Carbon Dioxide Removal Innovation Workshop

Pre-read Document

October 2023

Table of Contents

Acknowledgements

The support of the Department of Energy's Office of Fossil Energy and Carbon Management is gratefully acknowledged. Special thanks to Alex Rousina-Webb, lead author of this document. Thanks to Jason Qu and Neha Sharma for major technical contributions, and to Christa Reid for project management and editorial contributions.

Summary

The Carbon Dioxide Removal Innovation Workshop aims to identify emerging technologies that could reasonably be expected to have the potential to revolutionize CDR. Innovations in materials science, digital technology, and biotechnology offer prospects for more efficient, cost-effective, and scalable CDR methods. For instance, new sorbent materials could drastically reduce the energy needed for DAC, while advancements in biotechnology could introduce bioengineered organisms capable of capturing large amounts of CO_2 effectively.

CDR is inherently a multi-disciplinary challenge that requires insights from materials science, engineering, biology, information technology, and even social sciences and policy. For example, developing a sustainable and scalable CDR technology may require not just new materials but also data analytics for process optimization and policy frameworks for deployment.

CDR technologies stand as an essential pillar in the comprehensive strategy needed to address climate change. While current approaches are still being developed, significant challenges remain. This workshop seeks to catalyze the next wave of innovations in CDR by scrutinizing emerging technology trends in other domains and how they could accelerate CDR solutions.

Introduction

The Carbon Dioxide Removal (CDR) Innovation Workshop, sponsored by the U.S. Department of Energy's Office of Fossil Energy and Carbon Management and hosted by SRI International and SLAC National Accelerator Laboratory, will serve as a nexus for cross-disciplinary collaboration and discussion of opportunities for research to accelerate CDR outcomes. Taking place on October 24, 2023 at the Palo Alto Research Center in Palo Alto, CA, this full-day event seeks to identify novel solutions to CDR that go beyond traditional approaches.

The event will convene a diverse assembly of experts who bring innovative perspectives from various fields, ranging from materials science to digital technologies and synthetic biology, to explore a broad array of disruptive techniques and methodologies not yet applied to CDR. **The goal is to ideate on emerging technology breakthroughs that have the potential to significantly accelerate CDR outcomes. We aim to identify technologies with high impact *and* high likelihood of emergence within the next decade.**

Primer on Carbon Dioxide Removal

Carbon Dioxide Removal (CDR) represents a category of climate mitigation strategies aimed at directly capturing and storing carbon dioxide (CO_2) from the atmosphere. Given the escalating levels of atmospheric CO_2 and the corresponding acceleration in global warming, CDR is increasingly central in achieving climate targets (NASA, 2023).

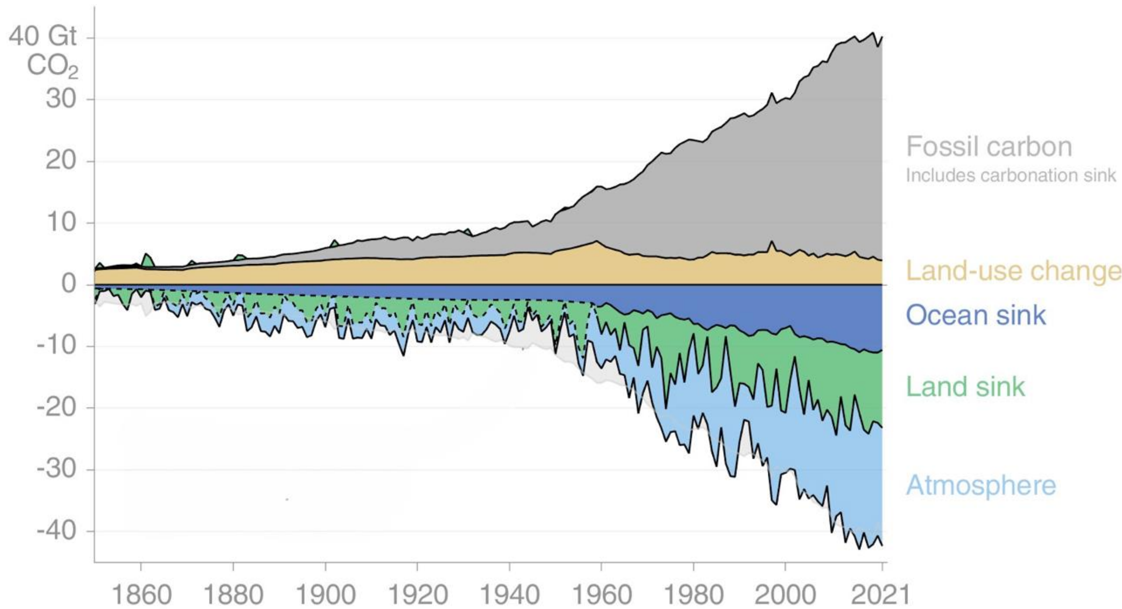

Figure 1: Balance of sources and sinks of CO_2 from 1850 to present (The Global Carbon Project, 2022)

The Need for CDR

While reducing emissions at the source remains the primary method to mitigate climate change, experts agree that this alone will not be sufficient to limit global warming to safe levels (Fawzy et al., 2020; Lin, 2019). Due to historical emissions and fossil fuels use, merely decreasing or even halting new emissions is insufficient; we must seek to actively remove existing CO_2 from the atmosphere.

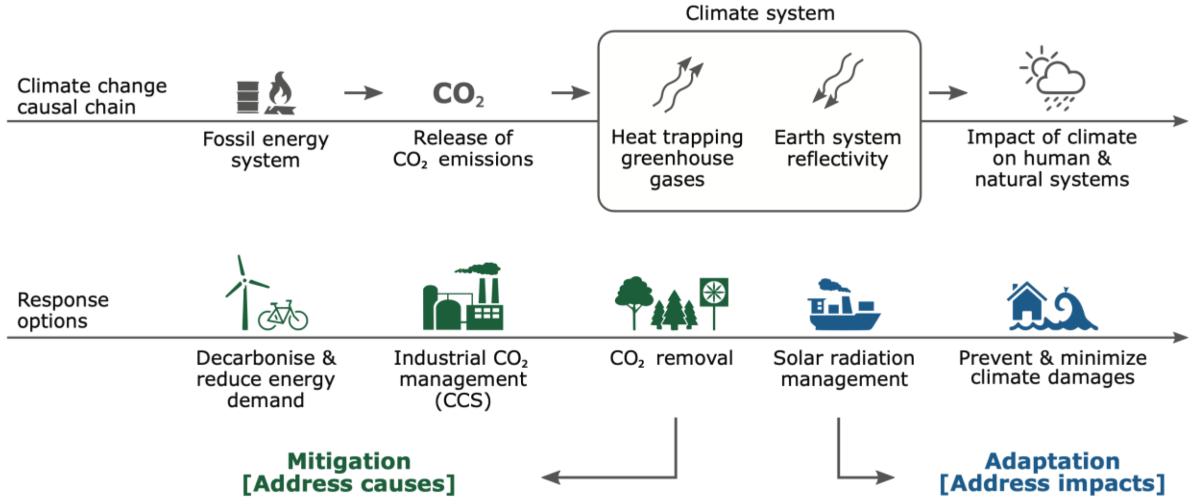

Figure 2: Causes and response options for climate change (Rouse, 2018)

Several CDR technologies have been explored and are at varying stages of development. Some of the more established methods include those shown in the graphic below (Minx et al., 2018):

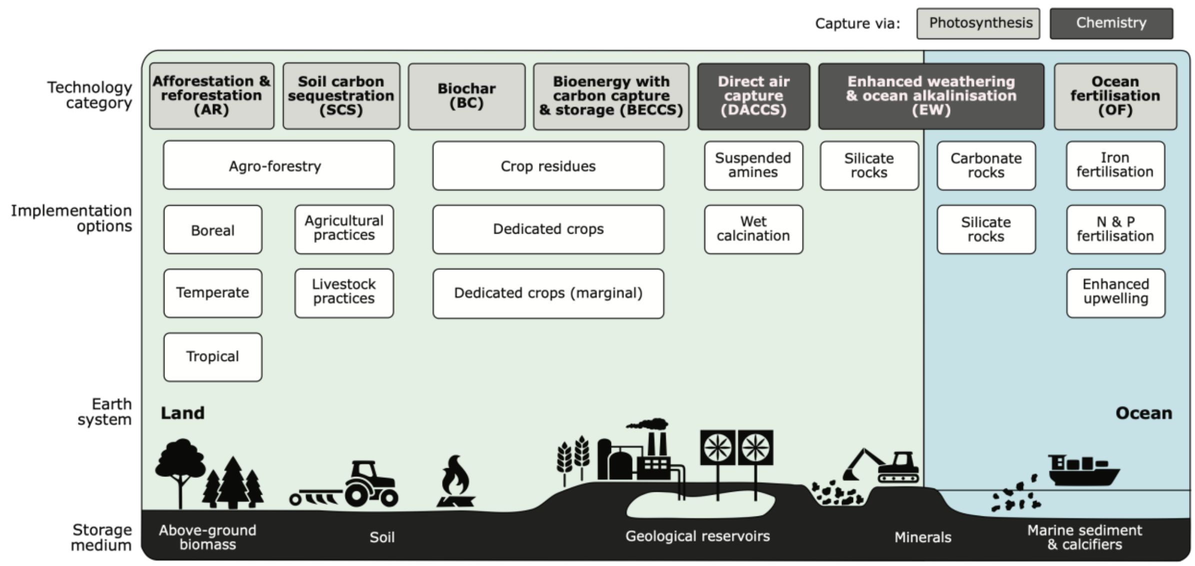

Figure 3: Carbon dioxide removal (CDR) options (Erans et al., 2022)

In scope for this workshop (Hepburn et al., 2019; Refrew et al., 2020; Terlouw et al., 2021):

- **Direct Air Capture with Carbon Storage (DACCS):** Chemical and mechanical systems that directly capture CO_2 from the air.
- **Bioenergy with Carbon Capture and Storage (BECCS):** Combines biomass use with geological storage of captured CO_2.
- **Enhanced Weathering (EW):** Accelerates natural weathering processes to store CO_2 in rocks.
- **Ocean Alkalinization and Fertilization:** Increases the pH of the ocean to enable greater CO_2 absorption.
- **Soil Carbon Sequestration:** Utilizes plants and soil management techniques to capture and store CO_2 in the ground.
- **Afforestation and Reforestation:** Natural methods involving the planting of trees to absorb CO_2.

Current CDR approaches face several challenges, including but not limited to, scalability, cost, energy use, and environmental impacts. For example, Direct Air Capture systems are energy-intensive, and the scale needed for significant impact is immense.

Emerging Technology Classes for CDR

This section provides an overview—examples only, not meant to be exhaustive—of some emerging technologies that display promise of accelerating CDR outcomes. We have identified four emerging technology classes, and there may be others, to draw focus towards those that are on a trajectory to have the greatest impact on CDR. For purposes of this workshop we are not interested in technologies related to clean energy generation, although we acknowledge these innovations could be enabling technologies for more widespread CDR adoption.

Material-Chemical Innovations

The domain of materials science offers novel chemistries and architectures for capturing carbon dioxide. Innovations in this area are targeting liquid and solid sorbents and materials that can not only capture CO_2 with high selectivity but can also be regenerated with minimal energy input. These developments could potentially revolutionize Direct Air Capture (DACCS) systems and make them more cost-effective and scalable.

Supply Chain, Infrastructure, and Process

These are logistical and infrastructure innovations that could dramatically streamline the CDR process. These innovations range from low-cost, high-throughput contactor production methods to new techniques in additive manufacturing aimed at improving heat and mass transfer efficiencies. Coupled with advancements in CO_2 transportation and sequestration, these could make CDR a more integrated and seamless process, lowering cost and speeding deployment at relevant scales.

Digital Technologies

As digital technologies become more pervasive, their application in CDR is becoming increasingly relevant. These include the use of blockchain for tracking and validating carbon credits, AI and Machine Learning algorithms for optimizing capture materials and processes, edge-computing based sensor systems and simulation models for better monitoring, reporting, and verification (MRV) of soil carbon sequestration and enhanced weathering methods.

Biotechnology-Based Solutions

Biotechnology offers avenues for bio-engineered solutions to CDR. These include genetically engineered organisms designed for more efficient photosynthesis and carbon capture, as well as biochemical pathways that can convert captured CO_2 into value-added products, like biofuels or building materials. If successful, these technologies could create an entirely new paradigm for CDR.

Interdisciplinary Approaches

Many of the most promising emerging technologies are at the intersection of different domains. Whether from the integration of AI algorithms in material screening for better sorbents or the combination of biotechnology with chemical engineering for new capture and conversion processes, interdisciplinary approaches are likely to drive innovative and effective solutions.

In summary, the emerging technologies in CDR are as varied as they are promising. The intent of this workshop is to explore the evolution of technologies particularly as they may intersect with CDR, evaluate their feasibility and scalability, highlighting in particular, gaps that may benefit from targeted research pursuits, and to foster collaborations that can accelerate their development and deployment. By considering a wide range of innovative solutions, we aim to catalyze meaningful advancements that can substantially alter the trajectory of global CDR efforts.

Questions to Consider for Workshop

1. Innovation Synergies: Which emerging technologies hold the most promise for creating synergies with current CDR methods?
2. Enabling Technologies: Do approaches exist today which are not economically or technically possible, but could be enabled by an emerging technology in another area, such to make these competitive or disruptive?
3. Scalability: What are the biggest challenges in scaling up current and emerging CDR technologies? How can these be addressed?
4. Interdisciplinary Collaboration: How can experts from diverse fields such as material science, biotechnology, data science, and environmental engineering be encouraged to work on applications in CDR? What needs to happen today for these integrations to occur?
5. Cost-effectiveness: How can emerging technologies be made more cost-effective to encourage large-scale adoption? What role can governmental and private funding play in this?
6. Environmental Impact: How can we ensure that CDR technologies are developed and deployed in an environmentally responsible manner?
7. Data Integrity and Monitoring: How can advancements in Monitoring, Reporting, and Verification (MRV) be leveraged to build trust and facilitate the adoption of CDR technologies?
8. Which emerging technology classes should be considered beyond those identified in this document, if any?

These questions aim to provoke thought and encourage a robust discussion that will contribute to a comprehensive report on technologies that have the potential to accelerate Carbon Dioxide Removal.

Example Emerging Technologies

In this section, we delve deeper into some examples of emerging technologies within the broad categories previously outlined. Each technology is explored in terms of its core innovation, its intersection with other emerging technologies, the problem it aims to solve, and the potential impact if it proves to be successful. These technologies are described to stimulate thinking and ideas for discussion at the workshop and are not intended to be a comprehensive compendium of innovations. We expect to expand and explore these options in much greater depth during the workshop.

Material-Chemical Innovations

1.1 Advancements in Material Science for Novel Sorbents

Core Challenge

Sorbent materials that absorb/desorb CO_2 are at the core of many capture processes, but traditional sorbents often suffer from limitations such as low capture efficiencies, slow kinetics, and high energy requirements for regeneration (Siegelman et al., 2021). Novel sorbent materials in development aim to substantially enhance the volumetric productivity of DACCS. These materials are engineered at the molecular level for high selectivity for CO_2 over other gases like nitrogen and oxygen. They are also optimized for energy-efficiency and maximal regeneration, which are critical factors in the overall economics of DACCS systems. The limiting step in implementing these technologies at scale is the high cost of material, low volumetric productivity, and their ineffectiveness in regeneration over prolonged use.

Emerging Research

- **Boron nitride nanotubes**, structurally similar to carbon nanotubes, have unique electronic and thermal properties. Their potential in carbon dioxide removal could allow for selective capture and release based on external electronic stimuli (Jakubinek et al., 2022).
- **Transition metal chelated weak base resins** integrate metal ions such as copper(II) to enhance carbon capture. These resins could offer significantly higher adsorption capacity by chelating multiple carbon dioxide molecules per transition metal complex (Chen et al., 2023).
- **Switchable solvents** change their physical properties in response to exposure to a gas molecule (like CO_2) or changes in temperature. The response to CO_2 can be altered by external factors such as temperature, pressure, or inert gas, which can be exploited for the capture and release of CO_2 (Kumar, 2021).
- **Ionic liquids** are unique solvents with negligible vapor pressure, high thermal stability, wide liquidus range, relative non-flammability, designability, and recyclability. These solvents could solve multiple shortcomings with traditional liquid sorbents including high volatility, high cost, substantial energy consumption and corrosiveness (Elmobarak et al., 2023).
- **Phase-changing polymers** alter their state based on external stimulus. The ability to change phase could provide opportunities to dynamically alter the adsorption-desorption enthalpy and reduce the energy requirement for reversible capture of CO_2 (Hu, 2020).

Intersection with other Emerging Technologies

One of the most exciting facets of these novel sorbent materials is their intersection with advanced material science and process techniques. For example, additive manufacturing (3D printing) could be employed to create sorbents with highly specific surface geometries that maximize capture efficiency in a manner that overcomes the relatively low concentrations of carbon dioxide in the atmosphere. Additionally, AI can be used in molecular design and nanotechnology may be leveraged to alter material properties at the atomic or molecular scale, further enhancing their performance.

1.2 Dual Function Materials: Combined Capture and Conversion to Value-Added Products

Core Challenge

Traditional carbon capture materials focus primarily on capturing CO_2, with downstream utilization happening in a separate unit operation or system. Dual-function materials, however, extend this concept by targeting not only the capture of CO_2 but also its simultaneous conversion into products of significant value at point of capture. By amalgamating these processes, these materials offer additional benefits with respect to process intensification, increased energy efficiency, reduced capital expenditure, and improved transport and storage capabilities. This integrated approach has the potential to transform CDR from a mere environmental imperative to an economically advantageous venture (Deutsch et al., 2021).

Emerging Research

- **Covalent Organic Frameworks (COFs)** are crystalline polymers known for their adaptability and high surface areas. Their advantages in pore structure, specific surface area, and thermal and chemical stability make them promising candidates for CO_2 capture and conversion (Lyu et al., 2022).
- **MOF (Metal-Organic Framework) Based Electrocatalysts** harness the porosity of MOFs to enhance electrochemical reactions. With this synergy, they could simultaneously absorb CO_2 from the air and transform it into valuable compounds or fuels (Zheng et al., 2021).
- **Photoactive Porous Polymers** capitalize on light energy to activate their porous structures. These polymers can be effectively impregnated with inorganic nanoparticles as active cites for photocatalysis (González-Béjar, 2021).

Intersection with other Emerging Technologies

The advancement of dual-function materials is intrinsically linked with the domain of catalysis. A multitude of the envisioned conversion processes necessitate the integration of potent catalysts within the capturing material. This convergence is evident in the burgeoning field of AI-driven catalyst designs, which has demonstrated significant potential in areas such as pharmaceutical drug discovery. Additionally, material science plays a pivotal role in devising efficient composites or coatings that can seamlessly perform both capture and conversion functions.

Supply Chain, Infrastructure, and Process

2.1 Advanced Manufacturing Techniques

Core Challenge

The primary focus of advanced manufacturing techniques within the domain of CDR lies in addressing the intricacies and inefficiencies inherent to the production of first of a kind systems. For CDR to be impactful, it must be executed at a grand scale and with expediency to meet gigaton-scale removal goals, all while remaining cost-effective. Advanced manufacturing technologies present a vehicle for these goals, suggesting the possibility of developing CDR systems that are precise, adaptable, and more economically feasible. By enhancing production methodologies, the road to large-scale, sustainable carbon capture could become increasingly tangible.

Emerging Research

- **Additive Manufacturing (3D Printing)** enables precise layering to fabricate intricate structures, facilitating the design of materials that are optimized for heat and mass transfer – configurations that traditional manufacturing would be unable to achieve (Ashokkumar et al., 2022).
- **Robotics and Cobots:** The advent of advanced robotics and collaborative robots promises a new era of precision, adaptability, and automation on the production floor, potentially revolutionizing the manufacturing aspects of CDR equipment.
- **Supercritical Fluids in Material Processing:** These fluids, which exist at their critical point (neither purely liquid nor gas), may serve as replacements for traditional solvents in extraction and other material production steps, edging CDR materials towards a carbon-neutral status.
- **High Throughput Manufacturing:** Emphasizing rapid, cost-effective production methods, high throughput manufacturing techniques such as roll-to-roll coating, fiber spinning, and extrusion processes are under exploration to increase production rates while driving down manufacturing costs.

Intersection with other Emerging Technologies

The advancements in the manufacturing arena intertwine with other domains such as digital design, computational fluid dynamics, nanotechnology, and process optimization. For instance, digital design facilitates the creation of optimized configurations for CDR systems, while nanotechnology can introduce novel materials that further the efficiency of capture processes.

Notable research or partnerships

Pioneering collaborations and research ventures underscore the significance of advanced manufacturing in the CDR sector. AirCapture and 3D Systems have collaborated to harness additive manufacturing for refining the design and production of various carbon capture components. In parallel, researchers at Oak Ridge National Lab have developed a unique 3D-printed device that merges a heat exchanger with a mass-exchanging contactor to enhance CO_2 capture. Diverse studies have also assessed the performance of different 3D-printed monolith adsorbent materials. Noteworthy developments include research on flexible extruded monofilaments and NETL's patented creation of an innovative fiber sorbent that integrates amine sorbents within a porous polymer fiber structure.

2.2 Process Innovations

Core Challenge

Process innovations in CDR aim to enhance the entire value chain from capture to sequestration. This encompasses the development of advanced pipeline materials, optimization of compression techniques, and exploration of alternative energy transmission. By honing these processes, the goal is to improve efficiency while minimizing costs associated with vital operational stages.

Emerging Research

- **Continuous DACCS:** A transformation from traditional batch systems, continuous DACCS focuses on simultaneous CO_2 capture and release. This continuous method promises a consistent and efficient carbon extraction process.
- **Microwave-based Desorption:** By selectively exciting water molecules attached to a radiation-transparent monolith using microwaves, this innovation targets energy efficiency.

The directed application of heat could reshape the energy requirements of CDR systems (van Schagen, 2022).

- **High Temperature Heat Pumps:** These devices, tailored for efficient heat transfer at high temperatures, may significantly decrease the energy consumed during sorbent regeneration. This could optimize the CDR process and reduce operational expenses (Hamid et al., 2023).
- **Polymer Bio Reactors:** Crafted from organic polymers, these bioreactors present a cost-effective alternative to their steel counterparts. Their potential lies in cost-efficient production of bio-organisms utilized in CO_2 capture, questioning the traditionally steep costs and limited scalability of bio-based processes.
- **Self-Healing Polymeric Materials:** These polymers, with their unique self-repair capability, could be vital for coating CO_2 transport pipelines and storage facilities. Their inherent resilience minimizes leak and damage risks, promoting reliable and secure transport and storage of captured CO_2 (Shen et al., 2023).

Intersection with Other Emerging Technologies

Process innovations in CDR intersect with diverse technological domains. Within transport engineering, innovations are required for the safe and efficient transportation of large volumes of captured CO_2, necessitating advancements in pipeline materials, pumping systems, and monitoring technology. Geological sciences are crucial in this juncture to understand subsurface compositions and identify optimal sequestration sites that ensure long-term stability and minimal risks. Collaboration with the renewable energy sector, particularly solar, wind, and geothermal technologies, offers potential avenues for powering CDR processes with a reduced carbon footprint. Moreover, the integration of advanced sensors, IoT, and monitoring systems can provide real-time detection of inefficiencies or leaks, enhancing the overall safety and efficacy of CDR operations.

Notable research or partnerships

Current endeavors in this domain are focusing on predictive modeling and simulation tools for subsurface geological carbon reservoirs, such as the ECHELON toolset. Furthermore, novel methods are being investigated to broaden transportation and sequestration options for captured carbon, an example being the exploration of stimulated abiotic subsurface hydrocarbon formation. The energy efficiency and cost-effectiveness of CO_2 compression processes remain a focal point of research, underpinning their importance in the carbon transportation and sequestration paradigm.

Digital Technologies

3.1 Digital Representation and Data Integrity

Core Challenge

As the CDR industry scales up, the importance of accurately representing physical processes and ensuring the integrity of process data for carbon accounting becomes increasingly important. There is a pressing need to visualize, monitor, and validate data in real-time, ensuring seamless operations and facilitating informed decision-making across all methods of carbon removal.

Emerging Research

- **Digital Twinning** is an approach to process monitoring and optimization, creating virtual replicas of physical assets. These twins allow for real-time data monitoring, simulation, and predictive maintenance, ensuring that CDR systems function optimally (Yao et al., 2023).
- **Augmented Reality (AR)** has the potential to make strides in facility and equipment maintenance. It allows on-site operators to see data overlays, enhancing their understanding of equipment and processes. This direct access to data, combined with real-time guidance,

promises to streamline troubleshooting and maintenance efforts, and allow for reduced operating costs (Dargan et al., 2023).

- **Blockchain and Distributed Ledgers:** A decentralized ledger system, blockchain introduces a new level of transparency and traceability in the CDR supply chain. With its ability to validate data at every stage, blockchain can play a critical role in lifecycle analyses and ensuring data integrity and validation for carbon credits (Bachman et al., 2023).

Intersection with Other Emerging Technologies

Digital Representation & Data Integrity technologies intertwine with the realms of IoT for real-time data collection, and advanced sensor technology for accurate data acquisition.

Notable research or partnerships

In the realm of blockchain, its integration in sectors like oil & natural gas—where complex transaction automation occurs through smart contracts—paves the way for its adoption in the CDR domain. Consortia like Blockchain for Energy are actively fostering the innovative application of blockchain, underscoring its significance in ensuring traceability and promoting collaborative endeavors for its continued incorporation.

3.2 AI and Digital Design

Core Challenge

At the heart of efficient carbon dioxide removal (CDR) processes lies the necessity for optimized materials and designs. Traditional trial-and-error methods, often reliant on long iterative cycles and extensive human intervention, are unable to keep pace with the current urgency for effective CDR solutions. There's a pressing need to accelerate the discovery, design, and optimization of materials and processes, guided by computational intelligence, and rooted in real-world process performance.

Emerging Research

- **Generative Adversarial Networks (GANs):** Pushing the boundaries of data generation, GANs offer a unique solution to MRV within CDR. With their capability to produce synthetic data, they could aid in critical tasks such as assessing the integrity of carbon storage wells and early detection of CO_2 leakages (Jozdani et al., 2022).
- **Generative Design with Multiphysics Optimization** combines the power of AI with design, proposing numerous design solutions concurrently, while factoring in defined constraints and goals. The differentiator is incorporation of multiphysics optimization which ensures that the proposed designs are not mere theoretical bests, but are rooted in and compliant with real-world physical laws. This could allow for multiparameter optimization of heat and mass transfer, pressure drop, and manufacturability simultaneously (Wu et al., 2019).
- **AI-Driven Process Optimization** enriched with neuromorphic computing blueprints that mirror the human brain's architecture, has potential to impact the landscape of CDR process optimization. These systems, through techniques like reinforcement learning, dynamically adapt and refine processes, ensuring optimal outcomes. Furthermore, context-aware computing tailors operations based on varied environmental or situational factors (He et al., 2023).
- **Autonomous Materials Discovery:** Pioneering the next phase in material science for CDR, AI-driven tools are replacing conventional methods with data-centric strategies. This shift promises a drastic acceleration in the R&D of material discovery, optimizing for CDR performance (Stach et al., 2021).

Intersection with Other Emerging Technologies

The infusion of AI and computational techniques in material discovery and process optimization closely intertwines with quantum computing, potentially further speeding up complex simulations. Moreover, they resonate with biotechnologies, especially in harnessing natural methods of carbon capture, and robotics for automating high-precision tasks in material synthesis and testing.

Notable research or partnerships

Accelerating material discovery has seen a bolstered interest, especially with the amalgamation of machine learning and high-throughput screening techniques, as demonstrated in the development of novel materials like porous substances. The efficiency strides in CO_2 capture processes have been significantly influenced by AI-centric algorithms. Research in this domain extends into real-time modeling of CO_2 capture, transport, and storage, aimed at enhancing the deployment of current systems and crafting futuristic infrastructure. Partnerships, like the Carbon Capture Simulation for Industry Impact (CCSI2), comprising national labs, academia, and industry, strive for an all-encompassing modeling of novel carbon capture solutions, factoring in critical constraints from manufacturing to cost.

Biotechnology Based Solutions

4.1 Bio-Enhanced CDR

Core Challenge

Bio-enhanced mineralization and biological processes in Carbon Dioxide Removal focus on using living organisms—such as bacteria, algae, or plants—to accelerate the capture and stable storage of carbon dioxide. By tapping into natural biological mechanisms, this approach aims to improve the mass transfer efficiency in various CDR methods, potentially reducing costs and increasing the speed at which carbon can be captured and stored.

Emerging Research

- **Carbonic Anhydrase for Enhanced Mineralization:** Carbonic anhydrase, a naturally occurring enzyme, catalyzes the conversion of CO_2 into bicarbonate. Harnessing this enzyme could bolster the rates of CO_2 mineralization, laying the foundation for more efficient bio-enhanced mineralization methods (Steger et al., 2022).
- **Optimization of Phytoplankton Growth for Ocean Sequestration:** Phytoplankton, the primary carbon sequesterers in oceanic environments, have specific growth characteristics that can be tailored for optimized carbon uptake. By targeting factors influencing phytoplankton growth, there's potential to streamline bio-enhanced ocean carbon sequestration (Babakhani et al., 2022).
- **Microalgae capture and conversion:** CO_2 capture by microalgae is a promising technology to drastically reduce emissions by converting it to scalable value-added products. Microalgae utilizes CO_2 to synthesize various biochemical compounds, including lipids, proteins, carbohydrates, pigments, and phenols. The enriched microalgal biomass with different biochemicals can be used to obtain range of products, including biofuels, biopolymers, feed, and biomedicine (Onyeaka et al., 2021).

Intersection with Other Emerging Technologies

Genetic engineering and CRISPR technology play pivotal roles in refining the biological components used in Bio-enhanced CDR. Concurrently, AI-driven genomic analyses and computational modeling can provide profound insights into the biological intricacies and potentials of these methods.

4.2 Biochemical Production Pathways for CDR Materials

Core Challenge

Biochemical production pathways for Carbon Dioxide Removal materials employ biotechnological methods to synthesize or modify materials that can effectively capture and store carbon dioxide. Leveraging the natural metabolic pathways of microorganisms, these approaches seek to produce sorbents, catalysts, or other essential materials in a more sustainable and potentially less expensive manner than traditional chemical engineering methods.

Emerging Research

- **Microbial Factories - Advanced Biomanufacturing:** Utilizing microbes as miniature factories, advanced biomanufacturing harnesses their metabolic capabilities to produce materials that could be tailored for CDR. By engineering their metabolic pathways, researchers can guide microbes to generate materials for CO_2 capture, or microbes with the capability to capture and sequester carbon directly (Cho et al., 2022).
- **Cell-Free Synthetic Biology for CO_2 Transformation:** This approach focuses on using the molecular machinery of cells, without the cell itself, to catalyze reactions. By extracting and utilizing cellular components in a controlled environment, cell-free synthetic biology can offer a faster, more scalable pathway to produce materials or chemicals from CO_2, without the constraints of cell growth and viability (Lu, 2017).
- **Metagenomic Mining for Novel Pathways**: Nature possesses a vast array of organisms with untapped metabolic potential. Through metagenomic mining, researchers can explore diverse environmental samples to discover novel biochemical pathways or enzymes that can be harnessed for efficient CO_2 capture or transformation into valuable materials.

Intersection with Other Emerging Technologies

This technology stands at the intersection of biotechnology and material science. It utilizes cutting-edge techniques in synthetic biology, microbiology, and enzymology to produce materials tailored for CDR applications. It also involves material science for the characterization and testing of these bio-produced materials to ensure they meet the required standards for effective carbon capture and storage.

Additional Resources

CDR Primer

A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration

Negative Emissions Technologies and Reliable Sequestration: A Research Agenda

Technology Evaluation Framework

To effectively assess emerging technologies for both impact and viability we propose the following matrix for evaluating opportunities within the Carbon Dioxide Removal domain. By delineating technologies based on their potential impact and the likelihood of their emergence, this matrix facilitates a nuanced understanding and discussion among workshop attendees. It aids in identifying and prioritizing technologies that not only hold promise for significant impact but also have a reasonable likelihood of becoming operational. This structured assessment will help to inform resource allocation, steering clear of overly speculative ventures while ensuring potentially transformative technologies are not overlooked. Through this matrix, a balanced view encompassing both the visionary and the pragmatic aspects of emerging CDR technologies may be achieved.

Likelihood of Emergence within Next Decade

Impact on Carbon Dioxide Removal	**Very Likely** (L4)	**Likely** (L3)	**Unlikely** (L2)	**Very Unlikely** (L1)
High Impact (I4)	**Breakthrough** *(Emerging technologies with high impact and readiness)*	**Promising** *(Emerging technologies with solid evidence, moderate risk)*	**Speculative** *(Potential game-changers with uncertain viability)*	**Moonshot** *(Long-term vision, high risk and reward)*
Moderate Impact (I3)	**Incremental** *(Refined technologies with known benefits)*	**Next-Gen** *(Upcoming technologies, moderate impact and evidence)*	**Experimental** *(Potential innovations with moderate impact and uncertain viability)*	**Conceptual** *(Early-stage ideas, minimal validation)*
Low Impact (I2)	**Peripheral** *(Supportive technologies with low impact and high readiness)*	**Supplementary** *(Auxiliary technologies with low impact and some evidence)*	**Peripheral Innovations** *(With low impact and uncertain viability)*	**Speculative Innovations** *(With low impact and very uncertain viability)*
Negligible Impact (I1)	**Marginal** *(Technologies with negligible impact and high readiness)*	**Marginal Innovations** *(With negligible impact and moderate likelihood)*	**Impractical Innovations** *(With negligible impact and very uncertain viability)*	**Theoretical** *(Ideas with negligible impact and no current viability)*

Table 1: Technology risk matrix for evaluation of emerging technologies in CDR (Rousina-Webb, 2023)

Emerging Technologies Mentioned (exemplars, not exhaustive)

Technology	Class	Theme
Boron Nitride Nanomaterials	Material-Chemical Innovation	Advancements in Material Science
Transition Metal Chelated Weak Base Resins	Material-Chemical Innovation	Advancements in Material Science
Switchable Solvents	Material-Chemical Innovation	Advancements in Material Science
Ionic Liquids	Material-Chemical Innovation	Advancements in Material Science
Phase-changing Polymers	Material-Chemical Innovation	Advancements in Material Science
Covalent-organic Frameworks	Material-Chemical Innovation	Dual Function Materials
Metal-organic Framework Based Electrocatalysis	Material-Chemical Innovation	Dual Function Materials
Photoactive Porous Polymers	Material-Chemical Innovation	Dual Function Materials
Additive Manufacturing	Supply Chain, Infrastructure, and Process	Advanced Manufacturing
Robotics and Cobots	Supply Chain, Infrastructure, and Process	Advanced Manufacturing
Supercritical Fluids in Material Processing	Supply Chain, Infrastructure, and Process	Advanced Manufacturing
High Throughput Manufacturing	Supply Chain, Infrastructure, and Process	Advanced Manufacturing
Continuous DACCS	Supply Chain, Infrastructure, and Process	Process Innovations
Microwave-based Desorption	Supply Chain, Infrastructure, and Process	Process Innovations
High Temperature Heat Pumps	Supply Chain, Infrastructure, and Process	Process Innovations
Polymer Bio Reactors	Supply Chain, Infrastructure, and Process	Process Innovations
Self-Healing Polymeric Materials	Supply Chain, Infrastructure, and Process	Process Innovations
Digital Twinning	Digital Technologies	Digital Representation and Data Integrity
Augmented Reality	Digital Technologies	Digital Representation and Data Integrity
Blockchain and Distributed Ledgers	Digital Technologies	Digital Representation and Data Integrity
Generative Adversarial Networks	Digital Technologies	AI and Digital Design
Generative Design with Multiphysics Optimization	Digital Technologies	AI and Digital Design

AI-Driven Process Optimization	Digital Technologies	AI and Digital Design
Autonomous Materials Discovery	Digital Technologies	AI and Digital Design
Carbonic Anhydrase for Enhanced Mineralization	Biotechnology-based Solutions	Bio-enhanced CDR
Optimization of Phytoplankton Growth for Ocean Sequestration	Biotechnology-based Solutions	Bio-enhanced CDR
Microalgae Capture and Conversion	Biotechnology-based Solutions	Bio-enhanced CDR
Microbial Factories	Biotechnology-based Solutions	Biochemical Production Pathways
Cell-free Synthetic Biology	Biotechnology-based Solutions	Biochemical Production Pathways
Metagenomic Mining	Biotechnology-based Solutions	Biochemical Production Pathways

Bibliography

Ashokkumar, M., Thirumalaikumarasamy, D., Sonar, T., Deepak, S., Vignesh, P. & Anbarasu, M. (2022). An overview of cold spray coating in additive manufacturing, component repairing and other engineering applications. *Journal of the Mechanical Behavior of Materials*, *31*(1), 514-534. https://doi.org/10.1515/jmbm-2022-0056

Babakhani, P., Phenrat, T., Baalousha, M., Soratana, K., Peacock, C. L., Twining, B. S., & Hochella, M. F. (2022). Potential use of engineered nanoparticles in ocean fertilization for large-scale atmospheric carbon dioxide removal. *Nature Nanotechnology*, *17*(12), 1342–1351. https://doi.org/10.1038/s41565-022-01226-w

Bachman, J., Chakravorti, S., Rane, S., & Thyagarajan, K. (2023). Incentivizing Gigaton-Scale Carbon Dioxide Removal via a Climate-Positive Blockchain. *arXiv*. https://doi.org/10.48550/arXiv.2308.02653

Chen, H., Dong, H., Shi, Z., & SenGupta, A. K. (2023). Direct air capture (DAC) and sequestration of CO2: Dramatic effect of coordinated cu(ii) onto a chelating weak base ion exchanger. *Science Advances*, *9*(10). https://doi.org/10.1126/sciadv.adg1956

Cho, J. S., Kim, G. B., Eun, H., Moon, C.W., & Lee. S. Y. (2022). Designing Microbial Cell Factories for the Production of Chemicals. *Journal of the American Chemical Society*, *2*(8), 1781-1799. https://doi.org/10.1021/jacsau.2c00344

Dargan, S., Bansal, S., Kumar, M., Mittal, A., & Kumar, K. (2022). Augmented reality: A comprehensive review. *Archives of Computational Methods in Engineering*, *30*(2), 1057–1080. https://doi.org/10.1007/s11831-022-09831-7

Deutsch, T., Baker, S., Agbo, P., Kauffman, D., Vickers, J., & Schaidle, J. (2021). *Summary Report of the Reactive CO2 Capture: Process Integration for the New Carbon Economy Workshop, February 18-19, 2020*. https://doi.org/10.2172/1814138

Elmobarak, W. F., Almomani, F., Tawalbeh, M., Al-Othman, A., Martis, R., & Rasool, K. (2023). Current status of CO2 Capture with ionic liquids: Development and progress. *Fuel*, *344*, 128102. https://doi.org/10.1016/j.fuel.2023.128102

Erans, M., Sanz-Pérez, E. S., Hanak, D. P., Clulow, Z., Reiner, D. M., & Mutch, G. A. (2022). Direct air capture: process technology, techno-economic and socio-political challenges. *Energy & Environmental Science*, *15*(4), 1360–1405. https://doi.org/10.1039/d1ee03523a

Fawzy, S., Osman, A. I., Doran, J., & Rooney, D. W. (2020). Strategies for mitigation of climate change: a review. *Environmental Chemistry Letters*, *18*, 2069-2094. https://doi.org/10.1007/s10311-020-01059-w

González-Béjar, M. (2021). Photoactive Hybrid Materials based on Conjugated Porous Polymers and Inorganic Nanoparticles. *Advanced Photonics Research*, 2(8). https://doi.org/10.1002/adpr.202100060

Hamid, K., Sajjad, U., Ulrich Ahrens, M., Ren, S., Ganesan, P., Tolstorebrov, I., Arshad, A., Said, Z., Hafner, A., Wang, C. C., Wang, R., & Eikevik, T. M. (2023). Potential evaluation of Integrated

High Temperature Heat Pumps: A review of recent advances. *Applied Thermal Engineering*, *230*, 120720. https://doi.org/10.1016/j.applthermaleng.2023.120720

He, C., Zhang, C., Bian, T., Jiao, K., Su, W., Wu, K.-J., & Su, A. (2023). A review on artificial intelligence enabled design, synthesis, and process optimization of chemical products for Industry 4.0. *Processes*, *11*(2), 330. https://doi.org/10.3390/pr11020330

Hepburn, C., Adlen, E., Beddington, J., Carter, E. A., Fuss, S., Mac Dowell, N., Minx, J. C., Smith, P., & Williams, C. K. (2019). The technological and economic prospects for CO2 utilization and removal. *Nature*, *575*(7781), 87–97. https://doi.org/10.1038/s41586-019-1681-6

Hu, H. (2020). Recent advances of polymeric phase change composites for flexible electronics and Thermal Energy Storage System. *Composites Part B: Engineering*, *195*, 108094. https://doi.org/10.1016/j.compositesb.2020.108094

Jakubinek, M. B., Kim, K. S., Kim, M. J., Martí, A. A., & Pasquali, M. (2022). Recent advances and perspective on boron nitride nanotubes: From synthesis to applications. *Journal of Materials Research*, *37*(24), 4403–4418. https://doi.org/10.1557/s43578-022-00841-6

Jozdani, S., Chen, D., Pouliot, D., & Alan Johnson, B. (2022). A review and meta-analysis of generative adversarial networks and their applications in remote sensing. *International Journal of Applied Earth Observation and Geoinformation*, *108*, 102734. https://doi.org/10.1016/j.jag.2022.102734

Kumar, S. (2022). Switchable solvents for CO2 Capture. *Green Sustainable Process for Chemical and Environmental Engineering and Science*, 61–99. https://doi.org/10.1016/b978-0-12-819850-6.00012-7

Lin, A. C. (2019). Carbon Dioxide Removal after Paris. *Ecology Law Quarterly*, *45*(3), 533-582.

Lu, Y. (2017). Cell-free synthetic biology: Engineering in an open world. *Synthetic and Systems Biotechnology*, *2*(1), 23-27. https://doi.org/10.1016/j.synbio.2017.02.003

Lyu, H., Li, H., Hanikel, N., Wang, K., & Yaghi, O. M. (2022). Covalent organic frameworks for carbon dioxide capture from Air. *Journal of the American Chemical Society*, *144*(28), 12989–12995. https://doi.org/10.1021/jacs.2c05382

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Lenzi, D., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente Vicente, J. L., Wilcox, J., & del Mar Zamora Dominguez, M. (2018). Negative emissions—part 1: Research landscape and synthesis. *Environmental Research Letters*, *13*(6), 063001. https://doi.org/10.1088/1748-9326/aabf9b

NASA. (2023, September 27). *Carbon Dioxide*. Retrieved from NASA Climate: https://climate.nasa.gov/vital-signs/carbon-dioxide/

Onyeaka, H., Miri, T., Obileke, K., Hart, A., Anumudu, C., & Al-Sharify, Z. T. (2021). Minimizing carbon footprint via microalgae as a biological capture. *Carbon Capture Science & Technology*, *1*, 100007. https://doi.org/10.1016/j.ccst.2021.100007

Refrew, S. E., Starr, D. E., & Strasser, P. (2020). Electrochemical Approaches toward CO2 Capture and Concentration. *ACS Catalysis*, 13058-13074. https://doi.org/10.1021/acscatal.0c03639

Rouse, P. (2018). *How to govern the risks of stratospheric aerosol injection solar radiation management.* University of Southampton.

Shen, P., Jiang, Z., Viktorova, J., Pollard, B., Kumar, A., Stachurski, Z., & Connal, L. A. (2023). Conductive and self-healing carbon nanotube–polymer composites for mechanically strong Smart Materials. *ACS Applied Nano Materials*, *6*(2), 986–994. https://doi.org/10.1021/acsanm.2c04370

Siegelman, R. L., Kim, E. J., & Long, J. R. (2021). Porous materials for carbon dioxide separations. *Nature Materials*, *20*(8), 1060–1072. https://doi.org/10.1038/s41563-021-01054-8

Stach, E., DeCost, B., Kusne, A. G., Hattrick-Simpers, J., Brown, K. A., Reyes, K. G., Schrier, J., Billinge, S., Buonassisi, T., Foster, I., Gomes, C. P., Gregoire, J. M., Mehta, A., Montoya, J., Olivetti, E., Park, C., Rotenberg, E., Saikin, S. K., Smullin, S., … Maruyama, B. (2021). Autonomous Experimentation Systems for Materials Development: A Community Perspective. *Matter*, *4*(9), 2702–2726. https://doi.org/10.1016/j.matt.2021.06.036

Steger, F., Reich, J., Fuchs, W., Rittmann, S. K.-M., Gübitz, G. M., Ribitsch, D., & Bochmann, G. (2022). Comparison of carbonic anhydrases for CO2 sequestration. *International Journal of Molecular Sciences*, *23*(2), 957. https://doi.org/10.3390/ijms23020957

Terlouw, T., Bauer, C., Rosa, L., & Mazzotti, M. (2021). Life cycle assessment of carbon dioxide removal technologies: A critical review. *Energy & Environmental Science*, *14*(4), 1701–1721. https://doi.org/10.1039/d0ee03757e

The Global Carbon Project. (2022). Global Carbon Budget 2022. *Earth System Science Data*.

van Schagen, T. N., van der Wal, P. J., & Brilman, D. W. F. (2022). Development of a novel, through-flow microwave-based regenerator for Sorbent-based direct air capture. *Chemical Engineering Journal Advances*, *9*, 100187. https://doi.org/10.1016/j.ceja.2021.100187

Wu, J., Qian, X., & Wang, M. Y. (2019). Advances in Generative Design. *Computer-Aided Design*.

Yao, J. F., Yang, Y. Wang, X. C., & Zhang, X. P. (2023). Systematic review of digital twin technology and applications. *Visual Computing for Industry, Biomedicine, and Art*, 6.

Zheng, W., & Lee, L. Y. (2021). Metal–organic frameworks for electrocatalysis: Catalyst or precatalyst? *ACS Energy Letters*, *6*(8), 2838–2843. https://doi.org/10.1021/acsenergylett.1c01350