogen gas
HCO_3^-	Bicarbonate ion
HMI	Human-machine interface
ICP-MS	Inductively coupled plasma-mass spectrometry
ICP-OES	Inductively coupled plasma-optical emission spectrometry
ISO	International Organization of Standardization

KOH	Potassium hydroxide
LCA	Life-cycle analysis
LPM	Liters per minute
mA	Milliamperes
$Mg(OH)_2$	Magnesium hydroxide
MRV	Monitoring, reporting, and verification
MSFD	Marine strategy framework directive
MWh	Megawatt-hour
NaOH	Sodium hydroxide
NDIR	Non-dispersive infrared
O_2	Oxygen gas
OEM	Original equipment manufacturer
OER	Oxygen-evolution reaction
OH^-	Hydroxide ion
OSHA	Occupational Safety and Health Administration
OSIL	Ocean Scientific International
PDD	Product design document that demonstrates conformance with this MRV methodology
PLC	Primary logic controller
ppm	Parts per million
Products	Products from the system include carbonate, bicarbonate and dissolved CO_2, hydrogen, and oxygen
QA	Quality assurance
QC	Quality control
SCFM	Standard cubic feet per minute
SF	Sample frequency
SSR	Source, sinks, reservoirs
TCLP	Toxic characteristic leaching procedure
TDS	Total dissolved solids
TGA	Thermogravimetric analysis

TSS	Total suspended solids
TTLC	Total threshold limit concentration
USEPA	United States Environmental Protection Agency
XRD	X-ray diffraction
µS/cm	Micro Siemens per centimeter

Section 4: Applicability Conditions

This MRV methodology applies to projects that draw seawater into a facility for electrolysis and CDR. The alkaline and acidic streams created at the cathode and anode are reacted with CO_2 (in air) and rock, respectively, and then released back into the ocean. Projects applying this MRV methodology must meet the below minimum requirements:

1. Projects must establish baseline ocean chemistry measurements.
2. Projects must meet all local permitting and regulatory body requirements before discharging into the ocean.
3. Safeguards must be taken to ensure that discharge is unlikely to cause significant adverse ecological impacts in the ocean.
4. This is not an applicable methodology for open ocean alkalization crediting.[3]
5. Carbon dioxide consumed by the process must be atmospheric.
6. To avoid double counting, co-products from the process cannot claim negative CI if CDR credits are being sold separately.
7. Conservatively, all project emissions are allocated to the CDR process. A mass balance approach is used to separately account for co-product emissions allocation.

---

[3] No open ocean modeling is required to demonstrate CO_2 drawdown.

Section 5: Project Proponent Description

For each project, the facility-specific product design document (PDD) and MRV should include the following:

- Project ownership, including details of any ultimate beneficial owners holding over 20% economic interest or control.
- Governance overview, including details of the board of directors at each entity level through to the parent company.
- Details of key executives responsible for operating the project in an organizational chart.
- Partner organizations and stakeholders of the project with a brief description of their rights to influence the project activities.
- Description of any commercial products being generated.
- Key customers and users.
- Regulatory bodies and permits relevant to the project activities.
- Any operating standards complied with, for example, ISO standards.
- Overview of systems implemented concerning a) environmental management, b) interested and affected parties (I&AP) management, c) legal and regulatory compliance, and d) health and safety.
- Utilities used by the project (electricity, natural gas, water, wastewater, garbage, etc.).
- Launch date of project activities, including the start of construction and commissioning.
- Project's anticipated time frame for CDR production and monitoring.
- Monitoring frequency in each phase of the process and associated reporting for regulatory bodies.
- A quality control plan.
- GHG report structure.
- Statement of uncertainty.

If monitoring or part of it is being implemented by the third-party service provider, the project proponent is to provide a brief breakdown (i.e., what entity, what services, how frequent).

Table 1: Facility Staff Roles as Described in the PDD

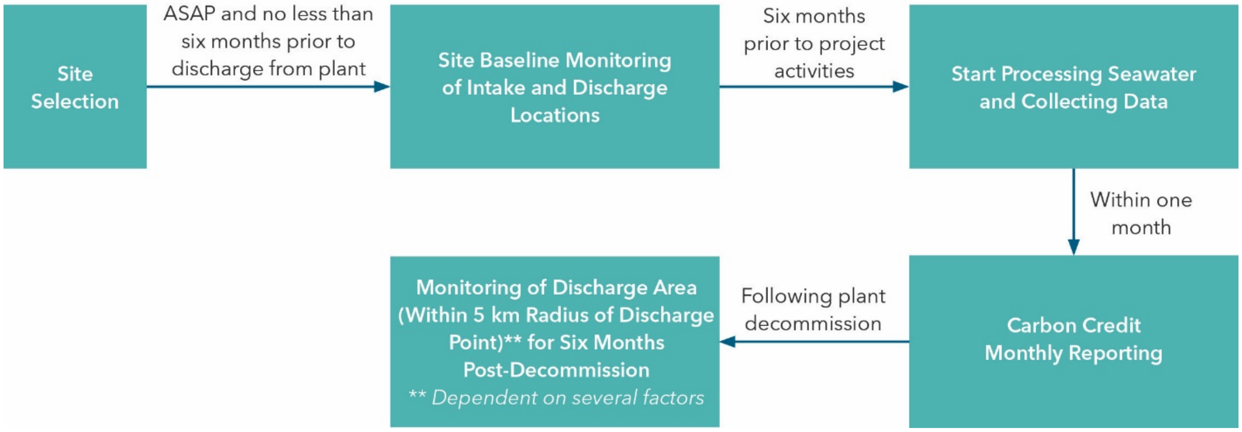
Role	Responsibility
Plant Superintendent	Plans and oversees all operations of the plant.
Operational Manager	Plans and oversees daily operations of the plant.
Quality Assurance Manager / MRV Manager	Reviews all data associated with CO_2 drawdown for completeness, accuracy, and quality.
Analytical Technician	Operation, calibration, and maintenance of the analytical equipment, including QC.
Plant Operator(s)	Routine operation and maintenance of the plant.

The PDD should also include a chronological plan or actual dates and justification for the following:

- Initiation of project activities.
- Baseline measurements.
- Project start date (see Figure 2 below).
- Termination of the project.
- Frequency of monitoring and reporting and the project period, including relevant project activities in each step of the GHG project cycle, as applicable.
- Frequency of verification and validation, as appropriate.
- Copy of the code for any modeling used (such as PHREEQC), including any changes made to the code over time and reasons why the changes were made.

A sample project timeline is illustrated below. The project start date is when the first verifiable carbon removals occur (i.e., when the electrolyzers and balance of plant operating steps 1-4 above are running consistently, and data tracked accurately). The first monthly credit report must represent this date. The initial credit reporting period is five years with an option to renew for another five-year term. However, if there is a substantial change to the understanding of ocean chemistry pertaining to monitoring and reporting of the project, then the methodology may be updated and the PDD must be re-validated to reflect.

Figure 2: Project Timeline



– *Equatic*

Section 6: Project Boundaries

Table 2: Carbon Pools - Sources, Sinks, and Reservoirs (SSR)

SSR	Type	GHG*	Status of CDR Accounting
Emissions	Operating and maintaining the electrolyzer and balance of the plant.	CO_2, N_2O, CH_4,	Declared
Emissions	Grinding rock (e.g., milling, if applicable).	CO_2, N_2O, CH_4	Declared
Emissions	Transporting ground rock to the plant.	CO_2, N_2O	Declared
Emissions	Building Equatic's CDR plant.	CO_2, N_2O, CH_4	Declared
Emissions	Absorbent for gases to meet regulatory requirements, if required.	CO_2, N_2O, CH_4,	Declared

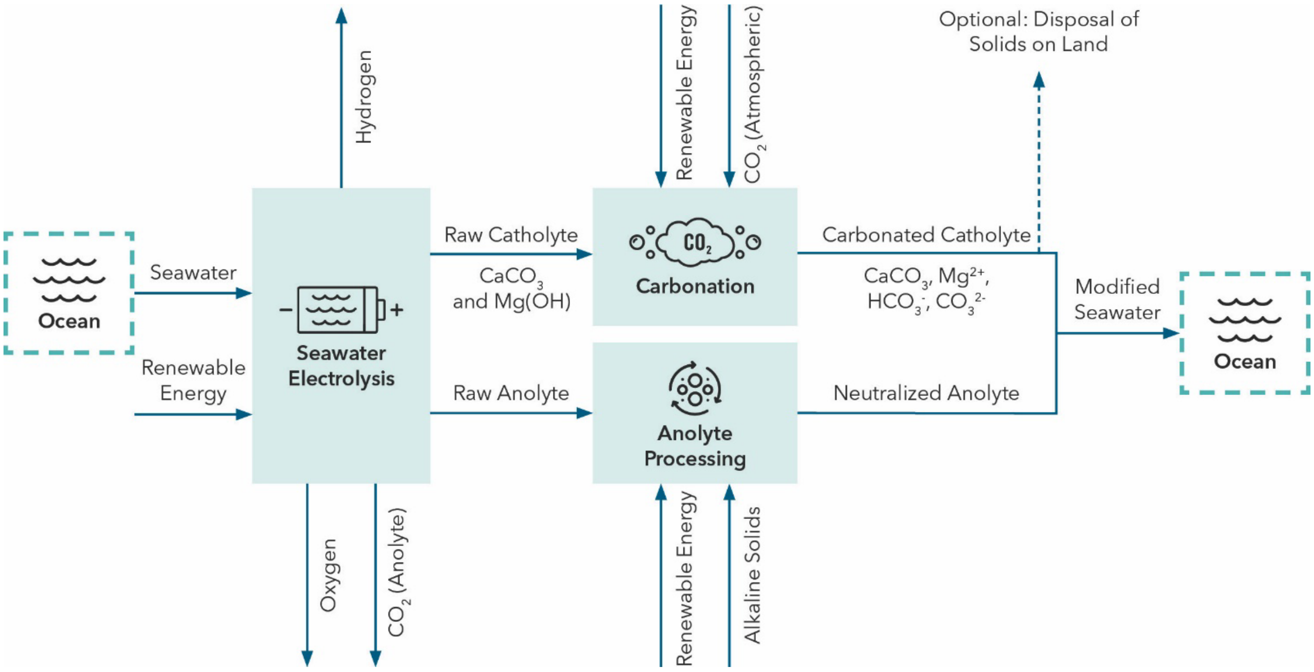
*Where GHGs are calculated on a CO_2e basis for GPW100, then it is not necessary to break out individual GHGs for analysis.

Sinks	Type	GHG	Status of CDR Accounting
Seawater Discharge	Carbonates and bicarbonates	CO_2	Declared
Disposal on land	Carbonates and bicarbonates	CO_2	Declared

Reservoirs	Type	GHG	Status of CDR Accounting
Seawater	Carbonates and bicarbonates	CO_2	Declared

The below figure illustrates the inputs and outputs within the bounds of the project.

Figure 3: Inputs and Outputs for the System



– Equatic

Chapter 6.1: Spatial Boundary

The project spatial boundary encompasses the footprint of the plant site and includes the intake and outfall locations within a defined radius of the intake and outfall location points. While monitoring of locations outside of the immediate intake and outfall may be sampled discreetly, these are not included in the spatial boundary of the project. The sampling performed outside of the project boundary is informed by a review of the potential environmental impacts, as well as by a hydrodynamic model, and is for purposes of monitoring any potential environmental impact and changes in the carbonate chemistry. The minimum monitoring requirements should be described in the project's environmental monitoring and sampling plan. Please refer to the section on Additional Risks for further details.[4]

The spatial boundary must be described using an overview map of the plant and the locations of the intake, outfall, and potential discharge plume. Nearby industrial processes and associated discharges of said industrial processes must be identified and their proximity to the intake and discharge of the project included in the overview map.

The beginning temporal boundary is well-defined. Project initiation begins when seawater is processed (see project timeline below). The ending temporal boundary for crediting is well-defined as the permanent termination of project activities (i.e., cessation of seawater processing, and planned de-commissioning of the plant).

Further activities may continue, which include measurements of discrete points outside of the project boundaries to serve environmental monitoring purposes and are not included in the temporal boundary of the project. This is further described in the project's environmental monitoring and sampling plan.

Section 7: Baseline Determination and Quantification

The initial environmental conditions of the project site (within the spatial boundary) must be clearly described. This includes the chemical water quality characteristics of the feed source (intake) and discharge (outfall) area. The chemical water quality parameters measured should include parameters relevant to both environmental impact assessment and CDR. Chemical water quality characteristics and chemical parameters relevant to CDR should minimally include:[5]

1. pH
2. Temperature
3. Salinity
4. pCO_2
5. Total alkalinity

---

[4] The Environmental monitoring plan is outside the scope of the methodology, but any PDD should refer to the site-specific plan, and auditors must ensure the requirements have been met.

[5] Per Equatic's website: https://www.equatic.tech/.

6. Dissolved inorganic carbon
7. Dissolved magnesium
8. Dissolved calcium

Project-specific analyses relevant to CDR include total alkalinity, pH, pCO_2, dissolved calcium, dissolved magnesium, and dissolved inorganic carbon. Tables 3 to 11 below are provided by Equatic and outline measurements of the above parameters.

Table 3: Conductivity/Salinity Parameters and Descriptions

Data/Parameter	Conductivity/Salinity
Unit	μS/cm
Description	The in-line conductivity meter is designed for continuous use. The conductivity meter meets CE requirements for heavy industrial use. The meter has a temperature sensor integrated into the unit with automatic compensation for changes in water temperature.
Source of Data	From 4-20 mA or MODBUS signal output to PLC/HMI and stored on cloud database.
Value(s) Applied	The data from this must be input into PHREEQC or other software to determine the carbonate speciation.
Measurement Procedures	In-line sensor. To be calibrated initially and then annually thereafter unless QC fails.
Monitoring Frequency	In-line, continuous measurement
QA/QC Procedures	Analyze a QC standard weekly. QC passes if recovery is within 97%-103%. The QC standard is a certified seawater standard provided by Ocean Scientific International (OSIL), or another ISO 9001 accredited vendor.
Additional Comments	Performance metrics of the meter should be the resolution of 1 μS/cm and accuracy of 0.1% of the reading.

– *Equatic*

Table 4: pH Parameters and Descriptions

Data/Parameter	pH
Unit	pH units
Description	The in-line pH meters are designed for continuous use. The pH meter(s) have a temperature sensor integrated into the unit with automatic compensation for changes in process temperature.
Source of Data	From 4-20 mA or MODBUS signal output to PLC/HMI and stored on cloud database.
Value(s) Applied	The data from this must be input into PHREEQC or another program to determine the carbonate speciation.
Measurement Procedures	In-line sensor. To be cleaned and calibrated daily.
Monitoring Frequency	In-line, continuous measurement
QA/QC Procedures	Analyze a QC standard every six hours of operation. QC passes if recovery is within ± 0.02 pH units.
Additional Comments	

– *Equatic*

Table 5: Calcium Ion or Calcium Hardness Parameters and Descriptions

Data/Parameter	Calcium Ion or Calcium Hardness
Unit	mg/L
Description	Calcium Ion: automated ion-selective electrode method. Calcium hardness: automated titration based on precipitation of magnesium and preferential complexation of calcium with calcon. Then a titration to a colorimetric endpoint. Or online/offline measurement using ICP-OES or ICP-MS.
Source of Data	From 4-20 mA signal output to PLC/HMI and stored on a cloud database.
Value(s) Applied	If Ca measurement is a result of a calcium hardness titration method, then the calcium ion (mg/L) is calculated by dividing the Ca hardness (in units of Ca as $CaCO_3$ mg/L) by 2.5.
Measurement Procedures	On-line analyzer or manual titration.
Monitoring Frequency	Automated: 1 sample/40 minutes Manual: 1 sample/hour
QA/QC Procedures	Analyze a QC standard for every six samples. QC pass if recovery is within 90-110%.
Additional Comments	To be cleaned and calibrated daily.

– Equatic

Table 6: Total Alkalinity or Dissolved Inorganic Carbon Parameters and Descriptions

Data/Parameter	Total Alkalinity or Dissolved Inorganic Carbon (DIC)
Unit	DIC: mg C/L OR total alkalinity: μmol/kg
Description	Total alkalinity: automated titration based the on colorimetric endpoint, using phenolphthalein indicator. Dissolved inorganic carbon: carrier gas flows over the sample to sweep away the CO_2 (g), which is emitted from the sample after a reaction with H_3PO_4 inside the sample chamber.
Source of Data	From 4-20 mA or MODBUS signal output to PLC/HMI and stored on cloud database OR data from .csv file uploaded to a cloud database (all measurements have a date/time stamp).
Value(s) Applied	Total alkalinity: the data from this must be input into PHREEQC or other software (along with associated pH, temperature, and salinity) to determine the carbonate speciation. Dissolved inorganic carbon: convert to mol C/L.
Measurement Procedures	On-line analyzer. To be cleaned and calibrated daily.
Monitoring Frequency	1 sample / 30 minutes
QA/QC Procedures	Analyze a QC standard for every six samples. QC passes if recovery is within 90%-110%. If QC fails, corrective action is taken before continuing sample analysis.
Additional Comments	

– Equatic

Table 7: Temperature Parameters and Descriptions

Data/Parameter	Temperature
Unit	°C
Description	Inline thermocouple
Source of Data	From 4-20 mA signal output to PLC/HMI and stored on a cloud database.
Value(s) Applied	The data from this must be input into PHREEQC or other software to determine the carbonate speciation.
Measurement Procedures	In-line temperature probe. To be cleaned and calibration checked monthly.
Monitoring Frequency	Continuous. Response time T90: 2.4 to 3.25 seconds.
QA/QC Procedures	Temperature is to be checked monthly against a handheld (calibrated) temperature probe. QC pass/fail criteria: pass if in agreement to handheld probe to within ±(0.15 + 0.002|t|. If QC fails, have the temperature probe recalibrated by a certified company.
Additional Comments	Temperature sensor must be Class A accuracy conforming to IEC 60751.

– *Equatic*

Table 8: Liquid Flow Rate Parameters and Descriptions

Data/Parameter	Liquid Flow Rate
Unit	Liters per minute (LPM)
Description	The electromagnetic flow transmitter and flowmeter shall be hydraulically calibrated in an ISO 17025-certified testing facility.
Source of Data	From 4-20 mA or MODBUS signal output to PLC/HMI and stored on cloud database.
Value(s) Applied	A daily average is used in calculations.
Measurement Procedures	To be cleaned and checked monthly for accuracy.
Monitoring Frequency	Continuous
QA/QC Procedures	Flow rate to be checked monthly against a manual method. QC pass/fail criteria: pass if in agreement with the manual method to within ± 5%. If QC fails, have the flow meter recalibrated by a certified company.
Additional Comments	Flow measurement must comply with industry standards such as ANSI B16.5 Class 150 RF.

– *Equatic*

Table 9: Magnesium Ion or Total Hardness Parameters and Descriptions

Data/Parameter	Magnesium Ion or Total Hardness
Unit	mg/L
Description	Magnesium ion: automated ion-selective electrode method. Total hardness: Eriochrome titration; calcium hardness: automated titration based on calcon complex and EDTA. Or online/offline measurement using ICP-OES or ICP-MS.
Source of Data	From 4-20 mA or MODBUS signal output to PLC/HMI and stored on a cloud database.
Value(s) applied	If magnesium ion measurement is a result of titrations (calcium hardness and total hardness), the magnesium ion (mg/L) is calculated by subtracting: (calcium hardness) and (Sr^{2+} *0.68) and dividing by 4.12. Then convert to g/L. Note: assume a normal seawater strontium concentration of 8.1 ppm.
Measurement Procedures	On-line automated titration analyzer; or manual titration.
Monitoring Frequency	Automated: 1 sample/40 minutes Manual: 1 sample/ hour
QA/QC Procedures	Analyze a QC standard for every six samples. QC passes if recovery is within 90%-110%.
Additional Comments	Automated analyzer: to be cleaned and calibrated daily. Titrant to be standardized monthly.

– Equatic

Table 10: Gas Flow Rate Parameters and Descriptions

Data/Parameter	Gas Flow Rate
Unit	SCFM (standard cubic feet per minute)
Description	The electromagnetic flow transmitter and flowmeter shall be hydraulically calibrated in an ISO 17025-certified testing facility.
Source of Data	From 4-20 mA or MODBUS signal output to PLC/HMI and stored on a cloud database.
Value(s) Applied	Conversion to the mass flow rate by multiplying by the density of air. A daily average is used in calculations.
Measurement Procedures	To be cleaned and checked monthly.
Monitoring Frequency	Continuous
QA/QC Procedures	The flow rate is to be checked quarterly by a certified technician. If QC fails, have the flow meter recalibrated by a certified company.
Additional Comments	GHG-certified to meet USEPA (40 CFR Part 98).

– Equatic

Table 11: CO_2 Gas Analyzer Parameters and Descriptions

Data/Parameter	CO_2 Gas Analyzer
Unit	% mass
Description	Dual-beam non-dispersive infrared absorption (NDIR) measurement method.
Source of Data	From 4-20 mA or MODBUS signal output to PLC/HMI and stored on a cloud database.
Value(s) Applied	The data from this must be input into PHREEQC or another program to determine the carbonate speciation.
Measurement Procedures	To be cleaned and checked monthly.
Monitoring Frequency	Continuous
QA/QC Procedures	To be checked quarterly by a certified technician and calibrated as specified by the manufacturer. The plant operator analyzes quality control standard weekly. QC pass/fail criteria: the result must be within ±1%. If QC fails, have the flow meter recalibrated by a certified company.
Additional Comments	GHG-certified to meet USEPA (40 CFR Part 98).

– *Equatic*

Section 8: Co-Products

Oxygen and hydrogen gasses produced by the project are regarded as co-products and emissions are allocated to them on a mass balance basis for all products and coproducts for determination of their CI score.[6]

---

[6] CDR credits are issued net of all emissions, and co-product emissions have emissions allocated according to ISO14067. This may lead to double counting of emissions allocated to CDR credits and is the recommended conservative approach.

Section 9: Permanence

The CO_2 captured from ocean and air sources are permanent and durably stored within a) solid mineral carbonates and b) solvated ions, mainly bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions. (See Appendix B for a detailed description of the permanence argument.) The project proponents show that the carbonate and bicarbonate compounds and ions permanently store oceanic and atmospheric CO_2. Reporting of the project carbon removals must show that the CO_2 was stored in these forms.[7]

Section 10: Additionality

1. Regulatory Surplus

The project shall not be the result of compliance with any mandated law, statute, or other regulatory framework. The project activity of producing solid and aqueous carbonates and bicarbonates by electrolyzing and carbonating seawater in a closed system is a novel approach. Whereas the absence of a governmental mandate for these projects does not alone guarantee additionality, the absence of such regulations pertaining to mandatory adoption, along with the absence of prohibitions of the same, is required for projects to meet this regulatory additionality requirement for crediting.

2. Positive List

The project must demonstrate that it meets all applicability conditions and regulatory surplus, and in so doing, it is deemed as complying with the positive list and as being additional. The activity penetration of this method is found to be near-zero at the time of the release of this methodology and, therefore, activities meeting the conditions of eligibility are likely to be additional to any existing project and any project within five years after the methodology is published.

Whereas hydrogen production from the electrolysis of seawater is not without precedent, it has never been demonstrated at scale and the specific electrolytic processes immobilizing dissolved bicarbonate ions in water and solid mineral carbonates while also generating hydrogen is unique and is the only activity envisioned by this methodology.

Hydrogen is a valuable commodity and when coupled with government incentives designed to support clean energy projects, companies stand to benefit from multiple sources of revenue. This combination can significantly improve the financial viability of hydrogen co-production and may become the driving reason for creating a project following this methodology. Alternatively, the hydrogen produced can be used in a fuel cell entirely within the project boundary to lower the external energy requirement of operating the project. At the time of the release of this methodology, revenue from H_2 must not drive project development. This methodology shall revisit the additionality

---

[7] Per 14064: the project should "establish and apply criteria, procedures and/or methodologies to assess the risk of a reversal… (i.e., permanence of GHG… removal enhancement)." Carbonate and bicarbonate in the ocean have a negligible reversal risk.

baseline every five years to ensure that the project activity described herein is still additional.

3. **Hydrogen GWP and Financial Reimbursement**

The financial additionality of the project changes when hydrogen gas is monetized. To that end additionality reassessment must trigger at the sooner of (1) at least every five years and (2) whenever the byproduct of hydrogen gas is monetized.

Section 11: Leakage

System leakage includes electricity and CO_2 sourcing leakage, as well as physical forms of potential CO_2 leakage.

Power Supply

1. Connections behind the meter are regarded as inside the plant 'box' and net emissions associated with the consumption of natural gas, biomass, or other fuel sources are included in the total plant emissions. This may include using a fuel cell to generate electricity from the hydrogen produced from electrolysis.
2. Book-and-claim renewable power is not allowed under this methodology unless the project can demonstrate that any remote power supply meets additionality requirements.
3. Scalability of Grid Electricity Usage: Grid electricity, where required, shall use the emissions of the regional mix of electricity sources except in cases where the demand exceeds the surplus electricity from renewable sources. In the latter case, electricity emissions must use the emissions from excess regional grid power supply. The typical grid oversupply of renewable electricity is around 3% of total renewable energy connected to the regional grid.[8] Small or pilot-size projects may operate under a conservative de minimis threshold where they are not burdened with complicated emission calculations. Therefore, the project's power supply should be shown to be either:
    a. Below a de minimis conservative threshold of 2% of the connected regional grid renewable energy supply and use the regional grid mix, or
    b. Emissions of grid power used above the de minimis should be calculated using CDM Tool 7 latest version.[9]
4. If the facility causes an increased production of the marginal (fossil-based) power plant in the grid, the additional emissions should be estimated based on the marginal emissions rate (emissions of the marginal power plant), rather than the average grid

---

[8] Mohammad Amin Vaziri Rad, Alibakhsh Kasaeian, Xiaofeng Niu, Kai Zhang, Omid Mahian, Excess electricity problem in off-grid hybrid renewable energy systems: A comprehensive review from challenges to prevalent solutions, Renewable Energy, Volume 212, 2023, Pages 538-560, ISSN 0960-1481.
[9] https://cdm.unfccc.int/Reference/tools/index.html.

emission factor, and project proponents must demonstrate how marginal emissions are assessed and justify the reason for the selection of a specific mechanism to do so.

CO_2 Leakage Due to Secondary Precipitation

While there is no physical CO_2 leakage known at this time from the primary pathway (production of solid carbonates and dissolved carbon species), it is important to still consider other potential sources of CO_2 leakage. These include (a) the release of CO_2 from secondary $CaCO_3$ precipitation, and (b) the mixing of un-neutralized acid from the anolyte is to be considered.

Monitoring the pH of the discharge and ensuring excessive alkali discharge does not occur, as well as standard maintenance and operations preventing mixing of the alkali and acid streams in the facility mitigate these risks.[10]

Section 12: Additional Risks

Potential Risk to the Environment

The project must have an established environmental sampling and monitoring plan that lays out environmental risks. The environmental monitoring plan must minimally follow the appropriate regulatory trade effluent discharge limits for waterways (e.g., *Allowable Limits for Trade Effluent Discharge to Watercourse or Controlled Watercourse* by the Singapore National Environment Agency[11] and the *National Recommended Water Quality Criteria - Aquatic Life Criteria Table* by the U.S. Environmental Protection Agency (USEPA)).[12]

Grab samples of the discharge must be analyzed according to the latest edition of "Standard Methods for the Examination of Water and Wastewater" published jointly by the American Water Works Association and the Water Pollution Control Federation of the United States[13] or other industry-approved methods. For gas emissions, the Occupational Safety and Health Administration (OSHA) or applicable local regulatory limits must be followed.

Samples must be collected at the inlet and outlet upon initial startup and during steady-state operations (see Figure 5 Appendix A, Point A and at discharge). For effluent samples, samples must be taken before mixing with any other discharge and before being discharged. Effluent limitations and reporting procedures must follow the Clean Water Act, Title 40 CFR Chapter I, Subchapter D, Part 122, or other regulations as determined by the location of project activities.

Regulations for the discharge into oceans vary between jurisdictions. The project must show compliance with discharge regulations including, but not limited to:

---

[10] See Appendix C.

[11] https://www.nea.gov.sg/our-services/pollution-control/water-quality/allowable-limits-for-trade-effluent-discharge-to-watercourse-or-controlled-watercourse.

[12] https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table.

[13] https://www.standardmethods.org/.

- United States Clean Water Act (CWA): The CWA regulates the discharge of pollutants from all sources, including ships, into U.S. waters. It sets water quality standards and requires permits for any releases.
- European Union Marine Strategy Framework Directive (MSFD): This directive aims to protect the marine environment and sets targets for good environmental status in the European Union. It includes rules on the discharge of pollutants and requires monitoring of marine waters.
- The Environmental Protection and Management Act (EPMA) in Singapore: The primary legislation dealing with the issue of environmental pollution control in the areas of air, water, and noise pollution in Singapore.

Any risk identified because of routine environmental monitoring must be addressed or mitigated as specified in the environmental monitoring and sampling plan and/or mitigation, monitoring, and reporting plan.

Hydrogen

A known product of water electrolysis is hydrogen gas, a gas with a potential global warming potential as it increases the residency time of methane in the atmosphere. The hydrogen produced resulting from project activities is captured and contained on-site. Onsite leakage of hydrogen from the containment must be determined by mass balance. Emissions from any combustion of hydrogen are converted to g CO_2e. Continuous monitoring of hydrogen is in place within the project system boundaries at appropriate points. Hydrogen that is unaccounted for by metering must be assumed to have a GWP of 14.4g CO_2e/MJ.[14] Any leakage must be promptly addressed and mitigated as specified in the project's environmental monitoring and sampling plan.

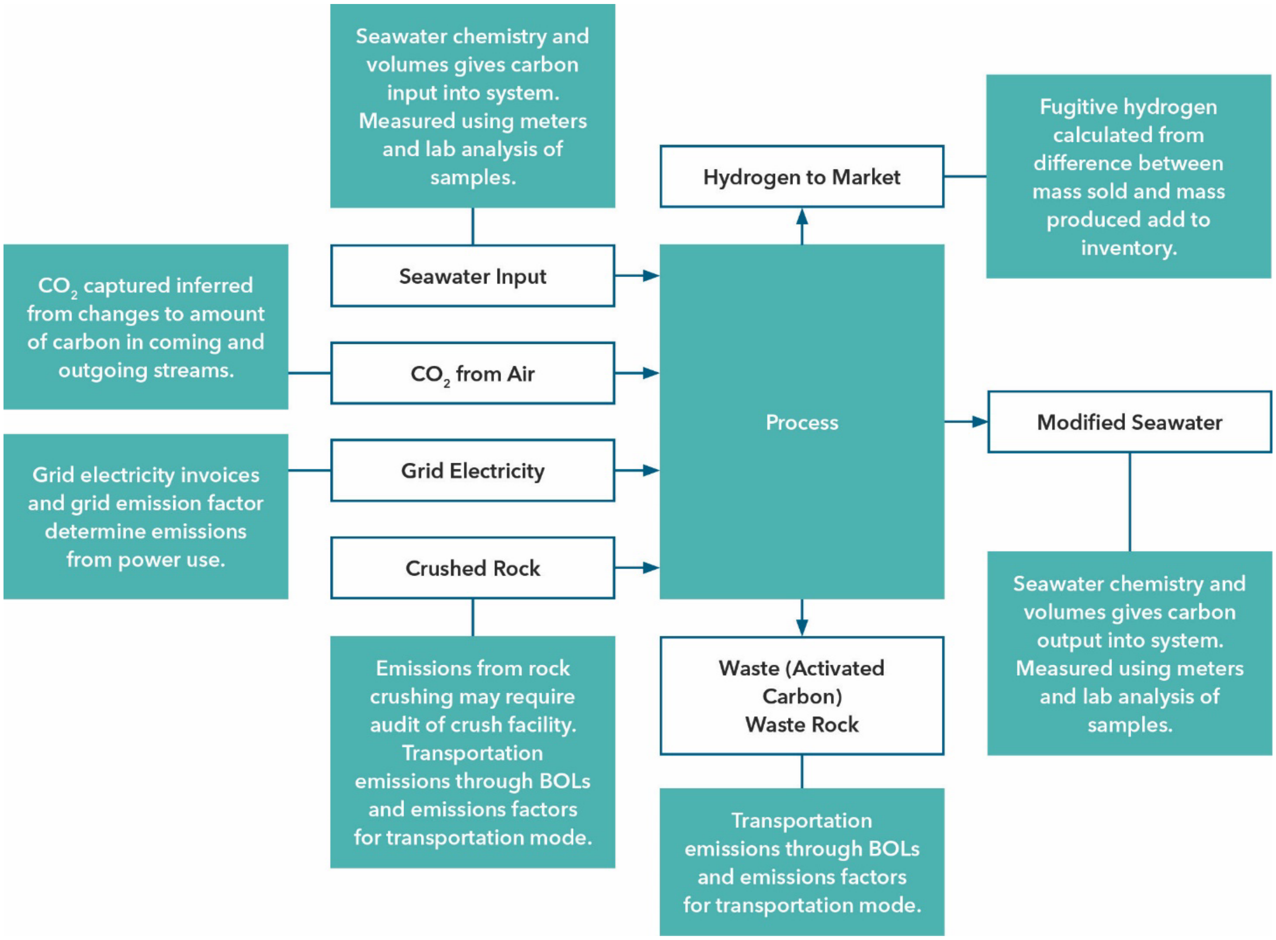
Section 13: GHG Removal/Reduction Quantification

The boundary of the LCA is illustrated in the figure below. Closed system crediting comes from measuring the changes in the carbonate system in both the incoming and outgoing seawater using off-the-shelf sensors for solid and liquid samples. The closed system includes the carbon emissions of any inputs and the transportation of all inputs and outputs.

---

[14] M Sand, RB Skeie, M Sandstad, S Krishnan, G Myhre, H Bryant, R Derwent, D Hauglustaine (2023), "A multi-model assessment of the Global Warming Potential of hydrogen," *Communications Earth & Environment*, nature.com.

Figure 4: Potential Life-Cycle Analysis (LCA) Boundaries



– *EcoEngineers*

Section 14: Managing Data

Procedures for measuring or otherwise obtaining, recording, compiling, and analyzing data and information relevant to quantifying and reporting GHG emissions and/or removals of the project and baseline must be established for each project. Procedures must follow ISO 14064-1 and 14064-2.

Data Quality Management

Project proponents must develop procedures for:

1. Data Acquisition
    a) All data associated with carbon credit accounting must be recorded.
    b) All points of metering and sampling must be recorded.

   c) Meters must be maintained according to OEM requirements to ensure accuracy.
   d) Sampling personnel must be trained and pass an initial demonstration of capability before any sampling or activities related to data acquisition.
   e) All training records must be stored and accessible electronically.

2. Data Processes
   a) When working with an external laboratory, data generated by the external analytical laboratory must be sent to the project proponent.
   b) The project must develop a methodology for the replacement of missing data.
   c) In both scenarios (analysis done externally or in-house), the data must be checked for consistency and incorporated into the database.
   d) Processed data must be stored in the database for access by auditors.
   e) Data must be checked for accuracy and completeness by the QA manager and MRV manager (or comparable).
   f) Any data that are omitted must be clearly labeled. A thorough explanation of the reason for the omission must be included.
3. Distribution of Data

Data are accessible directly from the database through web-based software by select project proponent team members. View-only access to the necessary data is also provided for external due diligence needed to be conducted by third parties. The inputs and outputs boundary are shown above for closed system accounting. The main inputs into the system include:

- Seawater
- Energy
- Atmospheric air or another carbonation source, if applicable, under conditions set forth (refer to Leakage section, CO_2 sourcing)
- Crushed rock

The main outputs include:

- Modified seawater
- Solid carbonates
- Dissolved inorganic carbon
- Hydrogen
- Oxygen

For details on the carbonates and bicarbonate species measurements, see Appendix A.

Section 15: Emissions

A life-cycle analysis (LCA), conducted concerning the above-stated system boundaries, must include measuring the drawdown of CO_2 while accounting for all associated project emissions.

CO_2 Emissions from Consumed Electricity, CO_2 Electricity

Electricity consumed by operating and maintaining the plant is associated with CO_2e emissions. The grid emissions factor is the average GHGs emitted per unit of electricity generated within the grid and differs depending on the country and source of power. The units of the grid emission factor are typically tCO_2e/MWh.

Total power consumption must be metered for the whole plant, including for the electrolyzer, H_2 compressors, pumps, blowers, and any auxiliary sources. Emissions from electricity usage are to be calculated using the equation shown below:

$$E_{elc} = EA * EF_{elc}$$

Where:

EA = Amount of electricity consumed in the reporting period, [MWh]

EF_{elc} = Electricity emission factor, [tCO_2e/MWh], local grid average emission factor, or supplier-specific emission factor if the project is using acceptable contractual instruments.

Note that there may be a consideration for leakage related to the increment of emissions resulting from meeting the additional electricity demand caused by the project (refer to Section 15 "Leakage" for guidance on electricity emission factor estimation considering leakage, if any).

CO_2 Emissions from Rock Grinding and Transportation, CO_2 Rock

Rock Grinding/Milling

The energy consumed during the rock grinding process is estimated using the Bond work index equation[15] — a measure of ore resistance to crushing and grinding, determined using the Bond grindability test shown below:

$W = Wi·(\sqrt{}100/\sqrt{}P80- \sqrt{}100/\sqrt{}F80)$

Where Wi is the work index for the mineral (resistance to grinding), F80 is the particle sizes corresponding to 80% of passings of sample feed and P80 is the particle sizes corresponding to 80% of the product feed. A locally appropriate grid emissions factor is then used to quantify the CO_2e associated with grinding.

Rock crushing audit and verification must rely on energy consumption at each source location. Baseline energy consumption per unit of output must be established. Any rock dust that is regarded as a waste stream (e.g., quarry cake) may have no emissions ascribed to the

---

[15] As referenced in "A quick method for bond work index approximate value determination," by D. Todorovic, M. Trumic, L. Andric, V. Milosevic, M. Trumic (2017). (PDF) A quick method for bond work index approximate value determination (researchgate.net).

output volumes (refer to Rock Dust as Waste section below). If additional energy is required to perform rock crushing, the following additional energy inputs must be considered, if applicable:

- Fuel consumption
- Grid electricity, or onsite energy generation
- Natural gas

Transportation of Rock to the Plant

Transportation distance to the project site must be aggregated on a mass-averaged distance. An aggregated region-specific emissions factor must be used for the given mode of transportation of rock to the project site.

Rock Dust as Waste

Rock dust, often considered a byproduct of quarries or mines, can potentially be classified as a waste material due to its limited direct applications. As rocks are extracted for various purposes, such as construction or mining operations, a substantial amount of rock dust is generated in the process. While this finely ground powder may not possess inherent value for immediate use, it can be regarded as a potential environmental concern if left unmanaged.

If the rock dust is shown to be waste material, then no emissions should be assigned to the material for crushing or extraction. Any transportation emissions typically used for the waste can be used as a deduction if it is to be transported to the project site.

Alkalinity Enhancement

Water released to the ocean must be monitored to ensure the pH is at or above intake seawater. The increased alkalinity must create a drawdown of CO_2 into the ocean over time. This methodology is not intended to provide a measurable way of crediting ocean alkalinity enhancement.[16]

Section 16: Validation and Verification

Validation is required for the initial project design and initiation of a new project. Verification is required for each crediting period to assess ongoing conformance to the project design and for confirmation of credits generated. Verification of the project reports must take place yearly and must ensure that all the information entered into the project report to calculate GHG removal is accurate and complete. Where discrepancies are found the project shall make good any reductions or credits generated.

Third-party verification of analytical results is performed quarterly.

---

[16] If the seawater reaches complete carbonation inside battery limits (ISBL) such that the pH is neutral and all products are at equilibrium (e.g., brucite completely dissolved), there is no further drawdown in the open ocean.

Section 17: Monitoring Plan

Projects must maintain a monitoring and reporting plan that must be used for both validation and verification. The document is designed to be the guidance document that auditors shall use to develop a project-specific risk assessment and sampling plan. The auditor uses the document to ensure the reported GHG removals have been correctly assessed. The plan allows an auditor to check the validity of all data that are used to calculate GHG credits.

The monitoring plan must minimally contain the following information:

- In cases where the project monitoring plan must be a public document, projects may request that information relating to the location of specific fields be redacted.
- Project consumption of electricity must demonstrate the emissions impact or lack of incrementally increasing the load on the local electricity grid.
- Description of how the applicability requirements are met.
- Definition of the roles and responsibilities of the monitoring team. This includes identifying the key personnel involved in data acquisition, monitoring, and reporting, along with their corresponding job titles. The plan should outline the capacity and expertise of the monitoring team, including training practices and associated training materials.
- Details on how data are controlled for the project, such as data storage, access controls, and data security measures. It is recommended to include a diagram illustrating the flow of data, indicating the responsible parties at each stage. See the Managing Data section of this methodology as an example framework that would be further defined by the project proponent.
- Data collection plan, including the type of data to be collected, associated details, and data collection techniques. The plan specifies the frequency of monitoring and sample designs for directly sampled parameters. Reference to the above sections for sample collection is appropriate as needed.
- Quality assurance and quality control (QA/QC) procedures to ensure accuracy of data collection and, for example, correction or removal of anomalous values, frequency of third-party independent checks on analysis results, and other safeguards as appropriate.
- Data and file archiving procedures, including procedures for any anticipated updates to electronic files. All data collected as a part of the monitoring process, including QA/QC data, must be archived electronically and kept for at least 10 years after the end of the last project crediting period.
- List of the equation(s) used to calculate flows in mass or volume units of measurement and equations from which any non-measured parameters are obtained.
- Descriptions of measurement devices, equipment, or instruments used to report data (if relevant) and how acceptable accuracy is demonstrated (e.g., installation, maintenance, and calibration method and frequency). If applicable, this would also include:

    - Original equipment manufacturer (OEM) documentation or other documentation that identifies instrument accuracy and required maintenance and calibration requirements for all measurement devices used to collect necessary data for reporting.
    - The dates of measurement device calibration or inspection and the dates of the next required calibration or inspection. This should include lab practices for analytical calibration methodology, internal lab QC and audit procedures, and external laboratory verification of analytical accuracy.
- Changes to the document and processes must be recorded, as must any discrepancies or non-conformities found by the audit.

Section 18: Reporting

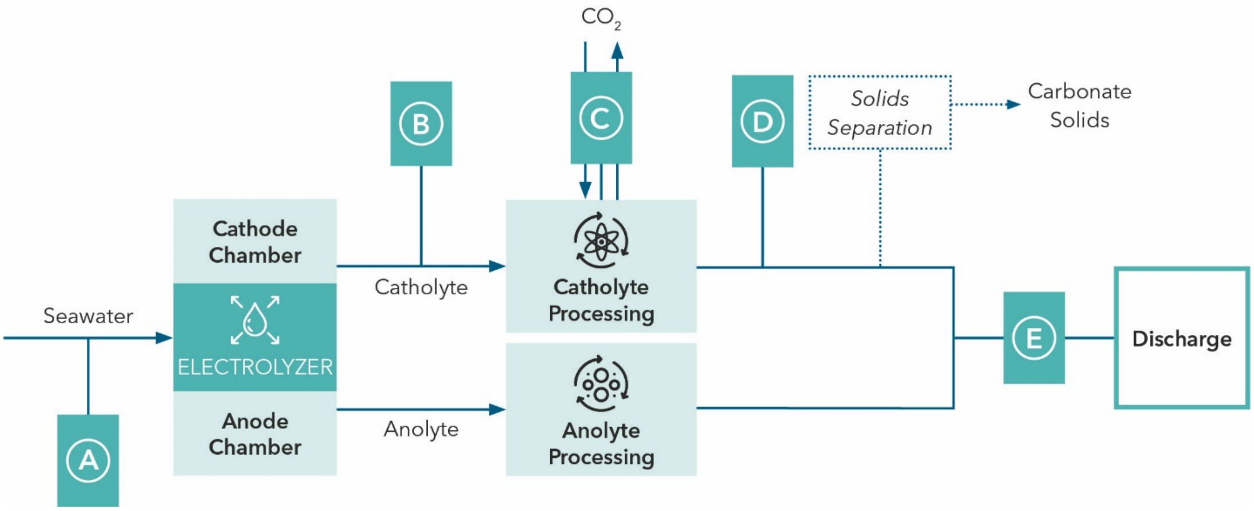
Reporting must show the success of the project in removing CO_2 by recording all inputs and outputs into the system per month. The relevant inputs and outputs are:

- Volume seawater input
- GHG equivalent input
- Volume seawater output
- GHG equivalent output
- Natural gas use from utility invoices
- Electricity use from utility invoices
- Rock delivered
- Weighted average rock emissions factor
- Weighted average rock transportation distance
- Ending rock inventory
- Rock use (calculated and as shown in the PDD)
- Mass co-products
- Waste mass
- Waste transportation distance
- GHG removal

Section 19: Appendix A: Measurement and Internal Plant Block Diagram and Measurements

The on-site measurements used to measure CO_2 drawdown within the project's system boundary are shown in the following diagram.

Figure 5: Metering and Sampling Locations for GHG Removal Calculation



– Equatic

The overall CO_2 removed is calculated by subtracting the CO_2 drawdown as a result of project activities minus project emissions.

Net Carbon Removal =Drawdown_{CO2e}– Emissions_{CO2e}

Liquid Phase Analyses

The CO_2 drawdown is in two forms: solid carbonates and dissolved inorganic carbon (DIC) species (mainly bicarbonate and carbonate ions).

The chemical composition of seawater inflow (Point A) is compared to the chemical composition of the seawater outflow (Point E) with respect to calcium ion, magnesium ion, and DIC (either through a direct DIC measurement or a combination of measurements of pH, temperature, salinity, total alkalinity, pCO_2, and calculation of carbonate system speciation). Measurements at points A, B, D, and E are used in the calculation of drawdown CO_2e. While the CO_2e drawdown is reported monthly, drawdown CO_2e is calculated daily, using average flow rates and accounting for the time the plant was in service.

CO_2solid – Calcium ion measurement

The difference in the measurements of the mass flow of the calcium cations IN (point A) and OUT (point D) is equivalent to the mass of calcium contained in the $CaCO_3$ solids produced. Daily average liquid flow rates are used in the calculation. The calculation of the mass flow of calcium is:

$\Delta Ca(g/min) = [Ca_A - Ca_D\ (g/L)] * \text{Flow Rate}_{avg}\ (L/min)$

The amount of CO_2 removed due to the production of solid $CaCO_3$ from points A to D (CO_2(solids)) is calculated daily as shown below. The ratio 1:1 is a result of the stoichiometric coefficients of the precipitation reaction. To obtain the total mass of CO_2 within the solids, the sample frequency of analysis is considered and summed over the time the plant was in service daily.

Mass of CO_2 in Calcium Solids=ΔCa (g/min)*(1/MW_{Ca}) *(1 mol CO_2/1mol Ca)*MW_{CO2}*Sample Frequency (min)

For example, if the plant was in service for 24 hours (non-stop) and the sample frequency is 60 minutes, then the sum of the mass of CO_2 in calcium solids is calculated for each sample analysis over the day and then summed for the whole 24-hour period.

Similarly, the difference in measurements of magnesium ions from Point A to Point D is equivalent to the mass of magnesium contained in solids produced. Assuming full carbonation, any undissolved magnesium is a hydrated magnesium carbonate and must be accounted for in the same way as calcium, as described above.

Thus, the total amount of CO_2 in solids is the sum of the mass of CO_2 in calcium and magnesium solids (if any magnesium solids are present) summed over the time the plant was in service daily (see Equation 6).

CO_2 Dissolved

During carbonation, an increase in DIC will occur, which is directly associated with the quantity of CO_2 drawdown and dependent on the establishment of equilibrium. The amount of CO_2 drawdown in the form of dissolved ions at the point of carbonation is determined through a direct DIC measurement and calculating the difference in DIC between inlet (Point A) and outlet before discharge (Point E). These measurements must be compared with simulation results obtained using geochemical modeling software such as, but not limited to, PHREEQC. To prevent degassing, by comparison with total DIC, the geochemical model must be used to verify that equilibrium has been attained within the plant for a given seawater composition, pH, pCO_2, and seawater:catholyte mixing ratio.

Direct Measurement of Dissolved Inorganic Carbon (DIC) for CO_2 Dissolved

The difference in measured DIC from Point A to Point E represents the amount of CO_2 pulled into the system in dissolved forms resulting from the carbonation of the alkaline catholyte stream.

ΔDIC (mol C/L) = [DIC_A-DIC_E*(1/12000)

Note: The output unit of typical DIC analyzers is mg carbon/L. This is converted to mol carbon/L by multiplying the result by 1/12000. If DIC analysis provides a result with a different unit, it is converted to mol carbon/L.

The mass flow rate of CO_2 in dissolved form is then calculated by multiplying the change in DIC from Point A to E by the average daily flow rate and the MW of CO_2, as the molar ratio of carbon to CO_2 is 1:1. To obtain the total mass of dissolved CO_2 resulting from carbonation, the sample frequency (SF) of DIC analysis is then taken into account, and summed over the time the plant was in service daily.

CO_2 in dissolved form(g CO_2)=ΔDIC(mol C/L)*FlowRate_{avg}(L/min)*MW_{CO2}(g/mol)*SF (min)

Dissolved CO_2 at Equilibrium - PHREEQC Modeling

PHREEQC software is used to determine the equilibrium concentration of dissolved CO_2 (known as total CO_2 in the software) for a catholyte solution equilibrated to an atmospheric partial pressure of CO_2. Discrepancies between the measured and calculated DIC must determine whether any off-gassing or in-gassing of CO_2 may occur after discharge. Geochemical modeling of the mixing of the plant discharge with seawater will be performed, and carbonation conditions within the plant will be selected such that the mixed water does not exceed atmospheric pCO_2.

A copy of the code for the model must be included in the project design document and treated as a controlled document (i.e., if any change is made, it must be approved by appropriate personnel and documented what the change is and why).

Carbonate System Calculation – Optional Method for Dissolved CO_2

A total alkalinity measurement may be made in place of directly measuring DIC and must include time and sample location, measurements of pH, salinity, and temperature. The total alkalinity measurement, along with pH, temperature, salinity, and pCO_2 are input into a program to determine the amounts of relevant carbonate system species, such as carbonate and bicarbonate ion. Programs that may be used include but are not limited to CO_2Sys and PHREEQC. All inputs and program settings are included in the project data. Program settings are not changed over the course of a crediting period.

An example of the use of CO_2Sys is as follows:

The CO_2Sys program calculates the concentrations of the inorganic carbon system if two of the carbonate system parameters are input out of total alkalinity, total inorganic carbon, pCO_2 or fCO_2, and pH along with temperature, pressure, and salinity. The output of the calculation program provides the remaining carbonate system parameters, including carbonate speciation. For this case, the CO_2Sys program inputs are total alkalinity, pH, temperature, and salinity, at atmospheric pressure. The relevant carbonate system parameters output by the CO_2Sys program are carbonate ion, bicarbonate ion, and dissolved CO_2.

CO_2Sys Program Settings: The program uses constants (K1, K2 from Hansson and Mehrbach refit by Dickson and Millero, 1987), the total pH scale, the formulation of the dissociation constant for the reaction $HSO_4^- = H^+ + SO_4^2$, from Dickson, 1990 (Dickson, *Journal of Chemical Thermodynamics*, 22:113-127, 1990), and Lee et al, 2010 for the [B]T value).

The units provided by the output of the CO_2Sys program are in micromoles per kilogram of seawater. Since the mol ratio of CO_2 per each inorganic carbon species is 1:1, the calculation of the amount of carbon sequestration resulting from this step is the summation of the CO_2 sequestration resulting from carbonation. To obtain the total mass of dissolved CO_2, the sample frequency of DIC analysis is then considered and summed over the time the plant was in service daily.

$CO_{2,dissolved}$ (g)= $\sum(\Delta CO_2 + \Delta HCO_3^- + \Delta CO_3^{2-})(10^{-6}$mol/kg Seawater) * CDR Factor_{DIC}* (Flow Rate_{avg}*d_{SW})*MW_{CO2} *Sample Frequency (min)

Solids Disposal on Land

If desired, carbonate solids can be separated after catholyte carbonation. A grab sample at point D must be collected and sent to a third-party laboratory for the determination of mineral phase distribution and water content through thermogravimetric analysis (TGA) and powder X-ray diffraction (XRD) analyses.

The total weight of the solids produced must be determined when the solids are picked up and weighed by a truck scale. The record of the weight is documented on the bill of lading (BOL) for each pickup. Truck scales are highly accurate and are well-maintained due to regulatory requirements, thus there is a high level of confidence in the accuracy of the total weight measurement.

Once the total weight of the solids is known, the water is subtracted from the total weight. The mass percentages from TGA/XRD must be used to account for the carbon captured in each solid mineral phase.

The amount of CO_2 sequestered resulting from the formation of each mineral phase is calculated by multiplying the total mass of the mineral by its molecular weight (MW) and the appropriate CO_2 factor (See Table 12). Please note that only carbon capture-relevant minerals in the case of solids disposal on land are shown in the table. See Equation 7. In general, the formula for CO_2 contained within each mineral phase is:

Mass of CO_2 = Mass% (g/g) * [Mass of Total Solids (g) – Mass of water (g)] * $MW_{mineral}$ * CO_2Factor * MW_{CO2}

Table 12: Possible Mineral Phases, Composition, Molecular Weight, and Associated CO_2 Factor

Mineral	Composition	Molecular Weight (g/mol)	CO_2 Factor (mol CO_2/mol Mineral)
Aragonite / Calcite	$CaCO_3$	100.09	1
Hydromagnesite	$Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$	467.64	0.8
Nesquehonite	$MgCO_3$	138.36	1
Dypingite	$Mg_5(CO_3)_4(OH)_2 \cdot 5H_2O$	485.65	0.8

– Equatic

The total CO_2 sequestered in the solids is a summation of all the CO_2 contained within each of the mineral solids: aragonite, calcite, hydromagnesite, nesquehonite, and dypingite. This assumes all solids remain in a solid phase. This does not include the amount of CO_2 in dissolved forms and is an option for CO_2 solids measurement other than the liquid phase measurements of calcium and magnesium ions.

Mineral Phase Distribution - Ongoing Verification

Upon initial startup of the plant, once a steady state has been reached, duplicate samples must be collected from Point D once a week for one month to be sent for solids analysis (TGA and XRD). If the mineral phase and water composition of the solids from these samples at this point do not differ greater than 5% (using relative percent difference, RPD) then the average of the analyses must be used for subsequent carbon accounting. A sample must be collected from sample Point D four times a year (once a season) to verify the mineral phase composition has not changed.

CO_2 Drawdown from Carbonation – Reconciliation/Validation Method

A mass flow meter and gas-phase CO_2 analyzer at Point C are used to measure the amount of CO_2 input in and out of the carbonation reactor. The difference in the input and output is equal to the amount of CO_2 drawn down as a result of the carbonation step. This is to be compared to the result of the CO_2 dissolved calculation from DIC or total alkalinity measurements at Point D.

Section 20: Associated Equations

<table>
<tr><td colspan="4">Equation 1: Net CDR</td></tr>
<tr><td colspan="4">Net Carbon Removal = Drawdown_{CO2e}– Emissions_{CO2e}</td></tr>
<tr><td>Where</td><td></td><td></td><td>Unit</td></tr>
<tr><td>Net Carbon Removal CO_2e</td><td>=</td><td>The net carbon removed associated with project operations in a given time period.</td><td>kg CO_2/month</td></tr>
<tr><td>Emissions_{CO2e}</td><td>=</td><td>The total amount of emissions associated with supplying power and materials for project activities in a given time period.</td><td>kg CO_2/month</td></tr>
<tr><td>Drawdown_{CO2e}</td><td>=</td><td>The total mass of CO_2 removed as a result of project operations in a given time period.</td><td>kg CO_2/month</td></tr>
</table>

<table>
<tr><td colspan="4">Equation 2: CDR (Drawdown_{CO2e})</td></tr>
<tr><td colspan="4">$\text{Drawdown}_{CO2e} = CO_{2,\text{ dissolved}} + CO_{2,\text{solid}}$</td></tr>
<tr><td>Where</td><td></td><td></td><td>Unit</td></tr>
<tr><td>Drawdown_{CO2e}</td><td>=</td><td>The total carbon removed associated with project operations in a given time period.</td><td>kg CO_2/month</td></tr>
<tr><td>$CO_{2,\text{solid}}$</td><td>=</td><td>The mass of carbon contained within the solids produced as a result of the project, in a given time period.</td><td>kg CO_2/month</td></tr>
<tr><td>$CO_{2,\text{dissolved}}$</td><td>=</td><td>The mass of carbon contained in dissolved form (as dissolved inorganic carbon species) produced directly as a result of the project, in a given time period.</td><td>kg CO_2/month</td></tr>
</table>

Equation 3a: $CO_{2dissolved}$			
$CO_{2dissolved} = \Delta DIC * CDR\ Factor_{DIC} * (Flow\ Rate_{avg}) * SF * MW_{CO2}$			
Where			Unit
$CO_{2dissolved}$	=	The mass of carbon contained in dissolved form (as dissolved inorganic carbon species) produced directly as a result of the project, in a given time period.	g CO_2
ΔDIC	=	The difference in DIC measurements between Points A and D.	mol C/L
CDR $Factor_{DIC}$	=	The amount of CO_2 removed per mol of DIC species.	1 mol CO_2/mol C
Flow $Rate_{avg}$	=	The average flow rate in a given time period.	L/min
SF	=	Sampling frequency	Minutes
MW_{CO2}	=	The molar mass of CO_2.	44.01 g CO_2/1 mol CO_2

Equation 3b: $CO_{2,\ dissolved}$ *Use in the case of total alkalinity, pH, temperature, salinity measurements, and an equilibrium calculation of carbonate speciation (e.g., CO_2Sys)			
$CO_{2,dissolved} = \sum(\Delta CO_2 + \Delta HCO_3^{-} + \Delta CO_3^{2-} + \Delta H_2CO_3) * \text{CDR Factor}_{DIC} * (\text{Flow Rate}_{avg} * d_{SW}) * SF * MW_{CO2}$			
Where			Unit
$CO_{2,dissolved}$	=	The mass of carbon contained in dissolved form (as dissolved inorganic carbon species) produced directly as a result of the project, in a given time period.	g CO_2
$\Delta CO_2 + \Delta HCO_3^{-} + \Delta CO_3^{2--} + \Delta H_2CO_3$	=	The sum of the DIC species resulting from either DIC measurement or calculation of carbonate species resulting from a combination of measurements (pH, total alkalinity, temperature, salinity, pCO_2, DIC) and where ΔCO2, ΔHCO3- and ΔCO32- are the differences from Point A to Point D.[17]	10^{-6}mol/kg Seawater * (case of CO_2SYS)
CDR Factor_{DIC}	=	The amount of CO_2 removed per mol of DIC species.	1 mol CO_2/mol DIC
Flow Rate_{avg}	=	The average flow rate over a given time period.	L/min
SF	=	Sampling frequency.	Minutes
d_{SW}	=	The density of seawater.	kg/L
MW_{CO2}	=	The molar mass of CO_2.	44.01 g CO_2/1 mol CO_2

Equation 4: ΔCa

---

[17] Typically, CO_2(aq) the ratio of H_2CO_3 low. (CO_2(aq) >> H_2CO_3. H_2CO_3 rapidly disassociates to produce carbonate ions.

$\Delta Ca = [Ca_A - Ca_D] * \text{Flow Rate}_{avg}$			
Where			Unit
ΔCa	=	The change in calcium ion from Point A to Point D.	g/min
Ca_A	=	The measurement of calcium ion at Point A.	g/L
Ca_D	=	The measurement of calcium ion at Point D.	g/L
Flow Rate_{avg}	=	The daily average flow rate.	L/min

Equation 5: ΔMg			
$\Delta Mg = [Mg_A - Mg_D] * \text{Flow Rate}_{avg}$			
Where			Unit
ΔMg	=	The difference in magnesium ion from Point A to Point D.	g/min
Mg_A	=	The measurement of magnesium ion at Point A.	g/L
Mg_D	=	The measurement of magnesium ion at Point D.	g/L
Flow Rate_{avg}	=	The daily average flow rate.	L/min

Equation 6: $CO_{2,\ solid}$			
$CO_{2,Solid} = [(\Delta Ca * SF * MW_{Ca}^{-1} * \text{CDR Factor}_{CaCO3} * MW_{CO2}) + (\Delta Mg * MW_{Mg}^{-1} * SF * \text{CDR Factor}_{MgCO3} * MW_{CO2})]$			
Where			Unit
$CO_{2,SOLID}$	=	The mass of carbon contained in solid form produced directly as a result of the project in a given time period.	kg CO_2/ month
ΔCa	=	The change in calcium ion from Point A to Point D.	g/L
SF	=	Sampling frequency ¾ the frequency a measurement is taken.	Minute
MW_{Ca}^{-1}	=	The inverse of the molecular weight of calcium.	1 mol Ca/40.078 g Ca
CDR Factor_{CaCO3}	=	The mol ratio of CO_2 per mol of $CaCO_3$.	1 mol CO_2/mol $CaCO_3$
MW_{CO2}	=	The molar mass of CO_2.	44.01 g CO_2/1 mol CO_2
ΔMg	=	The change in magnesium ion from Point A to Point D	g/L
MW_{Mg}^{-1}	=	The inverse of the molar mass of magnesium	1 mol/ 24.305 g
CDR Factor_{MgCO3}	=	The mol ratio of CO_2 per mol of hydrated magnesium carbonates.	0.8 – 1.0 *depends on phase as determined by XRD/TGA

Equation 7: CO_2, solid for land disposal

$$CO_{2Solid} = \text{Mass\% (g/g)} * [\text{Mass of Total Solids (g)} - \text{Mass of Water (g)}] * MW_{mineral}^{-1} * CO_2\ \text{Factor}_{mineral} * MW_{CO2}$$

Where			Unit
$CO_{2,SOLID}$	=	The mass of carbon contained in solid form produced directly as a result of the project in a given time period.	kg CO_2/ month
Mass%	=	The mass percentage of a particular mineral phase as obtained by XRD.	g/g
Mass of Total Solids	=	The total mass of solids produced every month as obtained by truck scale.	g
$MW_{mineral}^{-1}$	=	The molecular weight of the particular mineral phase.	Mol/g
CO_2 Factor$_{mineral}$	=	The molar ratio of CO_2 contained within a mole of the mineral phase.	mol CO_2/mol mineral phase
MW_{CO2}	=	The molar mass of CO_2.	44.01 g CO_2/1 mol CO_2
Mass of Water	=	The total mass of water in the solids as measured by TGA.	g

Equation 8: Emissions_{CO2e}			
$\text{Emissions}_{CO2e} = CO_{2rock} + CO_{2AE} + CO2_{GAC} + CO_{2elec} + CO_{2LCA}$			
Where			Unit
CO_{2rock}	=	The energy consumption as a result of rock sourcing, grinding, and transportation, reported monthly.	kg CO_2/month
CO_{2AE}	=	The calculation of the mass of CO_2 that is released as a result of acidification within the anolyte stream. Reported every month.	kg CO_2/month
CO_{2GAC}	=	The emissions associated with the production of granular activated carbon. Reported as a monthly amount based on LCA and dependent on monthly use.	kg CO_2/month
$CO_{2electricity}$	=	The mass of CO_2 resulting from emissions of electricity on a per-month basis.	kg CO_2/month
CO_{2LCA}	=	Mass of CO_2 from LCA of plant production spread over a 20-year cycle.	kg CO_2/month

Mass of CO_2 from Emissions

Emissions include the emissions from the power usage of the plant, the escape from the anode, estimated CO_2e of other ongoing processes such as rock grinding, and CO_2e of materials for construction of the plant.

Equation 9: CO_2AE			
CO_2AE = $[CO_2]$*Mass Flow Rate * Time in Service			
Where			Unit
CO_2AE	=	The mass of carbon outgassed from the anode compartment of the electrolyzer.	kg CO_2/month
$[CO_2]$	=	The concentration of CO_2 gas contained in the air of the anode headspace outlet.	Mass %
Time in Service	=	The time the plant was in service.	Minute
Mass Flow Rate	=	The mass flow rate of gas measured by in-line meter.	SCFM

Section 21: Appendix B

Scientific Basis on Permanence of Removal

Description provided by Equatic.

The oceans absorb and immobilize atmospherically derived CO_2 in the form of dissolved carbonate species (i.e., predominantly HCO_3^- at a prevailing pH of ≈8.1). Such aqueous immobilization is highly durable, although less so than mineral carbonate formation (i.e., which has a stability of up to billions of years)[18,19] and presents a lower bound of stability of more than 10,000 years.[20] Long-term (millions of years) storage of CO_2 on Earth occurs by mineralization through the formation of calcite ($CaCO_3$) and aragonite ($CaCO_3$).

The $CaCO_3$ solids produced via this process can be discharged back into the ocean where they remain stable because of their native prevalence and persistence (e.g., seashells in the ocean), and seawater's supersaturation with respect to the mineral carbonates or beneficially utilized (e.g., as sand in concrete or as a carbon-neutral feedstock to produce cement).

During catholyte processing, hydrated carbonate phases, including nesquehonite ($MgCO_3·3H_2O$), lansfordite ($MgCO_3·5H_2O$), hydromagnesite ($Mg_5(CO_3)_4(OH)_2·4H_2O$), and dypingite ($Mg_5(CO_3)_4(OH)_2·5H_2O$) may form. These solids will tend to dissolve if they were to be discharged into the ocean because of the ocean's undersaturation concerning these phases. The dissolution of calcium carbonates (e.g., below the carbonate compensation depth) and hydrated magnesium carbonates in the ocean increases the ocean's alkalinity and drives additional atmospheric CO_2 removal as dissolved HCO_3^- and CO_3^{2-} ions. Indeed, from stoichiometry, the formation of 1 mole of $CaCO_3$ or Mg–CO_3 hydrates (e.g., nesquehonite: $MgCO_3·3H_2O$) captures 1 mole of CO_2, while requiring 2 moles of OH^-. For comparison, only 1.2 moles of OH^- are required per mole of CO_2 stored as dissolved (bicarbonate: HCO_3^- and carbonate: CO_3^{2-}) ions.[21]

---

[18] Veizer, J.; Hoefs, J.; Lowe, D. R.; Thurston, P. C. Geochemistry of Precambrian Carbonates: II. Archean Greenstone Belts and Archean Sea Water. Geochimica et Cosmochimica Acta 1989, 53 (4), 859–871. https://doi.org/10.1016/0016-7037(89)90031-8;.

[19] Sundquist, E. T. Geological Perspectives on Carbon Dioxide and the Carbon Cycle. In The Carbon Cycle and Atmospheric CO2: Natural Variations Archean to Present; American Geophysical Union (AGU), 1985; pp 55-59. https://doi.org/10.1029/GM032p0005.

[20] Renforth, P.; Henderson, G. Assessing Ocean Alkalinity for Carbon Sequestration. Reviews of Geophysics 2017, 55 (3), 636–674. https://doi.org/10.1002/2016RG000533. Ken Caldeira; Makoto Akai. Ocean Storage. In IPCC special report on carbon dioxide capture and storage; Cambridge: Cambridge University Press, 2005.

[21] Renforth, P.; Henderson, G. Assessing Ocean Alkalinity for Carbon Sequestration. Reviews of Geophysics 2017, 55 (3), 636–674. https://doi.org/10.1002/2016RG000533. La Plante, E. C.; Simonetti, D. A.; Wang, J.; Al-Turki, A.; Chen, X.; Jassby, D.; Sant, G. N. Saline Water-Based Mineralization Pathway for Gigatonne-Scale CO2 Management. ACS Sustainable Chem. Eng. 2021, 9 (3), 1073–1089. https://doi.org/10.1021/acssuschemeng.0c08561.

Section 22: Appendix C

Scientific Basis on Potential CO_2 Leakage

Description provided by Equatic.

The discharge of seawater having increased alkalinity may result in localized increased ocean pH depending on the outfall design and the hydrodynamics of the location of the outfall. The presence of added alkalinity may result in secondary carbonate precipitation that releases CO_2.[22]

Secondary carbonate precipitation is defined as the unintended precipitation of $CaCO_3$ in the ocean, such that one mol CO_2 is released per mol $CaCO_3$ precipitated:

$Ca^{2+} + 2HCO_3^{-} \text{->} CaCO_3 + CO_2 + H_2O$

This aspect should be considered in further detail because:

a) $CaCO_3$ precipitation consumes OH^-, decreasing the efficiency of CO_2 absorption since it is more efficient to stabilize atmospheric CO_2 as aqueous species than within mineral carbonates, and

b) It could change the Ca:Mg ratios locally and at short time scales.

Nonetheless, to achieve CO_2 removal at the level of 10 Gt/year would require the dissolution of 8.3 Gt of $Mg(OH)_2$ corresponding to the addition of 1.1×10^{-7} mol $Mg(OH)_2$/kg seawater. If dispersion of $Mg(OH)_2$ is assumed to be averaged across the world's oceans, changes in seawater pH and mineral saturation indices are exceedingly small. For context, the critical saturation ratio, Ω, for runaway aragonite precipitation is 5 (SI = 0.69). Using a model that considers ocean circulation, i.e., ECCO (Estimating the Circulation and Climate of the Ocean) LLC270 physical fields, and constraints of $\Delta pH = 0.1$ and $\Delta\Omega_{aragonite} = 0.5$, regions within 300 km of the coast can accommodate 100s of megatons of atmospheric CO_2 removal. This shows that simple near-coastal alkalinity discharge, such as that proposed herein, can scale to several Gt per year of CDR if spread over available coastlines.

---

[22] At high pH levels – only if there is an accidental release of alkali and should be treated as such. Projects must have a monitoring and mitigation plan.

Authors – Equatic Team

Edward Sanders
Chief Operating Officer

Erika La Plante
Head of MRV & Environmental Impact Assessment, Co-Founder

Authors – EcoEngineers Team

David LaGreca
Managing Director, VCM

Roxby Hartley, Ph.D.
Climate Risk Director

Michael Welch
Manager, Carbon Consulting, VCM

Important Information

This report and its attachments and/or other accompanying materials (collectively, the "Deliverables"), were prepared by TPR Enterprises, LLC, d/b/a EcoEngineers ("EcoEngineers"), solely for the identified client ("Client") and no other party. Client may use the Deliverables solely for the express purpose for which they were prepared, subject to the assumptions and limitations set forth in them and any underlying scope of work, master services agreement, and/or other governing instrument. Client's use of the Deliverables is subject to certain assumptions and limitations, including the following: the Client is the sole intended user of the Deliverables; all information, summaries and/or conclusions set forth in the Deliverables are provided as of a particular date(s) and, as such, the Deliverables have not been updated to address changes and other matters that may have arisen after such particular date(s); and in preparing the Deliverables, EcoEngineers has reviewed and relied on data, documentation, and other information delivered to it or its affiliates and should such information be erroneous, misleading, or incomplete, in whole or in part, same may impact any conclusions set forth in the Deliverables. Any third party (other than Client) who receives, in whole or part, a copy of the Deliverables, may not rely on it for any purpose.