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# TRACER: Electrochemical Removal of Carbon Dioxide from Oceanwater: Field Validation (DE-FE0032417)

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2024 FECM / NETL Carbon Management Research Project Review Meeting

# Project Overview: Phase 1

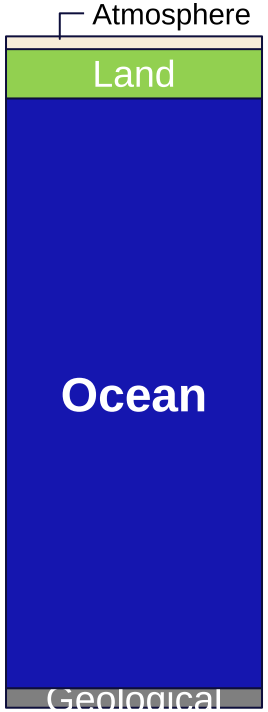
- Funding:
  - DOE: $200,000
  - Cost Share: $50,000
- Project Performance Dates: 12/20/23 to 09/19/25
- Project Participants:
  - University of California, Davis
  - University of California, Los Angeles
  - Woods Hole Oceanographic Institution
  - University of California, Santa Barbara
  - University of Rhode Island

  In partnership with:
  - Southern California Coastal Water Research Project
  - AltaSea
  - Equatic
  - GE Vernova

# Technology Background: Why use the ocean?

## >85% of the world's carbon is in the ocean

**Carbon is currently stored in:**



## We use electrolysis <u>AND</u> direct air capture to accelerate storage

- Equatic's technology captures and stores carbon dioxide in two forms that are prevalent and stable in the ocean:

- **$CaCO_3$ solids**
- **$HCO_3^-$ ions**

*Can be measured within the plant <u>before</u> discharge to the ocean*

## Efficient, permanent carbon storage on a planetary scale

- Kinetically advantaged
- 10,000-1,000,000,000 year carbon storage
- No $CO_2$ transportation or storage costs

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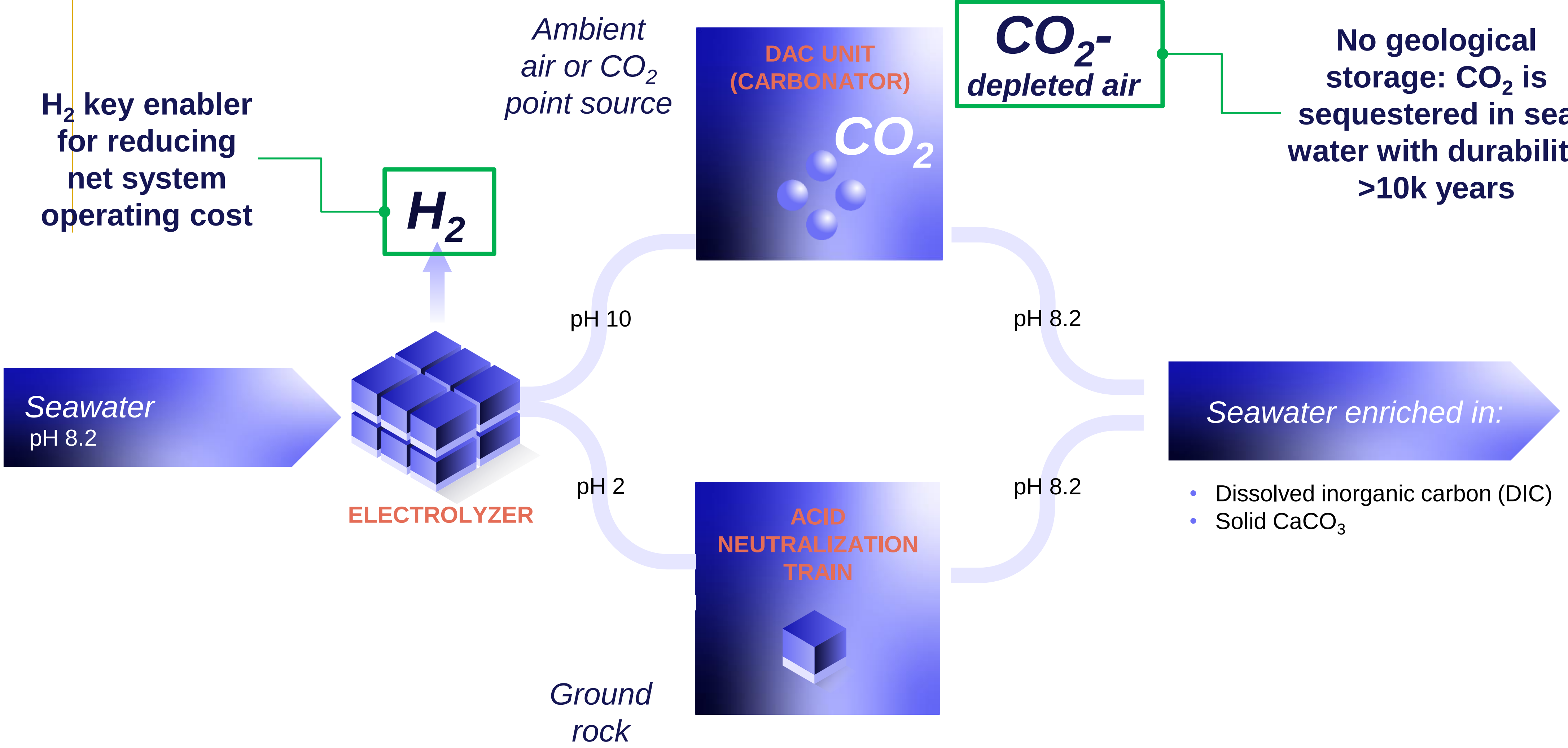
# Single-step $CO_2$ capture and storage



**$H_2$ key enabler for reducing net system operating cost**

*Ambient air or $CO_2$ point source*

**$CO_2$-depleted air**

**No geological storage: $CO_2$ is sequestered in sea water with durability >10k years**

- Dissolved inorganic carbon (DIC)
- Solid $CaCO_3$

Source: LaPlante et al (2021) ACS Sust Chem Eng; LaPlante et al (2023) ACS ES&T Eng

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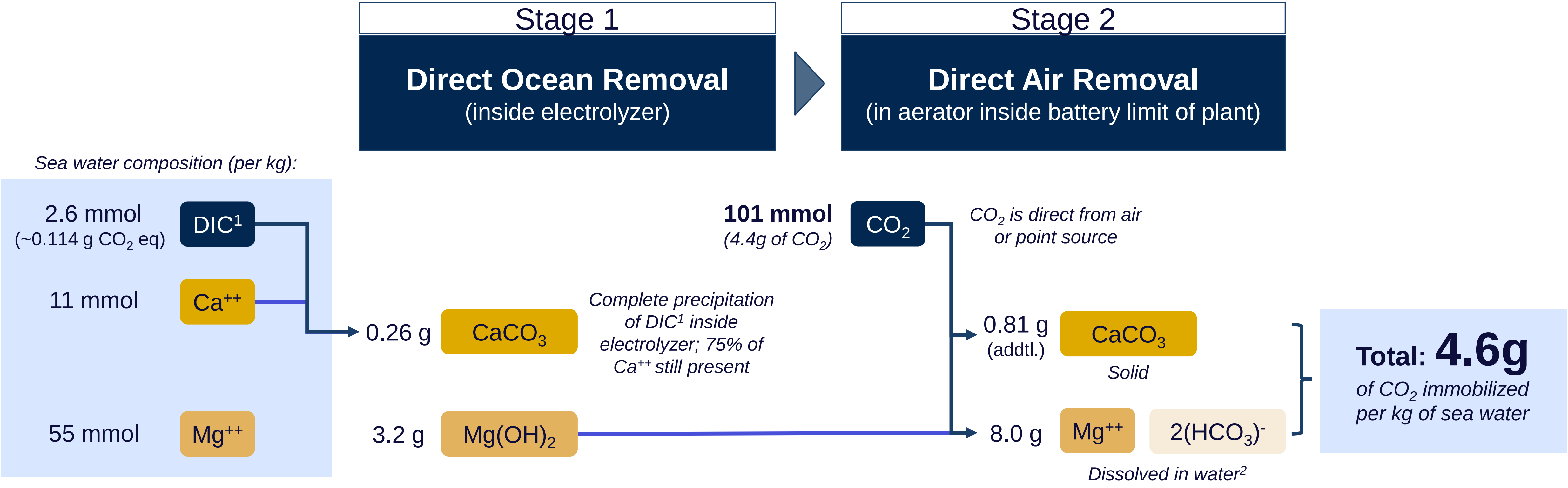
# Engineered CDR with combined ocean/air removal



Stage 1

**Direct Ocean Removal**
(inside electrolyzer)

Stage 2

**Direct Air Removal**
(in aerator inside battery limit of plant)

*Sea water composition (per kg):*

| | |
|---|---|
| 2.6 mmol<br>(~0.114 g $CO_2$ eq) | DIC[1] |
| 11 mmol | $Ca^{++}$ |
| 55 mmol | $Mg^{++}$ |

0.26 g $CaCO_3$

*Complete precipitation of DIC[1] inside electrolyzer; 75% of $Ca^{++}$ still present*

3.2 g $Mg(OH)_2$

**101 mmol** *(4.4g of $CO_2$)* $CO_2$

*$CO_2$ is direct from air or point source*

0.81 g (addtl.) $CaCO_3$

*Solid*

8.0 g $Mg^{++}$ $2(HCO_3)^-$

*Dissolved in water[2]*

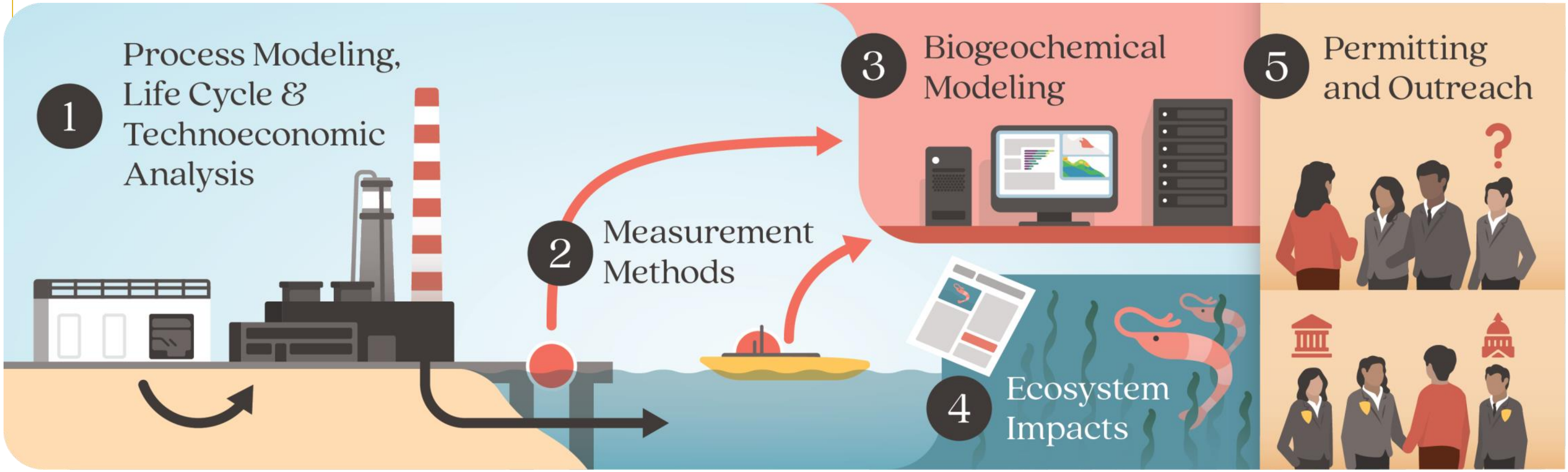
**Total: 4.6g**
*of $CO_2$ immobilized per kg of sea water*

## Two unique pathways to immobilize $CO_2$ for 10,000+ years

1. DIC: dissolved inorganic carbon; 2. 1.7 mol $CO_2$ are immobilized per mol of $Mg(OH)_2$ dissolved. Source: LaPlante et al, ACS EST Eng (2023)

# Project Objectives

- Phase 1 focuses on field validation, with emphasis on frameworks for measurement, reporting, and verification (MRV) and refining plans for deployment



# Technical Approach and Project Scope

- Task 1: Project Management and Planning
- Task 2: R&D Community Benefits Plan
- Task 3: Design of the integrated process (process modeling, MRV)
- Task 4: Initial assessment of potential biological impacts
- Task 5: Regulatory and permitting analysis, environmental health & safety
- Task 6: Preliminary life cycle and techno-economic analyses & technology gap analysis
- In Phase 1 (Conceptual Design and Feasibility), we will refine the conceptual design of the pilot scale system and evaluate the feasibility of deployment by assessing approaches for MRV and potential impacts to marine ecosystems, and performing life cycle (LCA), technoeconomic (TEA), and technology gap analysis (TGA), as well as regulatory and safety analyses.

# Progress and Current Status of Project: Quantifying and Verifying Net CDR

$$\textbf{Total Carbon Removal}_{\textbf{CO2e}} = \textbf{Drawdown}_{\textbf{CO2e}} - \textbf{Emissions}_{\textbf{CO2e}}$$

Net extent of CDR effected by the process

Sum of total dissolved $CO_2$ and total solid $CO_2$ sourced from the atmosphere that is permanently stored

Quantified using multiple on-stream, and real-time sensors and additional, off-line sensors to provide measurement redundancy and certainty

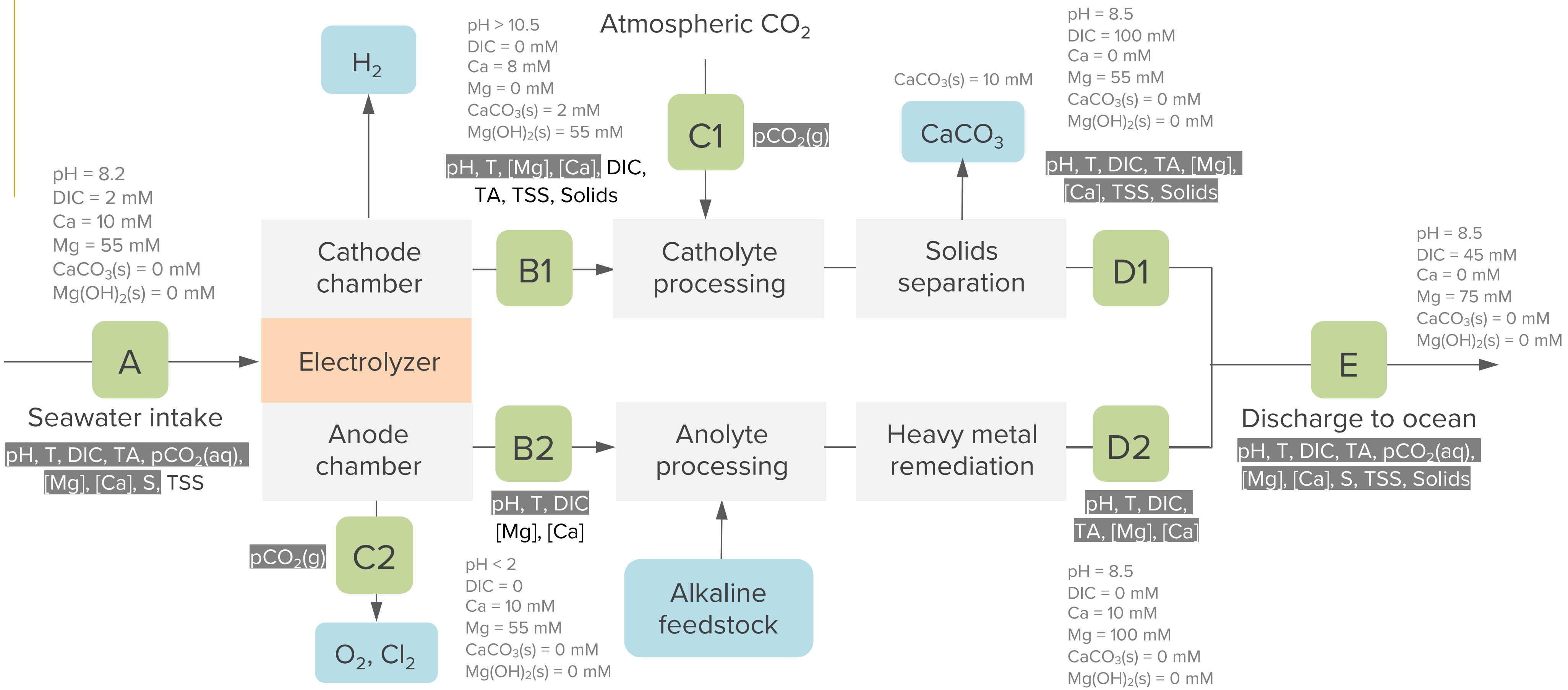
Net embodied $CO_2$ emissions from materials and energy use

- Electricity to operate and maintain electrolyzers and balance of plant
- Grinding rock, if applicable
- Transporting ground rock
- Building of CDR plant

# Methods of Measurement, Reporting, and Verification

- MRV for carbon budgeting is centered around additionality vs. counterfactual
- MRV strategy for this technology is divided into two parts:
  - ISBL (inside battery limits)
  - OSBL (outside battery limits)
- ISBL measurements quantify CDR based on the difference between the composition of the inlet and outlet streams.
  - The expectation is that carbon additionality will occur primarily ISBL.
- OSBL measurements are essential to quantify the extent of any CDR reversal upon mixing the discharge with ambient seawater.
  - The OSBL carbon budget might be expected to be either positive or negative depending on the discharge composition and interactions with the marine environment.

# Inside Battery Limits MRV



Seawater intake

A

pH = 8.2
DIC = 2 mM
Ca = 10 mM
Mg = 55 mM
$CaCO_3(s)$ = 0 mM
$Mg(OH)_2(s)$ = 0 mM

pH, T, DIC, TA, $pCO_2(aq)$, [Mg], [Ca], S, TSS

Electrolyzer

Cathode chamber

$H_2$

Anode chamber

C2

$pCO_2(g)$

$O_2$, $Cl_2$

B1

pH > 10.5
DIC = 0 mM
Ca = 8 mM
Mg = 0 mM
$CaCO_3(s)$ = 2 mM
$Mg(OH)_2(s)$ = 55 mM

pH, T, [Mg], [Ca], DIC, TA, TSS, Solids

Atmospheric $CO_2$

C1

$pCO_2(g)$

Catholyte processing

Solids separation

$CaCO_3$

$CaCO_3(s)$ = 10 mM

D1

pH = 8.5
DIC = 100 mM
Ca = 0 mM
Mg = 55 mM
$CaCO_3(s)$ = 0 mM
$Mg(OH)_2(s)$ = 0 mM

pH, T, DIC, TA, [Mg], [Ca], TSS, Solids

B2

pH, T, DIC [Mg], [Ca]

pH < 2
DIC = 0
Ca = 10 mM
Mg = 55 mM
$CaCO_3(s)$ = 0 mM
$Mg(OH)_2(s)$ = 0 mM

Anolyte processing

Alkaline feedstock

Heavy metal remediation

D2

pH, T, DIC, TA, [Mg], [Ca]

pH = 8.5
DIC = 0 mM
Ca = 10 mM
Mg = 100 mM
$CaCO_3(s)$ = 0 mM
$Mg(OH)_2(s)$ = 0 mM

E

Discharge to ocean

pH = 8.5
DIC = 45 mM
Ca = 0 mM
Mg = 75 mM
$CaCO_3(s)$ = 0 mM
$Mg(OH)_2(s)$ = 0 mM

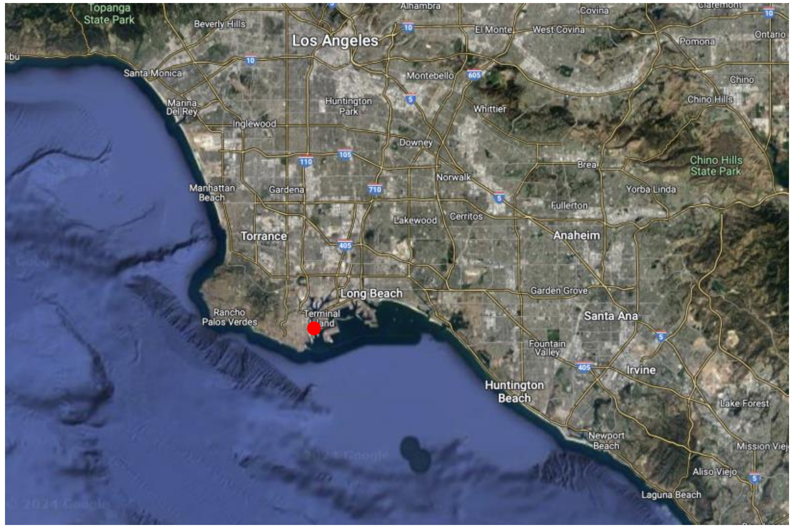
pH, T, DIC, TA, $pCO_2(aq)$, [Mg], [Ca], S, TSS, Solids

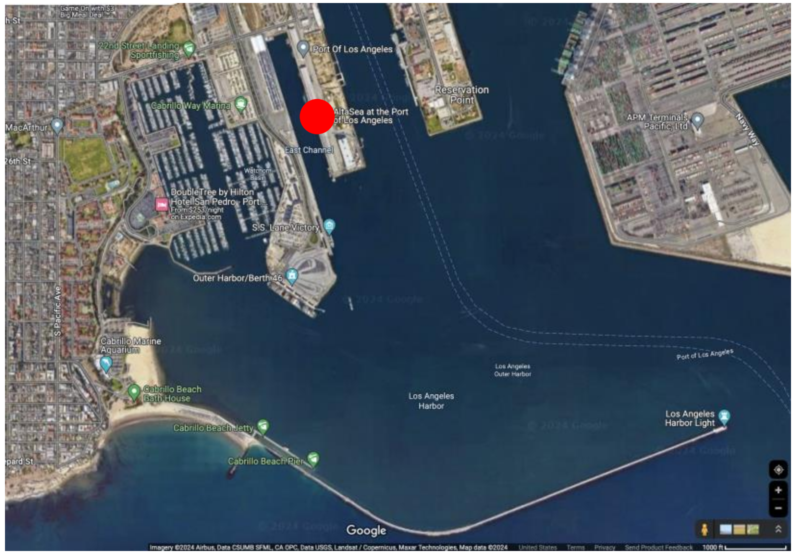
# Outside Battery Limits measurements to support ISBL MRV

- The discharge will modify surface $pCO_2$ directly through the nonlinearity of inorganic carbon equilibrium.
  - A conservative mixing model between the two expected end-member compositions with the same $pCO_2$ results in a lowered $pCO_2$ at intermediate mixing ratios
- Precipitation of carbonate minerals in the mixing zone removes alkalinity. This process will result in elevated $pCO_2$ in the mixing zone and may drive $CO_2$ outgassing (loss) from the surface ocean.
- Biological feedback may alter surface ocean net community production and therefore the net biological uptake of DIC from the surface ocean. This effect could have either a positive or negative sign.
- Other effects expected to be of smaller magnitude include alteration to the alkalinity flux across the sediment-water interface and changes to dissolved organic carbon cycling.

# Outside Battery Limits Measurements

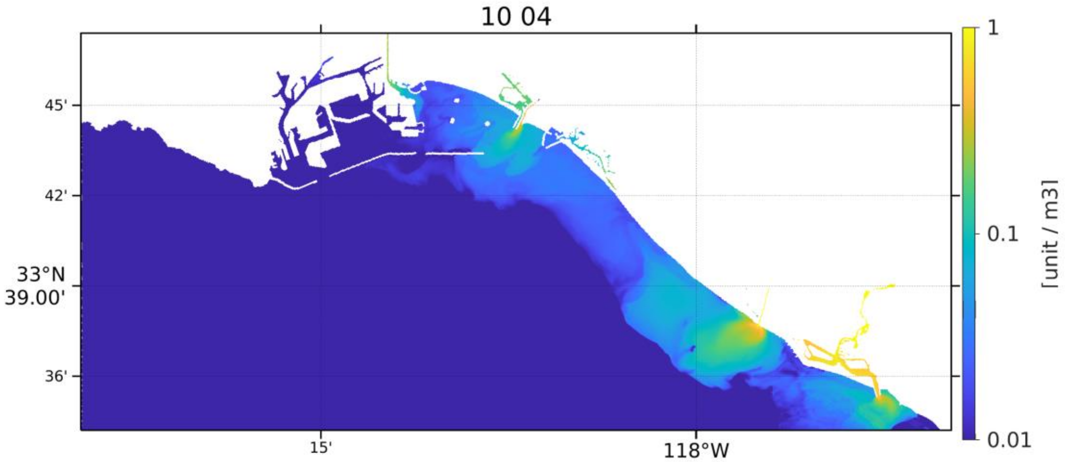
1. Circulation model simulation with a passive tracer to understand flow, mixing, and residence time upon discharge
2. Based on the circulation model, a dye tracer study with extensive sampling will be carried out for several days
3. Parameterized biogeochemical model simulation will be used to match direct measurements from the dye tracer study.
4. The results from above will be used to identify long-term monitoring locations





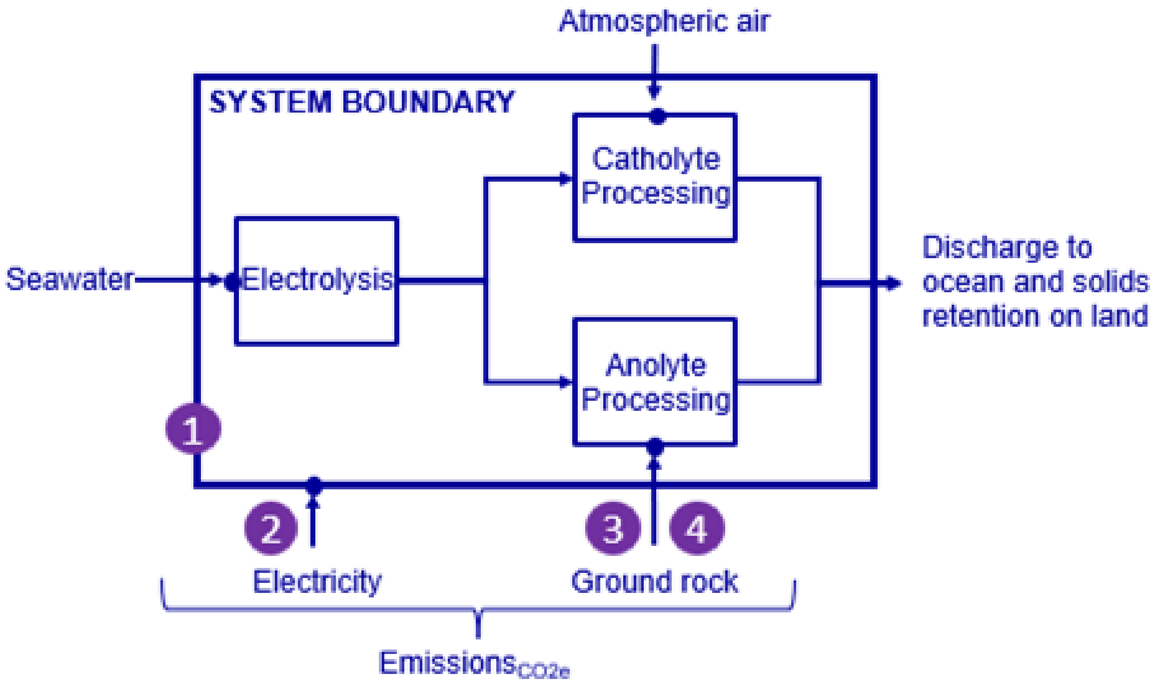
# OSBL modeling

- Footprint of seawater perturbed by discharge
- Ecosystem impact thresholds obtained from experiments will be used to interpret model
- Ecosystem parameterization:
    - Model scenarios with biological feedback to evaluate effects on net primary production, relative distribution of phytoplankton groups, as well as the nutrient, carbon, and oxygen cycles

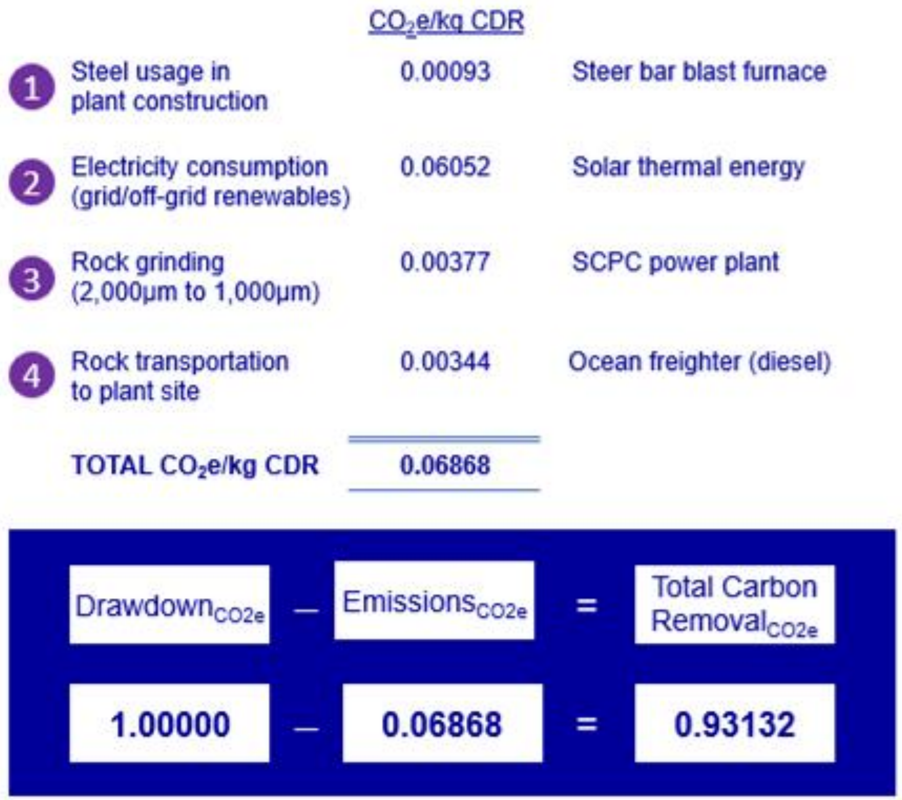


# Net CDR evaluated using LCA

## System boundary of Equatic inputs and outputs that will be assessed for the Life Cycle Analysis



## Cradle-to-gate and cradle-to-grave life cycle impacts will be validated by a third party (*OpenLCA figures*)



| | | $CO_2$e/kg CDR | |
|---|---|---|---|
| 1 | Steel usage in plant construction | 0.00093 | Steer bar blast furnace |
| 2 | Electricity consumption (grid/off-grid renewables) | 0.06052 | Solar thermal energy |
| 3 | Rock grinding (2,000μm to 1,000μm) | 0.00377 | SCPC power plant |
| 4 | Rock transportation to plant site | 0.00344 | Ocean freighter (diesel) |
| | **TOTAL $CO_2$e/kg CDR** | **0.06868** | |

$$\text{Drawdown}_{CO2e} - \text{Emissions}_{CO2e} = \text{Total Carbon Removal}_{CO2e}$$

$$1.00000 - 0.06868 = 0.93132$$

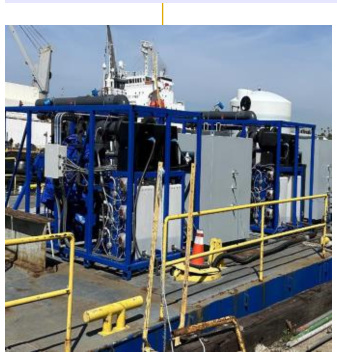
# Summary of Community Benefits and Societal Considerations and Impacts

- Milestones (at the end of Phase 1):
  - Quality Jobs: Narrative describing pathways for providing quality jobs
  - DEIA: >90% of personnel staffed to the project have received implicit bias training
  - Justice 40 Initiative: Narrative describing approaches to assess impacts
  - Community Engagement: Host an open house at the AltaSea campus

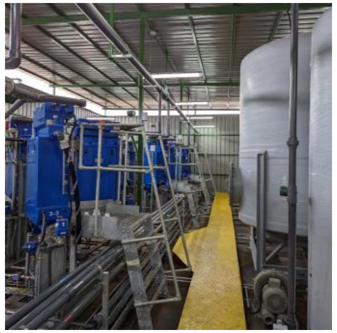
# Future Development and Commercialization

## Pilot

2023



**Pilot #1**
**Los Angeles**
**March 2023**



**Pilot #2**
**Singapore**
**April 2023**

100 kg CDR per day
3 kg of hydrogen per day

## Demonstration

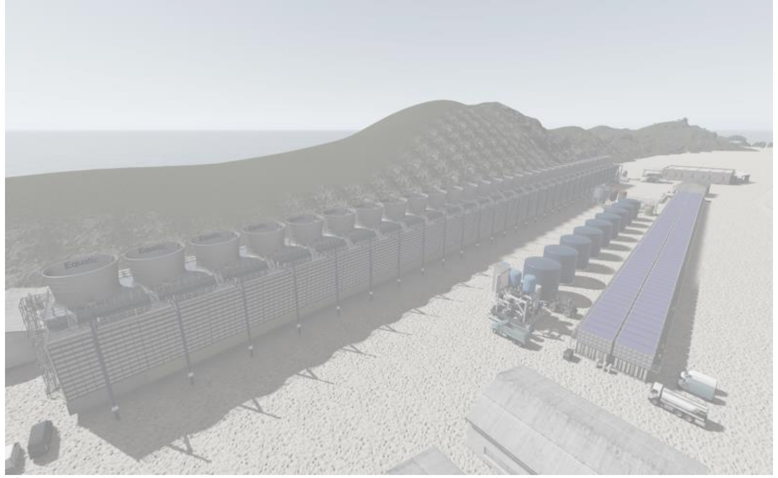
2024-2025

**“Equatic-1” Singapore**

10 tonnes of CDR per day
300 kg of hydrogen per day

## Commercial

2026+



**Future Equatic plant**

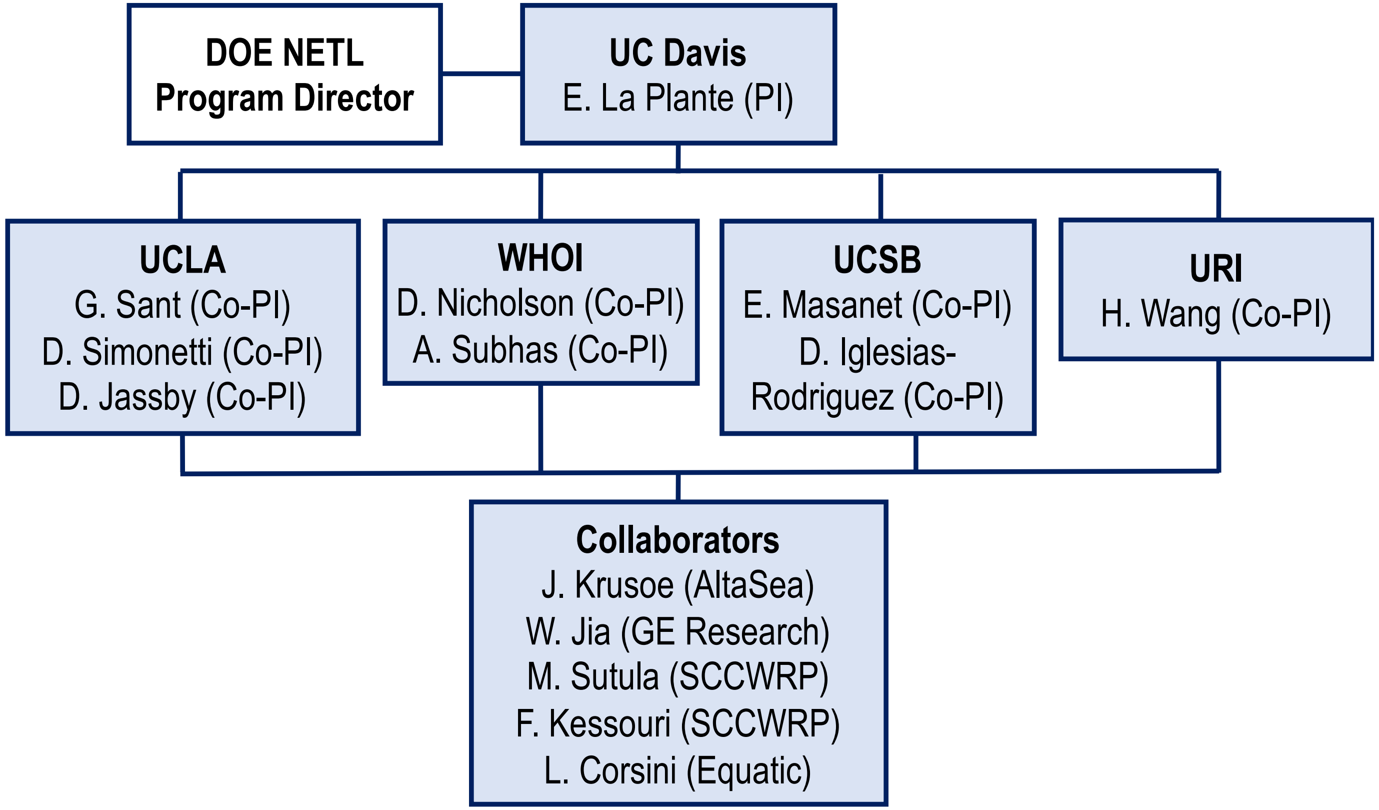
300 tonnes of CDR per day
9 tonnes of hydrogen per day

# Summary

- The proposed technology has the following attractive features:
  1. Utilizes processes and materials that maximize the durability of carbon removed from air and stored in the ocean, by storing $CO_2$ as mineral carbonates and dissolved inorganic carbon that are stable for 10,000 to > millions of years
  2. Minimizes environmental risks to ecosystems by minimizing oceanic perturbations and counteracting ocean acidification
  3. Can be deployed off-shore using renewable energy sources
  4. Minimizes land/environmental footprint while maximizing CDR
  5. Can be integrated with existing or new infrastructure for deployment of solids or solutions into seawater, such as desalination
  6. Minimizes energy requirements by process intensification
  7. Explicitly considers carbon accounting and MRV
- Phase 2 will implement MRV strategies formulated in Phase 1 in an integrated system

# Organization Chart

- We enlist a diverse team of engineers, geochemists, marine scientists: chemical, physical, and biological oceanographers, LCA experts, social considerations and impacts (SCI) specialists, and technology developers



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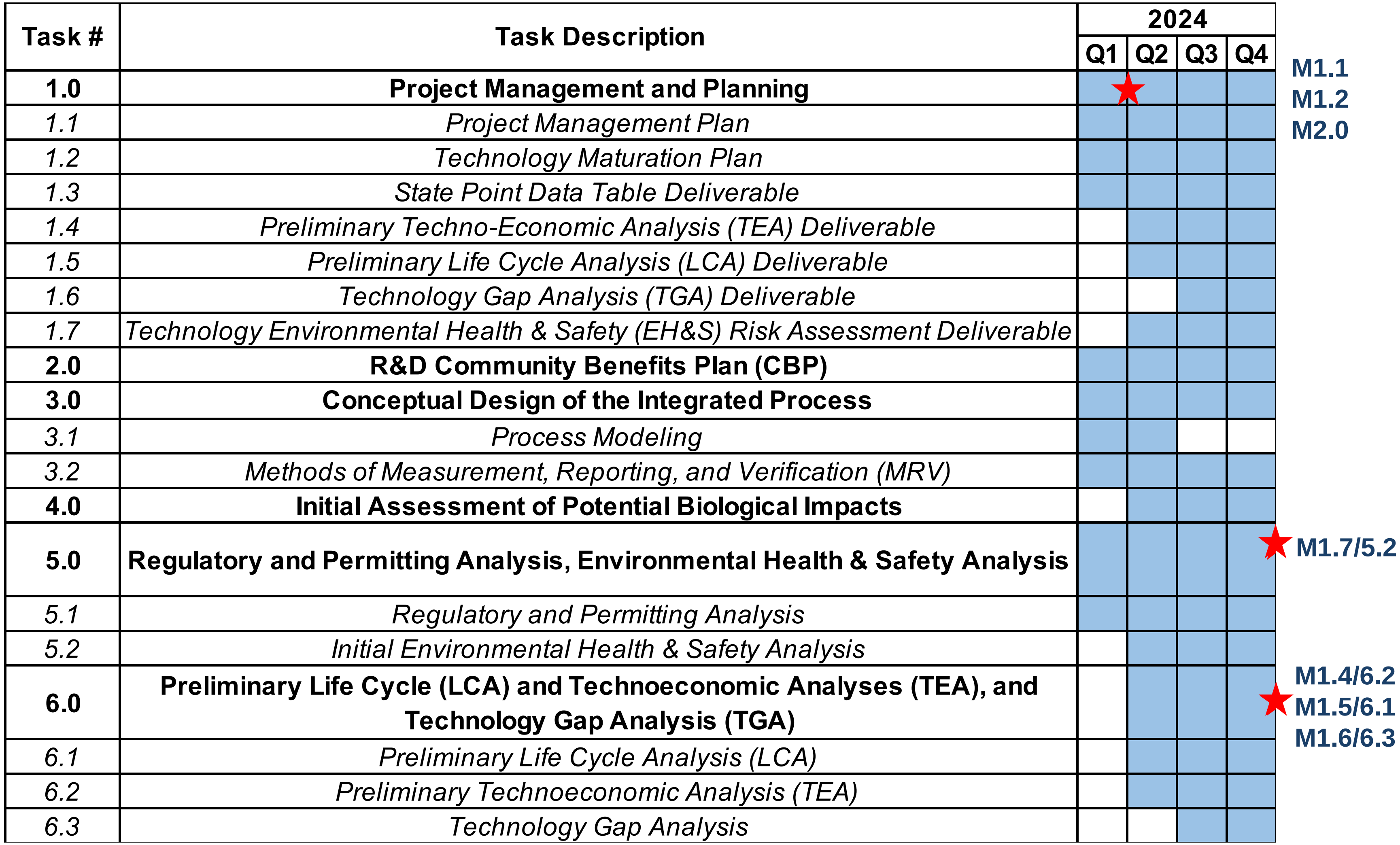
# Gantt Chart



| Task # | Task Description | 2024 | | | | |
|---|---|---|---|---|---|---|
| | | Q1 | Q2 | Q3 | Q4 | |
| **1.0** | **Project Management and Planning** | ■ | ★ ■ | ■ | ■ | M1.1<br>M1.2<br>M2.0 |
| *1.1* | *Project Management Plan* | ■ | ■ | ■ | ■ | |
| *1.2* | *Technology Maturation Plan* | ■ | ■ | ■ | ■ | |
| *1.3* | *State Point Data Table Deliverable* | ■ | ■ | ■ | ■ | |
| *1.4* | *Preliminary Techno-Economic Analysis (TEA) Deliverable* | | ■ | ■ | ■ | |
| *1.5* | *Preliminary Life Cycle Analysis (LCA) Deliverable* | | ■ | ■ | ■ | |
| *1.6* | *Technology Gap Analysis (TGA) Deliverable* | | | ■ | ■ | |
| *1.7* | *Technology Environmental Health & Safety (EH&S) Risk Assessment Deliverable* | | ■ | ■ | ■ | |
| **2.0** | **R&D Community Benefits Plan (CBP)** | ■ | ■ | ■ | ■ | |
| **3.0** | **Conceptual Design of the Integrated Process** | ■ | ■ | ■ | ■ | |
| *3.1* | *Process Modeling* | ■ | ■ | | | |
| *3.2* | *Methods of Measurement, Reporting, and Verification (MRV)* | ■ | ■ | ■ | ■ | |
| **4.0** | **Initial Assessment of Potential Biological Impacts** | | ■ | ■ | ■ | |
| **5.0** | **Regulatory and Permitting Analysis, Environmental Health & Safety Analysis** | ■ | ■ | ■ | ■ ★ | M1.7/5.2 |
| *5.1* | *Regulatory and Permitting Analysis* | ■ | ■ | ■ | ■ | |
| *5.2* | *Initial Environmental Health & Safety Analysis* | | ■ | ■ | ■ | |
| **6.0** | **Preliminary Life Cycle (LCA) and Technoeconomic Analyses (TEA), and Technology Gap Analysis (TGA)** | | ■ | ■ | ■ ★ | M1.4/6.2<br>M1.5/6.1<br>M1.6/6.3 |
| *6.1* | *Preliminary Life Cycle Analysis (LCA)* | | ■ | ■ | ■ | |
| *6.2* | *Preliminary Technoeconomic Analysis (TEA)* | | ■ | ■ | ■ | |
| *6.3* | *Technology Gap Analysis* | | | ■ | ■ | |