



EXPLORING THE HORIZONS OF CARBON CAPTURE - PART 2

Abstract

Novel and emerging technologies are being explored through innovative approaches that hold the potential for enhanced efficiency, reduced costs, and broader applicability across diverse emission sources. Emphasis is placed on the development of advanced materials with superior CO₂ adsorption capacities, the design of processes aimed at minimizing energy consumption, and the integration of renewable energy sources to facilitate net-negative emissions. Additionally, research is being directed towards the capture of carbon from more dilute sources, such as the atmosphere, and the conversion of the captured CO₂ into valuable products, thereby fostering the concept of a circular carbon economy.

1. Enhanced Weathering

Enhanced weathering accelerates natural rock weathering to capture CO₂. By spreading finely ground silicate rocks like basalt over large areas, chemical reactions with water and air form stable carbonate minerals that permanently store CO₂.

Key benefits of technology

- **Natural Process:** Sustainable and eco-friendly, building on the Earth's carbon cycle.
- **Carbon-Negative Potential:** Captures and stores CO₂, aiding climate change mitigation.
- **Versatility:** Applicable to various environments like agricultural lands, forests, and oceans.
- **Scalability:** Can be scaled to capture significant CO₂, aiding global carbon reduction.
- **Environmental Benefits:** Improves soil health and fertility, benefiting agricultural productivity.

Limitations and Challenges

Enhanced weathering faces several limitations and challenges that need to be addressed for it to become a viable large-scale solution

for carbon capture and storage (CCS):

- **Reaction Rate:** Slow natural process, even when accelerated, may not capture enough CO₂.
- **Energy and Resource Intensive:** Requires significant energy and resources for mineral processing.
- **Environmental Impact:** Potential negative effects like soil acidification and ecosystem harm.
- **Economic Viability:** High costs for mining, processing, and distribution may reduce competitiveness.
- **Regulatory and Policy Support:** Needs robust policies and frameworks for deployment and sustainability.
- **Monitoring and Verification:** Accurate measurement and verification of CO₂ sequestration require robust systems.

Example Project

Project Vesta: Founded in 2019, Project Vesta uses enhanced weathering by spreading finely ground olivine on coastal areas to capture CO₂ and mitigate ocean acidification. This nature-based strategy also provides shoreline protection and enhances marine habitats. Field pilots are assessing its large-scale effectiveness.

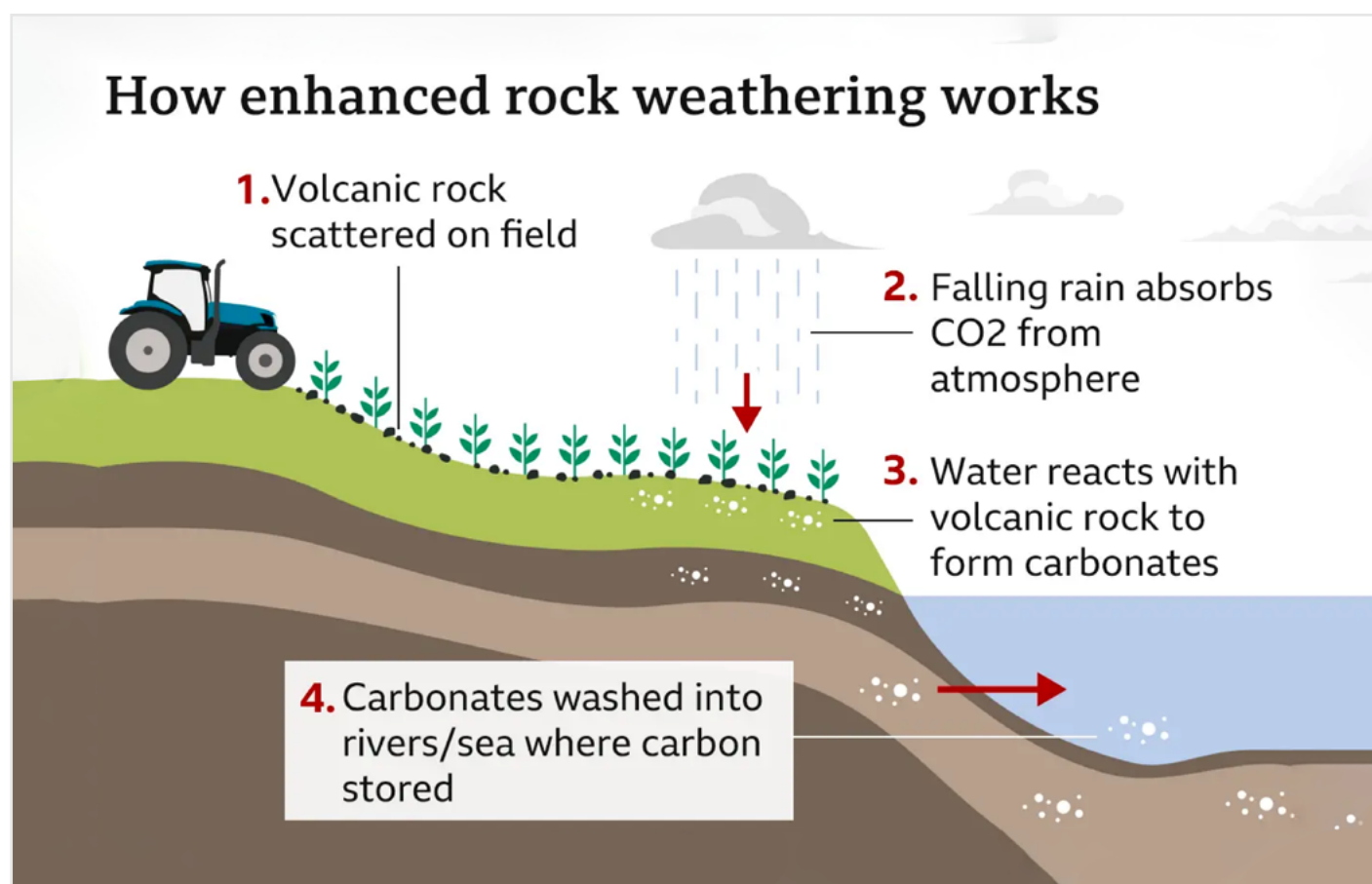


Figure 1: Enhanced Rock Weathering

Source: <https://www.bbc.com/news/science-environment-65648361>

2. Mineral Carbonation

The natural process of CO₂ reacting with minerals to form stable carbonates is accelerated by mineral carbonation, which locks CO₂ away for extended periods. The conversion of CO₂ into solid, stable minerals for secure storage is a process that is employed in CCS to mitigate climate change.

Key benefits of technology

- **Permanent Storage:** The carbonates formed through mineral carbonation are highly stable, ensuring that the captured CO₂ remains sequestered for geological time scales.
- **Utilization of Abundant Resources:** The process is a sustainable and scalable solution for carbon capture, as it utilizes abundant and naturally occurring minerals.
- **Environmental Benefits:** Besides capturing CO₂, mineral carbonation can neutralize acidic soils, improve soil health, and promote plant growth. This has the added benefit of enhancing agricultural productivity.
- **Industrial Applications:** The environmental impact of construction and other industries can be mitigated using the stable carbonates produced in a variety of industrial applications, such as building materials.

Limitations and Challenges

Mineral carbonation faces several limitations and challenges that need to be addressed for it to become a viable large-scale solution for carbon capture and storage (CCS):

- **High Energy Requirements:** The process of extracting and grinding minerals to increase their reactivity with CO₂ requires

significant energy, which can offset some of the carbon reduction benefits.

- **Scalability:** While mineral carbonation can be demonstrated on a small scale, scaling it up to industrial levels poses challenges, including the need for large amounts of minerals and infrastructure.
- **Cost:** The costs associated with mineral extraction, processing, and transportation can be high, making the technology less competitive compared to other CCS methods.
- **Environmental Impact:** Mining and processing minerals can have environmental impacts, such as habitat destruction and water usage, which need to be carefully managed.
- **Technological Maturity:** Mineral carbonation is still in the research and development phase, and more work is needed to optimize the process and ensure its long-term viability.
- **Regulatory and Policy Support:** Adequate regulatory frameworks and policies are needed to support the deployment of mineral carbonation technologies and ensure their environmental and economic sustainability

Example Project

CSIRO CarbonLock: Launched in March 2023, this project develops technologies for permanent CO₂ removal, aiming for net-zero emissions by 2050. The 2024 CarbonLock Conference gathered over 90 net-zero professionals to discuss strategies for atmospheric carbon removal. Supported by a multidisciplinary team, CarbonLock advances global climate change efforts through CO₂ sequestration.

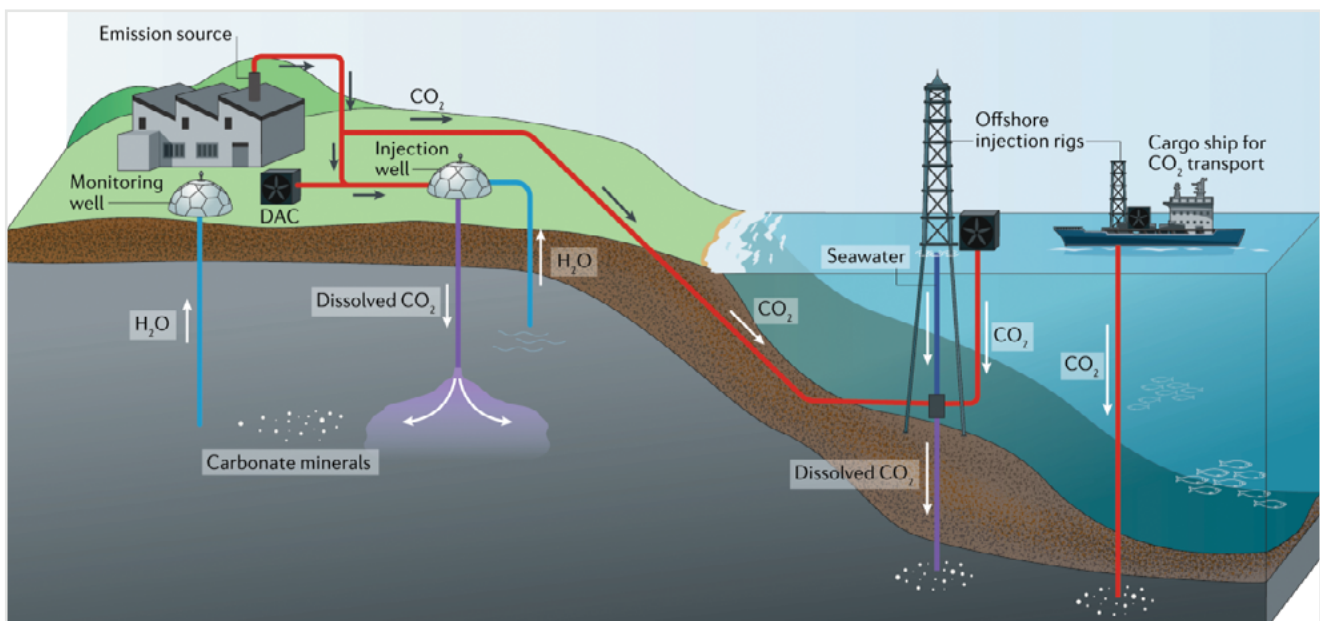


Figure 2: Carbon dioxide storage through mineral carbonation

Source: https://media.springernature.com/lw1200/springer-static/image/art%3A10.1038%2Fs43017-019-0011-8/MediaObjects/43017_2019_11_Fig6_HTML.png

3. Membrane Technology

The procedure is successful in both post- and pre-combustion processes, and it uses semi-permeable membranes to isolate CO₂ from other gases in the flue streams. Membranes are classified into three categories: polymeric (cost-effective and simple to manufacture), inorganic (high selectivity and stability, greater cost), and hybrid (which combines both advantages). The membrane allows CO₂ to travel through, while other gases are retained. Finally, the CO₂ that has been gathered can be either stored or utilized after being compressed.

Key benefits of technology

- **Energy Efficiency:** Membrane technology requires less energy compared to traditional amine-based absorption methods, reducing overall operational costs.
- **Scalability:** The scalability of membranes makes them an attractive option for large-scale carbon capture initiatives in the industrial sector.
- **Environmental Impact:** Lower energy consumption and reduced chemical use make it a more environmentally friendly option, contributing to sustainable practices.
- **Versatility:** Offers flexibility in implementation by applying to various carbon capture processes (post-combustion, pre-combustion).

Limitations and Challenges

- **Permeability and Selectivity Trade-off:** Achieving high CO₂ permeability while maintaining selectivity is a significant

challenge. High permeability often comes at the cost of reduced selectivity, necessitating ongoing research to balance these factors.

- **Membrane Degradation:** Long-term exposure to flue gases can degrade membrane materials, reducing their effectiveness and lifespan. Developing more durable materials is crucial for long-term viability.
- **Cost:** While membrane technology is promising, the initial costs for materials and system setup can be high. Cost-effective solutions and economies of scale are needed to make it more competitive.
- **Operational Conditions:** Membranes must withstand harsh conditions, such as high temperatures and corrosive gases, which can affect their performance. Ensuring robustness under these conditions is essential for reliable operation.

Example Project

The National Energy Technology Laboratory (NETL) is advancing this technology through the Point Source Carbon Capture (PSCC) Program, for a greenhouse gas-neutral economy by 2050. It focuses on developing advanced, cost-effective membranes with high permeance and selectivity. Key projects include high permeance blended rubbery membranes, targeting CO₂ permeance over 3,000 GPU and CO₂/N₂ selectivity over 25. NETL's research drives innovation, reduces costs, and ensures membranes can withstand harsh conditions, contributing to scalable, energy-efficient, and environmentally friendly carbon capture solutions.

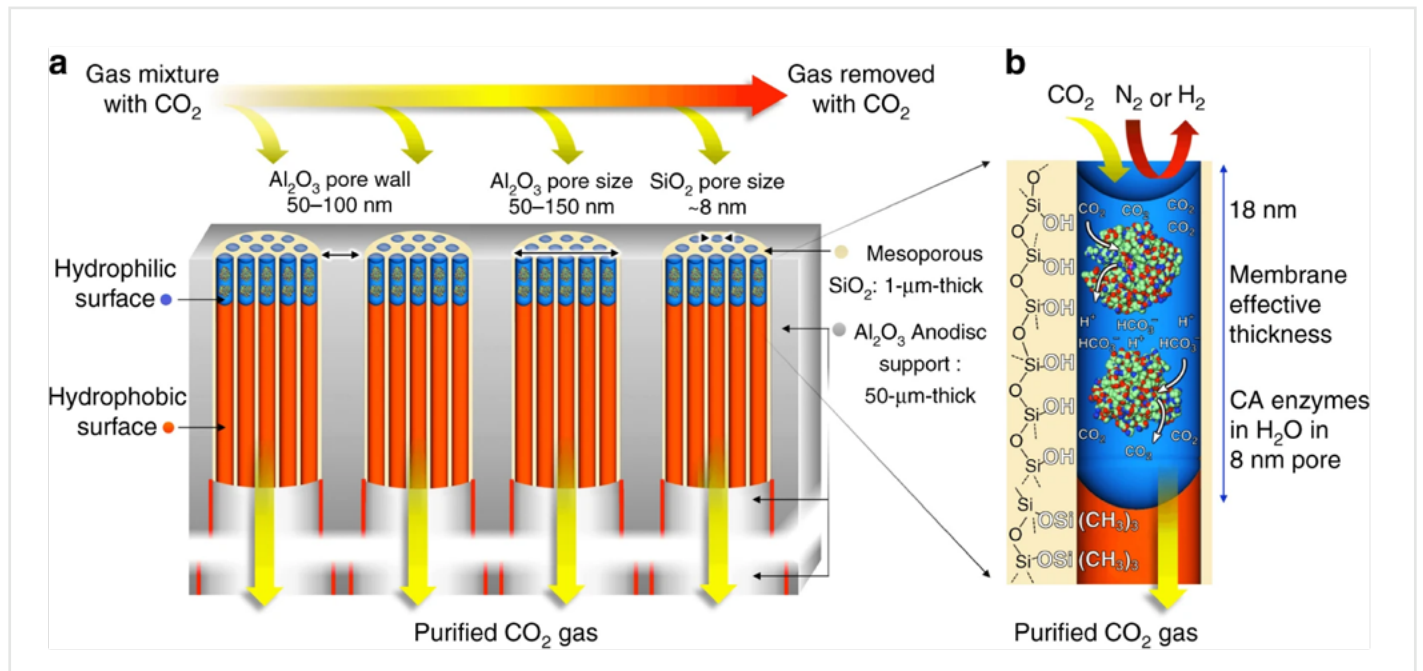


Figure 3: Ultra-thin enzymatic liquid membrane for CO₂ separation and capture

Source: <https://www.nature.com/articles/s41467-018-03285-x/figures/2>

4. Cryogenic Carbon Capture (CCC)

CCC captures CO₂ from industrial emissions by cooling the gas stream to temperatures below -78°C, causing CO₂ to condense into a liquid or solid state for separation and collection. This method achieves high CO₂ recovery and purity through low-temperature separation. Flue gas is cooled using refrigeration cycles or cryogenic fluids, condensing CO₂ for separation and storage. For industrial processes and enhanced oil recovery, CCC can generate high-purity CO₂ and obtain recovery rates exceeding 90%.

Key benefits of technology

- **High Recovery Rates:** CCC can achieve CO₂ recovery rates often exceeding 90%, making it one of the most efficient carbon capture methods available.
- **High Purity:** Applications such as increased oil recovery, food and beverage industries, and industrial processes can benefit from the captured CO₂ due to its high purity, which is generally around 99%.
- **Scalability:** This technology is modular and can be expanded for industrial applications, rendering it appropriate for large-scale carbon capture initiatives in a variety of sectors, including power plants, cement production, and steel manufacturing.
- **Environmental Impact:** Lower environmental impact compared to some other methods of carbon capture due to the absence of chemical solvents. This minimizes the risk of secondary pollution and reduces the overall environmental footprint.

Limitations and Challenges

- **Energy Intensive:** The process of cooling gases to cryogenic temperatures requires significant energy input, which can offset some of the carbon reduction benefits.
- **Operational Costs:** High operational costs are associated with maintaining cryogenic temperatures and the energy-intensive cooling process.
- **Technological Maturity:** Although CCC is a mature technology for certain applications like gas processing, it is still in the development phase for large-scale industrial carbon capture.
- **Environmental Impact:** While the primary process does not involve chemical solvents, the high energy consumption and associated emissions from power generation can have an environmental impact.

Example Project

IFESTOS Project by ThyssenKrupp and TITAN Group: One of Europe's largest carbon capture initiatives, is designed to manufacture zero-carbon cement and concrete at TITAN's Kamari facility in Athens. The initiative employs cryogenic and oxyfuel technologies to capture CO₂ emissions from the cement production process. It is anticipated to be operational by the conclusion of 2029 and is designed to mitigate 1.9 million tonnes of CO₂ annually. The EU Innovation Fund awarded the initiative a €234 million grant, underscoring its importance in the green transition.

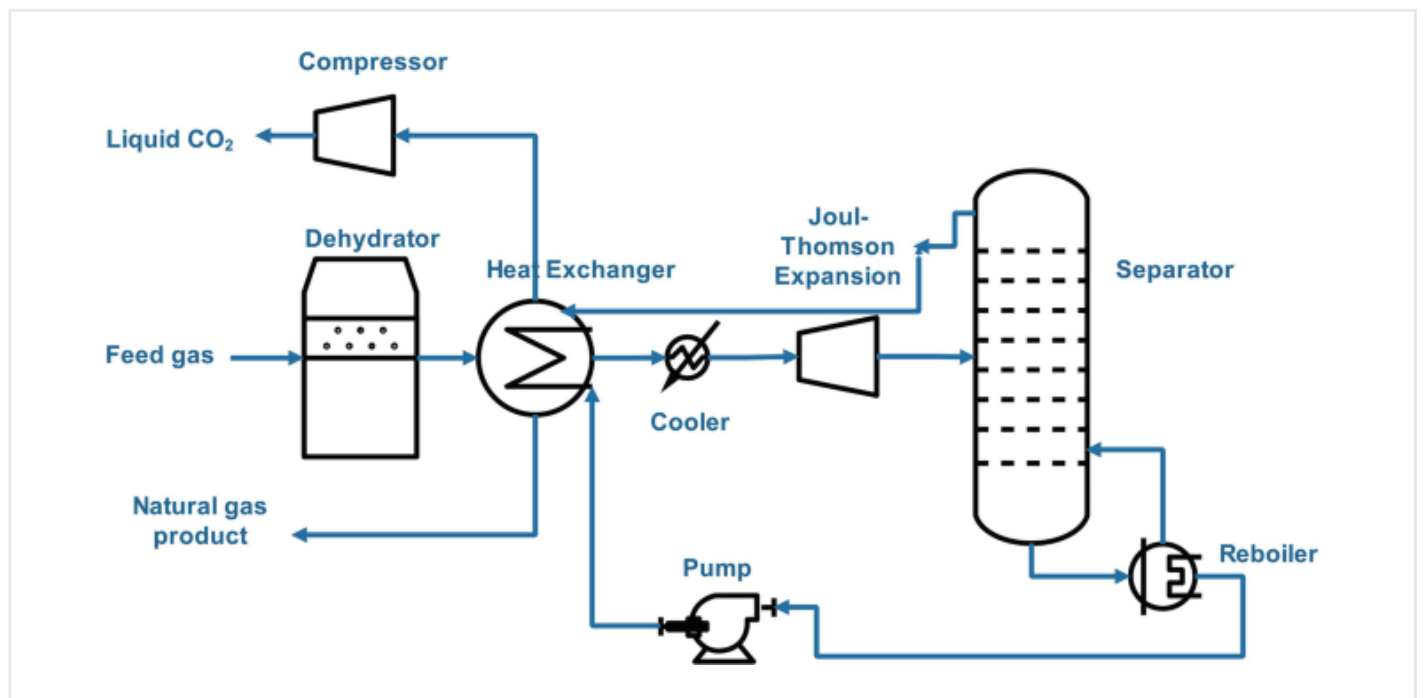


Figure 4: Cryogenic CO₂ Capture

Source: https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-030-29337-6_10/MediaObjects/486475_1_En_10_Fig7_HTML.png

5. Bioenergy with Carbon Capture and Storage (BECCS)

BECCS integrates carbon capture and storage with bioenergy production. In the process of capturing CO₂ emissions for storage, biomass is converted into energy (such as heat, electricity, or fuels). Through the process of photosynthesis, biological systems technology utilizes microorganisms, algae, and plants to assimilate CO₂. Key methods include afforestation and reforestation, which have the potential to sequester approximately 2.4 gigatons of CO₂ annually on a global scale, and BECCS, which has the potential to remove 0.5 to 5 gigatons of CO₂ annually by 2050, potentially sequestering 0.5 gigatons of CO₂ annually on a wide scale. These techniques effectively sequester CO₂ in biomass, soils, and geological formations.

Key benefits of technology

- **Negative Emissions and Renewable Energy:** Removes CO₂ from the atmosphere by capturing and storing CO₂ absorbed by biomass during growth, while generating renewable energy from biomass.
- **Versatility and Adaptability:** Suitable for various types of biomass and energy conversion technologies, adaptable to different environments and local conditions.
- **Environmental and Co-Benefits:** Mitigates climate change, enhances biodiversity, improves water quality, increases soil

fertility, and provides renewable energy.

- **Sustainable Integration:** Seamlessly integrates into agricultural and forestry practices, promoting biodiversity, soil health, and ecosystem resilience with long-term CO₂ sequestration.
- **Scalability and Effectiveness:** Can scale up to capture significant amounts of CO₂, impacting global carbon reduction efforts with high capture rates and efficiency.

Limitations and Challenges

- **Land Use:** Requires significant land area for planting trees or growing biomass, which can compete with food production and other land uses.
- **Time Scale:** Biological processes take time to capture and store CO₂, making it a slower method compared to technological solutions.
- **Monitoring and Verification:** Ensuring that the captured CO₂ remains stored and does not re-enter the atmosphere requires robust monitoring and verification systems.
- **Economic Viability:** The costs associated with land management, biomass production, and carbon capture and storage can be high, requiring financial incentives and policy support.

Example Project

GAIL Microalgae Pilot Project: At GAIL's Pata petrochemical complex, this project uses microalgae to capture 1 tonne of CO₂ per day, converting it into organic compounds for biofuel production, promoting sustainable biofuels and reducing CO₂ emissions.

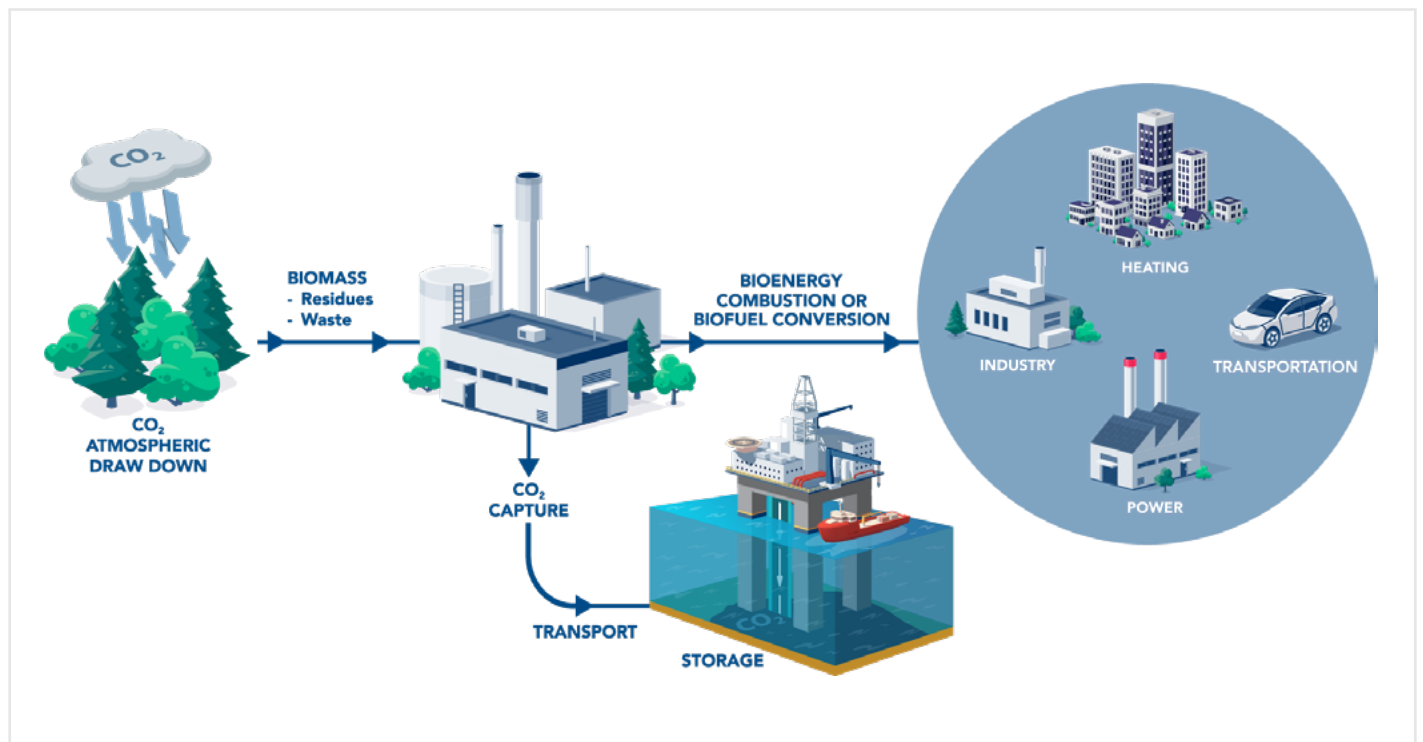


Figure 5: Bioenergy production with carbon capture and sequestration [BECCS]

Source: <https://www.babcock.com/home/renewable/biomass-to-energy/bioenergy-with-carbon-capture-and-sequestration/>

Role of System integrators

System integrators are vital in deploying and optimizing carbon capture technologies. They combine various subsystems into efficient, cohesive solutions tailored to clients' needs. By integrating advanced technologies like AI, IoT, and blockchain, they can help businesses reduce carbon footprints, enhance efficiency, and comply with environmental regulations. Their expertise ensures seamless implementation and maintenance, driving sustainability and cost-effectiveness in operations.

1. Quantum Computing for Carbon Capture

a. Optimization Algorithms: Quantum computing can solve optimization problems related to carbon capture more efficiently. IBM's quantum algorithms have shown the potential to reduce the energy required for carbon capture by up to 20%. This is achieved by optimizing the chemical processes involved in capturing CO₂, leading to significant energy savings and cost reductions.

2. Next-Generation AI Models

a. Deep Reinforcement Learning: AI models using deep reinforcement learning can dynamically adjust carbon capture parameters. A study conducted by researchers at MIT demonstrated that using AI to control the temperature and pressure in carbon capture systems resulted in a 15% increase in capture efficiency and a 10% reduction in operational costs. These AI models continuously learn and adapt to changing conditions, optimizing the process in real time.

3. IoT-Enabled Carbon Capture Systems

a. Smart Sensors and Actuators: Real-time data and control over carbon capture systems can be provided by IoT devices. In Springfield, Illinois, a pilot project was implemented at the City Water, Light, and Power (CWLP) facility to employ IoT-enabled sensors for carbon capture. This initiative entailed the deployment of intelligent sensors to monitor CO₂ levels and adjust the capture process in real-time. The findings indicated that predictive analytics resulted in a 15% decrease in maintenance costs and a 12% increase in capture efficiency.

4. Blockchain for Carbon Footprint Tracking

a. Decentralized Monitoring: Blockchain technology can ensure transparent and secure tracking of carbon capture activities. A pilot project in the energy sector, conducted by the

Energy Web Foundation, showed that blockchain could reduce verification costs by 40% and improve data integrity. This system allows for real-time tracking of carbon credits and ensures that all transactions are transparent and tamper-proof.

5. Digital Twin for Simulation and Optimization

a. Virtual Modelling: Digital twins are virtual replicas of physical carbon capture systems. They enable integrators to simulate system behavior, analyze performance under varying conditions, and forecast future states without disrupting operations.

b. Process Optimization: By simulating chemical reactions, fluid dynamics, and thermal processes in a virtual environment, digital twins help refine carbon capture processes. This allows for fine-tuning operational parameters to maximize efficiency and minimize energy consumption.

6. Earth Observation for Environmental Monitoring

a. Large-Scale Monitoring: Drones and satellites offer the ability to monitor carbon capture installations as well as surrounding environments over large geographical areas. This is critical for assessing the impact of carbon capture operations on local ecosystems.

b. Data Collection and Analysis: High-resolution imaging and remote sensing technologies can capture changes in vegetation, soil conditions, and atmospheric composition. This data can be used to validate the performance of carbon capture systems and ensure they are effectively reducing greenhouse gases.

Conclusion

Emerging technologies, such as improved weathering (potential to sequester 2.4 gigatons of CO₂ year) and BECCS (potential to eliminate 0.5-5 gigatons annually by 2050), show promise. In addition to membrane and cryogenic technologies, mineral carbonation improves efficiency and scalability. It is critical for system integrators to easily integrate these technologies into existing infrastructure, optimizing their efficacy and impact. By working together, these technologies and techniques provide a holistic plan for significant carbon reduction, encouraging a sustainable future through innovation and collaboration while also making a significant contribution to global carbon reduction efforts.



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