Making carbon management work – navigating technical and policy uncertainty towards a net-zero future

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Introduction

As global decarbonization efforts begin to confront more difficult-to-abate sources of greenhouse gas (GHG) emissions, the importance of carbon management for achieving net-zero emissions is becoming increasingly clear. Carbon management refers broadly to carbon capture, utilization, and storage (CCUS) and carbon dioxide removal (CDR). The Intergovernmental Panel on Climate Change (IPCC) recognizes carbon management as an essential component of limiting average global temperature increase to 1.5 degrees Celsius above the 1850-1900 average (IPCC, 2022). The technologies included under the umbrella of carbon management include point-source carbon capture, atmospheric carbon removal (e.g., direct air capture, oceanic CDR, soil and biomass CDR), CO_2 transport, and CO_2 storage by various means (onshore and offshore geologic storage, enhanced weathering, biomass, ocean storage, and others). Historically, these technologies have often been treated separately; for example, work on amine-based scrubbers for power plants is agnostic on the fate of the captured CO_2. Life-cycle approaches have been proposed (e.g., Müller et al., 2020), but none currently focuses on the entire carbon management

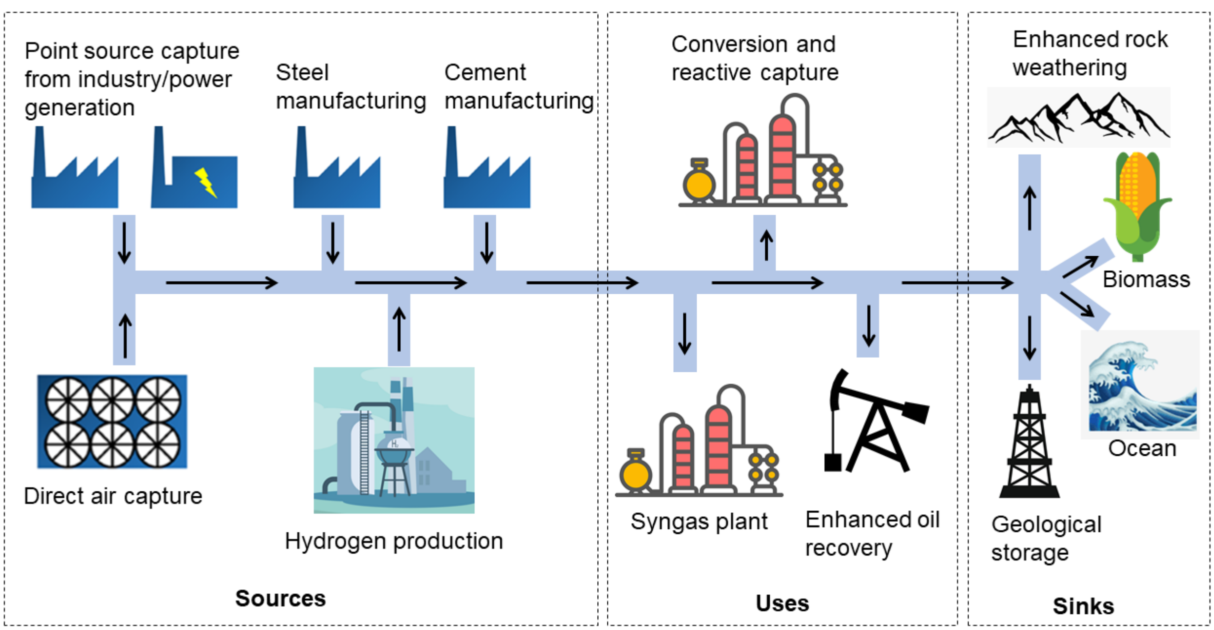

Figure 1. The carbon management system with example components.

ecosystem, and none provides an analysis of technology gaps. A granular understanding of the ways in which different carbon management technologies interact, and an optimized system based on those interactions (Fig. 1), will help identify gaps and opportunities in technology development and deployment, and analyze optimal policies to support them.

An integrated research roadmap

Achieving net-zero emissions targets critically depends on the success of effective carbon management (Pett-Ridge et al., 2023). A successful carbon management ecosystem meaningfully contributes to global climate mitigation by achieving high CO_2 throughput, and does so at an acceptable cost that is justified by its environmental, community, and other benefits. A survey of 699 experts by the Institute for Policy Integrity revealed that the four most significant barriers to widespread CDR are cost, insufficient demand or government incentives, incomplete regulatory regimes, and technology constraints (Howard and Sylvan, 2024). Any integrated research program must address these challenges.

We envision carbon management as akin to an industrial process, where the source material (CO2) is fed into a processing chain that delivers it to an end use (utilization or sequestration). Here, we identify six core research areas for developing an integrated carbon management ecosystem while addressing barriers to adoption: (1) capture and removal technologies, (2) measurement and accounting, (3) sequestration and utilization, (4) technology integration and systems analysis, (5) economic and policy dimensions, and (6) community impacts (Fig. 2).

Capture and removal technologies

Capture technologies, including post-combustion systems and direct air capture (DAC), remain expensive. Swiss firm Climeworks states that their Mammoth DAC facility in Iceland captures CO_2 at a cost of about $1,000 per ton (Gallucci, 2024), while point-source capture on power plants and industrial installations can range from about $15 to $120 per ton (Baylin-Stern and Berghout, 2021). Capital expenditures can be prohibitive as well, particularly for retrofits. Adding the capture system to the Petra Nova project in a Texas coal power plant cost about $1 billion in 2016, while the retrofit of the Kemper project in Mississippi cost nearly $7.5 billion in 2014 (US EIA, 2017). While scale-up will ultimately lead to lower costs, research into new materials and technologies is needed to help reduce capital and operating expenditures. One opportunity could come from considering the relative time scales of removal versus storage: solutions for rapid removal or abatement (i.e., point-source capture technologies) could be prioritized in the near term, while slower, long-term removal like DAC can be developed in the long term. Front-End Engineering Design (FEED) studies by the Department of Energy (DOE) can provide information on which innovations can bring costs down most rapidly. To position technologies to benefit as much as possible from learning-by-doing cost reductions, research should explore standardizing and modularizing capture system designs that can then be applied to many facilities. Another promising method of bringing down cost would be combining DAC or point-source capture with large-scale nature-based drawdown, for example, by some combination with enhanced rock weathering, ocean CDR, or biomass CDR.

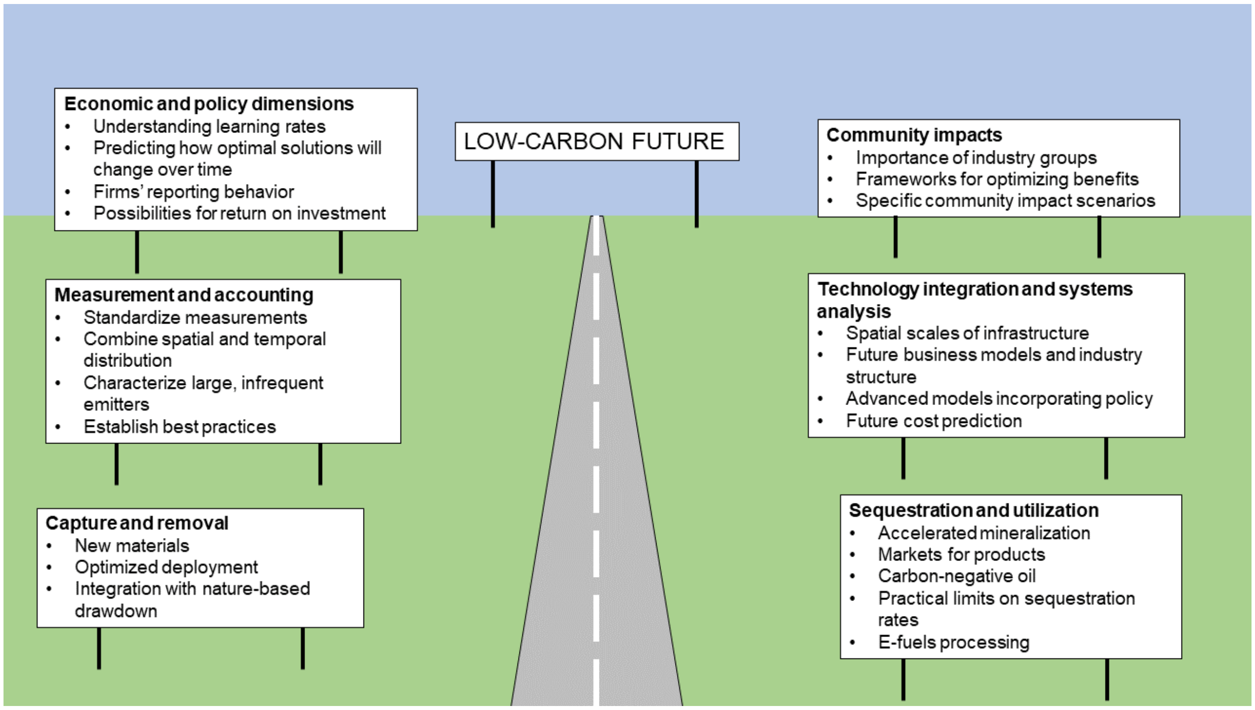

Figure 2. *The carbon management research roadmap with suggested topics.*

Measurement and accounting in carbon removal systems

Developing a robust MRV framework for CO_2 can follow many years of work on methane emissions monitoring (Allen et al., 2024). Four key lessons have been learned from work on methane MRV: (1) direct measurements of greenhouse gas fluxes are far superior to paper-based accounting; (2) spatio-temporal variation in net carbon accounting requires not just volume tracing but where and how CO_2 is captured or removed; (3) large but infrequent emitters can significantly alter net removals accounting – improving our understanding of and transparency in tail risks is critical for systems level carbon accounting; and (4) measurements performed for effective accounting are not always equivalent to those performed for transparent auditing. The U.S. Environmental Protection Agency (EPA) has run the Greenhouse Gas Reporting Program (GHGRP) since 2009, which could be a useful tool in establishing an MRV framework by requiring companies to report removals, but its future is currently uncertain. The cost of implementing and maintaining an MRV program could be prohibitive initially for smaller firms, and a dedicated institute (for example, at a university) could help establish uniform practices and bring costs down. Robust MRV is essential for building trust in carbon credit programs.

Sequestration and utilization

Any carbon management system requires an ultimate sink of CO_2 that will keep it out of the atmosphere. Sinks include sequestration, either underground, in the ocean, or in biomass; and utilization pathways where the CO_2 is converted into some usable material. Underground storage takes advantage of vast amounts of pore volume, but several decades of pilot tests have revealed significant challenges in geologic uncertainty, induced seismicity, and operations. A practical upper limit on injection rates of 1 Mt/y per well has been suggested to reduce the risk of induced seismicity (Williams-Stroud et al., 2020), which means that thousands of wells would be required for desired sequestration rates on the order of Gt/y. The longevity and security of underground storage are greatly enhanced when CO_2 is converted to a mineral phase through chemical reactions in the subsurface. Mafic rocks have the most rapid mineralization rates, on the order of months to years, and future work could build on studies in Iceland and Oman to determine large-scale feasibility. Utilization pathways suffer from a lack of large markets for products. Two notable exceptions are syngas or e-fuels and enhanced oil recovery. E-fuels are currently much more expensive than traditional fuels; for example, sustainable aviation fuel costs three times as much as conventional jet fuel (Azarova et al., 2024). Evidence suggests that enhanced oil recovery can be carbon-negative in some circumstances, but more research is needed to determine the factors that make net carbon storage possible, and projects often trend carbon positive over time (Bryant, 2024). Other utilization pathways might be used as a short-term solution as infrastructure is built to transport captured carbon to underground storage locations.

Technology integration and systems analysis

Successful carbon management requires methods for optimizing combinations of different technologies along the carbon value chain, and different ways of evaluating their performance. This includes research on constraints on technology deployment, spatial scales of technology integration, business and industry structures in the carbon management ecosystem, future cost projections, and best design practices for policy incentives. Optimization models have been developed (e.g., Colombe et al., 2024) to determine the most cost-effective (given a CO_2 storage target) or profitable (given policy incentives) ways to design and operate spatial carbon management infrastructure networks. More advanced models in development can integrate game theory to model the effects of subsidies and other policy decisions on CO_2 throughput and cost, considering the various firms that might participate in carbon management supply chains (Albeladi and Leibowicz, 2024). Future work should consider the spatial scales of carbon management infrastructure, as well as business models and industry structures in the carbon management ecosystem. Any model based on the U.S. would need to be redesigned for use in other parts of the world as different countries have different incentive, business, and regulatory structures, including government-owned national oil companies. Accelerating technology deployment is of particular urgency now given electricity load growth.

Economic and policy dimensions of carbon management

The key issues in this research area are whether more carbon management is socially optimal, the implications of imperfect climate policy on carbon management, and possibilities for return on investment and learning rates in technology deployment. Carbon removal is a complex array of different technologies, so the profitability of different technologies deployed at commercial scale is difficult to predict and subject to technical, market and policy uncertainty. There is not yet a large demand for CO_2 utilization. However, deploying carbon transport and storage could lower marginal costs of CCUS, increasing the potential for carbon markets which generate private surplus (beyond federal subsidies) for uses such as enhanced oil recovery, green cement and carbonated beverages. Learning rates can be difficult to predict, particularly in the presence of exogenous technological change (Nordhaus, 2011). Research should focus on combining learning rates with predictions of how optimal carbon capture solutions for a given use case will change over time. In this sense, DAC has an advantage over point-source capture: retrofits on existing power plants usually entail some features of a first-of-a-kind design problem, whereas

DAC presents opportunities for fast learning because projects will be new and could leverage the same capture system design across many locations.

Current U.S. federal CCUS tax credits (45Q) incentivize increased carbon storage, rather than carbon abatement, which has the potential to lead to higher *net* emissions (Grubert & Sawyer, 2023). Carbon pricing through a tax or cap-and-trade program would help to address this, but direct subsidies for technology investment would still be needed. MRV can be strongly incentivized by differential carbon pricing, where unmonitored emissions are charged a higher unit price inducing unmonitored firms to adopt monitoring to lower carbon payments. Differentiated markets outside of a pricing structure such as preferential procurement or market access rules such as those implemented by the European Union for trade in liquefied natural gas could be a precursor to pricing differentials (Hemous et al., 2023). Lastly, complete understanding of the benefits of carbon management need to consider the local air pollution co-benefits and -damages, which depends on the application and emissions control (Waxman et al. 2024).

Community impacts

Community engagement should be done early and often throughout the project co-design process. Although the DOE does not require Community Benefits Plans anymore for federally funded projects, there is still a need for robust community engagement. Benefits of community engagement include maintaining local support, fostering a local, engaged workforce, providing feedback on operations, and ultimately reducing risk for firms pursuing carbon management activities. Because of these benefits, it is likely that the private sector will continue community engagement for these reasons even in the absence of federal requirements, but the meaningfulness of those engagements from the communities' perspectives remains to be seen. Industry groups can take on a larger role as well in public education and investment in areas that have historically not seen large-scale energy infrastructure. There is no one-size-fits-all approach to maximizing community benefits. However, a framework analogous to public health could work, in which community needs are identified and addressed as part of the project design and operational process. Performing some up-front work on specific community impact scenarios prior to engagement (for example, air quality, traffic, light pollution) can be viewed as a sign of respect by the community and build a better relationship.

Conclusions

The growing need for carbon removal efforts requires a focused and sustained effort to overcome challenges in carbon management. Our approach of treating carbon management as a single, multicomponent system allows optimization of carbon throughput while minimizing financial and social costs and identifying gaps in technological innovation. We have identified multiple aspects of the carbon management ecosystem that require further research efforts, and it is our hope that this research roadmap can provide guidance on our path to net zero.

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