CO2RE THE GREENHOUSE GAS REMOVAL HUB

Marine Carbon Dioxide Removal (mCDR) in UK Net Zero: Mapping perspectives of risks, uncertainty and emerging issues

An agenda for further research

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Key messages

- The UK and overseas territories have substantive capacity and resources to develop marine carbon dioxide removal (mCDR).
- More publicly funded fundamental research is needed into mCDR to augment and validate the work being undertaken by private sector actors; a research agenda is outlined.
- Ensuring that mCDR options can be integrated into UK net zero policy frameworks is vital to provide optionality in mechanisms to achieve net zero and beyond. This includes establishing collaborations and international frameworks to allow the sector to exist and scale as efficiently as possible once its efficacy has been proven across multiple dimensions.
- There is also an urgent need to co-evolve and clarify the regulatory framework to allow effective sector establishment and subsequent scaling should efficacy be proven.
- The CO2RE Principles for Credible GGR (P4CGGR) as a policy analytic framework for UK CDR development need to be augmented to accommodate mCDR components.

1. Context

Marine-based CDR (mCDR) has substantive technical potential to sequester CO2 at Gigatonne scale.[1] Some techniques also have co-benefits such as addressing ocean acidification, enhancing biodiversity as well as generating negative carbon building materials.[2,3] The focus of CDR policy in two pioneer nations that are seeking to establish, develop and scale CDR to 2050 – the US and UK – have very much posited their innovation policy on terrestrial based CDR value chains. The US is now ramping up substantive research programmes in this area.[4] The UK is still very much focusing its CDR policy on terrestrial based technologies with the establishment of a 100MtCO2 pa CDR sector in the UK by 2050; this will have a non-trivial land footprint. There is a need, therefore, to consider the potential role and optionality that mCDR has with regards to UK net zero policy to 2050 and how this might be accommodated for to keep this option open should it prove efficient and scalable.

A brace of marine-based CDR sessions was therefore held as part of CO2RE's market transition risk series. The series seeks to highlight the risks, uncertainties and issues that are having to be negotiated by market participants in the establishment and scaling of the UK CDR sector. The mCDR elements sought to explore the following:

- Developing a better understanding of the proposed techniques and the mCDR value chains, opportunities, risks and challenges that each technique might present;[5]
- The lack of profile of the role of mCDR in the UK net zero strategy; how and when the UK policy space might better accommodate the opportunities that might be realised; and
- Exploring aspects of governance, including the challenges of demonstrating the effectiveness of mCDR though monitoring, reporting and verification (MRV), questions about the timing of its use, and robust and fair frameworks for decision-making on this topic. In addition, discussing how best to listen/respond, and how to enable open and constructive with key stakeholders and public discussion on this topic.

This document captures the two mCDR sessions that were held as part of the CO_2RE market transition risk series. The first was a public- and policy-maker-facing open panel meeting held at the Royal Society and the second was a half-day workshop held at Imperial College London which was closed to specialists. It involved mapping the opportunities, risks and challenges of integrating mCDR into UK Net Zero policy.

Section 2 provides an overview of the process and analytical framework for the two sessions. Section 3, the outputs from the mapping exercise – within which the following are outlined: (i) the augmentations that are needed to the CO_2RE Evaluation[6]

[1] For example, ocean alkalinity enhancement is an approach to carbon removal that involves adding alkaline substances to seawater to accelerate the ocean's natural carbon sink. Adding alkalinity to the ocean converts dissolved inorganic CO_2 in seawater into bicarbonates and carbonates, which are stable forms of carbon with a lifetime of approximately 10,000 years. The resulting CO_2 deficit in surface waters is quickly rebalanced via a net movement of atmospheric CO_2 into the ocean, to reestablish equilibrium. See link

[2] See Ocean Visions Website on link.

[3] US National Academies 2017. A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration | National Academies

[4] U.S. Department of Energy Initiatives to Scale Carbon Removal dated 15th August 2023 – see link

[5] GESAMP 2019. High Level Review of a Wide Range of Proposed Marine Geoengineering Techniques | GESAMP

[6] https://co2re.org/ggr-evaluation/

Framework to accommodate mCDR; (ii) the research, enabling and scaling/optimisation agenda to establish, develop and scale a mCDR sector in the UK that would potentially make a material contribution to UK Net Zero; and (iii) a proto-type sketch of a UK mCDR roadmap. Finally, sections 4 and 5 cover a '*Collective Success Criteria: What does good look like?*' for the UK mCDR sector and a conclusion, respectively.

2. Process and analytical framework

The first mCDR market transition open session was held on 7th November. It involved a panel made up of the following participants:

1. Dr Helen Czerski, (Chair) ocean scientist and science writer, University College London.
2. Dr Chris Pearce, Principal Marine Geoscientist, National Oceanographic Centre, University of Southampton.
3. Professor Ros Rickby, Chair of Geology, Department of Earth Sciences, University of Oxford.
4. Professor Ralph Rayner, Professorial Research Fellow, London School of Economics.
5. Dr Elspeth Spence, Research Associate, Cardiff University.

One hundred participants attended online and in-person. A video of the session can be found at this link.

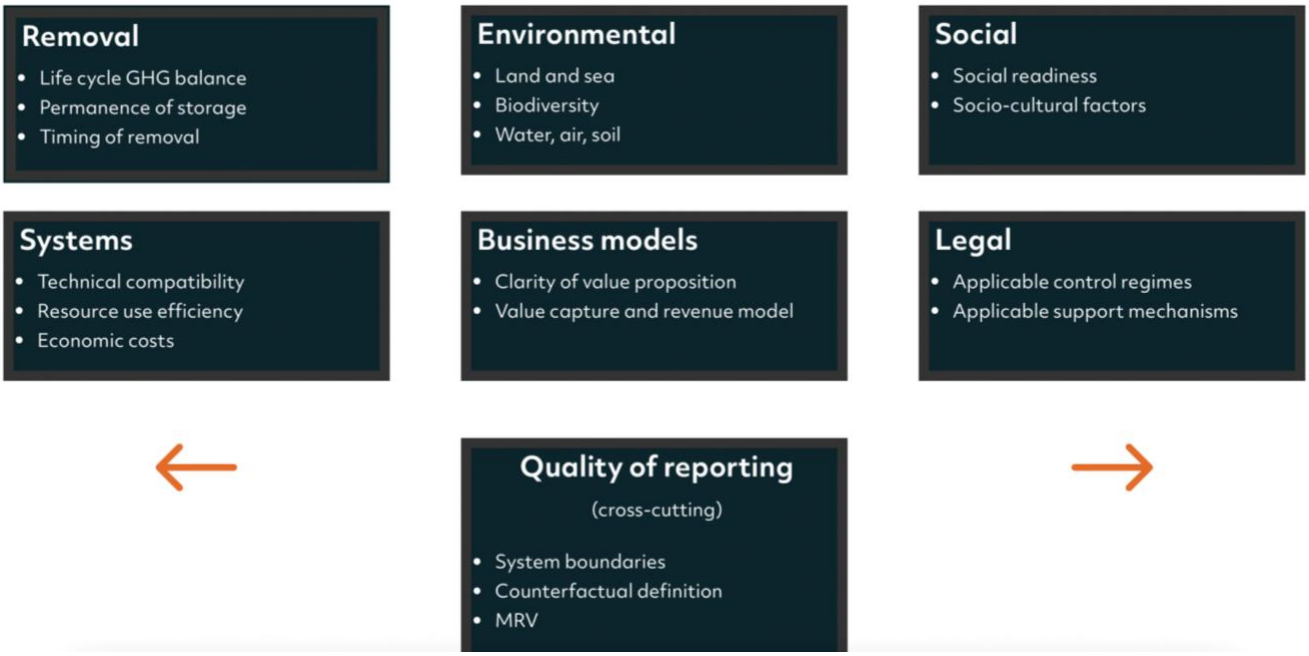
The participatory mapping of the opportunities, risks and challenges of integrating mCDR into UK net zero policy workshop was a half-day workshop held on 14th November. It involved the following participants:

1. Dr Shaun Fitzgerald, Cambridge Zero (Chair).
2. Dr Elspeth Spence, Public Risk Perceptions, Cardiff University.
3. Professor Phil Renforth, Monitoring Reporting and Verification Specialist, Herriot Watt.
4. Senara Wilson Hodges, local St Ives Resident.
5. John Auckland, CEO, Seafields.
6. Pete Chargin, Planetary.
7. Dr Natalie Hicks, University of Essex.
8. Roberta Franchi, Counteract.
9. Charlotte Marshall, Environment Agency.
10. Ian Myers, Environment Agency.
11. Jonathan Lindsell, DESNZ, GGR Strategy.
12. Cameron Henderson, DESNZ, GGR Business Model.

These participants were involved in a 4-hour workshop process which brought together the CO_2RE Principles for Credible GGR (P4CGGR) framework developed in the first 2 years of the consortium's activities[4] (Figure 1), and the socio-technical regimes literature,[7] including the simplified system elements developed by Foxon[8] (Figure 2). Foxon argued each systems element in Geel's socio-technical framework co-evolves with the others, iteratively shaping different transition pathways. This co-evolutionary approach uses an analytical framework with five discrete elements: ecosystems, institutions, technologies, user practices and business strategies. Scholars that use this co-evolutionary framework can isolate discrete elements of the system and study them in depth, without losing a broader systems perspective. The CO_2RE P4CGGR was overlain on the Foxon framework to assess its applicability to the integration of mCDR into UK net zero policy design whilst accommodating the integrative nature of each element.

[7] Geels, F. W. 2002. Technological transitions as evolutionary reconfiguration processes: A multilevel perspective and a case-study. Research Policy, 31: 1257–1274.
[8] T.J. Foxon, Transition pathways for a UK low carbon electricity future, Energy Pol. 52 (2013) 10–24.

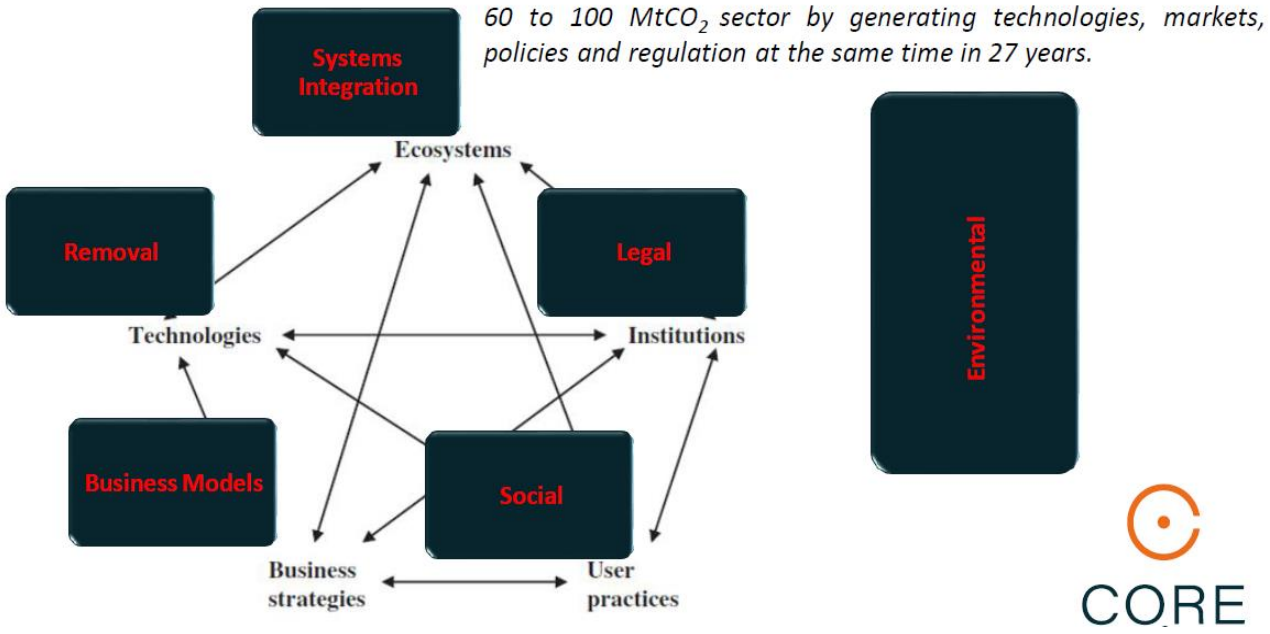
Figure 1: CO_2RE Principles for Credible Greenhouse Gas Removal Evaluation Dimensions[4]



The intention behind the participatory stakeholder mapping exercise was to provide a safe space for participants to generate, discuss and debate elements of the mCDR sector. By ensuring a relevant mix of perspectives, discursive insight as to the issues that need to be addressed in the mCDR sector in order to integrate it into UK net zero policy could be explored. The following exercises were undertaken:

- Assessing each principle of the P4CGGR in small groups on post-it notes that were then transposed to a Miro Board by scribes via a sense-making period of discussion.
- Holding a deliberative session between participants as to what collective success in the mCDR sector would look like; and
- From this a '*research, enabling and scaling/optimisation'* needs matrix and '*proto mCDR roadmap'* were generated by the support team.

Figure 2: Bringing the CO_2RE P4CGGR framework and Foxon frameworks together to assess the integration of mCDR into UK net zero policy



It is noteworthy that the exercises generated a substantive amount of data. As anticipated outputs across each principle were highly interrelated. Indeed, during discussions it was considered that the mCDR sector is of insufficient maturity to allow disaggregation to individual value chains. It was also emphasised that though this might be the case at present – that as mCDR value chains are more distinctive than land-based value chains – disaggregation would have to eventually be needed for effective policy.

3. Findings

3.1 Augmentations required to the CO_2RE P4CGGR framework to accommodate mCDR

P4CGGR	Broad issues similar, but detail differs…	A gap in EF?
negative emissions technology	Useful to have a consistent framework for comparing across land- and sea-based approaches. Technologies are at lower technology readiness levels (TRLs); there is less data for use in any evaluation. Greater potential for carbon removal/storage compared to land, but equally much greater uncertainty about effectiveness and risks. Ocean is an open system, three-dimensional, a fluid; local currents plus large-scale gyres acting on different spatial and temporal scales: much harder to do MRV/LCA and predict impacts as scale up. Signals are diffuse, margins of error could be substantive. What and how do you monitor and at what timescale? Do you monitor the whole of the ocean? Attribution is a further challenge, if there are multiple projects. Who pays? Role of modelling in MRV. How risks and rewards identified and materialise over time and space? An even greater tension between the urgent need to act and gaps in information than for land-based. Equivalent questions over baselines, counterfactuals, additionality, duration of storage.	
System integration	Multi-dimensional: seabed, sea surface, coastal areas, deep sea, water column. Potential for co-location with other industries, or other uses of the sea (e.g., kelp beds in wind farms?). But different trade-offs from land (e.g., can't co-locate shipping lanes and wind farms). Potential for supply chains to cross between land and ocean (and different jurisdictions within the ocean), as well as crossing international boundaries. Questions over who would actually be participating in the supply chain; potential to build on existing land-based industries (e.g., mining).	Impacts on productivity of the ocean, e.g. if nutrients increase or decline; potential for competing uses and competition for resources (e.g. water used in mining; coastal land suitable for CDR); analogous to land footprint but different. Could separate coastal and open ocean when looking at logistical, legal and resource availability issues. Water footprint rather than land footprint.
Environmental	Monitoring environmental impacts is complex and expensive (see also MRV in technological section). Environmental impact assessment at surface and seabed, or beyond that? Biodiversity impacts could be positive or negative. Depending on the species or ecosystem, cumulative effects (and unintended consequences) may only become apparent in future, e.g. in 20 years' time. For other species or ecosystems, the impact could be quicker. How to deal with this uncertainty?	

Social/cultural	Who are the public? What about other organisations such as NGOs? Who is impacted – local communities and beyond? Future generations? Do you have to identify groups locally, internationally and in between? How does that vary according to the type of GGR? Uncertainties, and people's strong emotional connections to the ocean, mean social acceptability becomes more sensitive. 'Tragedy of the commons' could apply. Comfort and cultural acceptance in what has gone before (e.g. fishing). How is the public involved in decision-making?	Political and geopolitical factors: relevant for marine, as an open system it crosses international boundaries. Coastal neighbours that may have more concerns or will want to share benefits.
Business model	Willingness of UK government to support technology development through R&D funding, contracts for difference etc. not yet demonstrated – but other countries funding. Familiarity and willingness of voluntary GGR market to engage with mCDR projects once business model support expires Risks to revenue as a result of challenges re. MRV. Are financial flows/economic impacts local or international? How are benefits shared?	Regulatory risk, credit risk, capital risk, taxation, opportunities re: international development.
Legal/policy	Given MRV challenges, what degree of measurement is enough from a regulatory standpoint, and what degree of uncertainty is acceptable. How are regulators thinking about discounting carbon credits according to uncertainty? Again, it will vary according to the different approaches. Complexity even within the UK, a greater degree of complexity with international regulations for oceans including the London Protocol. Who and how is the sector regulated? How can we learn from approaches to other technologies e.g., AI? Risk aversion: challenges for commercial organisations doing research, as permits/licences may not be given if activities are not purely for research purposes. Scope and relevance of regulation not aligned with community experience.	Does regulation stop a project happening?

3.2 Research, enabling and scaling/optimisation requirements for mCDR

This framework is based on the Ocean Visions roadmap.[9]

P4CGGR	Fundamental research	Enabling development	Optimisation and scaling
Negative emissions technology	Addressing permanence/off-gassing. Understanding growth potential and limits of different technologies. Understanding counterfactuals/baselines.	Enhancing funding for technological research – especially around MRV. Hosting demos. Identifying appropriate scale/geographies.	Starting with removals who have been most studied to date and have a lower risk of adverse consequences. Leveraging the UK's USP.
System integration	Understanding resource constraints/competition. Mapping life-cycle analysis boundary and second order impacts.	Syncing up industrial clusters. Understanding role of stakeholders (i.e. the Crown Estate for seabed)	Developing talent pools. Addressing decommissioning of infrastructure associated with mCDR.
Environmental	Understanding multifaceted nature and dynamics of ocean CDR, including impacts in different types of environments (i.e. coastal vs estuarine vs open ocean, etc.). Understanding the diffuse system.	Understanding the diverse risk on carbon cycles. Understanding co-benefits & risks.	Developing adequate systems for monitoring and reporting on impacts. Understanding cumulative impacts.
Social/cultural	Entering consultations with an open mind. Understanding diversity of stakeholders.	Providing independent and trusted information. Overcoming cultural stasis.	Moving from community engagement to involvement.
Business model	Understanding business models. Exploring utilisation prospects.	Addressing regulatory, capital & investment risk. Providing intermediary finance.	Developing robust industry, including confidence in credit purchasing from voluntary market, and what advantages mCDR projects could bring in competitive credit market. Establishing time to realisation.
Legal/policy	Addressing levels of uncertainty. Understanding attribution.	Developing and/or reconciling regulation. Identifying champions and blockers.	Understanding the role played by international regulation and facilitation (London Protocol, Article 6).

[9] Ocean Visions, 2023. Advancing Solutions for Ocean-Climate Restoration.

3.3 Proto-roadmap development

A proto roadmap for mCDR development in the UK, which was developed following the roundtable with outputs generated from the workshop, is outlined in Figure 3, below. This conceptual framework is articulated as follows:

a. Research. In the near term, there is a need to focus on the foundational research gaps with respect to nutrient cycling, reversibility, durability, duration of removal (and ecosystem responses), attribution and additionality. This will first require investigating the synergies and differences between land-based and ocean-based techniques. Ultimately, as the evidence base is developed it is likely that there will be a differentiated Measurement, Verification, and Reporting (MRV) approach for different interventions. It is also likely that in the mid-term it will be important to address the evidence gaps in marine ecosystem research and in-situ measurement - particularly as this relates to cycling and to specific mCDR approaches (e.g. sinking seaweed, ocean alkalinisation).

Within this research agenda, there is a need to understand the computational power, accuracy and reliability/consistency of models will be vital, including:

- what models can tell us now with some degree of confidence;
- what they cannot tell us with confidence; and
- how both of the above change over time (i.e., extrapolation of baseline assessment over 1 year, 5 years, 10 years, 20, 50, 100, etc).

Collaboration with global scientific efforts will be fundamental to addressing research needs.

b. Enabling Environment. Over the next five years, it is critical that activities and outputs from mCDR projects are consolidated - including the various licenses and planning permissions among different UK agencies and internationally.

To build towards a consolidated set of activities for mCDR project approvals, it will be important to facilitate a unified code of conduct for responsible research and project development. This code of conduct for companies developing mCDR approaches should be aligned with the UKRI's levels of scientific readiness and can draw from works in this area (CO_2RE,[4] Ocean Visions,[7] Aspen Institute[10]). Finally, developing common decision-making protocols for project decisions across agencies (e.g. IMO, MMO, CE, local planning permissions) would be an intermediary step towards consolidating the regulatory approval workflow. This would need to align with international frameworks including Article 6 of the Paris Agreement and the London Protocol.

There will also be a need to facilitate access to information and support for communities impacted by mCDR on the risks and benefits of interventions. Sustained public communication campaigns to elevate the mCDR priority will be needed through to 2030 and beyond to effectively incorporate mCDR into net zero policy.

Sustained government funding and partnership development with academic and research institutions, industry, and government agencies will be required through 2030 and beyond. In the mid-term, the UK government can also support the development of interoperability between MRV data structures and measurement approaches between companies.

[10] Aspen Institute, 2023. A Code of Conduct for Marine Carbon Dioxide Removal Research. November 2023, p.49. It is noteworthy that multiple mCDR companies have public codes of conduct that they have committed to.

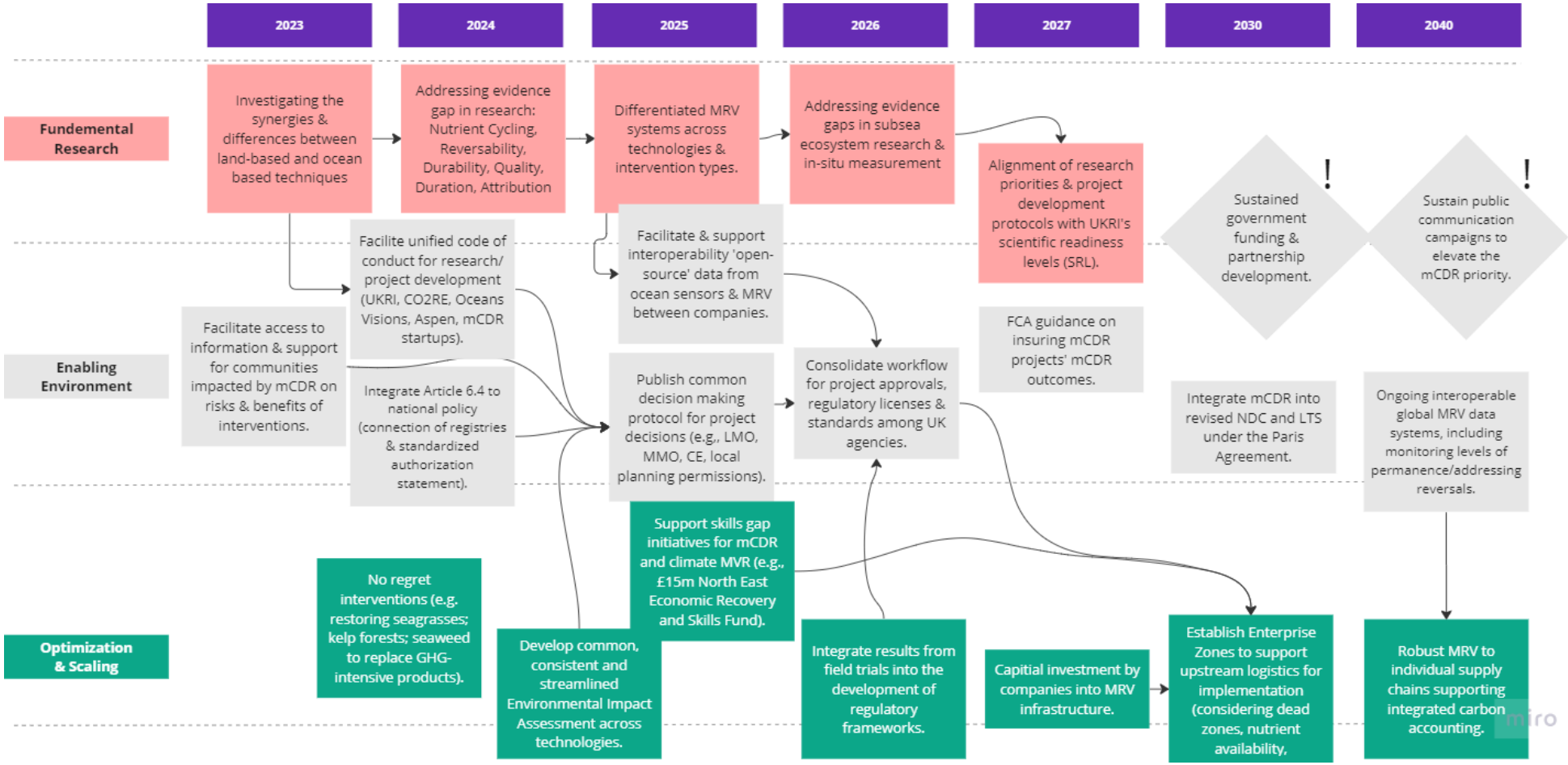


Figure 3: A proto-roadmap for mCDR development in the UK in order for it to be considered for accommodation into UK net zero policy. It is noteworthy that the last couple of columns are decadal, and are more destination-focused as opposed to specific in-year actions, which is relevant to the earlier years.

c. Optimization and scaling. Prior to the development of a suitable enabling environment, and guided by the Precautionary Principle – it is sensible to focus efforts on 'no regret interventions' (e.g. restoring seagrasses; kelp forests; seaweed to replace GHG-intensive products). Ultimately, there is a need to develop robust MRV to individual supply chains and to establish Enterprise Zones to support upstream logistics for implementation (considering material handling needs, nutrient availability, ecosystems etc.). Optimising and scaling mCDR technologies will also require an iterative process – wherein results from field trials are integrated back into the development of regulatory frameworks supporting the carbon removal industry at large.

4. Collective success criteria: what does good look like?

There are several elements that will be required – at varying levels of current knowledge – to ensure collective success in integrating marine-based CDR into the UK's net zero policy. Based on the 'Knowns, Unknowns, Feels' (KUF) framework (i.e. levels of certainty), the following was articulated by participants.

Knowns	Unknowns	Feels
• Rationalization of regulatory environment supporting mCDR interventions – by DESNZ or Defra. • Substantial government funding supporting mCDR research. • Strong evidence base of cost per ton of carbon removed by mCDR approaches. • Strong evidence base of environmental benefits & risks by mCDR intervention. • Social understanding & public support for mCDR approaches underwritten by inclusive decision-making in project decisions.	• Reconciliation of 'science-first' and 'public-first' perspectives on project decision criteria. • Responding changing political and environmental realities. • Balancing the Precautionary Principle with a strong bias to action & climate emergency. • Aligning international and national regulatory frameworks. • Scalability of technologies. • Attribution of causation & additionality. • Managing rapid growth.	• Carbon removal narrative to underwritten by emissions reduction priority. • International cooperation & coordination on mCDR (interventions & MRV methods). • Continued collaboration between industry, government, and academia. • Involvement of UN Oceans Treaty with techniques which impact deep sea. • Diversity of the technologies, long-term sustainable mCDR market requires many different actors and technologies.

5. Next steps?

The mCDR sessions on the CO_2RE market transition risk series sought to explore the considerations that needed to be accommodated for to establish, develop and scale an effective mCDR sector into UK net zero policy. The efficacy of many mCDR approaches is still largely uncertain but they could be significant and could provide optionality to the UK climate mitigation tool box. The two exercises on mCDR held by CO_2RE and supported by the Horizon Europe funded consortium SEAO_2-CDR strongly suggests that the mCDR option needs to be kept open.[11]

In order to progress the potential for mCDR in the UK climate mitigation it will be necessary to: (i) support further research, development and demonstration; (ii) support near-term opportunities through modifying existing policy mechanisms; (iii) commit to full GGR integration in carbon accreditation and broader climate policy frameworks in future; and (iv) develop sector-specific steps that lay the groundwork for future opportunities and avoid lock-out.

With regards to the integration of CO_2RE's activities and that of mCDR the following actions are recommended:

- Develop a modus operandi to keep connected with the mCDR/CO2RE Community, and in particular leverage the mCDR project SEAO_2-CDR, which has significant synergies with CO_2RE.
- Seek to determine how and when the UK policy space might better accommodate mCDR in partnership with government.

[11] Lomax, G., Workman, M., et al. (2015). Reframing the policy approach to greenhouse gas removal technologies. Energy. Policy, 7, 125–136.