**Measurement, Reporting, and Verification (MRV) Strategy for First OAE Carbon Removals by Planetary Technologies**

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August 12, 2022

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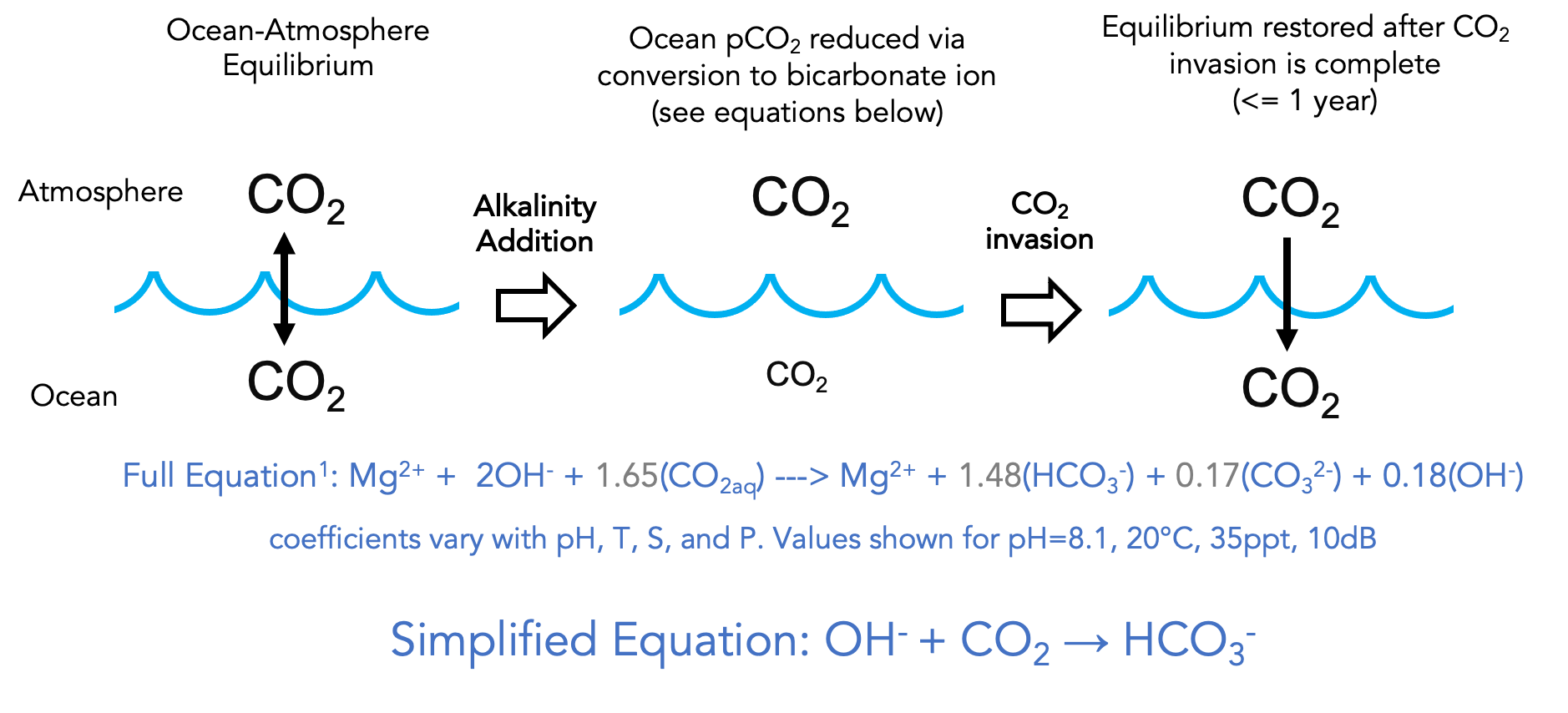
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# Background

Planetary intends to begin carbon dioxide removal (CDR) from the atmosphere using Ocean Alkalinity Enhancement (OAE) and Carbon Dioxide Removal from Wastewater (CDRWW) in the summer and fall of 2022. A robust, science-based Monitoring, Reporting and Verification (MRV) protocol (the OAE Methodology) that is agreed to by both the provider (Planetary) and the customer (Shopify) and is supported by climate science is required in order to ensure that the greenhouse gas removals (Removals) and any resulting OAE and waste water carbon dioxide removal units (CDRs) are appropriately measured, quantified, monitored, accounted for and permanently retired. CO2 removals will be verified by independent 3rd parties in accordance with the OAE Methodology in order to ensure that they are real, additional, unique, measured, and verified in accordance with the OAE Methodology.

As will be detailed subsequent sections, Planetary’s general approach to OAE is to add CO2-reactive alkalinity (specifically, magnesium hydroxide) to the surface ocean so as to consume some of its dissolved CO2 and induce CO2 undersaturation relative to air. Exposure to air of this undersaturated water then forces, via air-to-sea diffusion, removal of CO2 from air. The basic chemistry is illustrated here:



As we will describe, there can be various site-specific inefficiencies in this scheme that need to be measured or modeled in order to derive the gross CDR effected for a given alkalinity addition. Life Cyle Analysis (LCA) CO2 emissions associated with Planetary’s OAE are then subtracted from gross CDR to determine net CDR.

Planetary’s approach to OAE involves adding alkalinity to existing, permitted, ocean outfalls such as industrial and municipal wastewater discharges. In the case of municipal wastewater (Planetary’s first planned trial), the high biomass loading and metabolism characteristic of these waste streams means that they are very highly supersaturated in CO2 relative to air. Thus, by adding alkalinity to these streams there is significant potential for CO2 removal to occur in the delivery pipe even before the alkalized wastewater is delivered to the ocean.

As we will describe below, this presents a unique opportunity to simplify our MRV by 1) conducting on-land monitoring within the pipe to calculate in-pipe CDR, and then 2) differencing this with the total alkalinity added to calculate the amount of ocean CDR that can occur after discharge from the pipe, taking into account potential efficiency losses during the ocean CDR process.

The first of Planetary’s removals will take place at the city of Hayle’s Wastewater Works in Cornwall, UK in September of 2022. As a result, the OAE Methodology below is a generalized protocol, and is followed by an Appendix that provides the specifics of an MRV strategy to be carried out at Hayle. The intent is for the framework OAE Methodology to be generalized to reflect the ambient and ocean characteristics in any jurisdiction where it is applied, including a Halifax, Canada site that is intended to begin CDR trials in a similar timeframe.

## System Boundaries

In order to calculate the net CO2 removal inherent to an OAE process, we must define the boundaries of the system to be measured. This ensures a consistent measurement framework in order to calculate the life-cycle analysis (LCA) CO2 emission of the system - the total carbon emitted and consumed within the CDR system based on energy, transportation, feedstock, materials and processes. Ultimately the system boundary is critical to establishing a consistent LCA.

In OAE, the system to be analyzed includes all positive or negative CO2 emissions from:

* Sourcing of the raw materials for the alkalinity, generally rock or solution mining activities
* Transportation of those materials from the mine site to the processing facility
* Purification or preparatory processes (leaching, drying, commutation, etc…)
* The heat, energy and processes of the processing facility
* Transportation of the finished alkalinity to the wastewater facility
* Dosing systems and monitoring systems
* Alkalinity reaction with wastewater and seawater CO2
* Invasion of atmospheric CO2 into seawater and /or the retention of dissolved CO2 that otherwise naturally escapes to the atmosphere.

The alkaline feedstock used is fully consumed in the process of performing OAE and, as such, the LCA of its production must be included within the system boundary.

While GHG emissions other than CO2 (e.g., CH4 N2O etc.) may occur in the preceding, they are outside the boundaries being considered here and will not be evaluated unless demanded by a carbon creditor. This protocol does not consider production of co-products, such as hydrogen or battery metals that Planetary is also pursuing. No deductions are made for displacement from co-products.

## Calculation of Net CDR

The net tonnes CDR removed by our process can be calculated as:

**CDRnet** = CDRWW + CDROAE – LCAemiss (1)

where:

**CDRWW** is the tonnes of gross CDR that occurs in the wastewater pipeline prior to discharge to the ocean. This can be directly measured by differencing: i) the wastewater CO2 partial pressure, (pCO2) prior to addition of alkalinity to the wastewater stream, and ii) the pCO2 following alkalinity to the wastewater at or near the point of discharge to the ocean. This pCO2 decline together with its measured duration and affected wastewater discharge rate can be used to calculate tonnes of CO2 removed from the waste stream. Specifically:

**CDRWW** = (WW pCO2pre - WW pCO2post) x Sol. Constant x WW rate x t (2)

where:

CDRWW is the total CO2 removed in the wastewater pipe prior to discharge [in tonnes CO2],

WW pCO2pre is the wastewater pCO2 prior to alkalinity addition (in µatm), measured at or near the point of discharge to the ocean,

WW pCO2post is the wastewater pCO2 after alkalinity addition (in µatm), measured at or near the point of discharge to the ocean, as further described below.

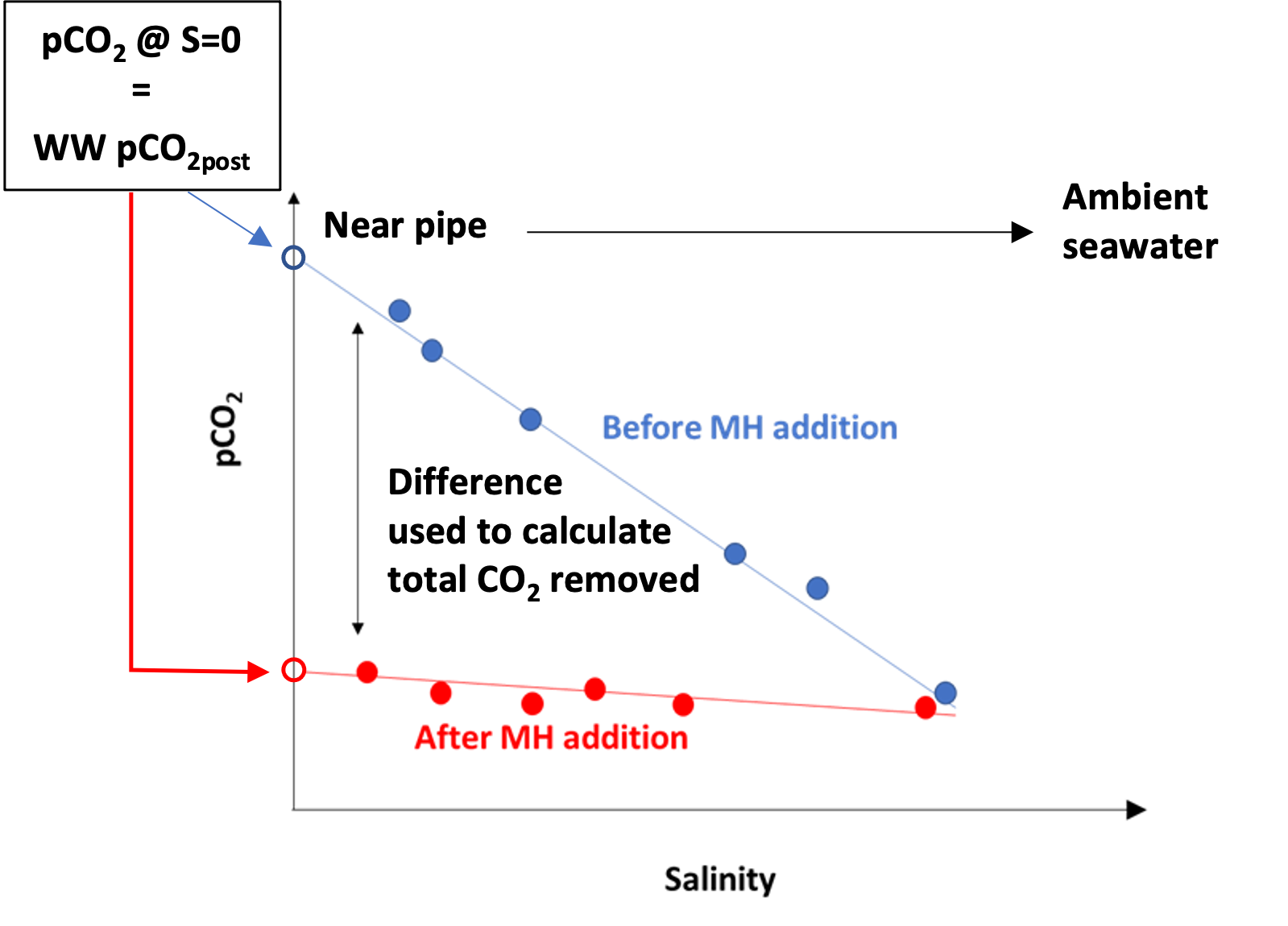
Sol. Constant is the temperature- and salinity-sensitive CO2 solubility constant   
(in units of tonnes CO2 µatm-1m-3),

WW rate is the discharge rate of wastewater, in m3/hr,

t is the duration of the alkalinity addition, in hours.

WW rate is typically monitored closely by wastewater operators, and/or can be measured using a flowmeter inserted into the pipe whose wastewater cross-sectional area is known. WW pCO2pre will be measured prior to any alkalinity addition, by a pCO2 sensor placed at or near the point of discharge to the ocean. This in effect provides the non-alkalized control measure to which end-of-pipe, post-alkalinization measures (WW pCO2post) can then be differenced to determine the amount of CDR occurring in the pipe. To account for any temporal change in upstream, unalkalized WW pCO2 during the course of alkalization, we will also monitor the pCO2 of the wastewater upstream of the alkalinity addition point before and during alkalization. Differencing upstream and end pipe pCO2 prior to alkalization measures changes in pCO2 due to non-alkalization processes, e.g., loss of CO2 to air, or in-pipe biogenic CO2 generation).

At sites where direct in-pipe measurement of WW pCO2post at or near the final discharge point to the ocean is not feasible, this value can be estimated using marine measurement surveys. Because wastewater typically has a much lower salinity that seawater, a potential ‘mixing line and extrapolation’ method for calculating WW pCO2post at wastewater salinity is illustrated below. Briefly, measurement of seawater pCO2 and salinity throughout and outside the effluent plume may yield co-variability along a ‘mixing line’. Extrapolating that mixing line to the y-axis (i.e. zero-salinity), both pre- and post-alkalinity addition, yields the respective WW pCO2post. Additionally, the area between these two mixing lines should represent the total CO2 removed via alkalinity addition, and thus could be used as a comparative ‘marine-based’ estimate for the CDRWW term. If the vast majority of magnesium hydroxide dissolution (and thus alkalinity addition) occurs in the pipe and within the area of the effluent plume, the approach outlined here could be a relatively robust estimate of total gross CDR (CDRWW+ CDROAE).



\*Note: Dissolved oxygen (DO) may also prove useful to trace the extent of the effluent plume, and thus could be plotted alongside pCO2 to help refine this mixing model approach. The utility of measuring DO data is: DO concentrations in municipal wastewater are typically very low, DO is not impacted by alkalization, and DO probes are commonly integrated into marine sensor packages.

**CDROAE** represents the gross CDR that occurs in the ocean:

**CDROAE** = Mg(OH)2**ocean** x OAE Ratio x (OAE Efficiency – OAE Holdback) (3)

where:

**Mg(OH**)2**ocean** is the tonnes of Mg(OH)2 (dissolved and particulate) remaining after the quantity of Mg(OH)2 consumed in CDRWW is accounted for. In particular, CO2 is removed from solution via this reaction:

Mg2+ + 2OH- + A(CO2aq) ---> Mg2+ + B(HCO3-) + C(CO32-) + D(OH-) (4)

where A= B+C and B+2\*C+D = 2. At an equilibrium seawater pH of 8.1 at 20 °C and at shallow depth (near seasurface pressure), A = 1.65 mols of CO2 per mol of Mg(OH)2, and B, C and D are 1.48, 0.17 and 0.18 moles/mole, respectively, based on seawater chemistry modeling (CO2SYS; Pierrot et al., 2006). The molar ratio A decreases with increasing seawater pH. For example, at pH = 8.3 the ratio drops to 1.56. This molar ratio can be converted to a mass ratio. For example, at pH=8.1,1.65 mols CO2/mol Mg(OH)2) x 44(wt./mol CO2)/58.3(wt./mol Mg(OH)2) = 1.25 t CO2/t Mg(OH)2. Thus, by knowing the total tonnes of Mg(OH)2 added to wastewater and CDRWW (above), we can determine remaining t Mg(OH)2 that is delivered to the ocean:

**Mg(OH)2ocean** = total t Mg(OH)2 added to wastewater – CDRWW/OAE Ratio. (5)

**OAE Ratio** is the theoretical maximum ratio of tonnes CDR per tonne Mg(OH)2 added as derived from eq 4. At pH 8.1 this ratio is 1.25 tonnes/tonne (the A value above), but the value used at a given site will be determined using baseline ocean pH, temperature and pressure (depth) data near the discharge site, under the assumption that those parameters in all alkalized water will, via dilution, eventually approximate those of baseline seawater.

To date, tests of this theoretical OAE Ratio are limited. 2 L scale seawater testing by the University of Miami show that under rapid stirring of 1mM Mg(OH)2 in seawater, approximately 50% of the theoretical carbon uptake is achieved the first day following alkalization, and 99% of the theoretical yield is achieved after 20 days. Further testing to refine and reproduce these yield estimates are underway, and will be needed, but these preliminary results seem to confirm the OAE Ratio predicted by modeling.

**OAE Efficiency** is the fraction of the theoretical OAE Ratio actually achieved within 1 year of the addition of the alkalinity in a specific location of distribution. Dissolution of solid Mg(OH)2 occurs on timescales of hours-to-days, and timescales for ocean-atmosphere CO2 equilibration range from weeks to months (Zeebe and Wolf-Gladrow, 2001; Caldeira et al., 2005; Sabine and Tanhua, 2010), thus a 1-year time horizon allows for the robust assumption that both dissolution and equilibration will be complete across the vast majority of ocean systems, while also providing a cap to better constrain the reporting and verification process. This choice of 1 year aligns well with global model output for CO2 equilibration timescales, which reported a global mean value of 4.1 months, a standard deviation of 3.4 months, and only a small fraction of areas in offshore waters where the value exceeded 12 months (Jones et al., 2014). This study also revealed higher wind speeds and deeper mixed layer depths as the dominant factors driving increases in equilibration timescales, highlighting the importance of understanding these specific dynamics near a proposed OAE site. Planetary’s OAE approach centers on alkalinity addition to relatively shallow coastal or nearshore waters, inherently lowering the risk of alkalized waters reaching these deeper offshore areas prior to equilibration. That said, if regional modelling efforts reveal a risk of transport to these ‘slow-equilibration’ areas, amendments to the 1-year time horizon may be required. Going forward, numerical modelling efforts, both led by Planetary but moreso from the greater research community, that build upon and apply this prior research to OAE-focused questions will undoubtedly help refine MRV protocols such as the one presented here.

Removals that are not achieved within one year are not considered here, but could still provide CDR at some future date up to about 1,000 years (the turnover time of the ocean and the maximum duration that seawater can remain out of contact with the atmosphere).

Realized OAE Efficiencies less than 1 can be due to: 1) incomplete dissolution of solid Mg(OH)2 in the surface layer, including sinking of solid Mg(OH)2 out of the surface layer and/or 2) incomplete equilibration of the induced, CO2-undersaturated seawater with the atmosphere, for example, due to subduction of that water prior to air equilibration. The efficiency factor must be derived from laboratory and field experimentation and physical ocean modeling (potential methods for which are described below). The calculated OAE Efficiency will be site specific to the point of addition.

**OAE Holdback** In order to balance the need to proceed with removals with the reality that the OAE Efficiency will consistently be refined as removals are measured, an “estimate and refine” model is used. In this model, new sites begin with an estimate of the OAE Efficiency based on the best available data for that site. From there, a holdback is attached to OAE Efficiency that relates to the maturity of data collected for the site. This holdback factor is subtracted from OAE Efficiency. For example, if the best available estimate for a site is 90% efficient, and the holdback factor is 15%, the initial OAE Efficiency Factor used will be 75%. This 15% can then be considered the upper limit of uncertainty we believe exists for a given OAE Efficiency estimate. As additional data are collected for the site, uncertainties presumably decrease and the holdback factor and OAE Efficiency Factor are adjusted accordingly. With each adjustment, the provider will adjust the credits issued against historical activities. That is:

|  |  |  |
| --- | --- | --- |
| Maturity Level | Criteria | Holdback Factor |
| Preliminary | * 2D Model Completed * Effluent pCO2 baseline completed * MH Particle Size Determined | 15% |
| Operational | * 3D Model Completed showing subduction * Model includes relative buoyancy of effluent and vertical mixing rates * Model incorporating average wind speed, mixed layer depth, and sea surface roughness * Model validated based on at least 3 sensing events (1 week deployments of ocean sensors) - pH, temperature, salinity, pH, pCO2 change against pre-alkalinity addition baseline | 10% |
| Mature | * Model validated based on at least 10 sensing events | 2% |

Various efforts are underway to advance sites to higher levels of maturity more quickly. The first is a conceptual modelling tool under development by Dalhousie partners that directly calculates OAE Efficiency using relatively few parameters that can be estimated, or in ideal circumstances, directly measured. This is possible because some key equations require relatively few inputs compared to the operational maturity level criteria: air-sea CO2 fluxes are highly dependent on wind speed, mixed layer depth, temperature and other factors, while the strength of advective and/or diffusive vertical mixing is strongly tied to rates of vertical turbulent diffusivity (with wind speed also playing a role). At this time, a foundational version of this model has been built and run using conditions at our pilot sites. Further versions of this model will incorporate ocean data from test sites to build complexity and minimize assumptions. The second utilizes more complex numerical simulations. These are 2D or 3D models that simulate the physical environment and are overlain by carbonate chemistry modules. Building such models are part of Planetary’s fundamental OAE approach. To date, the models built at pilot sites have been focused on shaping our understanding of the physical environment (e.g., dilution near the discharge point), and understanding the magnitude and physical extent of the chemical signals induced by effluent before and after alkalinity addition. In the coming months, these models will be tested and refined using actual onsite physical and chemical measurements.

**LCAemiss**is the tonnes of CO2 emitted in the production, transportation and distribution of the total Mg(OH)2 mass used in the CDR, thus allowing the calculation of net CDR (eq. 1). To calculate the LCAemiss of the Mg(OH)2 , the specific pathway used in its production is required. The methodology for various pathways are discussed below.

## Mg(OH)2 LCA Methodologies

The production of Mg(OH)2 can be accomplished through a number of different pathways. These pathways fall into four rough categories. The expectation is that this document will evolve as new pathways emerge. The pathways discussed here are Brucite Mining, Brine Process, Direct Carbonate Electrolytic Reduction, and Silicate Leaching and Electrochemical Reduction.

**Pathway 1: Brucite Mining**

The LCA of Mg(OH)2 mined directly out of the ground is calculated based on:

LCAmined brucite = CO2 emissions embodied in raw materials (1)

+ CO2 emissions from raw materials transport (2)

+ CO2 emissions from manufacture and processing (3)

+ CO2 emissions from product distribution (4)

1. Emissions embodied in raw materials consist of the emissions of the mineral from the ground. This typically includes electricity and diesel used in mining equipment, the emissions in any products used in the extraction process - such as plastic bags for packaging and transport.
2. Emissions from raw materials transport includes the emissions from the transportation of the materials from the mine site to the processing facility - typically by rail, road or sea
3. Emissions from manufacture and processing includes energy emissions generated from the grinding and milling of the raw material to the specified mesh size. This may also include process or energy related emissions from purification circuits and drying systems
4. Emissions from product distribution includes the transportation emissions from the point of manufacture to the point of distribution into seawater - generally the wastewater facility.

With this information, and for all of the processes described below, the ‘OAE Potential’ is then calculated as:

OAE Potential = 1250 gCO2/kg - LCA

where 1250 gCO2/kg is the theoretical OAE Ratio described above.

Chart, bar chart

Description automatically generated

Values for Base Case from Carbon Footprint Ltd, “Product Carbon Footprint: Life Cycle Assessment Report for Russian Mining Chemical Company LLC t/a Brucite+”, available at <https://brucite.plus/upload/medialibrary/294/2021_04%20Product%20Footprint%20Report%20RMCC%20v1.0.pdf>

As illustrated above, mined brucite can carry a carbon footprint of less than 100 gCO2 per kg Mg(OH)2 in its mining and manufacture. Transportation emissions tend to dwarf this value and, depending on the location of the mine in relation to the wastewater facility, can push the total LCA above 750 gCO2 per kg Mg(OH)2.

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### Pathway 2: Brine Process

The brine process consists of taking a Mg-rich brine, generally from seawater or subsurface geologic sources, and reacting it with a more alkaline form of hydroxide. Generally the process uses lime. The majority of the emissions in the LCA of the brine process stems from the production of the lime used in its manufacture. For clarity, we provide an overview of the LCA of the lime used in the brine process separately from the LCA of the actual pathway since there are a variety of lime pathways that can be used in the brine process.

LCAbrine process  = CO2 emissions from lime (1)

+ CO2 emissions from transportation of lime (2)

+ CO2 emissions from brine extraction and processing (3)

+ CO2 emissions from distribution from facility to site (4)

1. Emissions from lime depends on the pathways to produce the lime used. This is a major component of the LCA, with traditional calcination using natural gas and without carbon capture and storage (CCS) pushing the LCA of the produced Mg(OH)2 out of the range where net CDR is possible (shown as negative OAE potential in the diagram below). By substituting various forms of low carbon lime production – such as calcination with CCS and low carbon intensity (CI) fuel or electrolytic decomposition of limestone with CCS – this process can be viable for producing negative emissions.
2. Emissions from the transportation of lime consist of the emissions from the transportation of the produced lime from the point of production to the point of brine processing
3. Emissions from brine extraction and processing includes the emissions involved in the:
   1. Pumping of Mg rich brine (generally MgCl2) from the source,
   2. Purification of the brine removing heavy metals, sulfates and boron,
   3. Addition of lime to precipitate MgO
   4. Hydration of MgO
   5. Wet grinding of the resulting precipitate
4. Emissions from the transportation to site consist of emissions from transporting the final Mg(OH)2 from the processing facility to the wastewater site. As shown below, co-locating the Mg(OH)2 production and wastewater site lowers the overall process LCA substantially.

As in the previous Brucite example, the OAE potential is calculated by subtracting the total LCA from the theoretical maximum OAE potential of 1250g CO2/kg.

Chart, bar chart

Description automatically generated

Note: Negative OAE potential implies net carbon removal is not achieved.

Representative values for brine extraction calculated from proprietary supplier data and calculated lime production emissions. Values for lime production from calcination with and without CCS derived from “A Competitive and Efficient Lime Industry” at https://www.eula.eu/wp-content/uploads/2019/02/A-Competitive-and-Efficient-Lime-Industry-Technical-report-by-Ecofys\_0.pdf

Values for Electrolytic dissolution of limestone are derived from <https://www.pnas.org/doi/10.1073/pnas.1821673116>.

**Pathway 3: Direct Electrolytic Decomposition of Magnesite**

Magnesite (MgCO3) can be electrolytically decomposed in a similar manner to limestone. In this process, a pH gradient produced by neutral-water electrolysis is used to dissolve MgCO3 at the acidic anode and precipitate Mg(OH)2 at the basic cathode. CO2 is generated at the anode which can be captured and sequestered.

LCAelectrolytic magnesite = CO2 emissions embodied in magnesite (1)

+ CO2 emissions from transportation from the site to the reactor (2)

+ CO2 emissions from electricity (3)

+ CO2 emissions from limestone decomposition process (4)

- CO2 captured and sequestered from the decomposition process (5)

1. Emissions embodied in the magnesite include emissions related to the extraction, grinding, washing and milling of the source rock
2. Emissions from transportation from the site to the reactor
3. Emissions from the electricity used in the electrochemical process
4. Emissions from limestone decomposition process is the CO2 chemical reaction below:

MgCO3 + heat –> MgO + CO2

1. Emissions captured from step 4 and permanently sequestered

Chart, bar chart

Description automatically generated

Values for electrolytic dissolution of magnesite are derived from https://www.pnas.org/doi/10.1073/pnas.1821673116

### Pathway 4: Silicate Leaching and Electrochemical Reduction

In this process, Mg rich silicate rock (such as olivine or serpentine) is leached using an acid. The resulting leach solution is then purified to remove heavy metals, iron and aluminum. The final barren is fed into an electrochemical cell which regenerates the acid on the anode and produces Mg(OH)2 at the cathode. The resulting Mg(OH)2 is filtered and shipped to the wastewater facility.

LCA electrochemical silicate = CO2 emissions embodied in source rock (1)

+ CO2 emissions from transportation to processing facility (2)

+ CO2 emissions from purification processes (3)

+ CO2 emissions from electricity (4)

+ CO2 emissions from distribution from mine site to ocean (5)

+ CO2 emissions from waste management (6)

1. Emissions embodied in source rock includes any extraction, grinding, milling, washing of the source rock. If a tailings pile is used from a current or legacy mining activity, these can be considered close to zero
2. Emissions from transportation to processing facility
3. Emissions from the purification process include any feedstocks, such as lime, that may be used in the removal of impurities from the leach solution. These may be counteracted by the passive carbonation of the resulting hydroxides.
4. Emissions from electricity primarily include the emissions produced in the generation of the power used in the electrochemical process.
5. Emissions from distribution from mine site to ocean
6. Emissions from waste management includes any transportation or disposal emissions related to managing the resulting silicate rich waste left over from the leaching process. These wastes may have residual value for other uses such as in aggregates, in which case the emissions from transporting them for those uses would be outside of the system process limits.

Chart, waterfall chart

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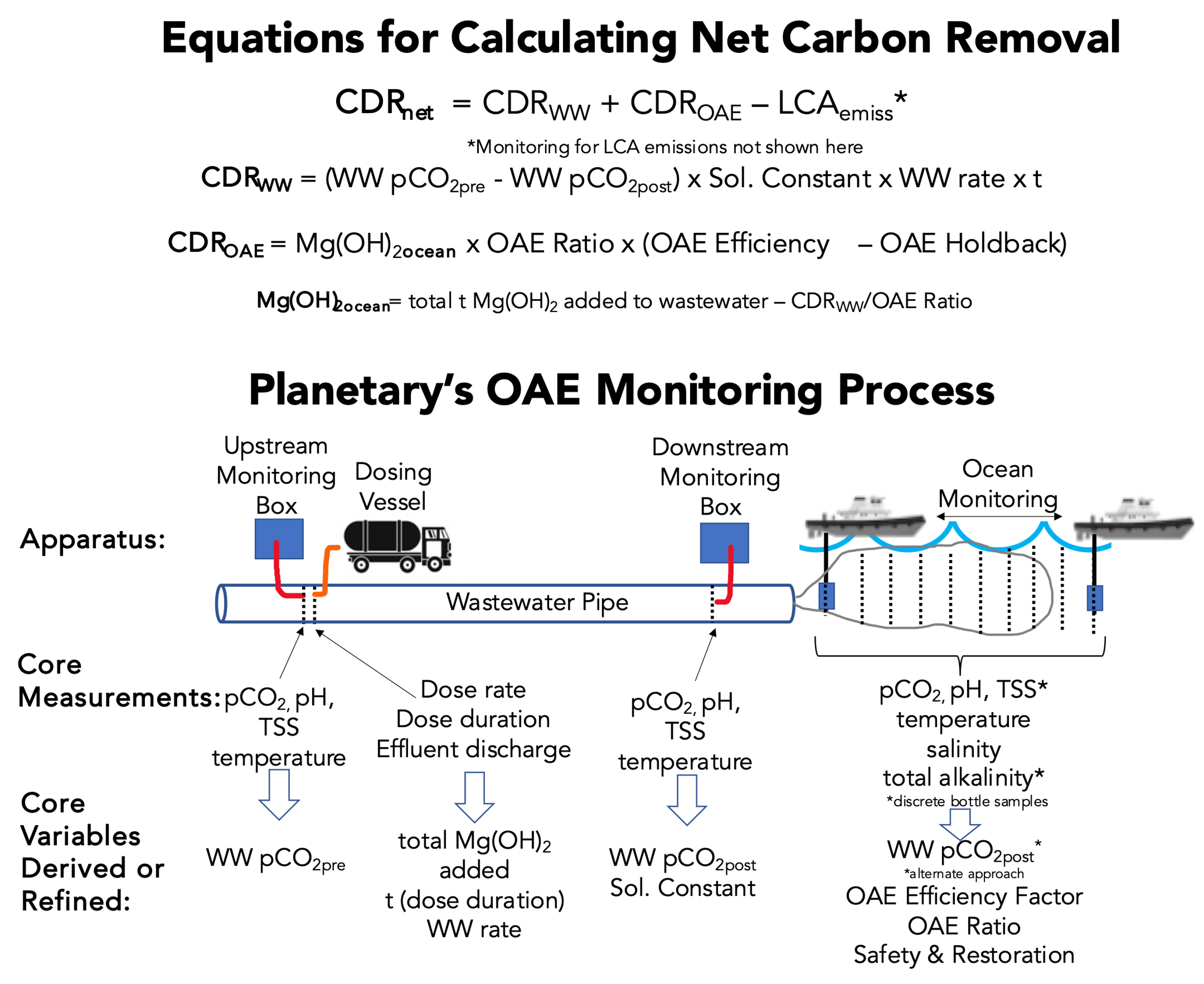
Values for the silicate leaching and electrochemical reduction are derived from internal Planetary lab testing and management experience.

### Summary of LCA Pathways

In summary, determination of LCAemiss will be very Mg(OH)2-source specific and will rely on a mix of published values, vendor data, and estimation, with every attempt made to refine these values as better information becomes available.

**Measurement and Monitoring**

In order to verify Planetary’s CDR, it is necessary to measure a set of core chemical and physical parameters before, during and after alkalization, and use the resulting data set to calculate all the core variables in the fundamental CDR equations described above (equations 1-5). These fundamental raw measurements, derived variables, and equations, alongside a schematic illustrating the proposed monitoring setup, are shown below:



The core parameters needed for the equations governing measurement of net CDR, along with their measurement technique and relevance are as follows:

Temperature (T), salinity (S) and pressure (depth) – Routinely directly measured, spot or continuously using a conductivity, temperature and depth (CTD) sensor. Essential for determining chemical conditions and carbon system concentrations. Also needed to calculate mixed layer depth. The contrast between seawater and wastewater salinity can be used as a tracer of wastewater dispersal and dilution.

pH – Routinely directly measured, spot or continuously. When measured alongside either pCO2, dissolve inorganic carbon (DIC), or total alkalinity (TA), all four parameters can be estimated. Also, pH is common item on wastewater permits. Seawater pH is also needed to calculate the OAE Ratio at a given site.

pCO2 – Spot or continuously directly measured with specialized sensors, or via water sampling and analysis. Can also be calculated from any pair of directly measured: pH, DIC, TA. Essential for determining seawater CO2 partial pressure relative to air and hence air-sea CO2 flux rate. Reduction of pCO2 in a closed system (no equilibration with air) such as in a wastewater pipe via alkalinity addition provides a direct measure of CDRWW. Units: μatm or ppm.

TSS – total suspended solids, determined by filtration of water samples. Elevations above background provide a measure of undissolved Mg(OH)2. Also, TSS is a common item on wastewater permits. Units: mg/L

An additional suite of measurements are required to calibrate and validate the core measurements. These include, but are not limited to, the following:

DIC – total dissolved inorganic carbon (HCO3- + CO32- + CO2) concentration is directly measured via laboratory analysis of water samples (effluent or seawater). Directly measured DIC, which is typically high precision (≲0.2% uncertainty), can be used to validate DIC calculated using core pH and pCO2 measurements. An increase in DIC with alkalization relative baseline conditions provides the most direct measure of air to sea carbon transfer and storage, CDROAE. Units: μM or μmoles/kg seawater.

TA – total alkalinity concentration is a measure of a solution’s ability to neutralize acid, and to absorb and store CO2. It can be measured by laboratory analysis of water samples (effluent or seawater). Like DIC, directly measured TA is used to validate the TA calculated using core pH and pCO2. Elevation above background provides a direct measure of the degree of ocean alkalization, but not necessarily CDROAE. Units: μM or μmoles/kg seawater. Notably, in situ TA sensors, capable of providing data similar to the pCO2 described above, are becoming available and thus could soon become a core part of Planetary’s OAE monitoring process.

Another suite of measurements can be considered secondary. These measurements may provide useful information that enhance data interpretation, but are not considered critical at this stage.

Dissolved oxygen (DO) – an additional tool to help trace the signal from a municipal wastewater effluent, which is typically very depleted in DO. Dissolved oxygen probes are often integrated into CTD sensor packages, making the addition of DO to a monitoring platform fairly straightforward.

Light Absorption or Backscatter – absorption or backscatter of light at certain wavelengths is a fairly common oceanographic measurement. This data could help determine the presence and abundance of Mg(OH)2 particles relative to background seawater, or can quantify the concentration of inert dye (e.g. rhodamine) that can be added to the dosing line to trace dispersal and dilution of the alkalinity. Like DO probes, these sensors are often integrated into CTD packages. Units vary, but typically m-1.

In order to appropriately generate carbon removal credits, this measurement plan must expand to account for positive and negative emissions across the entire OAE process. As such, the table below summarizes the measurements to be conducted and frequency of those measurements.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Step** | **Alkalinity Sourcing** | **Transportation to Site** | **Dose added** | **WW CDR** | **OAE Efficiency Factor** |
| **Measurement** | Provided by supplier | Bill of lading, distances and mode | Dosing system flow rate \* slurry concentration | pCO2 pre-addition - pCO2 post-addition | Effluent distribution model |
| **Frequency** | Upon new source and every 3 months | Per load | Continuous | Every 3 months | Daily, model re-validated with ocean sensing every year |

Ideally, the ocean measurement protocol determines the hydroxide added to the seawater (Dose added), the resulting seawater CO2 undersaturation relative to air, and the subsequent increase in seawater DIC as atmospheric CO2 invades. However, direct measurement of an increase in seawater DIC (CDROAE) over the entire volume of seawater affected is likely not possible. This is due to: i) the time and space scales involved, ii) the continuous and significant dilution of the added alkalinity and affected seawater, iii) the natural background variability of seawater chemistry and iv) the limitations of measurement precision and accuracy. As a result, beyond areas where a discernable increase in seawater DIC is measurable, we rely on well-validated ocean models in order to extrapolate the effective amount of CDR performed by our OAE.

## Consideration and Monitoring of Ecological Safety

Ecological safety cannot be guaranteed for any human activity that intersects the natural world, including alkalinity addition, and rigorous peer-reviewed studies will be required to identify and mitigate any potential ecological concerns surrounding these activities. However, Planetary is dedicated to ensuring, to the greatest extent possible given current knowledge, that ecological risks are minimized.

Most important among these safety considerations is Planetary’s choice of magnesium hydroxide as the alkalinity source. Magnesium hydroxide (MH) is not classified as dangerous under the Workplace Hazardous Materials Information System (WHMIS) nor is it classified as persistent, bio-accumulative or toxic under the Environmental Protection Agencies Toxic Release Inventory List or Toxic Substances Control Act. Perhaps most importantly, magnesium hydroxide is of low toxicity to aquatic organisms, with published limits greatly exceeding any concentrations Planetary is aiming to disperse into the oceans (https://beta.lakeland.edu/AboutUs/MSDS/PDFs/3675/Magnesium-Hydroxide-Millipore-Sigma-1-15-2020.pdf).

In addition, the critical characteristic of MH that greatly limits its potential environmental impact is its slow dissolution kinetics (i.e., its low solubility). Slow MH dissolution means that general dilution of an alkalized effluent by the marine environment will greatly outpace the chemical changes induced by the MH addition. The key example for this is pH, an important environmental quality standard (EQS) applicable to alkalized discharges. The relatively slow dissolution kinetics of MH in seawater prevent rapid pH rises at the dosing location, after which rapid dilution with ambient seawater will keep pH well within safe limits. This has been confirmed by controlled experimentation at pool-scale (Dalhousie Aquatron), where 4 probes located at differing close proximities (1.5m-13m) from a pipe dosing saturated MH slurry measured maximum pH increases of 0.13-0.32 units.

Finally, in addition to these inherent mitigation factors, close monitoring and control of alkalinity dosing rates alongside monitoring of important ecological parameters, such as pH and total suspended solids (TSS), will further ensure permit limits are strictly held and environmental impact is minimized. Alkalinity dosing rates will be monitored constantly, particularly during trial additions, using a flowmeter downstream of a highly-tunable pump (e.g. a peristaltic pump). In the ocean, and whenever possible, in the pipe downstream of the addition point, pH measurements will be monitored regularly.

Planetary is also developing technology whereby a feedback loop within a central computing system allows for environmental data collected downstream (i.e. pH and/or TSS within the effluent, or potentially from a ship) to automatically tune the dosing rate. For example, if in-pipe pH measured downstream exceeds a given threshold near the permitting limit (typically 9), dosing would automatically decrease or cease until the pH drops accordingly.

## Considering Benefits: Restorative Impact

It is important to keep in mind the potential ecological benefits of alkalinity additions, namely the restorative chemical impact. OAE has been shown to enhance calcification rates in coral reef ecosystems (see Albright et al., 2016), although more research is needed to build on this conclusion. Such research is underway in partnership with Planetary, with the aim of  is ongoing to assessing whether OAE leads to quantifiable increases in coral resilience to bleaching.

Monitoring this impact will be done predominantly using pH and carbonate saturation state. Specifically, mapping the magnitude and spatial extent of elevated pH (similar to mapping of pCO2 described above) will quantify the extent to which alkalinity addition has effectively countered ocean acidification in the local environment. Also, using bottle samples of dissolved inorganic carbon and alkalinity, we anticipate measuring localized increases in the calcite and aragonite saturation states, a parameter which describes the extent to which seawater is corrosive to (values <1) or preservative of (values >1 carbonate shell-forming organisms. Subsequently, this data will also be used to validate models that predict the extent to which pH and carbonate saturation states are increased both locally and downstream of the addition site.

## Permanence of sequestration

The mean residence time of alkaline dissolved carbon (bicarbonate and carbonate ions charged-balanced by cations other than H+) in the ocean is about 105 yrs, based on the annual input of alkaline C from rivers (0.3 Gt C/yr), the alkaline pool of dissolved alkaline C resident in the ocean (about 34,000 Gt C), and assuming steady state (Middelburg et al. 2020). We assume that any additional alkaline C added will behave in the same way. In the above time scale, about half of the dissolved alkaline C is eventually lost from seawater as CO2 (returns to the atmosphere) and the remainder precipitates as primarily as CaCO3 to ocean sediments to join the multi million year geologic C cycle.

## Reversal Risks

CO2 can be returned to the atmosphere from dissolve alkaline C in seawater via biotic and abiotic precipitation of CaCO3:

Ca2+ + 2HCO3- —> CO2g + CaCO3s + H2O.

Annually, CaCO3 precipitation and permanent burial amounts to about 0.3 Gt C in the global ocean, and in turn implies the same net C loss rate to air as CO2 associated with that precipitation and burial. Since the ocean contains 34,000 Gt of dissolved alkaline C, this implies a CO2 loss rate of 0.0009%/yr assuming steady state. We assume that the same loss rate applies to any new alkaline C added to the ocean via OAE.

A second way that alkaline C can be returned to the atmosphere is if the pCO2 of the overlying atmosphere were to be reduced below the pCO2 in the surface ocean, e.g. via very effective global CDR. In this case surface ocean CO2 would tend to escape to the atmosphere in order to equalize air/sea CO2 partial pressures. This ocean “rebound” consequence of very effective global CDR is well anticipated (e.g., Vichi et al. 2013, Mathesius et al, 2015). Such loss of CO2 from the ocean surface would, through chemical equilibria, force the loss of carbon among both alkaline and non-alkaline dissolved inorganic C constituents in seawater that if large enough could be directly measured as a loss of global mean sea surface DIC and an elevation in seawater pH. In theory this loss of DIC could be countered by performing additional OAE CDR, though this would further elevate seawater pH.

# Reporting and Verification

Reporting and verification is performed by an independent third party against this MRV plan. This ensures that the measurements are accurate and that the calculations of the amounts of carbon dioxide sequestered are correctly assessed.

1. Per the measurement section above, the **LCA of the alkalinity** used in the process must be properly audited - either directly by the 3rd party or through reliance of a trusted external verifier.
2. The **transportation emissions** must be assessed from transit paperwork.
3. The **dosing records** must be reviewed and matched to delivery load amounts. Parameters closely monitored will include, but are not limited to:
   1. pH
   2. TSS
   3. alkalinity dosing rate and duration
   4. slurry concentration
4. The **pCO2 sensing results** must be reviewed.
5. Finally, the model must be validated with **ocean sensing** and its output aligned with the understanding of the **OAE Efficiency**.
6. The calculation of the CO2 captured and sequestered must be assessed by the verifier on a regular time interval.
7. Metering must be shown to be accurate and reliable, and
8. Records must be maintained for at least ten years.

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**Appendix 1: Background of the First OAE CDR Event**

In mid-September, 2022 (or in October 2022 if weather conditions necessitate a delay), Planetary Technologies will conduct a 5 day field trial, monitored by Plymouth Marine Lab (PML), off the southwestern tip of the UK. The aim of this trial is to demonstrate CO2 removal (CDR) via addition of magnesium hydroxide (MH) to a wastewater effluent stream. To do this, ~5 tonnes of MH, dispensed within a freshwater slurry, will be added to wastewater over a ~24-hour period at the Waste Water Treatment Works in St. Erth, Hayle, UK, operated by South West Water PLC. The effluent then travels through an 11.2 km pipeline before discharging through a seabed diffuser into the ocean approximately 2 miles West of Godrevy Point (see Figure 1 for exact locations). The diffuser is located at the seabed, and the water depth at this location is approximately 23m.

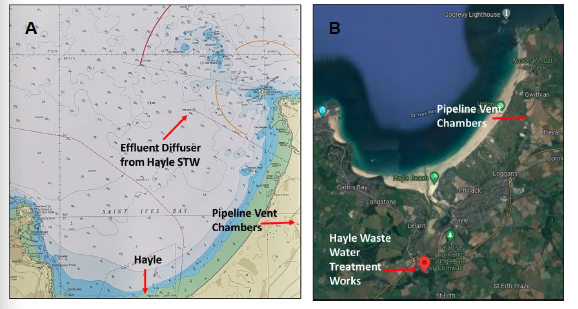


Figure 1: Maps showing Water Treatment Works and location of effluent diffuser in the ocean.

**Hayle Trial Monitoring Strategy**

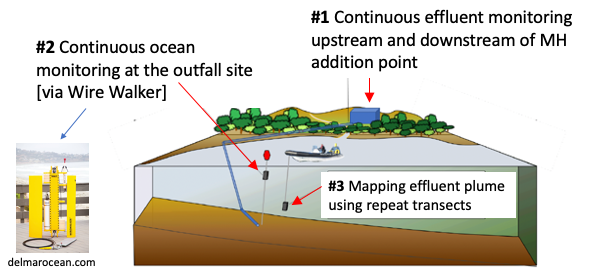


Figure 2: Monitoring strategy for the Hayle trial

The monitoring strategy, as illustrated in Figure 2, involves both effluent monitoring inside the wastewater pipe and ocean monitoring using both autonomous vehicles and ship surveys. In this section, we also describe potential methods for estimating the key terms required for the final calculation of net CDR.

\*Note, the CDRWW term is expected to be quite significant due the length of pipe at Hayle, which facilitates a long residence time of wastewater + alkalinity prior to ocean discharge and thus a large reduction in wastewater pCO2. Rough theoretical calculations based on dose rates, effluent flow rates, and hydroxide dissolution rates, suggest that CDRWW will represent as much as 50% of the total gross CDR at Hayle.

**In-pipe monitoring:**

Both upstream and downstream of the MH addition point, effluent from the pipe will be pumped through sensor packages for continuous measurement of in-pipe flow rate, pCO2, and pH. These monitoring stations will be deployed approximately 1 week prior to the trial, and remain installed until 1 week after the trial is complete.

**Goals:**

* Directly calculate wastewater (WW) CDRbymeasuring effluent flow rates alongside in-pipe changes in effluent chemistry during MH addition (see equation 2 above)
* Understand baseline variability in effluent chemistry in the days/weeks surrounding the trial to help refine dosing strategies for subsequent longer-term deployments.

**Operational Methodology:**

The upstream and downstream monitoring boxes will be built and lab tested by PML. The boxes will be equipped with a battery-powered peristaltic pump with solar charging. The pumps will pull effluent through Boxes will be deployed at both sites ~1 week prior to the trial, at which time sensor calibration samples (bottle samples) for dissolved inorganic carbon (DIC), total alkalinity (TA), dissolved CO2 (CO2(aq)), and pH will be collected and transported back to PML for analysis. Additional calibration sampling (and sensor maintenance) will occur at least twice during the ~1 week prior to alkalization, and during the 1-week post-alkalization. These samples will be used to calibrate and drift-correct the *in-situ* sensors. Additional calibration samples will be taken the day before, day of, and day after MH addition.

**Ocean monitoring:**

​​The wastewater effluent plume will be detectable in the marine environment because it is 1) fresh water (salinity of 0 compared to ~32 in typical seawater), 2) very low in dissolved oxygen, and most importantly 3) very rich in dissolved carbon dioxide (pCO2 is ~15x higher than typical seawater values, as measured directly from Hayle effluent). During MH addition, we anticipate the effluent plume to show significant decreases in the pCO2, coupled with increases in turbidity (i.e. undissolved MH).

Ocean monitoring will be done in two ways:

1. Continuous vertical profiles directly above the effluent diffusers for 4-5 days bracketing the MH release using a moored Wire Walker, which uses wave energy to autonomously profile a sensor package through the water column. The sensor package onboard will measure depth, temperature, salinity, dissolved oxygen, backscatter, pH, and pCO2.
2. Ship-based surveys throughout the day prior, day of, and day after MH release. Starting upstream of the effluent diffuser, the team will continuously profile a second sensor package (same or similar to package above) while drifting past the effluent diffuser location. Simultaneously, a submersed pump attached to the sensor package will deliver water on deck for collection of water samples (dissolved inorganic carbon and total alkalinity) used for sensor calibration.

**Goals:**

* Independently verify the CDRWW calculated using in-pipe measurements using the ‘mixing model’ approach.
* Collect ocean data that will facilitate future refinement of this MRV protocol
* Measure surface ocean pH to determine the site-specific OAE Ratio
* Collect data for subsequent model development/validation that, among other aims, will help refine the sites OAE Efficiency Factor.
* Understand the extent of MH dissolution in the effluent plume using measurements of turbidity as well as discrete bottle samples of total alkalinity.
* Measure small increases in seawater pH (i.e., ocean de-acidification) that directly demonstrate and quantify the restorative component of this process

**Operational Methodology:**

A joint PML-Planetary research team will conduct daily ship-based activities during a 5 day period surrounding the 24-hour MH addition. The current schedule for these ship-based activities is:

Day 1 - Deploy the Wire-walker mooring at the discharge site

Day 2 - Drift surveys around the discharge site to obtain the pre-addition ambient conditions

Day 3 - Drift surveys around the discharge site to monitor the 24-hour MH addition

Day 4 - Drift surveys around the discharge site to monitor post-addition conditions

Day 5 - Recover the Wire-walker mooring at the discharge site

Although exact sensor configurations for the two ocean sensor packages are not yet confirmed by PML partners, the packages are planned to include:

Wire-walker package\*

* RBR Maestro CTD (conductivity, temperature and depth) with additional probes for turbidity, dissolved oxygen, and pH
* Pro-Oceanus Pro-CV pCO2 sensor

Profiled package for shipboard drift surveys:

* RBR Concerto CTD (conductivity, temperature and depth) with additional probes for turbidity and dissolved oxygen
* Pro-Oceanus Pro-CV pCO2 sensor
* Sunburst SAMI-pH sensor (chosen for increased precision to detect spatial extent of the plume)

Water will be pumped onto the ship’s deck from a tube placed adjacent to the sensor package. This pumped *in-situ* water source will facilitate regular calibration bottle sampling (DIC, TA, CO2(aq), pH) for sensor calibration and drift-correction, as well as samples for TSS. We estimate ~100 bottle samples total to be collected during the 3 days of drift surveys.

**OAE Efficiency Factor at Hayle:**

In the Hayle case, shallow waters and strong tidally-driven mixing in the region surrounding the outfall (Brown et al., 2003) will result in rapid MH dissolution and dilution (timescale of hours) while also preventing any settling out of fine MH particles (mean diameter, 3 micron) to the seafloor during the dissolution period. Furthermore, physical oceanographic models of the ocean surrounding the UK (Brown et al., 2003; Holt and Proctor, 2008) indicate that western UK coastal surface waters remain in the ocean surface mixed layer as they migrate northeast along the UK west coast and eventually are transported eastward into the North Sea over a time span of several years. Once in the North Sea, waters continue to be in contact with the atmosphere due to shallow depths (averaging 40 meters) and seasonally strong winds. In sum, this means that very little vertical subduction of water away from the atmosphere can occur within the 1-year time horizon of CO2 air-sea equilibration, and thus any alkalinity added along the UK’s west coast will have a high probability of staying in contact with the atmosphere and effecting CDR, thus warranting a high OAE Efficiency Factor of 0.9.

The latest version of our conceptual model for OAE Efficiency Factor calculation was recently run using parameters that mimic the regional setting at Hayle (based on the literature described above). Four different scenarios (varying the mixing rates and the depth of alkalinity addition to assess model sensitivity), were run for 1 year. In all four scenarios the OAE Efficiencies rose above 0.9. Although this early model requires more data to support the various assumptions used, it represents a foundation for which to build, while also providing quantitative evidence in support of the efficiency chosen for the Hayle trial.

Based on the maturity of the Hayle site, a 15% holdback is applied to the 0.9, providing a net OAE Efficiency Factor of 0.75.

**Reporting and Verification:**

Data analysis, interpretation, and reporting will be conducted by Plymouth Marine Lab. A full report to Planetary detailing on the outcomes of the trial and delivery of all the data products is expected by the end of January, 2023.