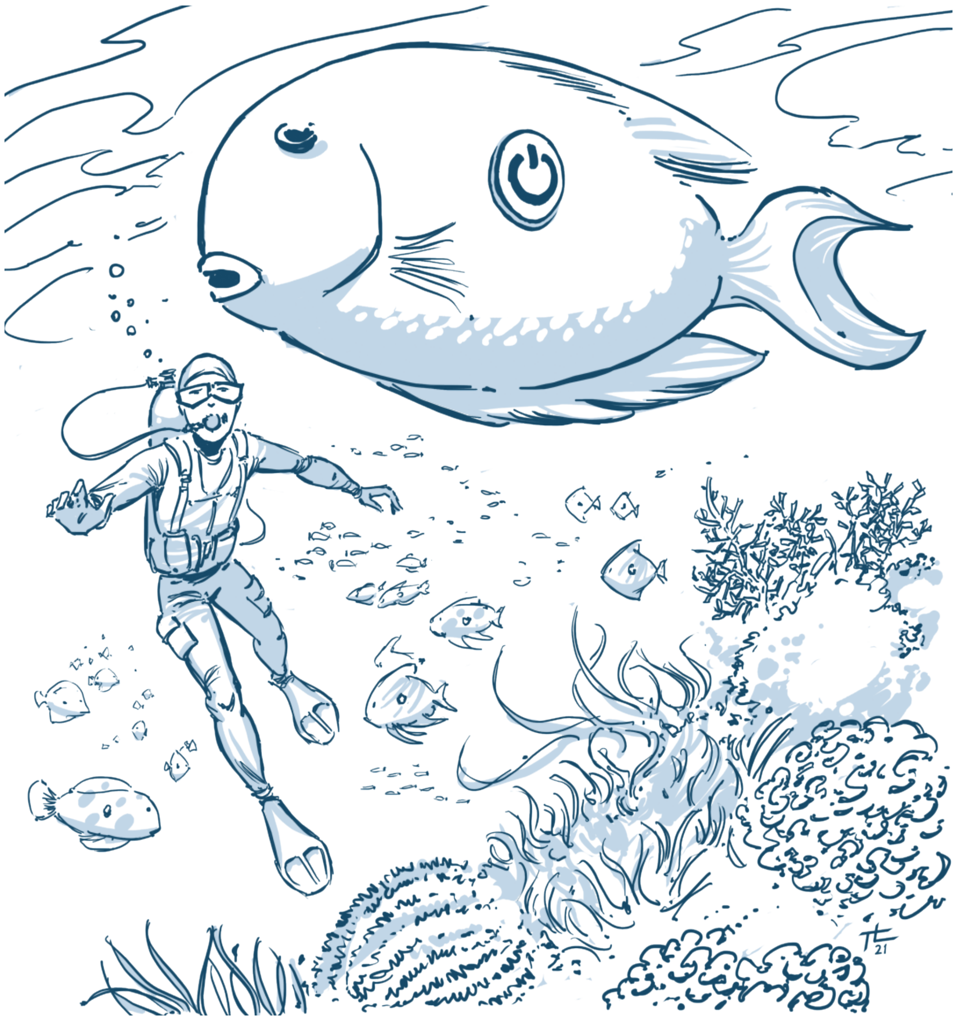
THE FUTURE OF CO2

WILL CO2 SEQUESTRATION, UTILIZATION, AND STORAGE TECHNOLOGIES DELIVER THE EXPECTED RESULTS?



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Over the past year, the European Union has made significant strides in implementing policies and advancing carbon capture, utilization, and storage (CCUS) projects. This acceleration has been driven by the newly established targets of a 90% emissions reduction by 2040 and achieving net-zero emissions by 2050. Previously left to develop without strong support, European CCUS has, in this short period, gained a concrete roadmap for scaling up projects, a mandate to expand CO_2 storage capacity within the EU, and a clear vision of how CCUS will contribute to overall climate policy and the achievement of the 2040 climate targets.

To achieve its 2040 and 2050 targets, the EU plans to phase out coal, transition from fossil fuels to renewable energy, and electrify transportation. However, emissions from vehicles, shipping, aviation, and certain oil and gas sources remain a challenge. To address these, the EU has accelerated the deployment of CCUS technologies.
Despite this momentum, the implementation of CCUS faces significant obstacles and remains controversial, drawing criticism from environmental organizations as well as industry stakeholders.

THE INVISIBLE CORNERSTONE: CARBON CAPTURE IN THE FIGHT AGAINST CLIMATE CHANGE

CCUS encompasses several approaches:

- Carbon Capture and Storage (CCS) directly from industrial emissions and storing it deep underground or in deep ocean formations, effectively preventing its release into the atmosphere;
- Carbon Dioxide Removal (CDR) extracting CO_2 directly from the atmosphere;
- Carbon Capture and Utilization (CCU) transforming captured CO_2 into products like fuels, chemicals, and building materials;
- Bioenergy with Carbon Capture and Storage (BECCS) where biomass is converted into fuels or burned directly to produce energy. Since plants absorb CO_2 as they grow, BECCS provides a pathway to remove CO_2 from the atmosphere.

The ambitious targets set by the Paris Agreement have spurred governments and industries to implement supportive policies and invest in research and pilot projects. The European Union, United States, United Kingdom, and several Middle Eastern nations are leading these efforts, making substantial commitments and launching innovative initiatives.

The path to widespread implementation of CCUS remains long and challenging. High costs, unproven technology, and the need for extensive infrastructure pose significant barriers. Additionally, concerns that CCUS may justify continued fossil fuel extraction, along with potential risks to human health and the environment, complicate efforts to gain public acceptance.

In the face of these challenges and opportunities, a series of questions arises:

WHAT IS THE CURRENT LEVEL OF ADVANCEMENT IN CCUS TECHNOLOGIES?

CAN TODAY'S CHALLENGES BE OVERCOME SWIFTLY ENOUGH TO AID IN MITIGATING CLIMATE CHANGE?

WHAT ARE THE ENVIRONMENTAL IMPACTS OF EACH OF THESE TECHNOLOGIES ACROSS THEIR FULL LIFE CYCLE?

WHAT KEY OBSTACLES MUST WE ADDRESS BEFORE CCUS CAN ENTER THE MAINSTREAM?

We will also examine trends and the latest technological advancements that may significantly reinforce or weaken these developments.

Progress across all technological pathways for carbon management is promising, driven by global initiatives and supportive government policies. However, to achieve the necessary scale of CO_2 capture and make a meaningful impact on emissions reduction, further substantial investments and innovations are essential.

Government Policies and Programs

Governments worldwide recognize the importance of CCUS in achieving their climate goals and are implementing supportive policies and programs to accelerate the development of carbon management technologies and projects.

The Net-Zero Industry Act (NZIA). The EU has set ambitious targets for carbon capture, utilization, and storage (CCUS), aiming to establish dedicated carbon capture and storage hubs and significantly increase funding for research and development in this area.

EU's Industrial Carbon Management Strategy. In February 2024, the EU introduced comprehensive, voluntary, Union-wide certification frameworks for carbon capture. This regulation sets EU-wide quality criteria and outlines detailed processes for monitoring and reporting.

Horizon Europe. The European Commission also supports research, development and innovation for industrial carbon management technologies through Horizon Europe and stakeholder engagement, such as the Strategic Energy Technology Plan Working Group on CCUS and its associated European Technology and Innovation Platform 'Zero Emissions Platform'. Under Horizon Europe Cluster 5 (Climate, Energy and Mobility), the Commission supports developing new and/or improving existing CO_2 capture technologies. A dedicated project, CCUS Zero Emission Network (ZEN), supports the integration of CCS and CCU in hubs and clusters, including knowledge-sharing activities. Under Horizon Europe Cluster 4 (Digital, Industry and Space), several calls address carbon capture and utilisation in topics related to industrial symbiosis and Hubs for Circularity.

The Innovation Fund. Since February 2024, the Innovation Fund has been supporting 26 industrial carbon management projects with a total funding of over €3.3 billion.

UK's CCUS Net Zero Investment Roadmap. The UK government has released a comprehensive roadmap outlining its strategy for supporting CCUS development. This includes investing in infrastructure, providing financial incentives, and streamlining regulations to attract investment and accelerate project deployment.

US Inflation Reduction Act and CDR Purchase Program. The Inflation Reduction Act in the US has significantly expanded tax credits for CCUS projects, making them more financially attractive. Additionally, the government has launched a carbon dioxide removal (CDR) pilot purchasing program.

Japan's CCS Long-Term Roadmap. Japan has released a long-term roadmap for CCS development, aiming to achieve substantial CO_2 emissions reductions by 2050.

Saudi Arabia's CCS Target. Saudi Arabia has set an ambitious target to capture and store 44 million metric tons of CO_2 annually by 2035. The country is investing heavily in CCS infrastructure and technology development to achieve this goal.

500 CCUS Projects Underway

There are currently over 500 CCUS projects in various stages of development worldwide, spanning the entire value chain from capture to storage and utilisation.

Capture: Several large-scale CCS projects are already operational, capturing CO_2 from power plants and industrial facilities. Notable examples include the Petra Nova project in the USA, the Boundary Dam project in Canada, and the Sleipner and Snøhvit projects in Norway.

Transport: CO_2 transport infrastructure is expanding, with pipelines and shipping networks being developed to connect capture sites with storage locations. Major projects like the Porthos project in the Netherlands and the Northern Lights project in Norway are leading the way in CO_2 transport and storage.

Utilisation: CCU projects are gaining traction, with innovative approaches being explored to convert captured CO_2 into valuable products. Companies like Twelve and LanzaTech are pioneering in scaling up CCU technologies, while others are focusing on carbon-negative cement production and CO_2 utilisation in 3D printing.

Storage: Geological formations, such as saline aquifers and depleted oil and gas reservoirs, offer vast potential for safe and permanent CO_2 storage. Several large-scale storage projects are underway, including the Sleipner and Snøhvit projects in Norway, the Quest project in Canada, and the Gorgon project in Australia.

Technological Advancements

Continuous innovation is driving improvements in CCUS technologies, making them more efficient, cost-effective, and scalable.

Capture: Advancements in capture technologies, such as post-combustion, pre-combustion, and oxy-fuel combustion, have improved CCUS efficiency and reduced costs.
Novel materials like metal-organic frameworks (MOFs) and solid sorbents are also enhancing capture capabilities.

Transport. Innovations in CO_2 transport, such as the development of specialised ships and pipelines, are improving the efficiency and safety of transporting captured CO_2.

Utilisation: Research and development efforts are leading to the discovery of new pathways for converting CO_2 into valuable products, expanding the potential applications of CCUS.

Storage: Advances in monitoring and verification technologies are enhancing the safety and security of CO_2 storage, addressing concerns about potential leakage and environmental impacts.

What's Next?

Significant progress has been made across the entire CCUS value chain, yet substantial investment, breakthrough innovations, and robust international collaboration remain essential.
Overcoming these challenges is crucial to fully unlock CCUS's potential in mitigating climate change and achieving net-zero emissions goals.

Public Policies & Government Support

- Current policies and programs for implementing CCUS technologies vary across countries and continue to evolve.
- Due to their novel and experimental nature, CCUS technologies must be tested in large-scale projects that require international collaboration.
- State support is essential for developing shared (transnational) infrastructure, along with indirect incentives for the private sector, clear guidelines for permitting and access, and well-defined risk management policies related to CCUS.

Project Implementation

- The projects are large and pioneering, requiring significant development time and carrying risks of early-stage failure. Of projects with capacities over 0.3 MT of CO_2 per year initiated between 1995 and 2018, 78% were either abandoned or halted.
- CCUS projects require coordination and collaboration among multiple companies and organisations with diverse goals, agendas, timelines, business models, and stages of project execution within the CCUS value chain.

Economic Viability

- High costs associated with capturing, transporting, and storing or utilising CO_2.
- Investments in infrastructure and economies of scale are essential to reduce costs.
- It is difficult to define revenue streams from CCUS, making it challenging to justify investment plans and secure project financing. Currently, projects are often funded from the internal resources of large corporations.
- Companies hesitate to commit capital without regulatory certainty.
- Projects differ widely in costs, with some ranging from €80 to €150 or more per ton of CO_2.

Public Acceptance

- Some view CCUS as typical "end-of-pipe" technologies that allow fossil-fuel-based industries to continue operating, rather than as green innovations.
- Social acceptance is hindered by concerns that geoengineering techniques do not address the root causes of climate change. In areas where underground CO_2 storage facilities are located, there are protests from local communities.
- One of the significant risks is the unpredictable subsurface conditions, potential leaks of greenhouse gases, and threats to human health and the environment.
- The lack of clear accountability for the costs associated with monitoring storage facilities and for any remedial actions and the mitigation of potential leaks is concerning.

CHALLENGES

Technological Maturity

- Uncertain technology, with many technologies still in early stages.
- Intensive research, development, and demonstration are needed for large-scale deployment and commercial viability.
- CO_2 storage sites can take 3-10 years to develop, potentially bottlenecking CCUS deployment. It may be too long to effectively counteract climate change or to meaningfully contribute to achieving the goals set by CO_2 emissions reduction policies by 2050.
- Demonstrating the reliability of CO_2-based construction materials is paramount.

Energy Intensity

- Capturing and compressing CO_2 requires significant energy, increasing fuel needs by 25-40% for coal-fired electricity plants.
- Current high-temperature needs of L-DAC configurations limit flexibility in using low-carbon energy sources.

Land and Water Requirements

- BECCS requires significant land for biomass sources.
- Water requirements for DAC vary with the technology used.
- Further testing is required for DAC plants in diverse climatic conditions.

Infrastructure

- Deployment of CO_2 transport and storage infrastructure is a major bottleneck.
- Coordination of value chain components is critical for effective carbon capture through CCUS-anchored industrial hubs.

Regulation

- Regulatory frameworks and market mechanisms are needed to create demand for CO_2 removal services.
- Developing internationally consistent methodologies and accounting frameworks for CCUS approaches is important.
- CO_2 storage regulations require rigorous monitoring for leakage and long-term storage integrity.

TRENDS

Current changes that could positively [↗] or negatively [↘] affect the future of CCUS.

↗ **Progressing climate change**
As concerns about climate change and its impact intensify, CCUS might be increasingly recognised as an important tool for reducing greenhouse gas emissions. This could lead to more experiments with environmental manipulations (geoengineering).

↗ **Increasing climate commitments from governments and businesses**
Implementing carbon taxes or cap-and-trade systems incentivizes polluters to reduce emissions, making CCUS financially attractive. Various policies and regulations are being implemented to support the development and deployment of CCUS technologies. Incentives such as tax credits, grants, and subsidies are encouraging companies to invest in CCUS projects.

↗ **Fast development of new technologies in materials science, synthetic biology, AI, blockchain and quantum computing**
Ongoing research and development efforts are leading to more efficient and cost-effective carbon capture, storage, transportation technologies and monitoring techniques and carbon-neutral and even carbon-negative alternative materials and products.

↗ **Growing energy consumption**
Growing energy consumption driven by global population increase and technological development (AI) might require the implementation of various solutions allowing to lower GHG emissions.

↗ **Increasing public awareness of climate change**
As the public becomes more aware of the risks of climate change, there may be more support for policies that promote CCUS.

↘ **Transition towards green energies and decarbonization**
CCUS provides a practical solution for capturing CO_2 emissions directly from industries such as cement production, steel manufacturing, and chemical processing. This technology aids these sectors in meeting their sustainability objectives and adhering to regulatory requirements. Considering the EU's net-zero plans, it is recognized that, from a technological perspective, it will be impossible to completely eliminate industrial emissions.
Therefore, the remaining emissions will need to be addressed through CCUS technologies.

↗ **Emerging new methods of harvesting energy**
New processes of nuclear energy production (fusion) can supplement or replace more traditional carbon-emitting energy sources. Waves, tides, and currents could also provide more reliable sources of energy in the future than wind or solar.

↗ **Growing interest in environmental, social, and governance (ESG) investing**
Investors are increasingly looking for companies that are taking steps to reduce their environmental impact. This could lead to more investment in CCUS projects.

↗ **The development of new business models for CCUS**
New business models, such as carbon capture as a service, could make CCUS more financially attractive to companies.

↘ **Deglobalisation**
Limiting international cooperation could negatively impact the development of CCUS. It may lead to fragmented regulations, disruptions in supply chains, and reduced exchange of technological innovations. The weakening of global climate agreements and a shift towards national energy priorities could further restrict investments in CCUS. As a result, stepping away from global integration could hinder the collective actions necessary to advance CCUS and achieve climate targets.

BIO-INSPIRED SOLUTIONS

Mimicking natural processes (photosynthesis, biomineralization) and utilising bioengineered organisms (microalgae, enzymes) for efficient carbon capture, conversion, and storage.

Artificial Photosynthesis

Imitating natural photosynthesis to capture and transform CO_2 into organic compounds using sunlight, for example artificial leaves that mimic natural photosynthesis but with enhanced efficiency.

Synthetic Biology

Engineering organisms to capture and/or convert CO_2 into a wide range of chemicals and materials could transform industrial processes and create new markets for CO_2-derived products. It could potentially be achieved by:

- creating custom-designed microorganisms with tailored properties for efficient CO_2 capture from various sources, including flue gases, direct air, and even seawater, as well as to enhance the stability, capacity, efficiency and safety of geological CO_2 storage,
- developing synthetic materials inspired by natural biological systems, such as enzymes or proteins, for highly efficient and selective CO_2 capture which could lead to breakthroughs in capture performance and material durability,
- utilising CO_2 as a carbon source for engineered microorganisms to produce a variety of bio-based products: fuels, chemicals, food ingredients, and materials: biodegradable plastics, textiles, and construction materials,
- using engineered biofilms (subsurface biofilm barriers) to enhance CO_2 sequestration in geological formations and to stabilise CO_2 in storage sites and reduce the risk of leakage,
- utilising extremophile microorganisms, adapted to extreme environments, for CO_2 conversion under harsh industrial conditions or in unconventional settings, such as deep sea vents or geothermal sites.

Bioengineered (Micro) Algae Cultivation

Utilising advanced genetic engineering techniques to develop microalgae strains with superior CO_2 uptake rates.

- Could significantly improve the efficiency and productivity of microalgae-based carbon capture and biofuel systems,
- This would create the ability to form carbon-rich biopellets that sinking to the ocean floor could create a self-sustaining carbon sequestration system, harnessing the ocean's natural processes,
- Growth of algae in wastewater treatment systems, simultaneously removing pollutants, and removing nutrients (e.g., nitrogen, phosphorus) and capturing carbon from wastewater. This could offer a circular approach to wastewater management and CO_2 mitigation, while also producing valuable biomass for biofuels or other applications.

Bio-Inspired Carbon Mineralization

Taking inspiration from natural biomineralization processes (e.g., coral reefs) to develop bioreactor systems that efficiently convert CO_2 into stable mineral carbonates (e.g. using olivine, a common mineral). This could offer a scalable and sustainable approach to permanent carbon storage. This process could be accelerated through engineered reactors or by spreading finely ground olivine on land or in the ocean, offering a large-scale and passive carbon removal method. The minerals could be potentially used in construction materials. One could achieve it by:

- developing microbial communities that work synergistically to capture CO_2 and convert it into stable mineral carbonates. These consortia could be tailored for specific geological formations and environmental conditions, optimising the efficiency and permanence of carbon storage,
- reacting CO_2 with magnesium silicate minerals to form stable carbonates.

GAME CHANGERS

BIO-INSPIRED SOLUTIONS (CONT.)

CO_2 Conversion Using Artificial Enzymes

Enzymes could efficiently catalyse CO_2 conversion reactions under mild conditions. This could enable the production of a wide range of chemicals and fuels.

CO_2-Based 3D Printing of Organs and Tissues

Developing bioprinting technologies that use CO_2-derived biomaterials to create functional organs and tissues for transplantation. This could revolutionise regenerative medicine and offer a sustainable solution for organ shortages.

Microbial Electrosynthesis

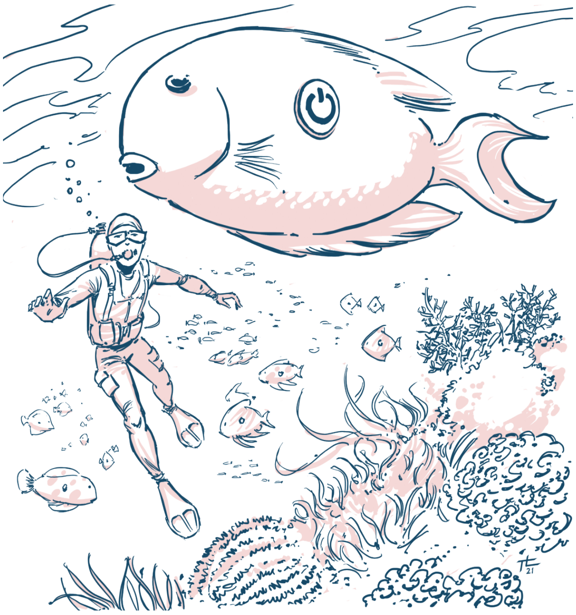
Microbial electrosynthesis uses electroactive microbes to convert CO_2 into valuable chemicals and fuels. By applying electrical current to microbial cultures, CO_2 can be transformed into products like acetate, methane, or biofuels.

Biomimetics

Mimicking natural carbon fixation processes using enzymes and other biological systems could enable efficient conversion of CO_2 into useful organic compounds, offering a sustainable approach to CO_2 utilization.

Microbial Carbon Capture and Storage in Deep Saline Aquifers

Utilising engineered microbes to capture CO_2 from flue gases and convert it into biofilms or other stable forms within deep saline aquifers. This approach could offer a secure and long-term storage solution with minimal environmental impact.



GAME CHANGERS

ADVANCED MATERIALS

Development of highly selective and efficient materials (MOFs, nanomaterials, metal hydrides) for CO_2 capture and advanced catalysts for CO_2 conversion into valuable products could create new markets for CO_2-derived products and promote the adoption of CCUS across various industries.

Nanomaterials
Utilising nanomaterials such as graphene oxide and carbon nanotubes enhances the efficiency and selectivity of CO_2 capture, storage, and conversion processes.

Nanoporous Materials
Nanoporous materials, including advanced forms of zeolites and silica, have large surface areas and pore volumes that make them ideal for gas adsorption. Researchers are developing new nanoporous materials with tailored pore sizes and functional groups to enhance their CO_2 adsorption capacities.

Metal-Organic Frameworks (MOFs)
MOFs are highly porous materials that can be designed at the molecular level to selectively capture CO_2 with exceptional efficiency. Their high surface area and customizable properties make them ideal for CCUS applications

Advanced Membranes
The development of advanced polymeric and ceramic membranes with high permeability and selectivity for CO_2 can drastically improve the efficiency of gas separation processes, making carbon capture more feasible and cost-effective.

CO_2 Capture Using Metal Hydrides
Exploring the use of metal hydrides, which can reversibly absorb and release large amounts of hydrogen, for CO_2 capture through a chemical looping process.

Solid Sorbent Materials
Innovative materials that absorb CO_2 at low concentrations and release it upon heating could revolutionise CCUS by enhancing efficiency and reducing operational costs.

Self-Healing Materials
Materials that automatically repair any damage or degradation in CO_2 storage infrastructure could increase reliability and lifespan of storage facilities, reducing maintenance costs and risks.

Piezocatalytic CO_2 Capture
Utilising piezoelectric materials to capture CO_2 under mechanical stress. Offers a novel mechanism for CO_2 capture that could be integrated into various structures.

Hybrid Organic-Inorganic Materials
These materials combine the advantages of organic polymers and inorganic compounds to create structures with enhanced CO_2 capture and conversion properties.

GAME CHANGERS

CHEMICAL ENGINEERING

Advancements in chemical engineering, particularly in electrochemical, catalytic, and photocatalytic processes, are enabling increasingly efficient conversion of CO_2 into valuable products such as methanol, ethylene, and synthetic fuels.

Electrochemical CO_2 Reduction
Advances in catalysts and electrochemical processes are making the conversion of CO_2 to valuable chemicals like methanol and ethylene more efficient and economically viable.

Electrochemical Mineralization of CO_2
Using electrochemical processes to accelerate the conversion of CO_2 into stable minerals.

Photocatalytic Carbon Reduction
Photocatalysis uses light energy to accelerate chemical reactions. Researchers are developing novel photocatalysts that can efficiently use sunlight to drive these conversions.

Catalytic CO_2 Hydrogenation
Using advanced catalysts to convert CO_2 and hydrogen into synthetic fuels.
Produces carbon-neutral fuels, integrating renewable energy with CO_2 capture.

CO_2-to-Fertilizer Conversion
Converting CO_2 into ammonia and other fertilisers through chemical processes. Supports sustainable agriculture and reduces greenhouse gas emissions from traditional fertiliser production.

Green Solvents for CO_2 Absorption
Developing environmentally friendly solvents for efficient CO_2 capture.

CO_2 Capture Using Ionic Liquids
Promising alternative to traditional solvents, offering tunable selectivity, lower energy regeneration, and reduced environmental impact.

Thermochemical CO_2 Conversion
Thermochemical cycles use heat, often from renewable sources, to drive chemical reactions that convert CO_2 into fuels or other chemicals. Advances in high-temperature materials and reactor designs are making these cycles more efficient and viable for industrial applications.

Direct Air Capture (DAC)
DAC technologies aim to capture CO_2 directly from the atmosphere using chemical sorbents and novel materials, offering a scalable solution to reducing atmospheric CO_2 levels.

Hybrid Electrochemical-Biological Systems for CO_2 Conversion
Integrating electrochemical CO_2 reduction with microbial electrosynthesis to create synergistic systems that leverage the advantages of both approaches for efficient and selective production of high-value chemicals and fuels. Could overcome the limitations of individual technologies and enable the production of a wider range of products from captured CO_2.

Integrated Biorefineries for CO_2 Utilisation
Combining CO_2 capture with biorefinery processes to co-produce biofuels, chemicals, and other value-added products. This would maximise resource efficiency and create synergistic benefits between CCUS and bioeconomy.

CO_2-Powered Electrolysis for Hydrogen Production
Utilising captured CO_2 and renewable electricity to co-produce hydrogen and valuable chemicals through electrolysis. This would create a carbon-neutral hydrogen source while storing renewable energy in chemical form.

GAME CHANGERS

INDUSTRIAL PROCESSES

Integrating industrial processes with CCUS technologies could support the transition towards a circular economy, contributing to emissions reduction and fostering the creation of new markets across various industrial sectors.

CO_2 Capture from Industrial Symbiosis
Integrating carbon capture with industrial symbiosis, where waste CO_2 from one process is used by another. Enhances resource efficiency and reduces overall carbon emissions.

Carbon Mineralisation
Enhancing natural processes that convert CO_2 into stable minerals suitable for long-term storage in construction materials and other applications.

Carbon Sequestration in Building Materials
Developing construction materials that actively sequester CO_2 during their production processes and lifecycle. Reduces emissions from a major industrial source while potentially enhancing material properties and turns buildings into carbon sinks, integrating CDR with urban development.

CO_2-EOR with Dedicated Storage
Implementing enhanced oil recovery (EOR) with CO_2, but with a focus on dedicated geological storage of the injected CO_2. This would ensure permanent CO_2 sequestration while still benefiting from increased oil production.

Supercritical CO_2 Plume Geothermal (SCPG)
It involves capturing CO_2 from waste emissions, such as those from coal-fired power plants, using CCUS technology, and then injecting it into natural, highly permeable geological formations to harness energy.

CO_2 Utilisation in 3D Printing
Developing materials for 3D printing that incorporate captured CO_2. Opens new possibilities for sustainable manufacturing and custom products.

Cryogenic Carbon Capture
Capturing CO_2 by cooling flue gases to very low temperatures, causing CO_2 to condense and separate from other gases. High purity CO_2 capture with potential integration into existing industrial processes.

Plasma-assisted CO_2 Conversion
Using plasma technology to transform CO_2 into useful chemicals and fuels.

Integrated CCU Systems for Waste Valorization
Combining CO_2 capture with waste valorization processes to co-produce valuable products from various waste streams. This would promote circular economy principles and maximise resource utilisation.

CO_2 to Renewable Energy Storage
Converting CO_2 into fuels that can store renewable energy, such as methanol or formic acid. Facilitates energy storage and grid stability, integrating carbon capture with energy systems.

Integration with Renewable Energy
Coupling CCSU systems with renewable energy sources would create a sustainable and closed-loop system where excess renewable energy is used for CO_2 capture and conversion processes.

Solar-to-Fuels Technologies
Developing solar-powered processes that convert CO_2 into fuels effectively stores solar energy in chemical bonds, providing a sustainable energy source while reducing atmospheric CO_2 levels.

Bioenergy Carbon Capture and Storage (BECCS) Innovations
Advances in BECCS, which integrates biomass energy production with CCS, could enhance the scalability of carbon-negative technologies.

GAME CHANGERS

CO_2 BASED SOLUTIONS AND PRODUCTS

Widespread use of CO_2 as a raw material for producing chemicals, fuels, polymers, building materials, and even food, transforming industrial processes and creating new markets.

Carbon Fibre
Developing processes to convert captured CO_2 into carbon fibre, supporting lightweight materials in transportation and construction.

Graphene
Converting CO_2 into graphene, a highly valuable material with numerous applications.

Carbon Black
Producing carbon black, a valuable industrial material, from CO_2 to be used in tires, inks, and plastics.

(Bio)plastics and other polymers
Using captured CO_2 as a feedstock for producing biodegradable plastics and other polymers. Reduces reliance on fossil-fuel-derived materials and creates a circular economy for plastics.

Carbon-negative Concrete
Researchers are developing new formulations of concrete that absorb more CO_2 during their curing process than is emitted during production. These carbon-negative concrete utilise industrial by-products like fly ash and slag.

Geopolymer Cements
Geopolymer cements are made from industrial by-products and can capture CO_2 during their production and curing processes. These cements offer a sustainable alternative to traditional Portland cement, with the potential to reduce the carbon footprint of the construction industry significantly.

CO_2-Based Microbial Fuel Cells
Utilising microbes that can consume CO_2 and generate electricity in microbial fuel cells. This could offer a dual benefit of carbon removal and renewable energy generation.

CO_2-Based Synthetic Fuels for Heavy Transportation
Developing synthetic fuels from captured CO_2 for use in hard-to-electrify sectors like aviation (Sustainable Aviation Fuel (SAF)), shipping, and long-haul trucking. This could significantly reduce emissions from these industries while utilising existing infrastructure.

CO_2 Utilisation in the Production of High-Value Chemicals
Expanding the range of high-value chemicals that can be produced from CO_2, including pharmaceuticals, specialty chemicals, and fragrances. This would create new economic opportunities for CCUS and reduce the reliance on fossil-based feedstocks.

CO_2-to-Protein Conversion
Converting CO_2 into protein-rich food products using microbial fermentation. Addresses food security while reducing atmospheric CO_2 levels.

CO_2-Based Biomaterials for Medical Implants
Developing biocompatible and biodegradable materials from CO_2 for use in medical implants and tissue engineering.

GAME CHANGERS

OPTIMIZATION THROUGH AI, MACHINE LEARNING, BLOCKCHAIN, AND QUANTUM COMPUTING

The integration of artificial intelligence (AI) and machine learning can significantly enhance the efficiency and cost-effectiveness of CCUS technologies and processes. These advancements span areas such as process design, real-time monitoring, predictive maintenance, and emission tracking. Meanwhile, leveraging blockchain technology to ensure transparency, traceability, and security in CO_2 markets can foster greater trust and drive increased investment in CCUS projects. Additionally, the computational power of quantum computers holds the potential to simulate and optimize complex CCUS processes at the molecular level, enabling the discovery of new materials, catalysts, and process configurations that are currently beyond reach.

AI-Optimised CCUS Design and Operation
Applying AI and machine learning to optimise the design and operation of CCUS plants, from site selection and process configuration to real-time performance monitoring and predictive maintenance. This could significantly reduce costs, improve efficiency, and enhance the overall reliability of CCUS systems.

AI-Driven Molecular Design for Capture Materials
Utilising AI algorithms to design novel molecules and materials with optimal CO_2 capture properties. This could lead to the development of highly efficient and selective sorbents tailored for specific applications and flue gas compositions.

Smart Monitoring Systems
Advanced sensors and AI for real-time monitoring of CO_2 storage sites. Improves safety and compliance, ensuring long-term stability of stored CO_2.

Machine Learning for Predictive Maintenance and Optimization of CCUS Processes
Applying machine learning algorithms to analyse operational data from CCUS facilities, predict equipment failures, and optimise process parameters for improved efficiency and reliability. Could reduce downtime, lower operating costs, and enhance the overall performance and safety of CCUS plants.

Machine Learning for Material Discovery
Machine learning algorithms accelerate the discovery of new materials for carbon capture by predicting the performance of potential candidates, thereby reducing the time and cost of experimental testing.

Blockchain-Enabled Carbon Trading and Accounting Platforms
Developing decentralised carbon trading platforms that utilise blockchain technology for secure, transparent, and efficient transactions of carbon credits and offsets. Could enhance market liquidity, reduce transaction costs, and increase trust and participation in carbon markets, fostering investment in CCUS projects

Quantum Dot-Enhanced Capture Materials
Using quantum dots to enhance the performance of CO_2 capture materials.

CO_2-Based Quantum Dots for Solar Cells
Utilising CO_2-derived quantum dots to enhance the efficiency of solar cells, creating a synergistic system that captures CO_2 and generates clean energy. This could contribute to a sustainable energy transition while promoting carbon utilisation.

GAME CHANGERS

OCEAN - BASED SOLUTIONS

The integration of ocean-based technological solutions can significantly enhance the efficiency and scalability of CO_2 capture and storage processes while supporting the production of clean energy. Harnessing the potential of the oceans in this context could also contribute to the preservation of marine ecosystems.

The integration of ocean-based CCUS technological solutions
The integrated utilization of the vast potential of oceans for CO_2 storage and clean energy production through the large-scale deployment of technologies such as OTEC, olivine mineralization, CDR, and marine permaculture.

Ocean Thermal Energy Conversion (OTEC) for CCUS
Leveraging temperature differences in ocean layers to power CCUS processes, creating a synergistic system that generates clean energy while removing CO_2. This could offer a scalable and sustainable solution, especially in tropical regions.

CO_2 Capture from the Ocean
Scaling up technologies that directly capture CO_2 from seawater, where it naturally concentrates. This approach could offer energy-efficient and potentially less intrusive carbon removal compared to DAC, while also addressing ocean acidification.

Marine Permaculture and Marine Carbon Sequestration through Algae Blooms
Large-scale (could be engineered) seaweed farming to absorb CO_2, can be also harvested as biomass for biofuels, and a food source.

Deep Ocean Storage
Storing CO_2 in deep ocean formations (could be in gas hydrates) offers a vast and potentially secure long-term sequestration solution.

Direct Ocean Fertilisation
Adding nutrients to ocean waters to promote phytoplankton growth and CO_2 absorption. Enhances the ocean’s natural carbon sink capacity while supporting marine ecosystems.

Ocean Alkalinity Enhancement
Adding alkaline materials to oceans to enhance CO_2 absorption and storage. Significantly increases the ocean's capacity to act as a carbon sink.

Artificial Upwelling
Simulating natural ocean upwelling to increase nutrient availability and enhance marine carbon sequestration.

GAME CHANGERS

SPACE-BASED SOLUTIONS

While still speculative, concepts like capturing CO_2 in space or utilising extraterrestrial resources for carbon utilisation could open up entirely new possibilities. Although these ideas are currently in the realm of science fiction, they represent the kind of out-of-the-box thinking that could lead to groundbreaking innovations in CCUS.

Space-Based CO_2 Capture
Using satellites or space stations to capture CO_2 from the upper atmosphere could provide currently futuristic but potentially large-scale solution for global CO_2 removal.

CO_2 as a Feedstock for Extraterrestrial Manufacturing
Developing technologies that utilise CO_2 from planetary atmospheres (e.g., Mars) as a feedstock for in-situ manufacturing of essential materials and fuels. This could support future space exploration and colonisation efforts while advancing CCUS technologies.

Space-Based Solar Power for CCUS
Beaming solar energy collected in space to Earth to power energy-intensive CCUS processes, such as DAC or electrochemical CO_2 reduction. This could provide a continuous and abundant source of clean energy for carbon removal and utilisation.

CO_2-Derived Carbon Fibres for Aerospace Applications
Developing high-performance carbon fibres from captured CO_2 for use in aerospace manufacturing. This could reduce the weight and emissions of aircraft while promoting carbon utilisation in a high-value industry.

OTHER GEOENGINEERING TECHNIQUES ENHANCING CO_2 REMOVAL

Other geoengineering techniques supporting CO_2 sequestration rely on modifying natural processes to accelerate the absorption and permanent storage of carbon dioxide. These include both direct actions to enhance CO_2 uptake by the environment and more indirect methods that can aid in combating climate change. Due to their passive nature and potential scalability, these technologies offer the prospect of a long-term solution to excessive carbon emissions, aligning with global efforts toward sustainable development. However, it is essential to recognize that all geoengineering solutions are highly controversial, given the risks they pose and the limited understanding of their potential consequences.

Enhanced Rock Weathering for CO_2 Storage
Accelerating natural rock weathering processes through the application of crushed minerals or engineered microorganisms to enhance natural CO_2 absorption and mineralisation. This could provide a passive, large-scale, and potentially cost-effective method for permanent CO_2 removal and storage.

Solar Radiation Management (SRM)
Techniques to reflect sunlight and cool the planet, indirectly affecting CO_2 levels. Highly controversial but could buy time for other carbon removal strategies to scale up.

Deep-Earth Carbon Injection
Injecting CO_2 into deep geological formations far below the Earth's surface offers a potentially limitless storage capacity and secure sequestration method.

GAME CHANGERS

AGRICULTURE, REFORESTATION AND AFFORESTATION

Agriculture, reforestation, and afforestation are key components of natural carbon sequestration strategies, with the potential not only to restore ecosystems but also to stabilize the climate. By regenerating ecosystems, we can enhance the planet's long-term capacity to absorb CO_2, creating a more stable and resilient environment for future generations.

CO_2-Enhanced Crop Growth
Using captured CO_2 in controlled-environment agriculture to enhance crop yields.

Soil CO_2 Sequestration
Improving land management practices to enhance soil CO_2 storage.

Biochar Production
Converting biomass into biochar through pyrolysis, sequestering CO_2 in a stable form. Enhances soil health and provides a scalable method for long-term CO_2 storage.

Soil Microbial CO_2 Pumps
Enhancing soil microbial activity to increase CO_2 sequestration in soils. Improves soil health and significantly boosts soil CO_2 storage capacity.

Enhanced Root Systems for CO_2 Sequestration
Developing plants with deeper and more extensive root systems to sequester more carbon in the soil. Increases the carbon sequestration potential of reforestation and agricultural practices.

CO_2 as a Feedstock for Artificial Food Synthesis
Innovative approach to food production, utilising CO_2 as a carbon source for creating sustainable and customizable food products, for instance cell-cultured meat.

Bioengineered Plants with Enhanced Photosynthesis
Modifying plant genes to improve the efficiency of photosynthesis, allowing them to capture more CO_2 and produce biomass more rapidly.

Large-scale Planting of Trees
A proven, cost-effective method for long-term CO_2 storage and ecosystem restoration.

Desert Afforestation
Large-scale planting of trees and vegetation in desert areas to sequester CO_2. Transforms barren lands into CO_2 sinks and supports ecosystem restoration.

CO_2 Sequestration through Agroforestry
Integrating trees into agricultural landscapes to sequester CO_2 and improve land productivity.

Peatland Restoration
Restoring degraded peatlands to enhance their natural carbon storage capabilities.

OTHER

To accelerate the adoption of CCUS technologies, groundbreaking innovations are essential to reduce costs and enhance the competitiveness of this solution compared to other low-emission technologies. Key factors that can drive cost reductions include technological advancements, infrastructure development, and regulatory changes that create more favorable economic conditions for CCUS investments.

CCUS Costs Reduction

So far, CCUS are too expensive and unable to compete with other sustainable solutions, while climate policies – including CO_2 pricing – are not yet strong enough to make CCUS economically attractive. There is considerable potential to reduce costs along the CCUS value chain, particularly as many applications are still in the early stages of commercialisation. CCUS should become cheaper as the market grows, the technology develops, finance costs fall, economies of scale are reached, and experience of building and operating CCUS facilities accumulates. This pattern has already been seen for renewable energy technologies over recent decades. Cost reductions have already been achieved in large-scale CCUS projects. For instance, the cost of capturing CO_2 in the energy sector has decreased by 35% (based on a comparison between the first and second major CCUS installations). This trend is likely to continue as the market develops.

Environmental and Geological Factors

The availability of suitable geological formations for CO_2 storage and the environmental impact of carbon capture processes are significant factors. Unexpected environmental challenges or discoveries of new storage sites can affect the feasibility and location of CCUS projects.

Climate Change Impacts

The accelerating effects of climate change could necessitate more aggressive carbon capture efforts. Conversely, extreme weather events and shifting climate patterns might disrupt existing CCUS infrastructure and operations.

Fossil Fuel Dependency

As some regions continue to rely on fossil fuels for energy security, the role of CCUS becomes even more critical.

Infrastructure Development

The development of robust infrastructure for CO_2 transport and storage, including pipelines and storage facilities, is critical. Delays or advancements in this infrastructure can significantly impact CCUS projects.

New Clean Energy Sources - Fusion Energy

The successful development of commercial fusion energy could provide a virtually limitless source of clean energy, which could be used to power energy-intensive CCUS processes. This would significantly improve the sustainability and scalability of CCUS technologies.

Technological Failures and Ecological Disasters

Unexpected failures or inefficiencies in existing CCUS infrastructure could undermine confidence and delay further investments.

CO_2 Pricing Mechanisms

Implementing innovative CO_2 pricing models and policies can provide stronger financial incentives for companies to invest in carbon capture technologies, driving broader adoption.

Public Perception and Social Acceptance

Concerns about the safety and environmental impact of CCUS technology may significantly affect its implementation.

CONCLUSIONS

In light of the slow implementation of other solutions in the fight against climate change, CCUS technologies are gaining importance as a crucial element of strategies aimed at achieving carbon neutrality. Although the development of CCUS has progressed slowly over the years, recent technological advancements and increasing government support in many regions of the world have given this process new momentum. As a result, the prospect of broader adoption of these technologies in the coming years is becoming increasingly realistic.

Unfortunately, the current level of CCUS implementation remains insufficient for the technology to significantly contribute to achieving net-zero emissions by 2050. High costs of sequestration, transport, utilisation, and storage of CO_2, as well as the necessity for massive investments in infrastructure, are just some of the challenges hindering large-scale deployment. Additionally, many questions remain about the safety and maturity of these technologies, which impacts limited public trust.

To overcome these barriers, further innovation, public policy support, and increased investment are essential. Key factors will include developing more efficient and cost-effective technologies, establishing stable regulatory frameworks, and creating incentives to mitigate the financial risks of these investments. Education and fostering public acceptance of this approach to combating climate change are also critical.

The adoption of CCUS is likely to progress most dynamically in regions meeting favorable criteria, such as the availability of CO_2 storage sites, long-term emission sources, government support, competitive energy costs, and industrial synergies. The ultimate success of this technology will depend on close collaboration between governments, industry, and research institutions.

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ABOUT US

CONTACT US, IF YOU ARE INTERESTED IN THE FUTURE!

4CF The Futures Literacy Company
4CF Sp. z o.o.
Pl. Trzech Krzyży 10/14
00-535 Warsaw, Poland
Dariusz Kozdra
head of communications
email: darek@4cf.pl
phone: +48 600 200 538
www: 4cf.eu

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