U.S. Department of Energy
Advanced Research Projects Agency – Energy

Announcement of Teaming Partner List
for an upcoming Funding Opportunity Announcement:
SEA CO2: Sensing Exports of Anthropogenic Carbon through Ocean Observation

The Advanced Research Projects Agency – Energy (ARPA–E) intends to issue a new Funding Opportunity Announcement (FOA) (draft technical section FOA language is included as Attachment A to this document) that seeks to enable the accurate, spatially scaled and temporally persistent measurement and validation of marine Carbon Dioxide Removal (mCDR) techniques (which includes "direct ocean capture" or "DOC"), in which CO_2 is captured from the atmosphere and surface oceans before sequestration at depth. While direct air capture (or "DAC") approaches can be validated easily through direct measurement of CO_2 collected, the same cannot be said for mCDR techniques, which may involve complex reactions over a very large surface or volume of the ocean over comparatively long periods of time, during which a fraction of the carbon drawn down may be re-emitted to the atmosphere. The envisioned program aims to vastly expand our ability to measure carbon flux parameters in the ocean, enabling comprehensive Measurement, Reporting and Validation (MRV) of mCDR and the creation of a data-driven, model-based marine carbon accounting framework. This program effort would consist of a primary technical area focused on new sensor development and a supporting technical area focused on the development of targeted regional-scale marine CDR models and accompanying carbon accounting processes. Scalable, cost-effective technologies that perform MRV for various mCDR approaches are a critical need in this highly active space where claims of efficacy and permanence cannot yet be rigorously substantiated. Such technologies could also ensure that the quantity and quality of removals are correctly valued in carbon markets and support any economic incentive to accelerate the adoption of mCDR to remove historic emissions. Validation of sequestered carbon will promote the commercialization of mCDR techniques that are most effective and energy efficient in carbon removal rather than those that are merely easiest to implement but may not actually be as effective or may be so energy intensive themselves that they result in poor overall net lifetime carbon removal.

Sensor development will be geared towards enabling indirect, volumetric, or area-based (when applicable) sensing of ocean carbon flux-related parameters outlined in Table 1, beyond depths at which surface remote sensing becomes inviable, to improve large-scale quantification of marine carbon fluxes through either biological or inorganic carbon pumps. ARPA-E would look to fund the development of sensors that can characterize these parameters at rates on the order of 150 km^3/h when scaled to a one-gigaton industry, while matching the accuracy and precision of existing state-of-the-art sensors. Technologies developed under this category must be deployable at sea on commercially available platforms (e.g., off-the-shelf, Equipment-as-a-Service, etc.) down to 1000 m repeatedly or continuously for a minimum of 12 months without servicing, battery replacement, or maintenance. There will be an emphasis on wave-based inferential techniques that do not require co-location of the sensor with the sample of water being evaluated. As such, sensing approaches of interest include, but are not limited to, active or passive acoustic, multispectral optical (including luminescence spectroscopy, etc.), laser-based, distributed optical fiber, and active or passive electromagnetic systems.

Table 1. Ocean carbon flux related parameters of interest

pH	Carboxylic Acid	Fugacity of CO_2	Biologically sequestered mineralized carbon
Carbonate	Total Alkalinity	Dissolved Organic Carbon*	Vertically transported biological Carbon
Bicarbonate	Fugacity of O_2	Particulate Organic Carbon*	Sediment organic carbon*
*Emphasis on recalcitrant forms			

Model development would target regional-scale, hypothetical but realistic near-future mCDR vignettes within the United States' Exclusive Economic Zone (EEZ). Models will be developed to demonstrate viability using historical data, before being used as benchmark mCDR models that can be iterated, improved, and validated with future data collected via new sensor systems. The vignettes may include mCDR approaches described in the National Academy of Sciences report on Ocean CDR[1], or other mCDR approaches not described but that could be reasoned as techno-economically feasible given a drawdown cost of approximately $100/ton CO_2e at megaton to gigaton scale. ARPA-E would plan to fund one or more teams to develop these models. Models are expected to combine physical and biogeochemical ocean modeling, including comprehensive flux modeling of relevant parameters described in Table 1. Developed models would need to achieve a Root Mean Square Error (RMSE) value of no more than 0.1 over time and a temporal Anomaly Correlation Coefficient (ACC) of at least 0.7 when benchmarked against hold-out historical carbon parameter data, before estimates of mCDR effectiveness could be made. Model outputs will need to be developed in coordination with a carbon registry to create a data-based mCDR accounting framework that enables the assignment of credit quality and hence financial value to modeled mCDR events. Selected team(s) will be required to coordinate with a carbon registry to outline an MRV framework that can later be used as a foundation by mCDR project developers to author full protocols, which are peer-reviewed, market-ready methodologies that provide the basis for generating carbon credits. Such an assignment would require robust estimation of the quantity of CO_2 drawn down beyond a given temporal threshold (i.e., 10-year or 100-year sequestration) and an indication of the probability that a given quantity of CO_2 would remain out of the atmosphere or surface oceans for that duration.

Anticipated teams may consist of personnel with expertise and affiliations in the following areas:

Sensing technical area (primary):

- Sensor design and sensing methods for the ocean parameters listed in Table 1.
- Oceanographic instrumentation, marine biogeochemical and ecological sciences

Modeling technical area (secondary):

- Regional climate, biophysical process, and earth system modeling
- Carbon markets and registries

[1] https://nap.nationalacademies.org/catalog/26278/a-research-strategy-for-ocean-based-carbon-dioxide-removal-and-sequestration

In the first half of the program, sensor teams would develop core technologies that may enable new methods of sensing the ocean chemical parameters described in Table 1 in a volumetric or area-based manner. Initial work would culminate with a demonstration of their concept in a controlled underwater setting. The second half of the program would be focused on building the sensor into a prototype that could be fielded in increasingly realistic at-sea scenarios, culminating in an ocean test aboard an off-the-shelf instrumentation platform within a representative environment where an appropriate mCDR activity may take place.

The modeling team(s) would spend the first half of the program developing mCDR models in appropriate regional vignettes. Model performance would be evaluated using historical ambient data or pilot mCDR data, if available. The second half of the program would involve adapting these models for compatibility with data from the sensors under development and simulating the potential increase in MRV effectiveness that could be brought about using these sensors if they were matured and deployed at scale in a regional mCDR scenario. Models would also be used to develop an mCDR accounting framework using output data, evaluate potential improvements to statistical certainty, and assess preliminary implications for the techno-economic validity of the MRV approach. As such, the program would be designed such that modeling and sensor teams are required to coordinate and share data to enable this collaboration.

ARPA–E held a workshop on these topics on June 15-16, 2022. Information from this workshop can be found at the event webpage (https://arpa-e.energy.gov/events/marine-carbon-sensing-workshop). The component information remains consistent, but the scope and structure of the program have been updated from that presented in the workshop slides.

As a general matter, ARPA-E strongly encourages outstanding scientists and engineers from different organizations, scientific disciplines, and technology sectors to form project teams. Interdisciplinary and cross-sector collaboration spanning organizational boundaries enables and accelerates the achievement of scientific and technological outcomes that were previously viewed as extremely difficult, if not impossible.

The Teaming Partner List is being compiled to facilitate the formation of new project teams. The Teaming Partner List will be available on ARPA-E eXCHANGE (http://arpa-e-foa.energy.gov), ARPA-E's online application portal, starting November 18, 2022. The Teaming Partner List will be updated periodically, until the close of the Full Application period, to reflect new Teaming Partners who have provided their information.

Any organization that would like to be included on this list should complete all required fields in the following link: https://arpa-e-foa.energy.gov/Applicantprofile.aspx. Required information includes: Organization Name, Contact Name, Contact Address, Contact Email, Contact Phone, Organization Type, Area of Technical Expertise, and Brief Description of Capabilities.

By submitting a response to this Notice, you consent to the publication of the above-referenced information. **By facilitating this Teaming Partner List, ARPA-E does not endorse or otherwise evaluate the qualifications of the entities that self-identify themselves for placement on the Teaming Partner List.** ARPA-E will not pay for the provision of any information, nor will it compensate any respondents for the development of such information. Responses submitted to other email addresses or by other means will not be considered.

This Notice does not constitute a FOA. No FOA exists at this time. A draft technical section of the FOA is included as Attachment A, for potential Teaming Partners' reference. Applicants must refer to the final FOA, expected to be issued in February 2023, for instructions on submitting an application and for the terms and conditions of funding.

The draft technical section included as an attachment to this Teaming Partner List may be discussed by ARPA-E Program Director Simon Freeman on January 25, 2023, at ARPA-E's SEA CO2 Proposers & Industry Day.

ATTACHMENT A

Draft of Technical Section for Sensing Exports of Anthropogenic Carbon through Ocean Observation (SEA CO2)

B. Program Overview

Marine carbon dioxide removal (mCDR) will be an essential component of a future negative emissions industry, which alongside emissions reduction is necessary to restrict climate warming to less than 2°C and avoid global, irreversible, and catastrophic changes caused by this temperature rise. Marine carbon dioxide removal (mCDR) will be an essential component of a future negative emissions industry, which alongside emissions reduction is necessary to restrict climate warming to less than 2°C and avoid global, irreversible, and catastrophic changes caused by this temperature rise. This program seeks to accelerate the development of the mCDR industry through the development of scalable Measurement, Reporting and Validation (MRV) technologies. MRV must be of sufficient quality to quantify carbon drawdown magnitudes, the degree of permanence, and bound the uncertainties associated with these parameters so that carbon markets can ascertain credit quality and financial institutions can make informed decisions regarding investment risk. To achieve these goals, a paradigm shift in chemical oceanographic data collection is required, moving from a point collection paradigm towards a goal of persistent sensing of parameters across large areas and/or volumes.

ARPA-E considers the advancements outlined in **Table 1** below to be those that would most rapidly enable effective MRV and the robust establishment of financial value for the mCDR industry.

	Technology Development Objectives
1	Sensing approaches able to quantify relevant oceanographic properties, either volumetrically or area-wise, for seafloor or other relevant applications.
2	Large spatial scale, volumetric, or area-survey sensors capable of precision and accuracy comparable to or better than today's single-point state-of-the-art sensing approaches.
3	Sensors whose size, weight, and power requirements enable utilization on existing ocean data collection platforms.
4	Sensors capable of deployment periods exceeding one year without a reliance on physical human interaction.
5	Regionally focused models suitable for Observation System Simulation Experiments (OSSEs) that demonstrate root-mean-square errors (RMSE) and anomaly correlation coefficients (ACC) at least comparable to general state-of-the-art ocean physical and biogeochemical models available today.

Table 1. ARPA-E objectives for technological advancement in MRV for mCDR.

ARPA-E anticipates two Technical Areas (TAs) under FOA: marine carbon sensors and ocean carbon flux models. Teams may apply to one or both Technical Areas. **See Section j. Submission Checklist** under Detailed Program Objectives for required material.

Technical Area 1 will address the development of new sensors, emphasizing high-endurance spatial coverage through approaches such as (but not limited to) radiated energy-based (i.e., optical, acoustic, electromagnetic) oceanographic **sensor technologies** that enable large-scale volumetric or swath quantification of mCDR-relevant ocean chemical parameters. Sensors must operate beyond depths sensed by satellite systems, at spatial and temporal scales sufficient to transform our fundamental understanding of the ocean carbon cycle, quantify mCDR efficacy, and to reduce or eliminate under-sampling concerns that limit carbon credit quality.

Marine CDR-relevant ocean chemical parameters of interest to ARPA-E are listed in **Table 2**. Submissions for sensor technology may focus on one or more of these parameters, but integration with other mCDR-relevant chemical sensors or essential ancillary data collection systems must be feasible within the constraints imposed by the program metrics. The major milestone for TA1 teams will be a sensor proof-of-concept demonstration in a laboratory setting, and a validation of sensor performance against SOA instrumentation at sea at the end of the project.

Technical Area 2 will focus on the development of regional-scale, ocean **carbon flux models** that integrate and estimate the combined major carbon cycles (i.e., physical, inorganic chemical, micro and macro-biological) likely to be impacted by one or more selected mCDR approaches for the selected region. Regional models and accompanying hypothetical or planned mCDR approaches should be sized in the 100's of megatons to one gigaton range and constitute techno-economically realistic mCDR scenarios that may become reality within a twenty-year timeframe.

Models will be developed under this program to achieve state-of-the-art performance levels for bias and variance for carbon parameters and will form the basis for a carbon accounting framework. The final program steps for TA2 teams will be the creation of a model-based, data-driven approach to carbon accounting and associated protocols that will be utilized by mCDR carbon registries in certifying credits and assigning quality ratings. Sensor development that seeks to mitigate specific sources of uncertainty in models is also in scope, and will require close collaboration between TA1 and TA2 teams.

Table 2. Ocean carbon flux parameters of interest to this program, along with representative state-of-the-art accuracies for each parameter. Yellow entries represent technology approaches of interest to ARPA-E with respect to their improvement to volumetric capability or autonomous operation.

Parameter		SOA Accuracy	Reference[1]
pH	ISFET	± 0.001	Takeshita *et al.*, 2021, Thompson *et al.*, 2021
	Acoustic Decay	Not yet established	Duda *et al.*, 2017
Total DIC	Carbonate	± 1–2 µmol/kg	Dickson *et al.*, 2007, Wang *et al.*, 2015, Johnson *et al.*, 1992
	Bicarbonate	± 1–2 µmol/kg	
	Carboxylic acid	± 2.5 µmol/kg	
Total Alkalinity	Titration	±2–4 µmol/kg	Dickson *et al.*, 2007
	Active ISFET	Not yet established	Briggs *et al.*, 2020
Fugacity	CO_2	± 0.5 µatm	Dickson *et al.*, 2007

[1] See full description of citations in Appendix 1.

	O_2	± 0.3 mg/l	
Dissolved Organic Carbon		±4 µg/L	Dickson 2010
Particulate Organic Carbon	Mass loss	±0.1 nmol/m^3	Baker *et al*., 2017, Riley *et al*., 2012, Alldredge 1998
	Optical counting	Not yet established	Giering *et al*., 2020
Sediment carbon %		±0.1 mg/m^2	House *et al*., 2006, Wai Ting Tung *et al*., 2003, Atwood *et al*., 2020
Biologically Ingested (i.e., macro-organism vertical transport)		Not yet established	Archibald *et al*., 2019; Pinti *et al*., 2022; Hernandez-Leon *et al*., 2010

The program is designed so that sensor and model development proceed independently during the first Phase. Closer collaboration between the two technical areas is anticipated to begin in Phase 2, after sensor capability and feasibility demonstrations take place and model performance has been established. TA1 and TA2 teams may propose together or enter collaborative partnerships at the beginning of Phase 2. A high-level diagram of the program progression is shown in Figure 1.

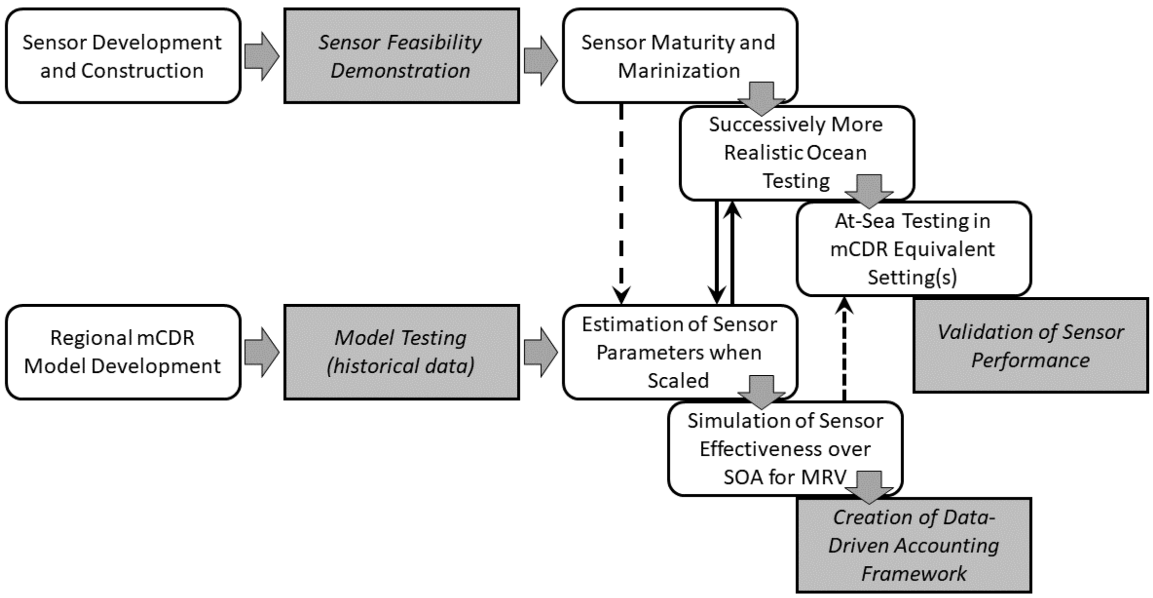

Figure 1. SEA-CO2 program design. Dashed arrows represent anticipated collaborative information transfer between TAs (coarse – sensor capability projections, fine – optimized sampling approaches). Solid arrows represent possible sensor-based mitigation of specific model uncertainties. Grey boxes represent milestones, occurring at ~18 months and project end. Acronyms: SOA – State of the Art; TEA – Techno-Economic Analysis.

The feasibility of a team's sensor technology will first be demonstrated in controlled seawater

conditions within a laboratory setting. Given that mature MRV processes are likely to rely largely on validated model outputs, teams with successful sensor demonstrations will coordinate with a TA2 team in the second half of the program. This integration will adapt the TA2 team model to estimate sensor capabilities when scaled and to conduct a simulation of sensor effectiveness over State of the Art (SOA) technology. These Observing System Simulation Experiments (OSSEs) will demonstrate the value of new MRV technology and will provide a platform for the quantification of uncertainties. Moving forward, these model outputs will inform at-sea experimental design and evaluation protocols to maximize the sampling effectiveness of future MRV approaches.

More detail on the program structure is provided in the **Program Approach** section.

a. Program Context

The IPCC has indicated that we must limit global warming to below 2 °C by 2100 to avoid significant, irreversible and negative climate change impacts to our society[2]. Achieving this goal can only occur through a combination of net-zero, and emissions abatement and removal technologies[3]. The more

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[2] IPCC, 2022: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

[3] Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian, and M.V.Vilariño, 2018: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas

aspirational goal of limiting global warming to 1.5 °C by 2070 requires even more decarbonization, both abatement and negative emissions technologies, at a much-accelerated rate. The United Nations Environment Program Emissions Gap Report 2017[4] estimated the impact of hard-to-decarbonize industries (steel, cement, air travel, shipping, etc.), and indicated that negative emissions technologies are required to offset the contribution of these, as illustrated in Figure 2. According to the National Academies report on "Negative Emission Technologies and Reliable Sequestration[5]", at least 20 Gt/yr. of CO_2 must be removed from the atmosphere by 2100 to achieve global climate goals.

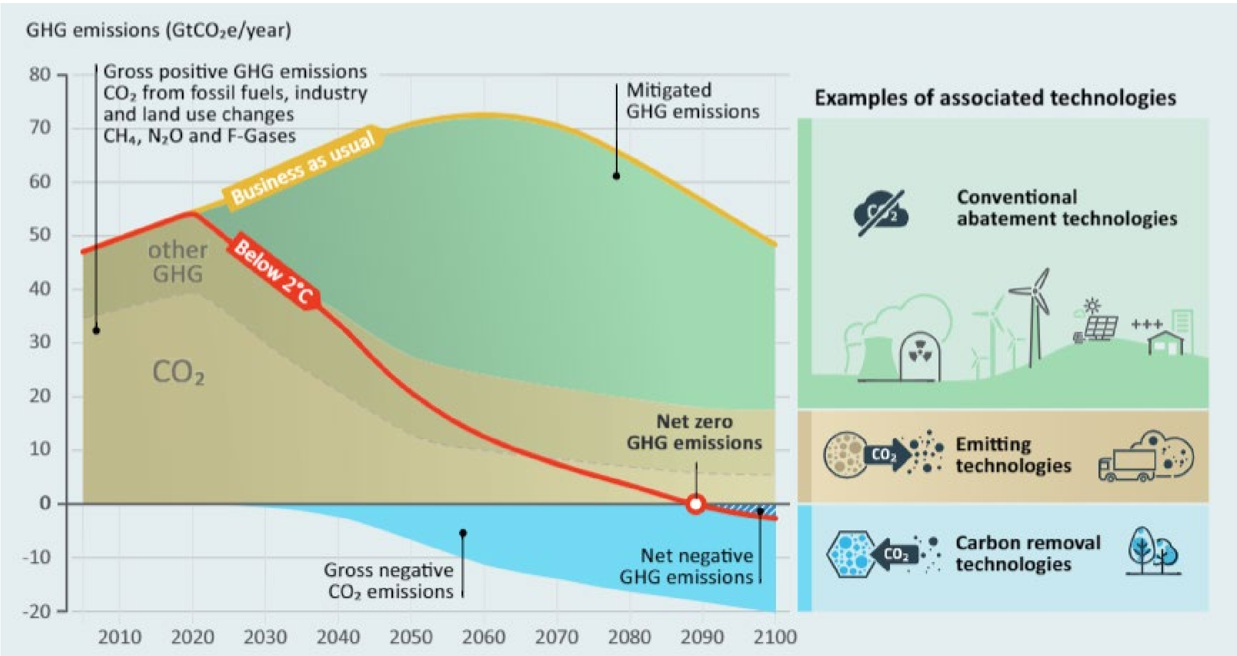

Figure 2. Conventional emissions reductions paired to negative emissions technologies modeled with at least a 66% chance of keeping warming below 2 degrees C relative to pre-industrial levels[4].

b. The Role of the Global Carbon Cycle in CDR

While most existing and nascent CDR strategies are land-based, terrestrial sequestration has the potential to conflict with human needs such as housing and agriculture, leading to adverse ecological and social impacts. Additionally, land-based strategies may require more investment due to comparatively limited land resources[6], while potentially becoming less effective as temperatures rise[7]. Given that land comprises 30% of the Earth's surface area while the ocean occupies 70%, adoption of mCDR is inevitable for scalable and affordable negative emission solutions.

The natural marine carbon cycle already uptakes 2.5 gigatons of CO_2 annually and contains 38,000

emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. 2019

[4] UNEP (2017). The Emissions Gap Report 2017. United Nations Environment Programme (UNEP), Nairobi 2017

[5] Board, O. S., & National Academies of Sciences, Engineering, and Medicine. (2019). Negative emissions technologies and reliable sequestration: A research agenda.

[6] Dooley, K., & Kartha, S. (2018). Land-based negative emissions: risks for climate mitigation and impacts on sustainable development. International Environmental Agreements: Politics, Law and Economics, 18(1), 79-98.

[7] Wang, S., Zhang, Y., Ju, W., Chen, J. M., Ciais, P., Cescatti, A., ... & Peñuelas, J. (2020). Recent global decline of CO2 fertilization effects on vegetation photosynthesis. Science, 370(6522), 1295-1300.

gigatons of carbon on a near permanent basis[8]. Considering the scale of this natural process, marine CDR technologies can bring about long-term sequestration, are scalable to gigaton levels, and could reduce energy and land use requirements of CDR. The IPCC and National Academies forecast that mCDR technology is essential to address the negative emissions requirements of the 1.5-2 °C warming goals.

Marine CDR includes a range of methods that broadly focus on enhancing natural carbon cycling through electrochemical, geochemical, or biological processes. These technologies are still in early stages of development but the community, understanding, and investment are growing rapidly. More detail on mCDR technologies is available in the National Academies report on *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration*[9].

Most mCDR methods currently under development offer a potentially viable mechanism by which at-sea, gigaton-scale CO_2 sequestration may be enabled. However, the process to assign economic value to this drawdown is not well defined as the verifiable quantity (tons of CO_2) and quality (permanence and uncertainty) of credits cannot be ascertained using current sensing and modelling tools. Large-scale carbon flux sensing and modeling is currently based on satellite and/or aerial remote sensing, which makes it impossible to obtain measurements once carbon is transported below optical depths. These remote measurements can be augmented through point measurements on surface vehicles, underwater vehicles, drifters, or buoys, but these point measurements cannot scale to the spatial or temporal scope needed for comprehensive evaluation. As mCDR scales, persistent detailed sensing at a regional scale will be required until validated mCDR models can be developed to predict the success of mCDR approaches.

Consequently, while the technical feasibility and scalability of some mCDR approaches is known, their economic feasibility cannot yet be compared when including MRV costs. Developing scalable sensing technology that enables viable MRV for mCDR will allow the carbon market to quantitatively evaluate the feasibility and efficacy of different approaches enabling competition and performance-based regulation. This quantitative evaluation will support the alignment of market forces with the most efficient negative carbon systems to accelerate the adoption of the most economical, highest quality mCDR methods.

With the economic feasibility of mCDR techniques at regional scales currently unknown, ARPA-E remains agnostic to the mCDR techniques for which MRV sensing and modeling technologies will be developed. As such, this program seeks to develop sensors and models that could be applied to one or more mCDR approaches. **Table 1** lists the parameters ARPA-E considers most important for enabling the sensing of ocean carbon fluxes, and thus defines the scope of sensing parameters associated with this program.

c. The Interdependency of MRV Sensors and Models

MRV of mCDR approaches is critical to the growth of the maritime negative carbon industry. Estimation of the following three parameters is essential to understand the effectiveness of mCDR approaches and for the monetization of CO_2 drawn down from the atmosphere and surface oceans:

[8] Friedlingstein, P., O'sullivan, M., Jones, M.W.,Andrew, R.M., Hauck, J., Olsen, A., Peters, G.P., Peters, W., Pongratz, J., Sitch, S., *et al*. (2020). Global carbon budget 2020. Earth Syst. Sci. Data 12, 3269–3340.

[9] NASEM (2022). National Academies of Sciences, Engineering, and Medicine. 2022. *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26278.

1. The additional quantity of CO_2 that has been drawn down through a particular mCDR approach, over and above ambient natural processes and variability. While potentially distributed over a large volume, this additional quantity may be miniscule per unit area (i.e., < 1% of natural levels) and standard error may overlap significantly with those of natural processes, presenting a significant signal-to-noise challenge that may only be mitigated through a data-assimilated, probabilistic model.
2. The duration over which CO_2 is removed from the atmosphere and surface oceans via mCDR. Such a measurement may require persistent sensing approaches that can operate to depths of at least 1000 m for open ocean mCDR methods.
3. The probability or uncertainty associated with the above two parameters, as required in order to assign financial value.

Quantifying these variables allows the assignment of insurable value to mCDR technologies, quantifies potential and real return on investments in a carbon market, and addresses many of the current "mobilization challenges" for rapid growth of the mCDR industry[10].

ARPA-E contends that any economically feasible and scaled MRV approach would consist of credit values and quantities being assigned through the utilization of parameter estimates (i.e., those listed in **Table 2**) and estimates of their uncertainties, made through a largely model-based approach. The effectiveness of the model will be constrained by the quantity and quality of observational data used to both train and validate it, explicitly linking model performance with sensor types and capabilities. The way value is assigned, and investments are made in the weather derivatives market is an example of this paradigm: the modeling of a partly stochastic system, for which the uncertainties are well characterized, is factored into financial models. In addition to sensor development, ARPA-E thus considers model development and design for utility in a carbon market to be a critical component of maturing MRV capabilities. Once an MRV industry has scaled, relatively few observational datasets would be used to continuously validate models and refine them to reflect how external environmental factors may change mCDR efficacy over time.

The bias and variance of model outputs will be dependent on the data used for their construction and continued validation. Consequently, the inclusion of unprecedentedly large quantities of data that come from wide-area or volumetric undersea sensing approaches will enable the application of modern data-based model training techniques to the development of mCDR models that cannot rely on satellite-derived data sets alone. It is hoped that the development of such sensors will enable step changes in model performance- estimating both the carbon drawdown quantity and permanence, and the uncertainties that drive the assignment of quality to carbon credits.

d. State-of-the-Art: Marine Carbon Sensors

The National Academies framework for ocean-based CDR states "(t)he present state of knowledge on many ocean CDR approaches is inadequate, based in many cases only on laboratory-scale experiments, conceptual theory, and/or numerical models"[9]. Real-world data at both the spatial and temporal resolutions necessary for a total accounting of the ocean carbon cycle is a requirement for the attribution of CO_2 capture and sequestration to an individual mCDR project and thus to the enabling of a marine CDR industry. Compounding this lack of real-world data is the annual-to-decadal cyclic variability

[10] TSVCM (2021). Task Force on Scaling Voluntary Carbon Markets, Final Report 2021 accessed at: TSVCM_Report.pdf (iif.com)

of many of the natural processes involved in the marine carbon cycle, making a holistic assessment of baseline carbon cycle variables difficult[11]. In general, there is a need for high quality and low-cost sensors to “close the loop” on the primary carbon flux processes related to an individual mCDR operation. These sensors are also needed to monitor secondary processes to establish a well-defined baseline against which the additionality of the operation may be quantified. Such MRV capability will represent a paradigm shift in oceanographic sensing.

Present-day MRV sensing capabilities for mCDR are inadequate for three main reasons:

1. Insufficient quantification of carbon drawdown magnitudes and the associated degree of permanence.
2. Unacceptably high MRV capital and operational costs at the required temporal and spatial scales for megaton- and gigaton-scale mCDR.
3. Very low mCDR Signal to Noise Ratio: Discerning and quantifying carbon flux signals produced by an mCDR system in an environment where the amplitude of natural variation exhibited by the relevant oceanographic parameters may be orders of magnitude greater than levels facilitated by mCDR. The variation referred to in this case occurs in both time and space.

Consequently, mCDR approaches cannot at present be rigorously evaluated for their effectiveness and associated credit value. Hence, mCDR credits are only traded on the voluntary market, mCDR infrastructure cannot be insured for a certified value, and investors cannot accurately evaluate investment risk in the industry. These factors impede the development of mCDR into the gigaton scale industry that is required to limit global warming to less than 2°C.

i. Monitoring Marine Carbon Processes

Conventional marine carbon cycle monitoring relies on sensors capable of probing four general processes, a simplified model for which is represented in **Table 3**[12].

Table 3. Parameters of interest in monitoring the carbon cycle: partial pressure/fugacity of CO_2 (fCO_2); dissolved inorganic carbon (DIC); total alkalinity (TA); dissolved organic carbon (DOC); pH3. Note “Transport” in this case refers to storage and transport in ocean waters, while “Export” refers to removal of carbon to depth. (Reproduced from Schuster 2009)

PROCESS	PARAMETER OF INTEREST				
	fCO_2	DIC	TA	DOC	pH
AIR-SEA FLUX	✓				
OCEAN ACIDIFICATION		✓	✓		✓
CARBON TRANSPORT		✓	✓		
CARBON EXPORT				✓	

The sensors underpinning many of these measurements can be broadly generalized as either (1) inorganic carbon sensors; (2) organic carbon sensors; or (3) physical/enabling sensors addressing the solubility cycle, the carbonate cycle, and the biological cycle, as well as initiatives to include the fourth (microbial) carbon cycle[13].

[11] Gonsior, M., Powers, L., Lahm, M., and Mcallister, S. L., New Perspectives on the Marine Carbon Cycle–The Marine Dissolved Organic Matter Reactivity Continuum, E*nviron. Sci. Technol.* 2022, 56, 9, 5371–5380.

[12] Schuster, U., Hannides, A., Mintrop, L., and Körtzinger, A., Sensors and instruments for oceanic dissolved carbon measurements, *Ocean Sci.*, 5, 547–558, 2009.

[13] Legendre, L., Rivkin, R.B., Weinbauer, M.G., Guidi, L. and Uitz, J., The microbial carbon pump concept: Potential biogeochemical significance in the globally changing ocean, *Prog. Oceanog.*, 2015, 134.

Regardless of the process being monitored, the challenges facing sensors for marine processes are equivalent to those for many other marine environmental monitoring applications, namely the achievement of the following performance factors:

- High accuracy (i.e., low bias) and ability to quantify signal over noise through high precision (i.e., low variance).
- Rapid response times
- Sufficiently high reporting frequency
- Insensitivity to other environmental parameters such as temperature and pressure
- Tolerance to biofouling or sedimentation
- Low power consumption
- Low drift/long-term stability
- Internal quality control/quality assurance or self-calibration capabilities

Generally, the accuracy of modern-day instruments is sufficient, but that accuracy requires untenable interventions (e.g., recalibration, recharging of reagents) or complex instrumentation that necessitates shipboard operation. There exists a significant body of work related to the development and implementation of sensors capable of discrete sampling at depth, autonomous mesocosm studies, and continuous near shore/shallow measurement for academic investigations[14]. Less attention has been paid to the cost requirements necessary to enable the scale of observational data collection at the monitoring intervals a mCDR industry requires[9]. Individual size, weight, power, and cost (SWaP-C) requirements vary based upon platform and measurement depth, but general cost and interdiction/service interval requirements need to be minimized for practical operability and to maximize the scaling potential of an applicable mCDR approach. Beyond initial sensor capability, there implicitly exists a tradeoff between volumetric or areal coverage, range capability, sensor endurance, and cost. These requirements are addressed in the **Technical Performance Targets** section of this Funding Opportunity Announcement.

ii. Inorganic Carbon Sensor Limitations

State-of-the-art sensors that quantify the inorganic carbon pump focus on fugacity, DIC, pH, and TA. If at least two of these four variables are measured, the others can be calculated using equilibrium constants and coupled physical measurements (salinity, temperature, etc.)[15]. Sensors for DIC and TA are the closest in readiness level for long term, autonomous or remote deployments with minimal intervention.

In general, sensors for inorganic carbon (DIC, pH, TA, fCO_2) are limited by the need for:

- Sample titration (coulometric and potentiometric methods),
- Indicators or reagents,
- Complex instrumentation (sensitive to biofouling; requiring consistent recalibration),

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[14] Byrne, R.H., DeGrandpre M.D., Short, R.T., Martz, T.R., Merlivat, L., McNeil, C., Sayles, F.L., Bell, R., and Fietzek, P., Sensors and Systems for In Situ Observations of Marine Carbon Dioxide System Variables in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2),* Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, *and references herein.*

[15] Dickson, A. G., Sabine, C. L., & Christian, J. R. (2007). *Guide to best practices for ocean CO2 measurements*. North Pacific Marine Science Organization.

- Sample integration times exceeding 1 second, and
- Volumetric limitations, i.e., the requirement that sensors are co-located with the water sample.

iii. Organic Carbon Sensor Limitations

State-of-the-art sensors to measure the organic carbon pump are categorized by dissolved organic carbon (DOC), particulate organic carbon (POC) and the quantification of carbon in marine sediment. A consensus on how to quantify carbon transport in the ocean through mechanisms that involve biological ingestion currently does not exist, due to associated ecosystem-specific and mCDR-approach-specific aspects. The DOC pool is the second largest known carbon pool in the ocean and the least instrumented fraction of the carbon cycle, and thus represents the largest gap in sensor capabilities[16]. Measurement

of dissolved oxygen; micronutrients; and the individual species involved in primary production (photosynthesis or chemosynthesis) are necessary to improve monitoring of the carbon transition between organic and inorganic pools. This would also allow for a more accurate accounting of sequestration by deep ocean export processes. In addition, quantification of the relative ratios or absolute magnitudes of labile and recalcitrant DOC are necessary to valorize the component of CO_2 drawn down to the DOC pool by mCDR processes.

Sensing of Particulate Organic Matter (POM) is typically performed via collection of vertical fluxes through a sediment trap that is then analyzed in a laboratory setting, or through quantification in an optical trap. Optical systems for quantifying POM are capable of discerning particle size, distribution, and density; and in some circumstances particle type (i.e., fecal matter, species composition, etc.) but presently do not offer mechanisms by which the bulk carbon content of particulates may be evaluated *in situ*.

The sequestration of carbon in stable, deep ocean sediments represents the goal for several mCDR approaches. Once entrained within these sediments, the residence time of carbon drawn down from the atmosphere and surface oceans may be measured in millennia or more. Some marine CDR approaches involve the enhancement of carbon storage in shallow-water sediments through the restoration of biological processes such as accretionary carbon storage, including recalcitrant carbon, through seagrass restoration or the deposition of mineralized carbon through the restoration of calcifying reefs and their associated ecosystems. In general, quantification of the sediment carbon fraction and identification of stable carbon compounds requires direct sampling of sediments through coring and subsequent analysis in a laboratory setting. Methods potentially enabling noninvasive quantification of carbon compounds in near-surface sediments exist, but the accuracy and scaling potential of these technologies is yet to be demonstrated.

In general, sensors for organic and organically-stored carbon are limited by the requirements for:

- Selectivity for specific species/analytes
- Signal-to-noise ratios
- The ability to discriminate between non-carbon and carbon constituents.
- The ability to discriminate between recalcitrant and labile compounds.

[16] Moore T.S., Mullaugh K.M., Holyoke R.R., Madison A.S., Yücel M., and Luther G.W. 3rd. Marine chemical technology and sensors for marine waters: potentials and limits. *Ann. Rev. Mar. Sci*. 2009.

- Laboratory-based analysis, requiring sample extraction and transportation.
- Volumetric or area limitations, i.e., the requirement that sensors are co-located with the water sample.

iv. Physical and Enabling Sensors

State-of-the-art physical oceanographic sensors are designed to measure ancillary properties required for a complete picture of the mCDR process being monitored. These include, but are not limited to, temperature, salinity, eddy covariance/turbulence, and pressure. These foundational sensors form the basis for oceanographic surveys and are generally well developed, available commercially at a reasonable cost, and robust to degradation. However, development of the envisioned MRV capabilities for mCDR evaluation may be aided by new approaches for sensing of these fundamental parameters

capable of estimating the dynamic ocean environment across large volumes efficiently, explicitly alongside the sensing of carbon parameters relevant to mCDR. Consequently, approaches for transformative physical oceanographic sensing approaches are in scope for this program, but only in a supporting role that is explicitly tied to the simultaneous implementation of a carbon flux sensor that requires the resultant oceanographic data.

e. State-of-the-Art and Limitations: Modeling

The long-term quantification and estimation of additional CO_2 drawdown in the vast, temporally dynamic, 3-D, heterogeneous ocean volume is not possible at gigaton scales with improved sensor capabilities alone. A simultaneous understanding of what would have occurred if a given mCDR approach did not exist (i.e., a baseline) is necessary to estimate the additional CO_2 drawdown created by the approach. Therefore, regularly validated mCDR models are necessary to comprehensively assess the dynamic ocean carbon cycles for MRV. Some existing global models, such as the CMCC Earth System Model and Circulation and Climate of the Ocean (ECCO)-Darwin model, integrate underlying physical and biogeochemical mechanisms and observations to estimate the global carbon cycle[17,18]. However, there are several barriers to overcome before estimation or even prediction of the efficacy of mCDR methods with such models, particularly at the required spatial and temporal scales[19].

Most advanced global carbon models today are not designed to evaluate mCDR approaches, produce estimates of carbon drawdown, or provide the necessary parameters and uncertainties from which calculations of financial value can be made. Earth system carbon models are typically coarse in spatial resolution (on the order of tens to hundreds of km). Anticipated mCDR approaches will be regional events and sufficient modeling of such scenarios requires sub-mesoscale chemical oceanographic and biological information, which is rarely available in sufficient quantities for high-resolution model development.

Another significant challenge involves accommodating the differences in time scales between the

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[17] Carroll, D., Menemenlis, D., Adkins, J. F., Bowman, K. W., Brix, H., Dutkiewicz, S., *et al*. (2020). The ECCO-Darwin data-assimilative global ocean biogeochemistry model: Estimates of seasonal to multidecadal surface ocean pCO2 and air-sea CO2 flux. Journal of Advances in Modeling Earth Systems, 12, e2019MS001888. https://doi.org/10.1029/2019MS001888

[18] Lovato, T., Peano, D., Butensch.n, M., Materia, S., Iovino, D., Scoccimarro, E., *et al*. (2022). CMIP6 simulations with the CMCC Earth System Model (CMCCESM2). Journal of Advances in Modeling Earth Systems, 14, e2021MS002814. https://doi.org/10.1029/2021MS002814

[19] Siegel, D. A., DeVries, T., Doney, S. C., & Bell, T. (2021). Assessing the sequestration time scales of some ocean-based carbon dioxide reduction strategies. Environmental Research Letters, 16(10), 104003.

various ocean processes influenced by mCDR, which in turn depend on each specific mCDR scenario and the oceanographic region in which the approach is situated. Therefore, the following timescale issues, the consequent model run expense, and potential mitigation of this expense, must be considered in any proposed modeling approach:

- The timescale of physical and chemical changes associated with mCDR may generally be shorter than for biological processes.
- Carbon dynamics in the deep ocean occur over longer timescales than in coastal or shelf regions.
- Some mCDR approaches are typified by periodic or localized injections of carbon to the ocean carbon cycle, which may occur over shorter timescales than climate and earth carbon systems.

It is expected that MRV modeling for each mCDR scenario will be tailored to the specific environmental circumstances of the region, the mCDR approach, and the anticipated major carbon pathways that are most likely to be modified through mCDR. Consequently, MRV may thus require higher temporal resolutions than what is typically modeled today.

The biological ocean carbon cycle is typified by nonlinear reactions and feedbacks, rendering the estimation of biological processes associated with mCDR efficacy a formidable challenge. ARPA-E considers the quantification of ocean biological carbon fluxes to be the least understood, but potentially the most critical element of effective MRV, especially for mCDR approaches that leverage biological productivity. The development of regional scale (i.e., spatial scales sufficient for the order of hundreds of megatons to one gigaton mCDR) biological carbon flux sensing approaches and modeling capabilities is therefore an important goal for this program.

Today, most biogeochemical models are based on the Nutrient-Phytoplankton-Zooplankton-Detritus (NPZD) formalism[20], and many of the model-development efforts have focused on describing the nutrient-phytoplankton relationships. In contrast, the representation of zooplankton is often limited to only two or three size classes (e.g., in NOAA's Ocean Biogeochemical Model COBALTv2) and a few have extended toward modeling higher trophic levels in a limited context. State-of-the-art biological models that could be adapted to predict carbon fluxes remain comparatively simple, in contrast with the known complexities of the natural ecosystem, due to our limited understanding of contributors to the biological carbon cycle such as the roles of gelatinous zooplankton, the microbial loop, the dissolved organic matter (DOM) – POM continuum, and the vertical migration of pelagic organisms in the deep ocean[21]. While significant challenges remain in accurately estimating ocean carbon fluxes through these pathways, or quantifying the unknowns associated with them, volumetric sensors and associated models developed through this program would offer new and fundamental insights toward understanding the roles of these carbon pathways in determining the fate of CO_2 drawn down in the surface oceans through biological processes.

C. Detailed Program Objectives

The anticipated timing and milestones described here are subject to change. If an applicant is selected for award negotiations, timing and milestones will be mutually agreed upon during the negotiation

[20] Fasham, M. J., Ducklow, H. W., & McKelvie, S. M. (1990). A nitrogen-based model of plankton dynamics in the oceanic mixed layer. *Journal of Marine Research*, *48*(3), 591-639.

[21] Burd, Adrian B., Buchan, Alison, Church, Matthew J., Landry, Michael R., McDonnell, Andrew M. P., Passow, Uta, Steinberg, Deborah K., Benway, Heather M., "Towards a transformative understanding of the ocean's biological pump: Priorities for future research - Report on the NSF Biology of the Biological Pump Workshop", 2016-08-24, DOI:10.1575/1912/8263, https://hdl.handle.net/1912/8263

period.

a. Program Approach

i. Technical Area 1: Sensors

The primary focus of this program is the development of sensors able to measure the ocean chemical and carbon-flux relevant parameters listed in **Table 2** in a manner that achieves the first four technical developments listed in **Table 1**. As such, more than half of program funding will be allocated to this technical area. ARPA-E will accept submissions to develop appropriate sensor technology applicable to one or more of the parameters listed in **Table 2**. Submissions proposing the development of sensing

capabilities for other parameters without exceptionally strong justification are discouraged. Preference will be given to sensors that quantify multiple relevant parameters that are known to be necessary for MRV across a wider range of mCDR approaches. **Applicants should justify, in a separate document not to exceed one page, the potential for applicability of a proposed sensor technology to one or more mCDR approaches** described in the National Academies report. Other feasible mCDR methods for which MRV technology could be developed may be in scope **if justification can be provided that defines a feasible roadmap** to a gigaton-scale mCDR industry through the approach.

ARPA-E emphasizes the significant knowledge gaps associated with quantification of the ocean biological carbon cycle. While the challenge of quantifying nonlinear biological carbon cycles in the ocean is significant, ARPA-E encourages submissions of any sensing technology that could quantify, at scale, the role biological processes play in carbon drawdown, transport, and sequestration in coastal, shelf, pelagic, and deep ocean environments.

The anticipated TA1 program approach will consist of two Phases, each lasting 18 months. In Phase 1, teams will develop the core technologies that enable their sensing concept. Phase 1 will culminate in a controlled test and in-water experiment to show sensor functionality using ocean-sourced seawater in a laboratory setting. This milestone is designed to demonstrate that the fundamental sensor concept functions as intended, and that the technology has the potential to mature toward a sensor of sufficient relevance to MRV needs that could be deployed at scale in the ocean.

If selected for continuation in Phase 2, sensor teams will mature their systems and test operability in increasingly realistic in-water scenarios. Integration of the sensor system onto a commercially available off-the-shelf (COTS) platform will occur during Phase 2. This system will be appropriate as an MRV platform for one or more indicated mCDR approaches and may include, but is not limited to, surface or subsurface autonomous systems, drifters, gliders, buoys, seafloor cables, or moorings. This Phase will culminate in an ocean-going test where the sensor and COTS platform will be deployed in an ocean region appropriate for an associated mCDR event. At a minimum, the TA1 team will deploy their sensor system to quantify carbon fluxes associated with natural baselines. If possible, teams may leverage pilot-scale mCDR operations that may be taking place at that time. ARPA-E encourages applicants to leverage other federal and privately funded programs that aim to further mCDR development and implementation.

a) Coordination between Technical Areas

TA1 teams will work with TA2 teams during Phase 2 to develop estimates of scaled sensor capability and adopt at-sea sampling strategies informed by models to minimize parameter uncertainty. In specific cases, sensors may also be developed to aid in model verification if quantification of a key parameter would significantly decrease model uncertainty, although the primary focus of sensor development is to enhance spatial and temporal capabilities. TA1 and TA2 applicants may prepare a joint submission in response to the FOA or enter collaborative partnerships at the beginning of Phase 2. Note that while sensor teams may focus on one or more parameters, modelers are required to simulate the dynamics of all relevant ocean carbon parameters for a given mCDR scenario simultaneously. Consequently, a TA2 team may work with multiple TA1 teams in Phase 2.

ii. Technical Area 2: Models

While sensor technologies will be developed independently of applications to specific mCDR types,

modeling teams are required to focus on one or more mCDR scenarios at regional scales where the size of the hypothetical operation has the potential to draw down hundreds of megatons to one gigaton or more of CO_2 per year. Modeled scenarios should consist of the following:

1. **Applicants must justify, in an additional document not to exceed one-page, specific mCDR approach(es)** (i.e., iron fertilization, seagrass restoration, alkalinity enhancement, etc.), and hypothetical logistical approach(es) (e.g., injection site, proximity to material resources, etc.) that will be modeled. Approaches must be realistic in that a feasible techno-economic scenario (at 100’s of megatons to 1 gigaton scale) can be developed based on a nominal CO_2 credit value of US$100/ton at that scale.
2. A regionally constrained area, geographically and oceanographically appropriate for the chosen mCDR approach scenario. Regional areas must be limited in size so that high resolution regional ocean models may be run within a reasonable timeframe. The purpose of TA2 is to develop new or enhance existing models that are more accurate and precise through improved modeling of fundamental processes, vs. a brute-force approach to improving model performance.

Models should simulate carbon fluxes from atmospheric or recently dissolved CO_2 in the mixed layer through what applicants consider to be the major inorganic and organic pathways that are economically relevant for the mCDR scenario(s) of interest. Teams should include a **table** with their proposal that identifies which of the parameters listed in **Table 2** are relevant to their proposal submission, as well as a rationale on why the chosen ocean carbon parameters should be considered major pathways within the vignette, and why the parameters that were not chosen should be excluded.

Model parameters should be chosen in coordination with carbon market consultants and/or carbon registries in a best effort to minimize computational burden and maximize output utility for valuing a mCDR exercise and developing a carbon accounting framework for the chosen mCDR approach(es). Given the significant number of unknowns, initial estimates of parameters such as resolution, time step, and spatial and temporal ranges may be updated as sensitivity analyses and potential data assimilation from existing or prototype sensors provide scope for optimization. Model and registry requirements are expected to evolve as collaborators determine an optimal framework to translate model outputs to accountability metrics developed as projects progress.

Model outputs will initially be tailored to demonstrate model performance against hold-out historical oceanographic data. Therefore, preference will be given to geographic regions for which existing, curated and high-quality historical oceanographic data sets are available, enabling expedited model

development and verification on previously collected data.
As models are developed to achieve performance benchmarks demonstrating state-of-the-art levels of bias and variance, an additional MRV-specific suite of model outputs will be developed to inform a data-driven accreditation process. TA2 teams will develop these processes jointly with carbon market consultants and/or a carbon registry.

a) Coordination between Technical Areas

During Phase 1 (1-18 mo.), TA2 teams will build mCDR models of their proposed regional mCDR approaches, incorporating the simulation of selected major organic and inorganic carbon pathways and coordinating with a carbon registry to determine model parameters most conducive to informing a data-driven carbon accounting framework. At the culmination of Phase 1, teams will demonstrate the

performance of mCDR models through the estimation of baseline ocean parameters using hold-out historical data (or actual mCDR event data, if available).

During Phase 2 (19-36 mo.), TA2 teams will collaborate with one or more TA1 teams to perform an OSSE that estimates the scaled sensing capability of prototype TA1 systems, and inform at-sea sampling strategies to minimize parameter uncertainty. The goal of this effort is to estimate how these sensor capabilities would impact carbon accounting and the quantification of uncertainty within the accounting framework designed in Phase 1 through more accurate CO_2 drawdown magnitudes, permanence, uncertainties and carbon credit quality. Model outputs should consist not only of carbon flux parameter values and uncertainties and temporal permanence estimates and uncertainties, but also the potential increase in financial value associated with the enhanced credit quality derived from more definitive projections of uncertainty. As such, **at the end of Phase 2,** a forward-looking techno-economic analysis of the mCDR vignette, including estimates of potential scaled MRV cost and enhancement of credit value, will be required.

Note that while sensor teams may focus on one or more parameters, modelers are required to simulate the dynamics of all relevant ocean carbon parameters for a given mCDR scenario simultaneously. Consequently, a TA2 team may work with multiple TA1 teams in Phase 2. If measurement of a specific parameter is critical for the satisfactory performance of a model, limited sensor development for the purposes of quantifying this parameter and thus strengthening models is within scope.

Verified, regularly refined mCDR models will enable cost-effective MRV and quantitative estimates of carbon additionality for a scaled mCDR industry. Data from sensor technology developed in TA1 will likely be instrumental in the development and continued verification of such models. Because sensor development and maturation timelines are likely to exceed the duration of this program, models that predict the potential enhancement to MRV in terms of accuracy in quantifying CO_2 drawdown, its permanence, and quantification of uncertainties will be important in demonstrating the utility of new sensor technologies to the mCDR community.

iii. Independent Verification & Validation (IV&V)

IV&V teams may evaluate sensor maturity against ARPA-E performance metrics including compatibility with COTS platforms, and seaworthiness of sensing systems (see the 'Program Metrics' in the **Technical Performance Targets** Section) at agreed-upon intervals beginning at the end of Phase 1.

B. Technical Areas of Interest

i. Technical Area 1: Sensors

Sensor technology of interest to this program must be a demonstrable step away from present-day capabilities. The primary goal of TA1 is to develop sensors that can quantify the carbon-related oceanographic properties in **Table 2** at a large spatial scale, ideally volumetrically or area-wise, expanding both spatial and temporal sensing capabilities for these parameters and providing significantly larger quantities of higher-resolution data to model development efforts. No specific volume or area metric per sensor is provided, only a survey rate associated with a scaled MRV system appropriate for a gigaton-scale mCDR operation. As such, this metric (and the qualitative metric addressing cost at scale) creates an implicit tradeoff between the range of a sensor and the cost. A single, expensive sensor must be capable of surveying significant ocean volumes at a high rate. Conversely, a larger number of less expensive sensor systems with limited or even no range may be equally permissible. Systems incorporating large numbers of networked sensor nodes must still satisfy the endurance and accuracy metrics on a per-sensor basis. In the case of point sensors, evidence must be provided showing that the **correlation length scales of the parameter remain consistent** over ranges such that a techno-economically realistic sparse network of point sensors could sufficiently resolve fluxes from a CDR event.

The depths to which sensors must operate depends upon the location and mCDR approach. A nominal depth rating is a minimum of 1000 m. However, more accurate estimations of maximum operating depth can be deduced from studies indicating depths beyond which transported carbon is effectively removed from the atmosphere and surface ocean for 100 years or more[19]. Thus the 1000 m requirement may be relaxed if it is sufficiently reasoned that a proposed sensing technology could perform effective MRV for an mCDR approach with a lesser depth rating.

To adhere to the requirements for scalable MRV, ARPA-E encourages a non-exclusive emphasis on radiated energy-based sensing approaches in which a system could potentially quantify ocean carbon parameters in a location not co-incident with the sensor. While these types of 'remote' sensing have facilitated a revolution in our understanding of atmospheric and surface ocean-related processes, most remote sensing approaches that resolve oceanographic properties today cannot be extended beyond the first optical depth (also known as the penetration depth[22]) in the ocean. In addition, the drift and recalibration requirements for radiated energy-based sensors are expected to be significantly reduced in comparison to reagent-based sensing approaches.

Potential sensor approaches of interest are listed below. Approaches could serve to quantify any parameter listed in **Table 2**. This list is not exhaustive and is only meant to serve as a guide to the types of sensing approaches of interest to ARPA-E.

- Optical fiber-based chemical oceanographic sensors, with simultaneous sensing of environmental parameter data necessary to disentangle the effects of temperature, vibration, etc.

[22] Gordon, H. R., & McCluney, W. R. (1975). Estimation of the depth of sunlight penetration in the sea for remote sensing. *Applied optics*, *14*(2), 413-416.

- Acoustic methods, both passive and active. ARPA-E encourages the submission of concepts that leverage chemically dependent in-water acoustic properties such as that between the borate-boric acid equilibrium reaction, acoustic attenuation, and pH. ARPA-E additionally encourages the submission of high frequency, spatially integrative or directional 'acoustic color' concepts for characterization of particulate matter and seabed material properties.
- Optical methods including, but not limited to, reflectance and/or absorption based, hyperspectral/multispectral, optical MEMS systems, dual frequency comb laser-based spectroscopy, remote Raman, florescence/luminance-based, and laser induced breakdown spectroscopy (LIBS) as pertinent to quantification of relevant seawater and sediment parameters. Methods may be active (coherent or incoherent sources) or passive (i.e., bioluminescence-based, sunlight-based). ARPA-E encourages the submission of concepts that enable range-dependent optical sensing that may be facilitated by, for example, nanosecond time-gated backscatter spectroscopy. Given that transmission of light in the ocean is limited by strong attenuation in comparison to atmospheric scenarios, sensor cost and the potential to leverage economies of scale may be important considerations uniquely associated with optical sensing techniques.
- Electromagnetic techniques, both passive and active. Little is known regarding the ability to quantify seawater and seafloor chemical parameters listed in **Table 2** using variations in resistivity and other electromagnetic properties. In addition, little is known regarding the characterization of biological activity and potentially the transport of ingested carbon sensed through electromagnetic methods. However, if demonstrated in a manner that is scalable, electromagnetic sensing of seawater parameters could fundamentally change the understanding of chemical and biological oceanographic processes.
- Other sensor approaches that are not included in the above list, but which could serve to create spatially scaled, volumetric or area-based carbon flux parameter sensing capability.

ARPA-E has not set a definitive metric regarding the spatial resolution of new sensor technology, as the minimum spatial resolution at which collected data would characterize the smallest relevant parameter structures is undefined and likely dependent on the mCDR approach. However, preference will be given to approaches that either integrate parameters of interest over a given sampling path or are capable of sampling multiple discrete points stepping out from the sensor itself to the limits of sensor range.

ii. Technical Area 2: Models

The goals of TA2 are to develop marine carbon cycle models capable of simulating fluxes from regional scale mCDR events at an accuracy comparable with state-of-the-art Regional Ocean Modeling Systems (ROMS). These models will then be used in Observation System Simulation Experiments (OSSEs) to estimate the impact of new sensor technology on evaluating the quantity and quality of credits earned through mCDR, and to design model operations and outputs to support the development of a data-driven carbon accounting framework for mCDR. In addition, model runs will be used to inform TA1 groups during at-sea experimental design to maximize the effectiveness of new sensor systems in performing MRV. The variety of mCDR approaches and the heterogeneity of suitable regional environments mean that only general metrics concerning bias (Root Mean Square Error) and variance (Anomaly Correlation Coefficient) are applied to evaluate models. These model bias and variance metrics apply only to parameters listed in **Table 2** for which concentrations/distributions may be significantly modified by mCDR. Note that TA2 applicants must identify and rationalize which parameters in **Table 2** are considered significantly modified for their modeled mCDR approach.

Models must incorporate the simulation and tracking of multiple chemical oceanographic parameters, the dynamics of which are likely to be influenced by physical and biological processes at multiple scales. Given that fundamental uncertainties exist regarding representation of the biological system, ARPA-E encourages the submission of efforts that also seek to resolve basic research questions regarding combined physical-biological models that incorporate multiple, interacting biological carbon pathways that may be of consequence to one or more mCDR approaches. However, note the same project outcomes regarding the support of OSSEs and the development of carbon registry frameworks apply.

Potential modeling approaches of interest are listed below. This list is not exhaustive and is only meant to serve as a guide to the types of TA2 proposals of interest to ARPA-E:

- Physical oceanographic models at sub-mesoscale resolutions to discern important small-scale variability in processes relevant to some mCDR approaches (e.g. alkalinity enhancement, iron fertilization). An ideal physical model should be able to accurately estimate ocean processes at fine temporal and spatial scales, including the dynamics of key physical pumps such as the mixed layer pump, the eddy subduction pump, and large-scale subduction pumps.
- High-resolution physical models should also be used to advance the development of biogeochemical models, particle tracking modeling, ecosystem models, and other models related to mCDR. Parameterizing these processes for future computational efficiency will be an important deliverable in this case.
- Biogeochemical models simulating the dynamics of the carbonate system affected by mCDR activities. ARPA-E encourages proposals for models that further consider the effects of mCDR on related phytoplankton community shifts between calcifiers and silicifiers.
- Biogeochemical models that could evaluate the effects of mCDR on one or more processes, including a) primary production and consequent sinking/export of particulate and dissolved carbon to depths at which storage would exceed 100 years, b) multi-trophic-level carbon fluxes from microbial to macro-organism communities, and c) the vertical gradient and flux of dissolved carbon. ARPA-E encourages interdisciplinary, multispecies and ecosystem modeling with a focus on the detailed dynamics of carbon fluxes throughout these complex systems.
- Unprecedented biological models that track the transport and storage of organic carbon through vertical migration. An ideal model should consider ingestion, excretion, and respiration in the water column, as well as the potential effects of mCDR on the composition, population, and vertical migration behaviors of these organisms. It is also desirable for the model to consider multiple species at various trophic levels, including crustacean, gelatinous zooplankton, fish, and other animals that conduct vertical migration, and their life stages.
- Data assimilation capabilities to improve model parameters, facilitate the design and selection of model structures, quantify uncertainties, and estimate true aggregated carbon fluxes in the ocean. An effective data assimilation approach is critical for enhancing model performance in the event sensor data from TA1 is available before the culmination of the program. Assimilation will eventually allow for the real (rather than simulated) assessment of new sensing technologies on carbon flux quantification accuracy, error, and consequently credit quality. This program only seeks to simulate assessments through an OSSE approach as the length of time required to develop new sensor technology is uncertain.

If the bounding of a specific parameter is critical for the satisfactory performance of a CDR model, limited sensor development for the purposes of quantifying this parameter for model validation and thus strengthening model outputs is within the scope of this program. Sensor development proposals for this purpose should be submitted under TA1 and explicitly state the specific parameter with rationale, and ties to a TA2 modeling effort.

ARPA-E intends to support interdisciplinary collaboration between sensor developers, oceanographic scientists, modelers, and the carbon market industry to develop viable and scalable MRV technologies for mCDR. As such, ARPA-E encourages TA2 applicants to consider utilizing a collaborative forum for information and idea exchange between modelers, oceanographers, sensor developers, and carbon registries. Such a platform would require interoperability between members of these diverse disciplines

and offer information storage and/or computational capabilities to enable the translation and processing of relevant data sets. The forum would expedite community acceptance of standardized protocol and encourage the correct use of modeling tools, leading to credible results that are accepted by the market. In addition, a modular approach in which the same physics or biological process kernel, assimilation process, user interface and cluster access protocol are applied to several different mCDR approaches over a variety of regional scenarios may be proposed as standardization and integration between different modeling efforts is also encouraged.

c. Technical Performance Targets

Given that the mCDR market does not yet exist, this program sets goals designed to inspire transformative ocean carbon sensing technologies to accelerate the formation of this market. Five key performance metrics drive the technical innovation thrusts in this program, listed below in **Table 4**.

Table 4. Summary of SEA CO2 key performance metrics.

Metric #	Description	Quantitative Value	Details
M1	Volumetric Capability	150 km^3/h (volume or 3D sensing) 150 km^2/h (sediment or 2D sensing)	Volumetric or area-sensing requirement when the MRV approach is scaled to 1 gt CO_2/yr size. Note that this metric implies the requirement of a competitive techno-economic analysis for a future scaled market, where MRV costs should not exceed 5% of the value of CO_2 drawn down.
M2	Accuracy	See **Table 2**	Accuracy of new sensor designs must be within 10% of the state-of-the-art for individual carbon parameters.
M3	Size, Weight and Power	COTS platform	Requirement to match what is offered by an appropriate COTS platform available today or within 18 months of project start.
M4	Sensor Endurance	1 year	Sensors must function continuously or at appropriate cycle rates without physical human intervention for one year or more.

M5	Model Accuracy (historical data)	RMSE ≤ 0.25 ACC ≥ 0.7	Performance of MRV models based on hold-out historical data must meet state-of-the-art values, unless model types are unprecedented.

In addition to the quantitative metrics defined in **Table 4**, ARPA-E will evaluate proposals and projects under the following context:

- The volumetric or area-based survey rate metric implies a tradeoff between cost and spatial sensing capability per sensor. A survey rate of 150 km^{2-3}/h for a 1 gigaton per year mCDR system could be achieved by a small number of sensor systems capable of long-range quantification, a larger number of sensor systems capable of sensing over a shorter distance, or a solution in between these extremes. Consequently, TA1 teams will need to estimate **through a forward-looking techno-economic analysis included with their proposal** that their sensor technology, if scaled, will satisfy a future cost-performance market. Given that such a market does not yet exist, the following speculative estimates should be used as assumptions:
    - An MRV cost of no more than 5% of the value of CO_2 drawn down via an example scaled mCDR system.
    - A nominal price of $100 per ton of CO_2 drawn down, for a minimum 100-year period at 95% probability.

Consequently, sensors could feature higher priced technologies if they enable large-volume sensing capability from a small number of systems. Or, if sensing approaches are volumetrically limited then sensor cost will be more important for success while maintaining accuracy and precision, reliability, endurance, and leveraging economies of scale. In the latter case, teams are encouraged to consider technologies that could lead to maximal leveraging of economies of scale and resilience against supply chain vulnerabilities.

The sensor technology developed under this program must be able to effectively survey the ocean for one or more parameters listed in **Table 2** below the first optical depth at rates of at least 150 km^3/h, persistently for periods of at least one year, when deployment is scaled to a size commensurate with a gigaton-level negative carbon mCDR approach. In cases where MRV requires the quantification of seafloor parameters, this metric reduces to 150 km^2/h. In a scaled scenario, new volumes and areas would need to be surveyed per hour rather than, for example, the same 150 km^3 water mass. This rate of volumetric survey is expected to enable sufficient quantification of carbon fluxes through observation alone at regional scale. It would also provide enough data at suitable resolution for effective mCDR models to be developed and validated.

The oceanographic chemical sensing community has been pursuing sensor accuracy and dependability goals for some time (e.g.,[23]) ARPA-E feels that advancements in accuracy over state-of-the-art would confer incremental improvements to MRV, rather than the transformative improvements that enhancements of survey scale would bring. Consequently, teams are required to demonstrate sensor accuracy to within 10% of the state-of-the-art values listed in **Table 2**.

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[23] Martz, T. R., Connery, J. G., & Johnson, K. S. (2010). Testing the Honeywell Durafet® for seawater pH applications. *Limnology and Oceanography: Methods*, *8*(5), 172-184.

The size, weight, and power consumption of sensor systems must be compatible with autonomous ocean sensor platforms and the mission profiles for which they are designed. Virtually all COTS platforms are limited in their payload capacity by a variation of these three metrics. Timely deployment and maturation of sensor technology requires efficient integration with appropriate ocean-going platforms, best brought about through the consideration of these limitations at the initial design phase. Sensor systems must thus be sized suitably so they may physically fit within an appropriate COTS platform, remain within manufacturer-recommended payload weight/density limits, and within manufacturer-recommended power consumption rates so that typical mission profiles are not significantly limited by energy consumption. Choices regarding the type of sensor platform are left open to teams, although selections should be made considering anticipated mission profiles associated with one or more mCDR approaches. ARPA-E encourages the adoption of persistent platforms that can harvest energy in-situ and offer a surplus sufficient to operate the sensor payload. Such a platform is consistent with the spirit of the sensor endurance metric and combined with a sensor system that meets that metric, could result in a sensor-platform system capable of extended deployments without physical

human interaction for purposes such as swapping batteries. This approach would offer greater value to a commercial mCDR operation as the cost of MRV hardware could be amortized over a greater quantity of carbon credits surveyed.

Sensors must demonstrably be shown to operate in a manner that would be suitable for autonomous, error-free operation over a period of at least one year without physical human intervention. This metric is intended to address sensor drift issues (i.e., systems will require automatic re-calibration if drift is large enough to fail metric #2 in **Table 4**), reliability, avoid a reliance on consumables, energy consumption and practical considerations such as biofouling and corrosion. ARPA-E considers one year a nominal minimum due to the seasonal characteristics of some mCDR approaches such as ocean iron fertilization in regions such as the Southern Ocean, and seaweed sinking in temperate waters.

Models developed under TA2 must meet state-of-the-art performance metrics for bias and variance. When tested on historical hold-out data, predictions of parameters listed in **Table 2**, to the maximum reasonable extent permissible by available historical datasets, should demonstrate a root-mean-squared error (RMSE) of ≤ 0.25 (averaged over time, when predicted at equivalent spatial scales to historical data), and a time-series anomaly correlation coefficient (ACC) of greater than or equal to 0.7. Models should meet these performance metrics by the culmination of Phase 1, before estimations of MRV enhancement through new sensing technologies are made. An exception may be made for attempts to model mCDR processes that cannot be reasonably compared to existing SOA models. In these cases, if a proposal is selected, metrics for the purpose of verifying accuracy and precision will be determined during award negotiation.

d. Technology-to-Market Expectations

Commercialization of the technologies developed under this ARPA-E program is a high priority. Teams will be required to develop technology-to-market strategies to bring their MRV products to market, which will need to account for uncertainties regarding a forthcoming mCDR industry. The paths to market are anticipated to vary by team and will largely depend on the modularity of the MRV solutions developed, the technical area of focus, and the marine CDR approaches considered. The primary customer of these MRV solutions is ultimately expected to be marine CDR project developers, who will be responsible for data acquisition and reporting to carbon registries before the final issuance of carbon credits.

Potential commercialization frameworks include, but are not limited to, the following: a) licensing novel marine carbon sensor designs to established oceanographic sensor manufacturers; b) direct sales of MRV devices, perhaps through manufacturing partnerships with established marine platform developers; c) offering end-to-end MRV solutions as a Data-as-a-Service (DaaS) or Equipment-as-a-Service (EaaS) provider.

i. Technology-to-Market Considerations for Technical Area 1: Sensors

The primary use-case of the marine carbon sensing capabilities developed through this program will be to support and potentially accelerate the adoption of marine CDR technologies by validating the scientific and technical efficacy of various engineered marine CDR processes. This validation will require teams to conduct outreach and partner with NGOs and/or other research groups that need robust carbon accounting technologies to track carbon fluxes and sequestration in their pilot or demonstration-scale marine CDR projects.

Marine CDR MRV will require sensing technologies that are economically suitable for collecting continuous data across large areas, substantial depths, and over long durations. Therefore, the sensing capabilities developed under this ARPA-E program will also be valuable to existing ocean observing programs, which may act as a first market for these technologies until the marine CDR industry reaches commercial and regulatory maturity. Ocean observing is primarily driven by government, academic, and philanthropic funding, where autonomous, low-cost, persistent, and scalable sensing solutions are desirable. Robust marine carbon sensing capabilities in ocean observing will contribute to broader scientific efforts to baseline natural carbon fluxes and model climate change-influenced processes in the ocean. Collecting data about natural marine carbon pathways will serve the future marine CDR industry by defining the baselines from which engineered processes can be measured or estimated (i.e., "additionality"). Therefore, teams will be encouraged to conduct outreach with national/regional ocean observing programs to potentially address additional technical needs that do not conflict with the primary use-case (i.e., mCDR MRV).

ii. Technology-to-Market Considerations for Technical Area 2: Models

Marine CDR MRV's high-growth potential is based in measuring/verifying the quantity, additionality, and durability of carbon dioxide removals for valuation in carbon markets. Ascribing value in the voluntary carbon market requires not only direct measurement and modeling capabilities, but also vetted protocols that define the metrics by which carbon dioxide removals are translated into verified carbon credits with tangible financial value in the marketplace. Modeling teams will be required to conduct outreach and coordinate with an existing carbon registry (of their choosing) to co-develop an MRV framework. These vetted, comprehensive frameworks can serve as a foundation for future full-fledged carbon registry protocols, which will support market adoption of an mCDR industry. Collaboration with carbon registries should inform model development and refinement to emphasize parameters most important for valorization.

e. Leveraging Collaboration with mCDR Program Efforts

While this program does not seek to fund mCDR development itself, ARPA-E is aware of several other government and non-government funding efforts that seek to understand, develop, and implement mCDR technology. ARPA-E has coordinated with the agencies participating in the recent NOPP call for mCDR implementation and development. The Agency encourages collaborations between teams working in these areas and a best effort will be made to coordinate technology leveraging, sea tests, and information sharing.

f. Team Expectations

TA1 teams are encouraged to include the following roles on their project teams. These are not intended to be mandates and are only suggestions for team composition.

- Sensor development experts who would perform the core technical development work
- Oceanographic instrumentation experts who would marinize the sensor technology, adapt it to the constraints associated with COTS ocean data collection platforms, and conduct tests in ocean conditions
- Marine biology and biogeochemical experts who could advise on sensor specifications, and perform analysis and interpretation of acquired data
- Project management and administrative staff

It is recommended that TA1 teams incorporate partners with ready access to both sensor fabrication and maritime testing facilities in environments generally representative of mCDR-appropriate regions for the anticipated rapid testing and iteration of sensor development and maturation in Phase 2.

TA2 teams may consist of the following personnel.

- Regional Ocean Modeling Systems (ROMS) experts
- Ocean biogeochemical modeling experts
- Marine biology and biogeochemical experts
- Carbon registry and marketplace experts
- Project management, administrative, data handling and IT support staff

g. Data Sharing Requirements

An appropriate legal agreement between project teams that collaborate during Phase 2 will be required. These agreements must require maintaining strict confidentiality regarding the information shared between the collaborating teams and the results generated as a result of the collaboration..

h. Data Curation Plan

If selected for a full submission, applicants must provide a detailed data management plan that describes how metadata and data collected through the project funding will be archived and made accessible to the broader community. Teams should plan to store their data at a long-term archive and the costs for data management, archiving, and access should be clearly articulated in the budget and reflected in the total project cost. If applicable, applicants are encouraged to address how historical or legacy data will be integrated into the project. Applicants that propose to collaborate with data centers or networks are advised to obtain letters of commitment that affirm the collaboration. Where possible, all applicants are strongly encouraged to use existing data centers and data portals to archive and disseminate their data.

Applicants will provide the widest practical access to data collected and must include a data management plan describing how these requirements will be satisfied. The data management plan should be submitted as a separate section of up to two pages describing the types of data and information to be generated during the course of the project (environmental and biological); the target date by which data will be shared and archived; policies addressing data stewardship and preservation; procedures for providing data access and security; prior experience in publishing such data; and an indication of the project member/level of funding dedicated for the data management components of the project. The data management plan should include an estimated inventory of all datasets collected (or planned to be collected), which will be updated yearly. Submissions should identify one or more members of the team to document and archive data in accordance with the plan and to ensure that the data products and visualization tools co-developed with the end-user resource manager participants in the project are made available via open access portals and data platforms.

i. Topics Not of Interest

ARPA-E programs fund high-risk, potentially disruptive new technology development efforts that may presently be unattractive to follow-on funding groups due to the number of unknowns, risk of failure, or uncertainty regarding performance. As such, ARPA-E is not interested in submissions that propose work that could be described as the following:

- Exclusively existing ocean sensor technologies for parameters listed in **Table 2** used in a new application.
- Proposals describing incremental improvements to existing sensing or modeling systems.
- Efforts to coordinate the scientific community that do not emphasize specific proposed technological development as the primary directive.
- Sensor technologies not conducive to spatially scaled, volumetric or area-sensing strategies.
- Sensors designed to mount on disposable platforms, or disposable sensors themselves.
- Sensor platform technology development
- Proposals consisting of significant policy and regulatory framework in the absence of verified new sensor technology.
- Investigations that prioritize non-monetary environmental impacts (i.e., measurements that do not serve to directly quantify the number of, quality of, and duration of potential carbon credits earned)
- Regional or Global CDR models or vignettes outside of the U.S. EEZ, unless proposals are led by a U.S. institution and a clear mechanism exists for the valorization of potential carbon credits earned outside the U.S. EEZ in a U.S. carbon market by a U.S. entity. Note that ARPA-E is open to proposals from international teams, but the lead organization must be a U.S. based group eligible to receive federal funding.
- MRV approaches for mCDR techniques that cannot reasonably scale to 1 gigaton per year carbon drawdown, or for mCDR techniques that cannot be shown to remove CO_2 from the atmosphere and surface ocean for periods of time exceeding 100 years at minimum.
- MRV for CDR methods that are not ocean-based.

j. Acronyms & Definitions Specific to this FOA:

ACC: Anomaly Correlation Coefficient
Accuracy: The closeness of a measured or simulated value to the true value.

Additionality: Artificial addition or subtraction of material from naturally occurring quantities that would not have occurred without the artificial process.
Bias: How well a model matches a training set. A model with high bias won't match the data set closely, while a model with low bias will match the data set very closely.
CMCC: Centro Euro-Mediterraneo sui Cambiamenti Climatici
COTS: Commercial Off The Shelf
DIC: Dissolved Inorganic Carbon
DOC: Dissolved Organic Carbon
POM: Particulate Organic Matter
DOM: Dissolved Organic Matter
EEZ: Exclusive Economic Zone
Export: Removal of carbon to desired depths for carbon credit quality.

Fugacity: A thermodynamic property of a real gas which if substituted for the pressure or partial pressure in the equations for an ideal gas gives equations applicable to the real gas.
IPCC: Intergovernmental Panel on Climate Change
ISFET: Ion Sensitive Field Effect Transistor
Labile: A compound that is readily and likely to be re-mineralized
mCDR: marine Carbon Dioxide Removal
MEMS: Micro-Electrical Mechanical Systems
MRV: Measurement, Reporting and Verification
NCEI: National Center for Environmental Information
NOAA: National Oceanographic Atmospheric Administration
NOPP: National Oceanographic Partnership Program
NPZD: Nutrient-Phytoplankton-Zooplankton-Detritus
OSSE: Observation System Simulation Experiment
POC: Particulate Organic Carbon
Precision: The closeness of a measured or simulated value to other measured or simulated values that are expected to be identical.
Recalcitrant: A compound that does not re-mineralize or does so at very slow rates.
RMSE: Root Mean Squared Error
ROMS: Regional Ocean Modeling System
SNR: Signal to Noise Ratio
SOA: State Of the Art
Sub-mesoscale: 1-10km
TA: Total Alkalinity
TEA: Techno-Economic Analysis
Transport: Movement of carbon in ocean systems before carbon reaches desired reservoirs for storage.
Variance: The degree to which a modeled result differs when it is trained using different portions of a data set. A model with high variance will have the flexibility to match any data set that's provided to it, potentially resulting in dramatically different models each time.

Appendix 1: References for **Table 2**

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