U.S. Department of Energy
Advanced Research Projects Agency – Energy (ARPA-E)

Request for Information (RFI)
DE-FOA-0002728
on
Novel Approaches to Measurement, Reporting and Validation for Marine Carbon Dioxide Removal

Introduction

The purpose of this RFI is to solicit input for a potential future ARPA-E research and development program focused on supporting new technologies to measure, report, and verify distributed carbon dioxide removal (CDR) processes in the deep ocean. ARPA-E is seeking information at this time regarding transformative and implementable technologies that could:

- Enable physics-based or reagent-less carbon sensing rapidly and/or in wide swaths to track the formation of carbon-rich plumes in the water column created through one or more CDR processes, as well as its journey to and deposition/fate on the seafloor, if applicable. Technologies could be applicable to both in-water and seabed sensing.
- Facilitate full-ocean-depth carbon flux sensing by enabling inexpensive, scalable, depth-agnostic, autonomous sensor platforms that can operationally persist via energy harvesting in the pelagic deep ocean environment.
- Provide regional ocean modeling to incorporate new sensor data streams for improved estimation accuracy in tracking carbon fates and other environmental effects.

The goal of this potential program is to support the nascent marine CDR industry by developing sensor technologies and approaches to quantify and verify the full-ocean-depth carbon flux from marine CDR systems. This validation is critical to assign certifiable value to CDR technologies, which would otherwise have no quantifiable financial value and be unable to participate in a carbon market.

Program Background

The ocean is the largest carbon sink on the planet and has already absorbed approximately 40% of the anthropogenic carbon dioxide emitted into the atmosphere.[1] Enhancing and facilitating the ocean's natural carbon storage processes offers a promising addition to terrestrially-based carbon capture and storage systems. Several marine CDR techniques are currently under development, including but not limited to ocean nutrient fertilization, artificial upwelling and downwelling, seaweed cultivation, recovery of marine ecosystems, ocean alkalinity enhancement, and electrochemical engineering approaches.[2] This list is not meant to be exhaustive, however, as ARPA-E is also interested in measurement, reporting and verification (MRV) technologies targeting other CDR techniques, including those not described in the NASEM 2021 report titled "A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration".

---

[1] McKinley, G. A., Fay, A. R., Eddebbar,Y. A., Gloege, L., & Lovenduski, N. S.(2020). External forcing explains recent decadal variability of the ocean carbon sink. AGU Advances, 1, e2019AV000149. https://doi.org/10.1029/2019AV000149

[2] National Academies of Sciences, Engineering, and Medicine. 2021. A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration. Washington, DC: The National Academies Press. https://doi.org/10.17226/26278.

Regardless of CDR technique, tracking the lifecycle of ‘removed’ carbon will be required by the carbon market to validate sequestration quantity and permanence for marine CDR methods as carbon markets cannot effectively incorporate marine CDR if this capability does not exist. This is not currently achievable to the degree required to assign robust value at sufficient scale with existing technologies (see Tables 1 and 2 below) and transformational improvements are needed. MRV of ocean CDR requires integrated sensors and platforms to enable measurements of carbon concentrations potentially throughout the entire water column and on the sea floor. ARPA-E is exploring opportunities for innovation in carbon sensing and deep ocean platform technologies. Data collected from these MRV systems will require regional ocean models to extrapolate these values to the total carbon removed by a specific marine CDR system, and estimate timescales associated with this removal. Therefore, ARPA-E is also seeking information on the capabilities and limitations of biogeochemical ocean models for the accurate estimation of ocean CDR processes and related environmental effects, and potential techniques for assimilating large-scale, time-varying datasets from volumetric ocean monitoring systems.

Carbon Sensing

Transformative methods of sensing ocean carbon parameters for MRV are required to support large-scale marine CDR, to quantify the amount and rates of carbon sequestered and therefore assign value to these technologies in a carbon market.[3]

The ocean carbon parameters being considered for MRV in this RFI include:

- Dissolved Inorganic Carbon (DIC) components including pH, pCO2, carbonate/bicarbonate
- Dissolved Organic Carbon (DOC), with a focus on total carbon mass per unit volume.
- Particulate Organic Carbon (POC) density, downward velocity and carbon fraction of particulates/flocculates
- Total Alkalinity (TA)
- Seafloor sediment carbon fraction

Other ocean carbon parameters may be suggested in addition to this list, but parameters must be explicitly linked to proposed marine CDR techniques. Present-day methods of quantifying these variables can be very accurate but are limited in spatio-temporal scope and would not be conducive to tracking regional-scale, downwelling plumes of carbon-enhanced water and resultant carbon fates. In addition, re-calibration constraints, limited reagent supplies and Size, Weight, Power and Cost (SWaP-C) can limit the use cases of these technologies.

ARPA-E is interested in physics-based or reagent-less solid-state ocean carbon and related chemical sensing technologies that can leapfrog capability from the largely ship-based, point-source measurements taken today to enable the quantification and tracking of a carbon-rich plume from formation to deposition, remineralization or otherwise. Notional metrics for deep ocean carbon sensors are listed below.

---

[3] For a synopsis of marine CDR techniques, the reader is directed to the National Academy of Sciences report titled “A research strategy for ocean-based carbon dioxide removal and sequestration, 2021”.

Table 1. Metrics for Deep Ocean Sensing

	SOA Sensor Metrics[4]	Notional ARPA-E Sensor Metrics
1D: distance/time @ resolution	1 km/h @10 metres/sample	1 km/h @ 25 mm/sample (100ms)
2D: area/time	N/A	0.25 km^2/h
3D: volume/time	N/A	0.125 km^3/h
pH accuracy	0.02	0.04
Time required per sample	0.1s – 12 min.	Instantaneous – 100ms
Sample distance from sensor	Flow-through or direct contact	10mm – km
Operating temperature (°C)	0 – 50	-1.9 – 50
Calibration drift time constant	Variable	None required or autonomous recalibration
Size	~0.3m^3	< 1000 cc
Weight (kg)	3 – 10	< 1
Power (W)	0.4 – 10 continuous	< 1 continuous or averaged
Consumable duration	N/A to 600 measurements	N/A
Maximum depth (m)	Typically <1000	6,000 ('full ocean depth')

Autonomous Marine Platforms

The at-sea MRV of enhanced downwelling carbon and carbon fates on the sea floor will require persistent unmanned sensor platforms capable of routinely operating at full ocean depth (i.e., to 6000 m). Current deep ocean access is challenging as platform deployment is limited primarily by cost and secondly by a lack of endurance due to propulsion inefficiencies and the limited power density of existing battery systems. In order to minimize validation costs on the future marine CDR industry, ARPA-E is exploring autonomous platforms that are inexpensive and mass-producible, highly autonomous, and persistent in that they incorporate energy harvesting systems that can extend endurance to a potentially indefinite period. Proposed metrics for a new generation of deep ocean platforms are listed below.

Table 2. Metrics for Deep Ocean Platforms

	SOA Platform Metrics[5]	Notional ARPA-E Platform Metrics
Endurance @ 2 knots	10 hours mission duration	> 6 months mission duration
Procurement cost ($/unit)	3 million	< 200k, scaled to < 20k @ 1,000 units
OpEx/Day ($)	50-90K, including ship	<1,000[6]
Size	3-5m length, 12" diameter	< 2 m length
Weight (kg)	300+	< 100
Energy Harvesting	No	Yes

CDR Modeling

To accurately process and interpret the data collected from these sensor-platform systems, regional ocean models (ROMs) that can perform best-estimate simulations of ocean carbon flux are required. ARPA-E seeks input on the state-of-the-art in ROM biogeochemical modeling of carbon flux and ocean carbon processes to inform minimum data and spatiotemporal scaling requirements for deep ocean sensing systems. Emphasis is placed on the simulation of carbon removal processes likely to remove

---

[4] Based on conversations with academia and industry and therefore may not fully encompass SOA.

[5] e.g. 6000m capable, modified REMUS 600

[6] i.e., one remote operator for entire network

carbon from the atmosphere and surface oceans for periods of 100 years or longer. Information on the gaps in and limitations of these models is also sought.

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below. Please note, in particular, that the information you provide will be used by ARPA-E solely for program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME.**

Purpose and Need for Information

The purpose of this RFI is solely to solicit input for ARPA-E consideration to inform the possible formulation of future research programs. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI without any attribution to the source. This RFI provides the broad research community with an opportunity to contribute views and opinions.

REQUEST FOR INFORMATION GUIDELINES

No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E may contact respondents to request clarification or seek additional information relevant to this RFI. All responses provided will be considered, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents shall not include any information in the response to this RFI that could be considered proprietary or confidential..**

Responses to this RFI should be submitted in PDF format to the email address **ARPA-E-RFI@hq.doe.gov** by **5:00 PM Eastern Time on April 14, 2022**. Emails should conform to the following guidelines:

- Please insert “Responses for Marine Carbon Sensing RFI” in the subject line of your email, and include your name, title, organization, type of organization (e.g., university, non-governmental organization, small business, large business, federally funded research and development center (FFRDC), government-owned/government-operated (GOGO), etc.), email address, telephone number, and area of expertise in the body of your email.
- Responses to this RFI are limited to no more than 10 pages in length (12-point font size).
- Responders are strongly encouraged to include preliminary results, data, and figures that describe their potential processes.

Questions

ARPA-E is interested in surveying stakeholders interested in technologies to quantify the efficacy of marine CDR techniques within the scope of approaches outlined above. The questions posed in this section are classified into several different groups as appropriate. Please provide responses and information about any of the following. We do not expect any one respondent to answer all, or even many, of these prompts. Simply indicate the group and question number in your response. Citations are encouraged as appropriate. Respondents are also welcome to address other relevant avenues/technologies that are not outlined below. For questions referring to specific CDR techniques, please specify which CDR technique is being referenced. If referencing a CDR technique that is not included in the Program Background Section, please provide up to a one-page summary of the CDR technique, along with any applicable citations.

General Approach

1. Are the metrics listed in the Background section for sensors and platforms appropriate for describing the state of the art, and aggressive enough to require transformative advancement? Are there parameters missing?
2. Are there other marine CDR approaches we should focus on besides the six cited by the National Academies and listed in the Program Background? If so, what would be considered viable over the next 50 years?
3. How would you integrate a temporal component into the underwater validation of carbon sequestration in order to best resolve marine carbon fates over a timeframe conducive to a carbon market? i.e., Carbon with a 1,000-year period of removal would potentially be worth more than 10-year carbon, but quantification must happen fast enough for the continuation of business operations.

Survey Region

4. How could the minimum viable spatio-temporal boundaries for ocean processes with respect to marine CDR be determined for each technique? For example, would a boundary encompassing expected water movement for one year originating from the CDR site, above a depth from which re-surfacing of carbon would most likely occur over more than 100-year timescales, be a reasonable starting point?
5. What area/volume and temporal durations need to be covered for a particular marine CDR event? Does this vary significantly by the type (please specify) of CDR event?
6. Are there approaches to estimate which marine areas conducive to marine CDR, are also conducive to MRV? How could physical, environmental as well as shared use, logistical and regulatory features of an area be incorporated into planned MRV activities?

Carbon Sensing Parameters

7. Are different types of sensing required for the different forms of carbon in the ocean? If so, what needs to be sensed for each form of carbon (DIC, DOC, POC, PIC), for each marine CDR approach?
    a) What are the minimum parameters that need to be quantified for each CDR technique?
    b) What precision and accuracy must these parameters be measured with, given the anticipated speed and coverage requirements of marine CDR MRV?
8. In regions likely to be most conducive to each marine CDR approach, what are the spatio-temporal scales of oceanographic variability in the carbon forms above? To what degree will they skew observations in the event that measurements are restricted in spatial and/or temporal resolution?
9. Are there scalable undersea options for sensing the carbon atoms themselves, irrespective of form? For example, some spectroscopy techniques can provide elemental concentration irrespective of how those elements are bound in molecule form.
10. What challenges may be associated with measuring organic and inorganic carbon associated with organisms that mineralize silica or carbonate (e.g., diatoms and coccolithophores)? Are there any solutions to these challenges that do not involve frequent, direct sampling?

Carbon Sensing Technologies

11. What technologies exist for deep ocean sensing of pH, alkalinity, pCO_2, DOC, and DIC? What is the potential for scaling these technologies, and what are the technology gaps and physical limitations?
    a) Apart from SWAP-C, are there specific technical approaches to ocean carbon sensing that are fundamentally limited by depth?
    b) How do SWAP-C parameters currently limit the deployment duration of ocean carbon sensing systems?
    c) What indirect methods could quantify sequestration in seafloor sediments (i.e., carbon fraction vs. depth) on or slightly under (i.e., "recent", see 13d) the seabed?
12. How do we improve the spatio-temporal scope of present-day ocean carbon sensing methods?
    a) What methods or technologies could enable indirect or displaced, swath sensing of in-water carbon parameters in the deep ocean, vs. point sourced sensing?
    b) What large-aperture stationary sensing approaches utilizing volumetrically integrative or distributed sensing capability may be applicable for pH, alkalinity, pCO_2, DOC or other relevant parameters?
    c) How can the tradeoff between the minimum required spatio-temporal sampling regime, surveying speed, sensor capability and endurance in a given environment be framed and compared in a multi-dimensional optimization framework? How could we characterize the relative importance of the relationships between each variable?
13. What sensing modalities show promise for transformative deep ocean carbon flux sensing?
    a) What physics-based or reagent-less, direct or inferential sensing approaches for seawater carbon variables may be feasible? Can these measurements be displaced (i.e., the sensor is not coincident with the sampled water volume)? Will these measurements be integrative (i.e., acoustic thermometry) or will they provide range resolution (i.e., LIDAR or tomography)? For suggested approaches, please include estimates of the area/volume per unit time that could be surveyed and estimated measurement settling times, if any.
    b) What sensing approaches could facilitate instantaneous or almost instantaneous direct-contact, point-measurement approaches, suitable for quantifying carbon flux from fast-moving undersea platforms?
    c) What direct-contact sensing approaches could offer large-scale distributed sensing array concepts utilizing a single platform, moving or stationary?
    d) What rapid, non-contact and zero-disturbance methods exist for high resolution evaluation of the carbon concentration in recent seafloor sediment layers? In this case, "recent" and "high resolution" refer to the capability necessary to resolve changes in seafloor carbon deposition and sequestration due to discrete, anthropogenically driven carbon transport events.
14. What is the most appropriate sensing platform configuration (Lagrangian, depth cycling, powered mobile sensor, or network of platforms) for each marine CDR method and what is the justification for the optimal configuration presented? Is there overlap between optimal methods i.e., could one sensor network be used to perform MRV on multiple CDR approaches?
    a) What are the strengths and weaknesses of each of the approaches in (14) for a particular CDR system?

    b) Is there a multi-platform approach that may enable adequate MRV performance with lower total capital expenditure, and if so, what would the approach look like and what are the techno-economic advantages compared to a homogeneous system?

15. Are there potential carbon sensing methods that can identify what fraction of undersea measured carbon may have been recently transported across the air-sea boundary as opposed to carbon that has resided in the ocean for a longer period of time?

Platforms

16. What design optimization approaches could minimize SWAP-C and maximize area/volume surveyed per cost for the longest duration, for platforms capable of persistent full-ocean depth operation?
    a) What new technologies if any are being developed that may mitigate the need for the highest-cost components of today's autonomous underwater data collection systems?? In your responses please specify which components are targeted.
    b) Are there compact, hydrodynamic vehicle design and component strategies that minimize component buoyancy differential, potentially negating the need for syntactic foam as a buoyancy compensator in full ocean depth platform applications?
    c) What unique platform requirements does carbon flux sensing impose over other purposes, if any?
    d) What platform operational and data collection strategies may be optimal for large-volume, continuous MRV of marine CDR?
    e) Are there evolutionary selection pressures that are analogous to deep ocean MRV mission requirements? Thus, are there biological analogues that could be drawn from to develop viable hardware configurations and operational profiles?
17. What hydrostatic pressure-agnostic technologies exist for electronic circuitry, propulsive and control actuators, and optical sensors that may have previously required an air gap?
    a) What is the essential componentry that requires protection through a pressure vessel, and can these components be replaced by solid-state equipment that is agnostic to hydrostatic pressure?

Platform Ancillary Systems

18. What is the minimum navigational precision and accuracy required and what technology is available to provide this capability at full ocean depth over the envisaged ranges (100's of km)?
19. What environmental energy sources exist in the pelagic ocean that could be harvested for persistent operation of a mid-size, actively propelled, underwater autonomous platform (i.e., on the order of kWh/day), or a smaller drifting or vertically profiling platform capable of full ocean depth (i.e., on the order of Wh/day)? What operational strategies are required to exploit these energy sources?
    a) What energy harvest approaches are most relevant for carbon sensing platforms? How does the powering/energy source change with different CDR methodologies?
20. What energy storage systems will enable operation at full ocean depth with minimal buoyancy compensation, capable of storage capacities on the order of kWh/day for actively propelled systems or Wh/day for Lagrangian/profiling systems?
21. What reliable, low-power, repeatable communication methods exist or may be feasible from full-ocean depth platforms to persistent high altitude or satellite data networks?

22. Are there MRV scenarios in which high-bandwidth, underwater communication is required and if so, what options exist for both small numbers of high-speed and/or large numbers of low-speed platforms?

<u>Modeling</u>

23. What is the minimum suite of parameters that a regional ocean carbon flux model must include in order to capture the carbon fluxes originating from CDR activities?
24. At what spatio-temporal scales do resolution enhancements yield diminishing returns for regional-scale CDR activities?
25. What appropriate biogeochemical ocean models are available that could be utilized to assist in CDR MRV?
    a) What biogeochemical and oceanographic models for marine CDR techniques exist with an emphasis on estimating which chemical oceanographic variables should be prioritized as sampling targets?
    b) How can existing biogeochemical models integrate with new measurements to enhance estimation accuracy for CDR MRV?
    c) Are there regional ocean models that have already been developed to estimate processes and outcomes that result from CDR? If so, which CDR processes do they address and how could these models be strengthened through incorporation of observed data?
    d) Are there significant variations between modeled and observed regional biogeochemical parameters today? What are the current shortcomings in regional ocean models and how may they impact carbon flux modeling?
26. What concepts regarding hybrid environmental-sampling and modeling techniques could offer cost-effective yet robust methods of quantifying marine CDR success?
27. How could statistical models and/or machine learning approaches reduce the minimum resolution, scale, precision of measurements, etc. required to determine carbon additionality with a given marine CDR method? What training data or validation by independent variables could strengthen a machine learning approach?
28. Are there modeling approaches that can estimate the effectiveness of a marine CDR approach (i.e., underwater carbon ‘removal’) for removing atmospheric carbon at relatively short timescales across the air-sea interface? How could these modeling approaches be coupled to in-situ, underwater MRV data in order to evaluate the impact of marine CDR on atmospheric carbon quantities?

<u>Costs</u>

29. What price per ton of carbon can reasonably be assigned to MRV before the process becomes unfeasible? I.e., how could the MRV accuracy vs. cost optimization space be described?
30. How could ocean MRV dovetail with existing carbon credit approaches utilized in other environments?

<u>Other</u>

31. What is missing from this program approach? How might this concept be improved to best support the marine CDR industry?