PNNL- 35092

Marine carbon dioxide removal (mCDR) test site needs

A joint PNNL-PMEL workshop report

September 2023

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Jessica N. Cross
Simon Geerlofs
Christian Meinig

Prepared for the U.S. Department of Energy
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Pacific Northwest National Laboratory
Richland, Washington 99354

Executive Summary

This workshop report summarizes testing and capability needs for marine Carbon Dioxide Removal (mCDR) research identified by researchers from DOE's Pacific Northwest National Laboratory (PNNL) and NOAA's Pacific Marine Environmental Laboratory (PMEL) as essential to advancing the state of the science and technology. A one-day workshop was held for 36 hybrid participants on June 2, 2023 at PNNL's Marine and Coastal Sciences Laboratory in Sequim, WA. The workshop began with DOE and NOAA leadership offering perspectives on the mission alignment and long-term implementation of mCDR research within NOAA's Office of Ocean and Atmospheric Research (OAR), DOE's Water Power Technologies Office (WPTO), and DOE's Office of Fossil Energy and Carbon Management (FECM). As identified by the participants and by program leadership at both agencies, many mCDR strategies are in early stages of development making it difficult to reliably estimate their impact. The essential next step in proving the efficacy, safety, and sustainability of these solutions and identifying market potential requires studies under field-relevant conditions.

To rapidly and responsibly advance the state of the science and technology for mCDR towards deployment, a comprehensive and interdisciplinary effort is necessary. **A dedicated mCDR program that leverages expertise in: (i) technology development, monitoring, and modeling, (ii) ecosystem and environmental impact assessment, and (iii) community education and outreach, both within the DOE national Lab complex and across the federal agencies is required.** In this context, the discussion at the workshop was attuned to identifying the key qualities for mCDR test sites around four themes, including Community Engagement; Energy; Monitoring, Modeling, and Sensing; and Ecosystems. To develop test sites, participants identified the need for specific siting guides. These guides would contain decisional information, including place-based estimates of efficacy based on environmental conditions; supply chain efficiency provided by regional industry; and community relationships fostered by ongoing co-development of testing sites and education and outreach associated with the projects. Additionally, early test sites are each likely to include bespoke MRV solutions that resolve and monitor the ocean carbon system, track key ecosystem impact indicators, and monitor end-to-end energy use to support lifecycle assessments. However, participants also shared that this early work should support a long-term goal of developing standardized but adaptable options for environmental monitoring and meeting regulatory expectations.

In the interest of rapidly addressing mCDR research needs, **participants identified near-term tasks to include utilizing existing and emerging capabilities for in-lab assessments and field studies; building strategic intra- and inter-agency partnerships to advance mCDR science; connecting national labs, academia, and industry to build a regional network of mCDR test sites; and engaging with local community and tribes to understand societal concerns around mCDR**. The participants then considered the available resources across PNNL, PMEL, and more broadly the pacific northwest (PNW) and identified that testing sites are likely to be most valuable in a networked context, with robust networking offering varying scales of deployment, differing environmental settings, and a standardized data pipeline. Overall, these types of assets would make transition across early and mid-stage technical readiness more streamlined, bridging the "prototype valley of death" and pushing mCDR solutions towards commercial deployment. **The workshop participants concluded that the combination of existing (i) dedicated technical expertise in marine and coastal sciences across DOE, NOAA, and the universities, (ii) permitted test sites across these organizations, (iii) established community and tribal relationships, and (iv) access to abundant renewable energy sources makes the PNW uniquely suited for establishing mCDR research and test site network.**

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Outcomes of this workshop would not be possible without the support of dedicated engagement from workshop participants.

PNNL Participants:

- Cavagnaro, Rob,
- Copping, Andrea
- Cotter, Emma
- Edmundson, Scott
- Geerlofs, Simon
- Haxel, Joseph
- Heibel, TJ
- Hemery, Lenaig
- Huesemann, Michael
- Khangaonkar, Tarang
- Marsh, Paul
- Myers, Tristen
- Pinza, Meg
- Regier, Peter
- Sather, Nikki
- Subban, Chinmayee
- Vavrinec, John
- Ward, Nicholas
- Yang, Zhaoqing

PMEL Participants:

- Alin, Simone
- Burger, Eugene
- Cross, Jessica
- Fassbender, Andrea
- Feely, Richard
- Gold, Zachary
- Lawrence-Slavas, Noah
- Shambaugh, James
- Stanitski, Diane
- Sutton, Adrienne

Non-PNNL/PMEL Participants:

- Garson, Jenn (DOE/WPTO)
- Deich, Noah (DOE/FECM)
- Rodriguez, Carmen (DOE/WPTO)
- Chadsey, Meg (Washington Sea Grant)
- Carter, Brendan (UW)
- Cheng, Wei (UW)
- Mu, Linquan (UW)
- Stoll, Mary Margaret (UW)
- Zhang, Dongxiao (UW)
- Tran, Jonathan (U Penn)

Acronyms and Abbreviations

ARPA-E: DOE's Advanced Research Projects Agency – Energy
BECCS: Bioenergy with Carbon Capture and Storage
CDR: Carbon Dioxide Removal
CO2: Carbon Dioxide
DACCS: Direct Air Capture and Carbon Storage
DOE: US Department of Energy
eDNA: environmental DNA
FECM: DOE's Office of Fossil Energy and Carbon Management
IPCC: Intergovernmental Panel on Climate Change
LLNL: Lawrence Livermore National Laboratory
mCDR: marine Carbon Dioxide Removal
MRE: Marine Renewable Energy
MRV: Monitoring, Reporting, and Verification
  eMRV: Environmental Monitoring, Reporting, and Verification
  cMRV: Carbon system Monitoring, Reporting, and Verification
NASEM: Nation Academics of Science, Engineering, and Medicine
NOAA: US National Oceanic and Atmospheric Administration
NOPP: National Ocean Partnerships Program
OAR: NOAA Office of Oceanic and Atmospheric Research
OCAP: Ocean Climate Action Plan
OPC: White House Ocean Policy Committee
OSTP: White House Office of Science and Technology Policy
PMEL: NOAA's Pacific Marine Environmental Laboratory
PNNL: DOE's Pacific Northwest National Laboratory
PPP: Public-Private Partnership
R&D: Research and Development
SEA-CO2: ARPA-E's Sensing Exports of Anthropogenic Carbon through Ocean Observation Program
TRL: Technical Readiness Level
USGCRP: US Global Change Research Program
WPTO: DOE's Water Power Technologies Office

Contents

1.0 Introduction

Limiting warming to levels that avoid extreme risk (1.5 - 2°C) will require removing multiple gigatons of carbon dioxide from the atmosphere each year, on top of immediate and substantial reductions of greenhouse emissions (SR1.5: IPCC, 2018). While emissions-reduction approaches are the primary component for addressing this challenge, the delay in implementing these strategies over the previous decades means that negative emissions strategies are now integral to keeping global temperatures at or below target levels (IPCC AR6 WGIII SPM C.3).

Anticipating carbon markets and spurred on by massive nonprofit investments from JP Morgan (Powell and Haratunian, 2023), Stripe (Stripe Climate, 2021), ClimateWorks (Gagern and Kapsenberg, 2021), the Bezos Earth Fund (Amazon.com, Inc., 2020), and the $100M Carbon Removal X-Prize (Carbon Removal X-Prize, 2021), the private sector is already implementing carbon removal strategies. Offsets already have deep market penetration: for example, consumers can purchase carbon offsets with airline flights or monthly utilities (e.g., TerraPass (TerraPass, 2023); PSE Carbon Balance program (Puget Sound Energy, 2023)). However, despite the fact that carbon offsets and negative emissions shares are currently for sale, the effectiveness and verification of these programs are highly questionable (West et al., 2023). In some cases, it may not be clear if the strategies are safe or equitable (e.g., Mawonde and Togo, 2019; Samaniego et al., 2021), let alone effective (e.g., Haya et al., 2023; West et al., 2023). This uncertainty is leading to substantive challenges to market confidence (e.g., Twidale and McFarlane, 2023), with some independent corporate accountability assessments indicating that 78% or more of the largest carbon offset projects are ineffective (Lakhani et al., 2023), and leading to hearings from the CFTC on market integrity (Goldsmith Romero, 2023). Buyers are increasingly aware of and committed to purchasing high-quality offsets, but struggle to find adequate supplies relative to their climate commitments (e.g., Joppa et al., 2021).

Much of the current market integrity questions stem from terrestrial offsets. This section of the market is governed loosely by proliferating voluntary market standards (Arcusa and Sprenkle-Hyppolite, 2022). By comparison, there are far fewer voluntary standards currently governing ocean carbon dioxide removal assets, given that research into these removals is at an earlier stage and there are far fewer commercialized mCDR products available. According to Arcusa and Sprenkle-Hyppolite (2022), this is both a liability and an opportunity: ocean or marine-based CDR removal products markets and technologies are theoretically compelling but currently immature, limiting near-term commercial potential relative to DAC and BECCS and restricting sales of Advance Market Commitment assets which could fund further research. However, application of strong, science-based standards early in mCDR product development may eventually lead to stronger, more stable markets. This opens the door for government-funded research to invest in early technical development stages, lending the credibility of the independent academic process to the development of best practices and standards (Palter et al., 2023).

In response to these challenges, the 2023 White House Ocean Policy Committee's Ocean Climate Action Plan (OCAP) called for a "ramp-up in marine CDR research and development investments" (OCAP, 2023). There is a broad consensus across the natural and social scientific communities that additional research in mCDR requires large-scale field demonstrations (e.g., Palter et al., 2023; Ocean Visions, 2023; Gagern et al., 2022; Webb et al., 2023): The idealized settings of laboratory research in many ways do not reflect the same processes or uncertainty as may be observed in real-world settings, and additional laboratory-based experiments may not be able to identify ecosystem interactions or potential unknown-unknowns. Accordingly, one of the 7 key OCAP actions addressing mCDR includes the “creation of new mCDR demonstration sites.” The OCAP identified both NOAA and DOE as key agencies supporting the development of mCDR infrastructure, pilot programs, test sites, and field studies throughout the plan’s discussion of mCDR.

Through the implementation of the OCAP and other recent federal guidance, multiple programs at NOAA and DOE are beginning to consider commitments to mCDR research, including NOAA’s Ocean Acidification Program (OAP) as well as DOE’s Water Power Technologies Office (WPTO), DOE’s Office of Fossil Energy and Carbon Management (FECM), and DOE’s Advanced Research Projects Agency-Energy (ARPA-E). At this workshop, remarks were offered on behalf of OAP, WPTO, and FECM showcasing the potential opportunities for engaging in mCDR research through pilot programs and test sites. These presentations showcased the variety of pathways for funding mCDR research at both NOAA and DOE. Notably, each included a statement about the need for pilot studies and infrastructure development that will push the field of mCDR forward.

- Remarks from the NOAA OAP focused on the recent publication of NOAA’s Carbon Dioxide Removal Research Strategy (Cross et al., 2023). Here, the agency identifies four key pathways to advancing mCDR, including measurements and observing systems; biogeochemical modeling infrastructure on multiple scales; ecosystem studies; and marine spatial planning products. The ultimate goal of these four complementary research focus areas is the creation of scalable, interdisciplinary spatial mapping tools that support decision makers in their exploration of mCDR implementation. NOAA also highlighted recent investments in the implementation of this strategy through the National Ocean Partnerships Program (NOPP) mCDR initiative, citing both the OCAP and recent consensus guidance from the NAS.

- Remarks from the FECM provided a progress update on DOE’s Carbon Negative Shot, including information on base appropriations that can provide opportunities for FECM to collaborate with NOAA and other offices to fund ocean CDR pilot studies. FECM highlighted that investments in robust MRV are also apparent in the Carbon Negative Shot program, including ARPA-Es SEA CO2 initiative, which focused investment on development of new tools and systems that can support mCDR MRV.

- Remarks from WPTO highlighted investments that address the opportunity for marine energy and mCDR co-development and integration. Co-locating marine renewable energy and mCDR (or coupling marine energy with observing systems necessary to monitor mCDR impacts and efficacy) could alleviate potentially significant power constraints and cost barriers, as well as support favorable LCA for mCDR processes. WPTO is supporting these investments through WPTO’s Powering the Blue Economy initiative and cross-agency support for the Carbon Negative Shot.

2.0 Workshop Objective: Scoping mCDR Test sites

Demonstration studies and pilot projects were recommended for almost every mCDR pathway outlined in the NAS mCDR consensus study report (See Table 9.3, NASEM, 2022). The OCAP both highlights the need for a diversity of sites, considering variation across the marine environment, as well as the need to leverage interdisciplinary approaches at each individual site.

In this sense, federally funded research labs are extraordinarily well suited to advance mCDR work, given the interdisciplinary teams located at these institutions. Further, they are also well attuned to working across the science and technology spectrum with experience in transitioning their research from bench-scale to commercialization in partnership with private entities:

- PNNL is home to DOE's only marine sciences research facility. This includes multiple pre-permitted test sites that may be suitable for mesocosm or coastal field trials.
- PMEL is the premier global laboratory for ocean carbon measurement and sensing, setting the gold standard for accuracy and developing new methods and sensors for carbon system assessment.
- Both laboratories have strong relationships with academic partners with diverse marine science expertise, including the University of Washington, Oregon State University, and the University of Alaska system. Regional partnerships extend beyond the borders of the US, including into British Columbia, Canada.
- Both laboratories have extensive experience with successful public-private partnerships (e.g., Wilczak et al., 2015; Meinig et al., 2019).

Especially in the Pacific Northwest, NOAA's PMEL and DOE's PNNL are already engaged in multiple interdisciplinary mCDR projects built around public-private partnerships. For example, the "Electrochemical Acid Sequestration to Ease Ocean Acidification (EASE-OA)" project is a collaboration between PMEL, PNNL, and Ebb Carbon and is co-funded by NOAA, DOE-WPTO, and ClimateWorks Foundation. EASE-OA has designed, built, and installed a pilot-scale mCDR system at PNNL-Sequim, including system monitoring, modeling studies that can assess potential environmental impacts, and lab-scale ecosystem impact studies. In a second example, NOAA PMEL is a key project partner and stakeholder in the DOE-FECM funded "An Adaptive MRV Framework for Mineralization-Based CDR Technologies" project led by PNNL. The project brings together industry partners, community members, and regulatory stakeholders—building a dedicated mCDR research consortia.

At this workshop, participants representing PMEL and PNNL worked to define features of a ***minimum-viable mCDR test site*** that can help transition small-scale and early-stage mCDR strategies to full-scale, operational programs; a phase of R&D often referred to as the "prototype valley of death." Tight budgets, narrow risk margins, regulatory permitting delays and growth complexities can often limit the capacity of a project at this stage to achieve a large-scale demonstration that can garner additional investment. Overcoming the prototype valley of death is particularly challenging for emerging technologies, as the regulatory agencies may not have the framework or pathway established to permit pilot operations. Especially since no mCDR large-scale field demonstrations currently exist, and mCDR approaches can be fairly diverse, it is difficult to articulate a clear vision for the infrastructure required. To help scope such test site requirements, participants were engaged in guided discussions.

The first discussion activity at this workshop asked the 36 hybrid participants to develop a vision for a mCDR test site using the Discovery – Development – Delivery Design Thinking framework. Originally developed to assist creative workflows, Design Thinking (e.g., Panke, 2019) helps to better define broad concepts or unknowns by addressing (a) ideal end results, (b) the presently available material and technical resources, and (c) the constraints and opportunities in using those materials to develop results as close to the ideal as possible. Often, insights developed during any phase of this thinking process are brought back to inform the others; for example, identifying the ideal end results in (a) may bring forward a key barrier to success in the existing development pathway or framework in (c). In another example, new or previously unknown resources identified in (b) may showcase new opportunities for achieving the desired end results identified in (a).

Here, the organizers asked discussion participants to envision (a) an ideal mCDR test site, by considering (b) the minimum resources necessary, and (c) constraining the problem in a Discovery – Development – Delivery process framework. Participants were asked three key questions that could help frame their thinking around the primary users of these test sites, the infrastructure the test sites would need, and who pays for the capitalization and operation of these facilities. Finally, participants were asked to cycle back to their first answers by linking their key users and funders by describing the networks shared by both. Feedback from all participants was captured through a Mural board (see Appendix B).

In this initial discussion, participants identified three primary end goals for users of a test site, including verification and validation of operational technologies; environmental assessment; and testing and troubleshooting. These three uses also reflect three different phases of development, highlighting that the **test sites will need to be adaptable**. Since multiple parties may have an interest in the results across the development phases, including public and private accountability organizations (e.g., EPA, SBTI, private MRV companies); technology developers and credit providers; offset or removal purchasers (e.g., carbon markets or private businesses); and academic researchers, many different sources were suggested as the primary buyer of testbed data, time, or access. This again reflects the need for the site to be adaptable. However, it should be noted that most responses (21 of 34) indicated a private sector user or buyer of testbed data, time, or space.

In considering the development of the test site, most participants focused on technical equipment and assets that would be required at each individual site. Notably, sites were thought to require **redundant pathways of measurement for multiple interdisciplinary variables, including carbonate chemistry, ecological responses, and energy and power usages and profiles**. However, much of the discussion around test site development also focused on high level concepts, such as the need for **modular but standardized measurement and monitoring protocols** and **robust data management**, computing, security, and data delivery. Each site should be equipped with **scaled local and regional biogeochemical and ecological modeling packages**. Each site was also said to require **pre-permitting for a variety of different mCDR techniques** and measurement options.

Participants also spent significant time discussing the culture of the networked set of diversified test sites. This included close collaboration and co-development with local communities and strong codes of conduct governing users, emphasizing transparency. However, participants also acknowledged the tension between **transparency and potentially sensitive intellectual property**. In describing test site operation, participants highlighted a spirit of positive failure, including **space for collaborative and friendly competition** but also openness to trial and error and iterative development.

Asked who could potentially pay for **capital and operational expenses** associated with the test site network, most respondents indicated that **government and private industry shared responsibility**, although government was highlighted as the most likely partner for capitalization. Consensus input from communities and other sectors was also emphasized. Although philanthropies were barely mentioned, here they were targeted for “donut hole” capitalization, given that philanthropic interests often prefer single investments over a short time period that may be especially suitable to the capitalization phase.

The role of government, especially federal programs, emerged substantively when participants were asked to identify key partners, partnerships, and networks where buyers, developers, and builders collaborated. Many of the responses highlighted federal government agencies or programs (11 / 24), more than double those listed for any other sector. It should be noted that this may reflect the bias and experience of the respondents, who all worked for or with federal agencies. In other parts of the discussion, it was noted that “community members” was a disconcertingly broad term and should necessarily be better defined.

Full responses recorded in the session Mural board are provided in Appendix B. Comments were downloaded and sorted by question, and then post-classified into broader categories for the purposes of the analysis provided above. Histograms of these categorized answers are also provided in Figure 1.

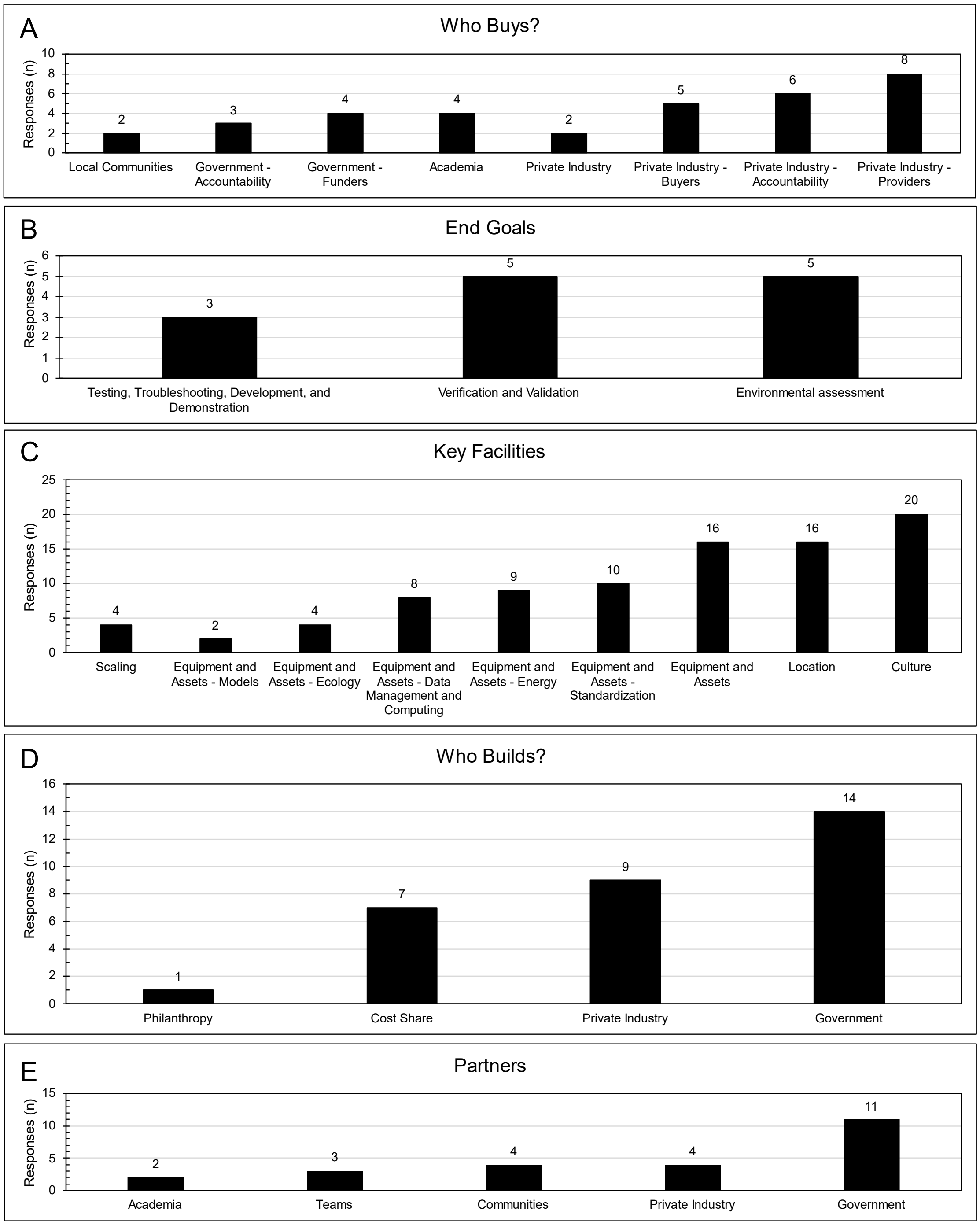

Figure 1. Histograms of categories used in post-classification of Mural comments in each section of the group design thinking activity. Private industry was indicated as the largest buyer of test site data, time, or access (a), with end goals including testing and troubleshooting, verification and validation of operational technologies, and environmental assessments (b). Discussion of key facilities included detailed descriptions of equipment and assets, but also conversations concerning the location of diverse, scalable, but standardized test sites and the culture of test site networks (c). Participants identified government as the builder and operator of test sites, but also indicated some cost-share responsibility for private industry (d). The partners required to design and develop these test sites were mostly identified as government (e), likely reflecting the limitations of commercial space and the clear role of government research and infrastructure in an emergent field.

3.0 Digging into details: Breakout Groups

Following the group design thinking activity, which oriented the group to what an ideal test site may look like, participants chose a specific themed breakout group to further engage a particular facet of test site development through Agile thinking activities (e.g., Lemay, 2019), where they reflected on ways of working to effectively develop the ideal test site model. Activities gradually moved from strategic thinking to tactical thinking as described below.

- **Breakout Activity 1** (*Sailboat Perspective*). Participants were asked to visualize a particular project or problem as a sailing journey to identify the goals of the project, the factors providing forward momentum, any anchors holding the project back, and potential barriers ahead that may require some adaptable steering. This activity helped focus strategic thinking around each particular theme.
- **Breakout Activity 2** (*Development Pathway*). This activity is based on the technical readiness levels (TRLs) associated with project development, particularly in the federal system (e.g., NOAA, NAO 216-105B). To encourage more specific tactical thinking based on the results of the sailboat perspective activity, breakout teams were asked to identify particular development tasks and their best sequence to transition test site development through the various readiness levels for each theme. To identify options for parallel development pathways or potential bottlenecks to progress, teams were encouraged to think in terms of the simultaneous model activities, field activities, partnerships, and governance pathways that could support progress on their particular breakout theme.
- **Breakout Activity 3** (*Identify Key Challenges*). This summary alignment activity encouraged participants to consider the results of the other discussions throughout the day and identify one or two key problems—and solutions—that may bridge the gap between current assets and the ideal path forward. This very specific tactical thinking exercise was designed to help participants think about the first tasks or challenges to address in a project.

Full responses for each activity from each group were recorded in the session Mural board, and all boards are provided in the Appendix B. Similar to the first activity, comments were downloaded and sorted by question, and then post-classified into broader categories for the purposes of analysis. A full synopsis of comments for the sailboat activity is provided in Figure 2. While participant responses frequently diverged between breakout rooms, given the divergent topics at hand, note that most groups extensively discussed funding, partnerships, public perceptions, and timing, including the benefits and drawbacks of each of these topics. When applied in the right way or at the right time, many topics were found to be beneficial; when applied in the wrong way or at the wrong time, many topics were found to be detrimental. Overall, the most-discussed end goals included technical advancements, partnerships, and collaborations. Public perceptions, funding, and technical challenges were the most common responses limiting forward progress (Anchors). In the future, participants suggested that public perceptions, timing, permitting, and infrastructure might hold progress in the field back (Barriers). To overcome these perceived restraints, participants were motivated by emerging technical capabilities and theoretical possibilities for further technical advancements, as well as by emerging funding (Momentum).

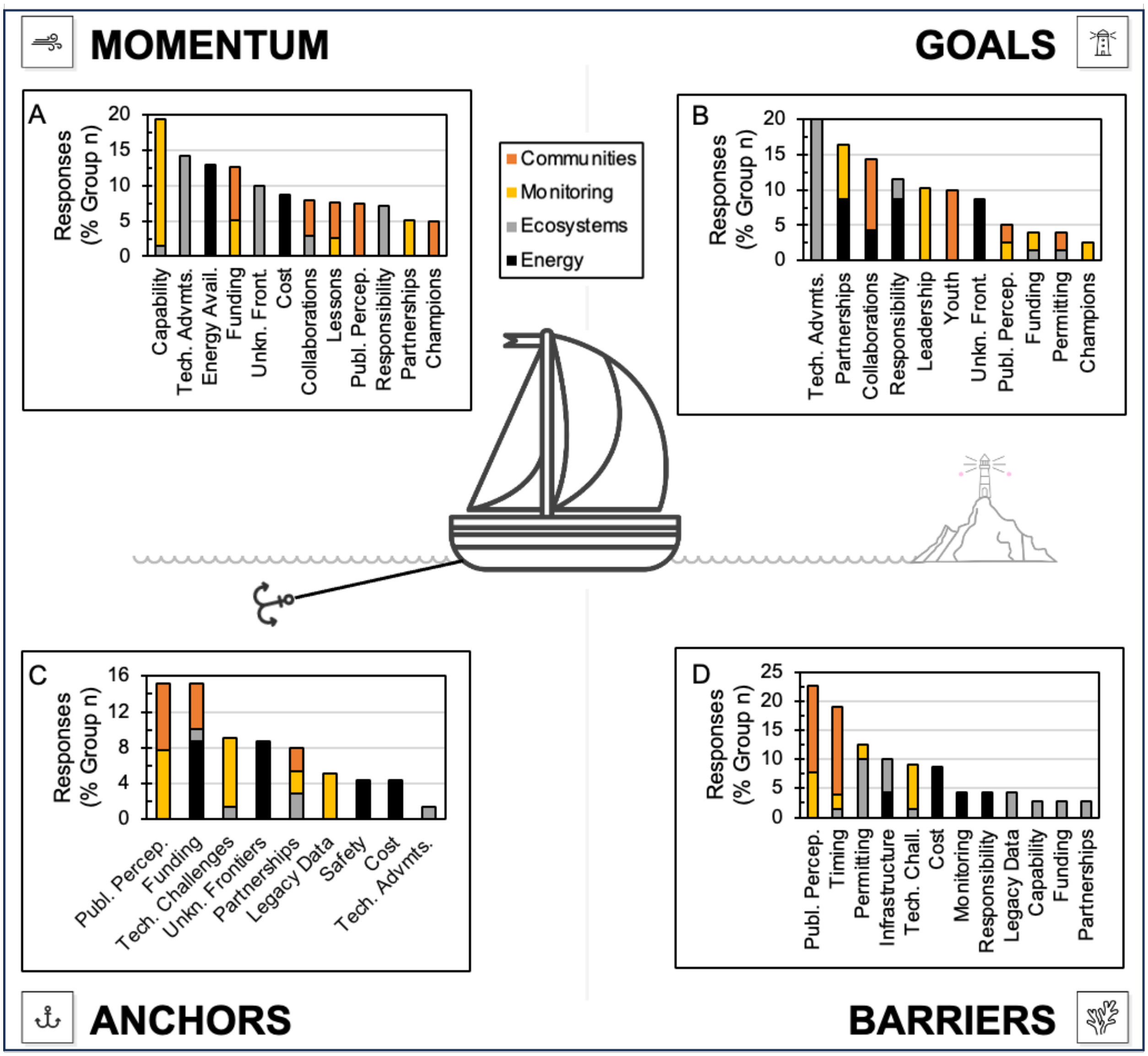

Figure 2. Histograms of categories used in post-classification of Mural comments in each section of the sailboat perspective activity (Momentum, A; Goals, B; Anchors, C; and Barriers, D) by each breakout group. Shading (see inset) indicates breakout rooms, including Energy (black), Community Engagement (Orange), Ecosystems (Gray), and Monitoring (yellow). To normalize responses across breakout groups (e.g., correct for some groups that may have been more responsive), each bar represents the percent of responses from each group in an individual question, relative to the total comments left by each breakout group across all questions. Where bars are taller, an individual group offered more responses discussing this topic. Where bars are stacked, multiple groups spent time discussing this topic. Bars in an individual panel will not sum to 100%, but each series of bars does sum to 100% across all four panels. Note that some topics were listed both in positive and negative terms; for example, funding was commonly listed as an anchor or a barrier, but in some cases as a potential source of momentum. The monitoring and community engagement breakout rooms focused on public perceptions as the biggest limitations to progress, but both also considered public enthusiasm to be a potential source of momentum.

3.1 Community Engagement on mCDR

During each of the breakout activities, the community working group heavily emphasized the need for partnerships that would equip local communities with the information and knowledge that would help them meaningfully engage with mCDR projects. In the end, their vision is for funded permanent staff who manage these partnerships on behalf of test site users. In essence, social license and community partnerships become part of the test site infrastructure. This helps maintain long-term connections between communities and the test site operators even as test site users may change. In order to develop the right partnerships, the community breakout recommended in their TRL activity that outreach should begin early, and these partnerships are then brought through all the other stages of the development, including transparency and participation around field activities. Accordingly, the First Challenge listed in their design thinking activity was identifying the communities and stakeholders who will be directly affected or who can gain opportunities from participation in the project. While it is essential to invite these communities into the test site facilities and planning process, it is also important at the start of this activity to meet these communities where they are already participating and operating.

- **Goal**: Creating a collaborative, transparent mCDR working environment around test sites that includes community stakeholders and youth.
- **Momentum**: New and mostly positive interest and public perceptions driving additional funding available to support partnering.
- **Anchors**: Some negative public perceptions limiting possible action. While new funding is available, it is insufficient to complete the necessary education and outreach required by this effort.
- **Headwinds**: Divergent perceptions of optimism and pessimism that will fuel division across the community and may limit future funding and motivation for community partnerships.
- **Development Pathway**: Partnerships should be developed early and brought transparently through each phase of test site development.
- **First Challenge**: Identify the partners and stakeholders that may be affected by, or gain opportunities from, test site development and operation.

3.2 Ecosystem Impacts of mCDR

In particular, the ecosystems working group was motivated most strongly by technical advancements and emerging scientific questions, revealing a deep intellectual curiosity and a desire to drive the field forward. During the sailboat activity, this group emphasized how quickly the field is iterating and the new tools that will be rapidly coming online in the near future. While this will provide ample opportunities for new research, this group also emphasized the need to move carefully through multiple phases of trial and error. This approach would allow the field to find and understand not just the tools that work, but how to use these tools to identify and monitor the right proxies and indicators that can best describe ecosystem functions. By contrast, this group also identified the development of infrastructure as their First Challenge. The small-scale tools that are currently available are rapidly reaching their useful limit; more and more useful information about the power of new tools and the nuances of ecosystem function can come from larger experiments. In the near term, this may indicate the need for more instrumented tanks to run longer, more varied experiments. The results of these initial experiments should inform the development of larger-sale infrastructure projects.

- **Goal**: Rapid, dynamic assessment of environmental indicators of the risks and benefits of CDR at test sites.
- **Momentum**: New technical advancements creating more diverse and information-rich ecological datasets than have ever been available before.
- **Anchors**: Ecological assessment is a slow process, diverging from the timelines that other parts of test site development may operate on.
- **Headwinds**: Moving experiments into the field to determine ecological risks and benefits may require permits, which inherently require the results of these same field experiments, creating a circular bottleneck.
- **Development Pathway**: Infrastructure, particularly regarding spaces, will be essential to develop alongside new technical advancements and new knowledge that utilize presently available facilities.
- **First Challenge**: Building a phased research pathway that uses currently available resources and works within existing permitting limits, while also targeting the development of long-term infrastructure that will help move research forward.

3.3 Energy Needs of mCDR

Throughout their conversations, this group emphasized that operational test site projects must prioritize reliability. This is in part a safety issue, but also a mission critical one: test site users that require renewable power will need a consistent source in order to operate equipment effectively. While this group emphasized the potential of marine renewable energy to power all aspects of an mCDR activity—including both operations and monitoring—they also acknowledged that this potential may be difficult to achieve, as the capitalization required to support both research and operations in this space will be expensive and could distract from cost efficiencies that may emerge later. During the TRL activity, participants in the energy group identified an orderly progression from technical models to field deployments, to iterative development. Partnerships with users were introduced to the project only after reliable power generation could be guaranteed—essentially, development of marine renewable energy sources for test site monitoring and deployments must remain exclusively within the research realm until the TRL is much higher than in other cases. This group identified their First Challenge as establishing the safety and reliability standards that are required for the equipment and sensors included in an mCDR test site network. In discussing the solutions to this challenge, participants identified the need for a collaborative and interdisciplinary research community that bridges silos between sensor developers, electrical engineers, and researchers.

- **Goals**: Responsible provision of renewable power sources for operation and MRV that create as efficient and net-negative technical pathway as possible at each test site.
- **Momentum**: The theoretical potential of ocean energy, if accessed, could provide cost efficiency as well as removal efficiency to CDR projects.
- **Anchors**: Current funding and infrastructure limit the capacity to make large advancements in paired development of CDR and MRE, despite theoretical readiness.

- **Headwinds**: The cost of developing the infrastructure required to test and produce and provide reliable MRE to CDR facilities at early TRLs could distract from potential future cost efficiencies.
- **Development Pathway**: While research partnerships will be essential at the start, operational partnerships should only be developed after reliable power generation is achieved.
- **First Challenge**: Developing the standards and benchmarks that define sufficient reliability of power generation.

3.4 Monitoring and Modeling of mCDR

Relatedly, the monitoring working group was motivated by the opportunity to provide leadership to the field by using the test site facilities, especially in conjunction with the right partners to advance results quickly. During these activities, the monitoring working group quickly narrowed in on the technical challenges in the field. Despite setting ambitious goals to provide robust validation and verification services to regulatory authorities, participants noted that technical capabilities may limit the information that can be provided at this stage. Accordingly, their development timelines focused on creating new technical capabilities and capitalizing facilities that support highly technical work. Participants felt that there were few places in the world better equipped to meet this challenge, given the world-class carbon modeling, sensing, and technology development teams and partners in the Pacific Northwest region. Model development initialized this scoping and underpinned subsequent activities, but interdisciplinary parallel development of partnerships and sensing was emphasized. For this group, governance activities were held off until after operational deployments could indicate clear sets of standards. Similar to the energy group, operational partnerships with users were held off until TRL levels were much higher. As their First Challenge, this group discussed parsing the timescales of carbon accounting vs. assessments of storage durability. Jointly assessing these two factors will require careful consideration of how to combine both measurements and models to provide meaningful results. This research question is likely to underpin the design of current and future experiments. Resolving with early field testing of how to jointly assess this question would help inform the assets and facilities required to provide this data to future operational users of the test site network.

- **Goal**: Lead the field in the development of MRV standards and best practices implemented at these test sites.
- **Momentum**: World-class researchers, facilities, and modeling capabilities currently available at the institutions.
- **Anchors**: Technical challenges of measurement and modeling that limit certainty in carbon removed, eroding public trust in results.
- **Headwinds**: Technical challenges that create slow progress in reducing uncertainty, further eroding public trust in results that limits sustained funding that may support technical advancements.
- **Development Pathway**: Academic and government research should precede operational private deployments and underpin evidence-based governance.
- **First Challenge**: Identifying clear, achievable, trusted standards and best practices for MRV, which can help make clear how to sufficiently equip a network of test sites.

4.0 Workshop Conclusions

For each of the working groups, the first challenge described the formation of infrastructure of some kind: forming the right community partnerships; scaling the right ecological experiments with bigger sets of existing tools; building marine energy capacity; and considering what operational standards may look like. As one participant responded: "Now is the right time for a test site research collaborative. In a world where we have millions and not billions of dollars, this is the right way to gain the foundational data we need to move forward in a responsible way in the future."

The results of this workshop represent a first step towards the design of these test sites, but this effort will obviously require additional collaboration and consensus building. Even over the course of the breakout activity, conversation continued to change participant's perceptions. Following the breakout discussion, participants were asked to re-engage the topics discussed during the initial group Discovery-Development-Delivery activity. In this iteration, participants included more nuance in most of their answers, reflecting the deeper engagement with these ideas that emerged over the course of the day. As shown in Figure 3, participants identified more specific end goals for a test site project. The communities and energy working groups both listed collaboration as an intentional end goal of a test site network. Many groups discussed a service model, where in addition to the time, space, and facilities required to test marine CDR methods and environmental impacts, data regarding these efforts were provided as a collaborative service with the test-site operators. This service model also reflected emerging perspectives about the key users and buyers of test site data, time, and access. Verification and validation were expressed not necessarily as a private sector need, but as meeting a government-based accountability requirement. Local communities also emerged as important test site users, especially given this accountability perspective.

In considering the key facilities and assets required to deliver on this emerging model of verification and validation-as-service, **an overall model for test site development reflected three key areas**: one, concerning **the site itself**; second, including the monitoring and **verification practices at that site**; and third, considering **technology development practices** at that site. Each site should be pre-permitted both from a legal perspective, but should also be community-vetted and supported. Sites should also span a variety of environmental settings (e.g., coastal vs. open ocean). The goal of a validation-ready test site should be something akin to "MRV-in-a-box," where projects of any technical type can engage with a plug-and-play system that can easily output standardized MRV and power data that is easily compared between tests. However, participants noted that this may take some time to develop and should reflect interdisciplinary perspectives. Each site should also be capable of testing multiple different kinds of technology, and provide capacity and capability to test at multiple scales and in multiple settings.

Participants also frequently discussed the culture of these test sites, reflecting a need for a balanced, scientific approach to mCDR development and moderation of test site user attitudes. As reflected in Figure 2, topics were discussed both in positive and in negative terms. Most groups mentioned both the benefits and drawbacks of public attention, timing, and funding. When applied at the right time and in the right way during the development process, all could be beneficial; at the wrong time or in the wrong way, all could prove especially challenging. For example, while the potential threats of climate change could compel the field to act quickly, participants noted that this **urgency must be balanced with a precautionary approach** that tests for potential environmental and societal impacts to maintain social license over time. Participants also noted the motivation to begin researching mCDR in the field as soon as possible with the resources available, even as developments of infrastructure and permits are ongoing in parallel. However, right-sized funding was also listed as an important boundary. Rogue actors with access to substantive resources in a limited regulatory environment could prove a threat to the overall social license for CDR across the entire research community, as has previously been the case for ocean fertilization and in the marine energy community, although access to funding could help the scientific community more quickly advance the field of CDR.

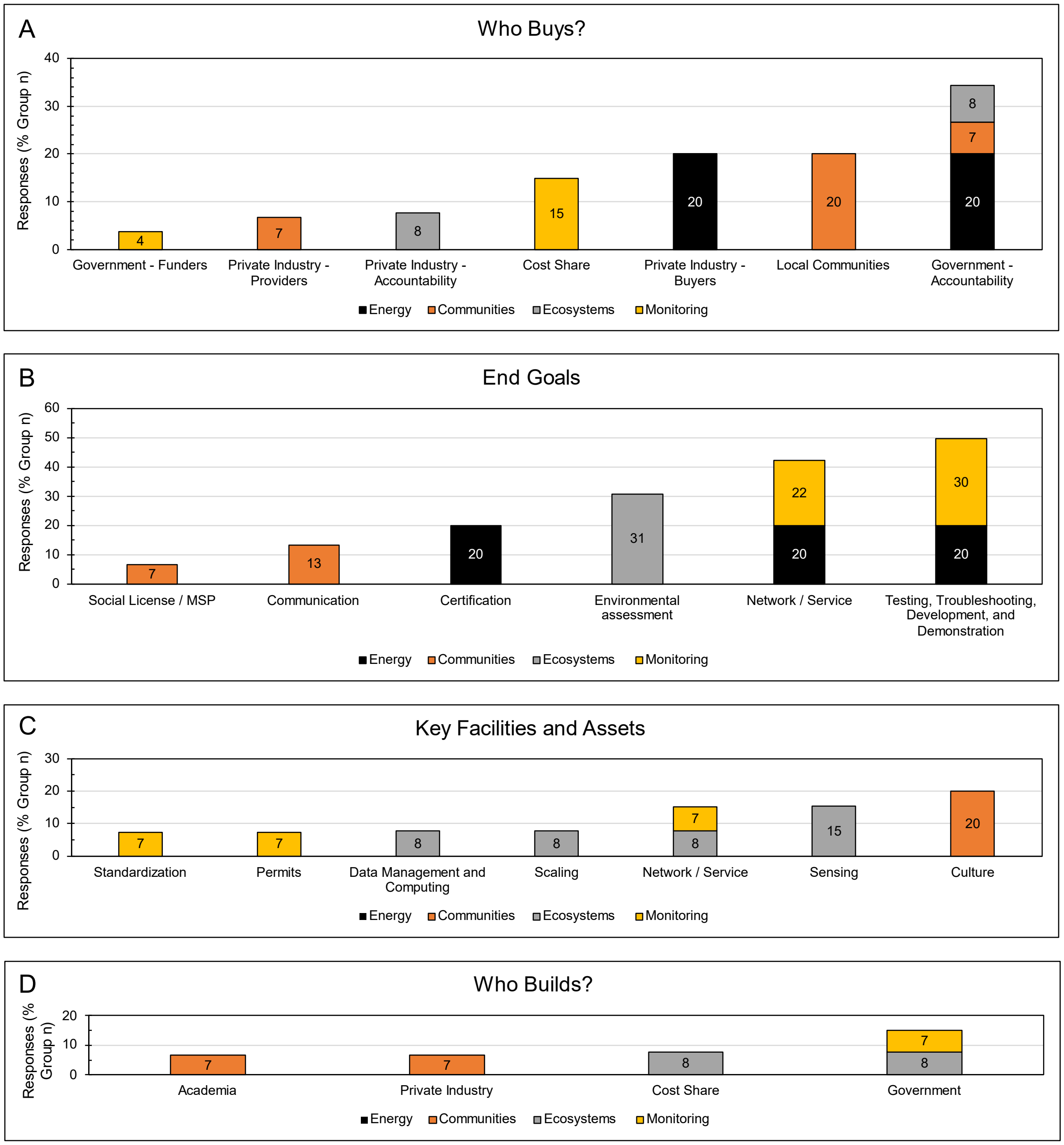

Figure 3. Histograms of categories used in post-classification of Mural comments in each section of the design thinking activity, revisited by each breakout group. Shading indicates individual breakout rooms, including Energy (black), Community Engagement (Orange), Ecosystems (Gray), and Monitoring (yellow). To normalize responses across breakout groups (e.g., correct for some groups that may have been more responsive), each bar in a panel represents the percent of responses from each group in an individual question, relative to the total comments left by each breakout group across all questions. Where bars are taller, an individual group offered more responses discussing this topic. Where bars are stacked, multiple groups spent time discussing this topic. Bars in an individual panel will not sum to 100%, but each series of shaded bar does sum to 100% across all four panels.

5.0 Next Steps

Synthesizing feedback from the breakout sessions and the group discussion following the breakout session, the participants identified three key phases of test site network development:

Phase I: Scoping test site capabilities and user models (Years 1-2)

- Identification of partners, partner priorities, community benefit models, and test site models
- Survey of existing resources, capabilities, and expertise across institutions
- Instrumentation and initiation of baseline measurements at key sites across institutions
- Development of relevant regional and local biogeochemical models and "virtual test sites"
- Research and development of suitable sensors and data management capabilities
- Design of test site infrastructure and evaluation of associated permitting needs
- Investigation of environmental impacts through laboratory studies
- Development of framework for carbon balance and permanence assessments
- Build additional consensus around Phases 2 and 3

Phase II: Establishing partnerships around minimum viable mCDR test sites (Years 3-6)

- Utilization of existing mesocosm capacity to assess environmental risks and co-benefits and identify transparent metrics of test site ecosystem health
- Validation and iterative update of biogeochemical models using test site sensing data
- Extensive monitoring of first in-situ field experiments
- Integration of renewable energy sources with test site operation
- Participation and engagement of local communities and tribes around test site permitting

Phase III: Building a network of dedicated mCDR test sites (Years 6-12)

- Identification of key proxies for operational monitoring (e.g., what can we stop measuring?)
- Development of reliable marine renewable energy delivery to test site
- Monitoring and transparent delivery of information about test site ecosystem health
- Integration of monitoring and modeling to accurately track carbon removal in field settings
- Establishment of operational mesocosm services for rapid assessment of potential ecological risks of new mCDR strategies before deployment
- Demonstration of end-to-end energy and carbon assessments of diverse mCDR strategies using modular test sites across a network of test sites

The first step in developing this test site network is to make sure that it meets the detailed needs of users and is broadly supported by the community. While it is difficult to develop these details in large group settings, additional conversations with some of the workshop leaders could help identify this specific vision. While groups of researchers are busy developing technical details and emphasizing research questions that will help inform the development of the field, it is also essential to begin forming relationships with key community stakeholders. All working groups (except the energy group) also identified partnerships as holding them back—in some cases related to capacity and participation fatigue, as there are not necessarily enough interdisciplinary partners available to participate in every venue; in others, noting that the time required to build trust could potentially slow the development of the field.

In part, PNNL and PMEL are already participating, with DOE and NOAA, in a variety of these efforts. For one, NOAA's Washington Sea Grant is leading a regional place-based network for marine CDR researchers and stakeholders. Washington Sea Grant is ideally placed as a key boundary organization that can help interface with a variety of different regional stakeholders, as well as a large swath of the scientific community. Additionally, both PMEL and PNNL researchers participate in the Washington State Marine Resource Advisory Council and Washington State Coastal Marine Advisory Council—organizations that are connected to the Washington Governor's Office and which will be essential to defining regulatory boundaries and standards for marine CDR testing. Last, WPTO has supported the development of a larger community engagement network focused on finding stakeholders for these test sites as part of PNNL's Ocean's for Climate: mCDR Lab project. Continuing to support these and emerging engagement activities will be important as any plans for test sites develop. Inviting, welcoming, and listening carefully to community concerns and questions at these early stages of development may also help to inform the research questions that a test site must be designed to assess.

While these projects—and this workshop—represent a critical step forward, scoping phases 2 and 3 and aligning the work in those phases with a rapidly developing field of research and emerging sponsor priorities will require additional conversations and support. Based on the feedback from this workshop, participants are motivated to continue to advance this project, and there are many positive sources of momentum. However, given the potential risks involved, participants suggest that these conversations should work to tread carefully between environmental pessimism and excessive techno-optimism, include a variety of stakeholders, and prioritize transparency where possible.

Workshop participants concluded the Pacific Northwest to be particularly well suited to host and manage a network of test sites for advancing mCDR rapidly and responsibly. The next step towards realizing such a network of test sites is to map the innovation ecosystem in the region through a survey of technical expertise and physical capabilities available across partner institutions.

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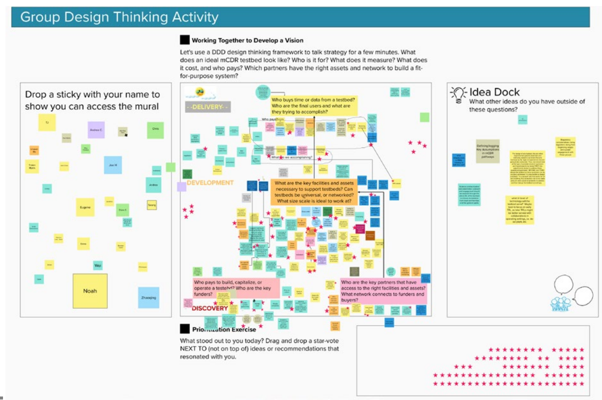
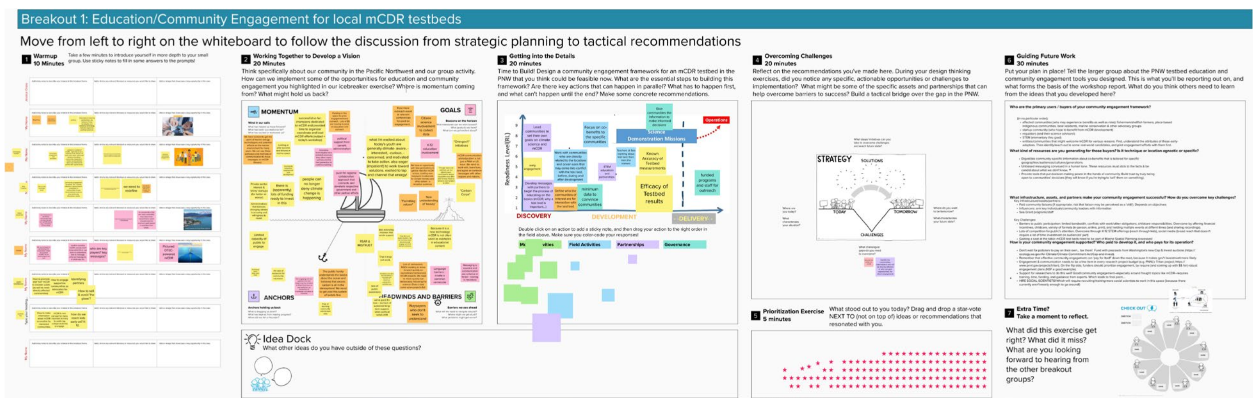
Appendix A – Workshop Photographs

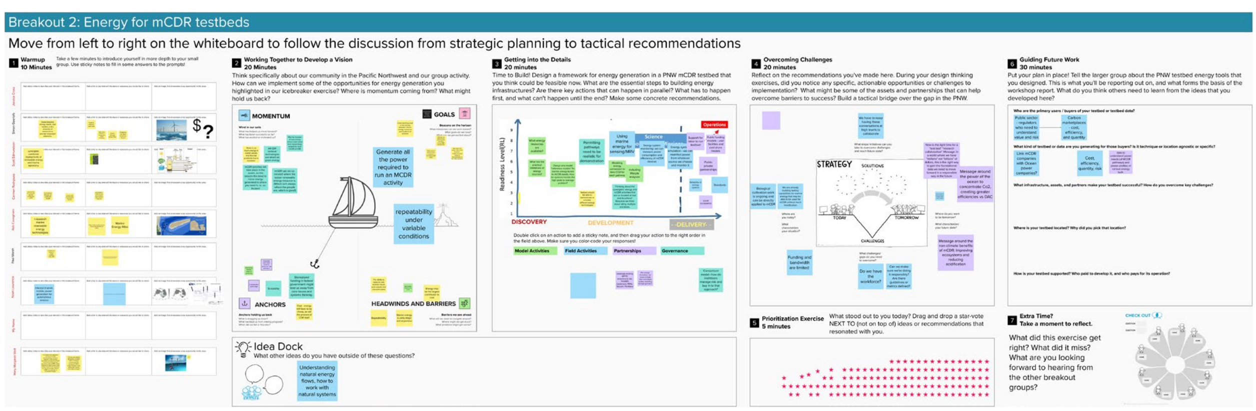
Representative photographs from the workshop at PNNL-Sequim highlighting the discussion and facilities tour. Photo credit: Shanon Dell, PNNL.

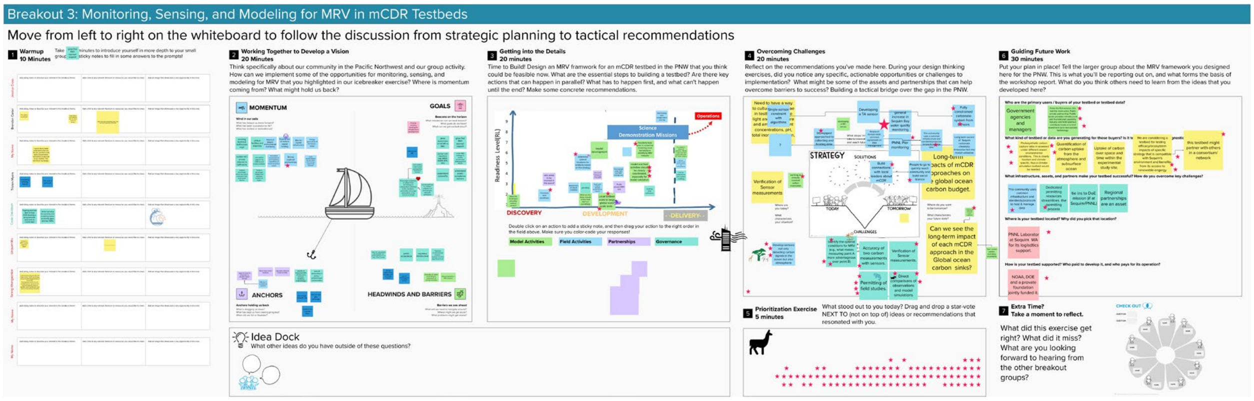

JONESY

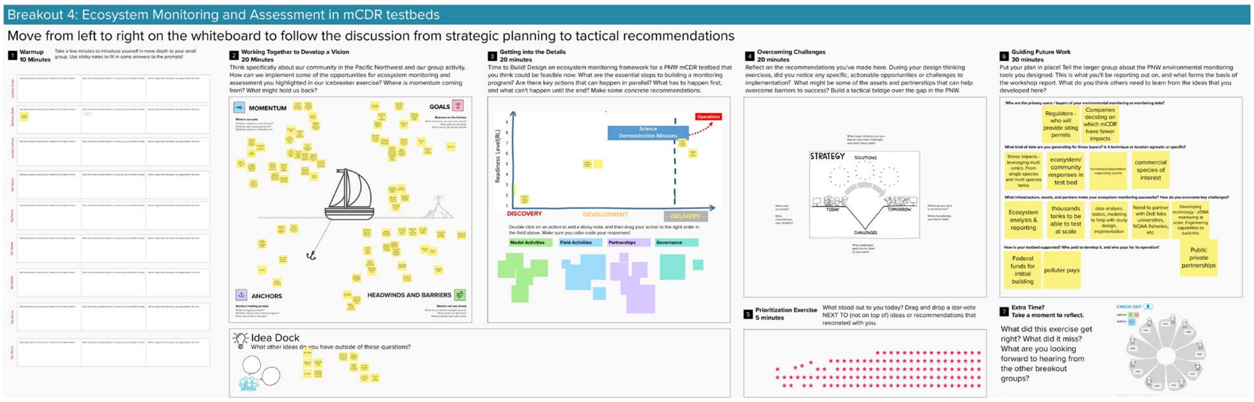
Appendix B - Full unedited Mural Boards











High-resolution archived PNGs for the Mural boards are available upon request, as is the post-classification dataset of all mural comments. Mural boards are also available via the interactive online interface, at:

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Breakout 1: Community Engagement
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Breakout 2: Energy
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Breakout 3: Monitoring
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Breakout 4: Ecosystems
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Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354

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