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Exploring Carbon Capture, Utilization, and Storage (CCUS) Technology and its Impact in Addressing Climate Change

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Introduction

Attending a recent seminar by Professor Lei Zhu on Energy Investment/Technology Evaluation sparked my curiosity about advanced carbon capture technologies. While I had a basic understanding of Carbon Capture and Storage (CCS), the seminar provided a comprehensive overview of the latest innovations, particularly in Carbon Capture, Utilization, and Storage (CCUS). This motivated me to expand my knowledge on the subject. In this article, I will explore CCUS technologies and their significant role in addressing climate change, offering insights tailored to those new to the topic.

CCUS has emerged as a pivotal technology in the global combat against climate change. While the basic concept of capturing and storing carbon dioxide (CO2) is straightforward, the historical development and application of these technologies are complex and captivating. This article will delve into the origins, mechanisms, and impacts of CCUS, alongside its adoption across various industries. It will also explore case studies from leading projects worldwide, examining how CCUS is playing a crucial role in mitigating climate change.

The Genesis of Carbon Capture Technology

The concept of capturing carbon dioxide (CO2) from industrial sources dates back to the 1970s. Initially driven by the need to Enhance Oil Recovery (EOR) in declining oil fields, it also emerged in response to growing concerns about climate change and the greenhouse effect. As the environmental impact of industrial CO2 emissions became more recognized, serious discussions about capturing CO2 from industrial sources for environmental benefits began. The first practical application of CO2 for EOR was in 1972 in the Permian Basin of West Texas, where CO2 was injected into oil reservoirs to boost production. The idea was to capture CO2 from power plants and other industrial sources before it could enter the atmosphere, while also serving economic benefits.

The momentum for CCS technology surged in the 1990s with pilot projects and research initiatives aimed at reducing CO2 emissions from power plants and industrial facilities. One of the pioneering large-scale CCS projects commenced at the Sleipner gas field in Norway in 1996, successfully capturing and storing CO2 beneath the North Sea.

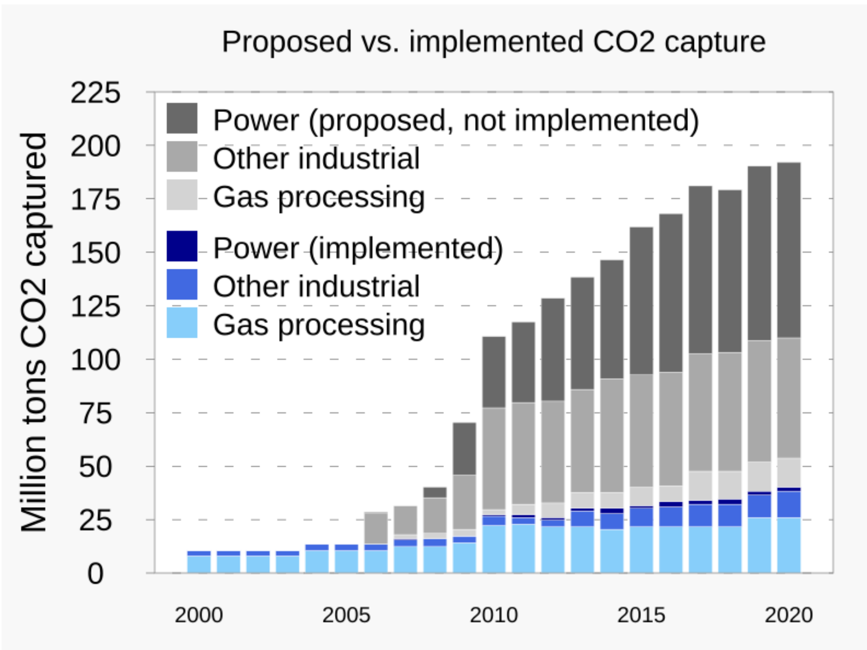

Figure 1.0: Carbon capture and storage (CCS) proposed and implemented projects

Credit: By RCraig09 - Own work, CC BY-SA 4.0,
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Over the decades, CCUS technology has evolved significantly, playing a pivotal role in curbing climate change impacts, especially in industries where mitigating CO2 emissions proves challenging. As of 2023, projections indicate a 35% increase in the capacity for capturing CO2 by 2030, with storage capabilities expected to rise by 70%. This translates to a potential capture of approximately 435 million tonnes (Mt) of CO2 annually and a storage capacity of around 615 Mt per year by 2030. While these figures illustrate positive momentum, they still represent only a fraction of the approximately 1 gigaton (Gt) of CO2 per year targeted for capture and storage under the Net Zero Emissions by 2050 (NZE Scenario), (IEA, 2024).

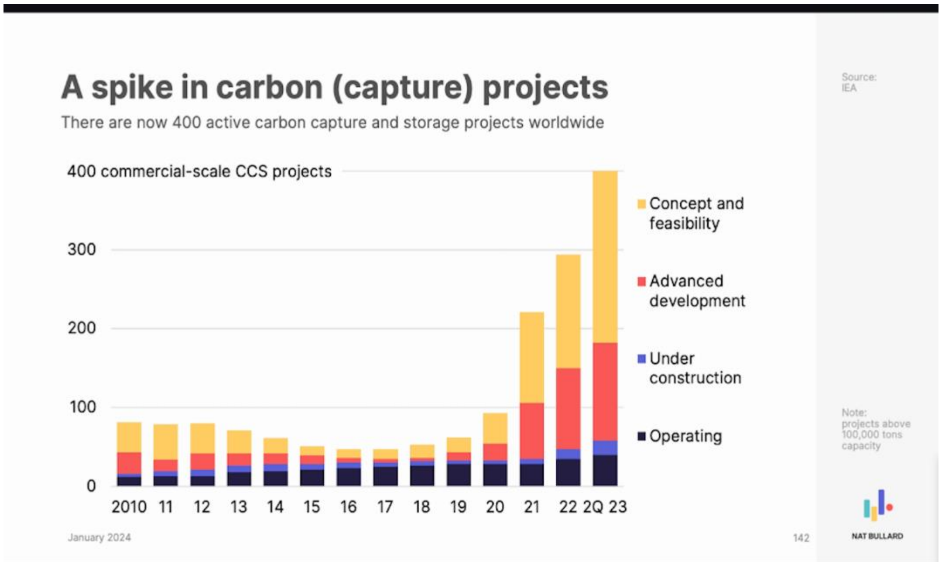

Figure 2.0: Chart *illustrating CCS projects and their developments over time*

Credit: Margaret Morales; GreenBiz

Early Innovators of CCUS

The development of CCUS technology traces back to the 19th century but saw accelerated progress in the late 20th and early 21st centuries, driven by advancements in chemical engineering and heightened awareness of climate change.

- **Charles Keeling**: Charles Keeling is a trailblazer in climate science. Keeling's meticulous measurements of atmospheric CO2 levels underscored the urgent need for solutions to rising emissions (IEA, 2021).

- **Oil Industry Innovations**: In the 1970s, the oil sector pioneered the use of captured CO2 for Enhanced Oil Recovery (EOR), injecting CO2 into oil fields to enhance production. This practical application was pivotal in demonstrating the feasibility of CO2 capture and storage technologies (Global CCS Institute, 2021).

Current Status and Pioneering Projects of CCUS

Since the emergence of CCUS, several countries have taken bold strides in implementing CCUS technologies, marking significant progress in the global effort to combat climate change. Nations such as

Norway, Canada, the United States, and Australia have spearheaded pioneering projects that not only reduce emissions but also provide invaluable insights for future developments.

- **Sleipner Project, Norway:** The Sleipner Project, launched in 1996 at the Sleipner gas field in Norway and operated by Equinor (formerly Statoil), represents one of the earliest and most impactful CCS initiatives globally. This project focuses on capturing CO2 emitted during natural gas processing and storing it in an offshore saline aquifer. Aligned with Norway's ambitious Climate Change Act, which targets a 50%-55% reduction in greenhouse gas emissions by 2030 and aims for a low-emission society by 2050, the Sleipner Project has successfully stored approximately 1 million tonnes of CO2 annually. This long-term endeavor underscores the viability of geological storage solutions while providing crucial data for advancing future CCUS projects (Norwegian Petroleum Directorate, 2021).
- **Weyburn-Midale CO2 Project, Canada:** Initiated in 2000, the Weyburn-Midale CO2 Project in Canada exemplifies a pioneering effort in capturing CO2 from a coal gasification plant in North Dakota and transporting it to oil fields in Saskatchewan for EOR purpose. Notably, the Boundary Dam project in Saskatchewan stands out as one of the world's first large-scale CCS initiatives at a coal-fired power plant. By capturing up to 90% of its CO2 emissions, this project not only significantly reduces emissions but also generates economic benefits. In March 2021, the Boundary Dam project achieved a milestone by capturing its four millionth metric ton of CO2, highlighting its role as a flagship example of retrofitting existing power plants with CCS technology (Global CCS Institute, 2021; Boundary Dam Carbon Capture Project, 2021).
- **Petra Nova, USA:** Located in Texas, the Petra Nova project in the United States is another notable CCUS project. This project captures CO2 from a coal-fired power plant and also utilizes it for EOR. Petra Nova showcases how CCS technology can enhance oil recovery efficiency while simultaneously capturing substantial amounts of CO2, contributing to emissions reduction efforts in the energy sector (U.S. Department of Energy, 2021).
- **Gorgon CO2 Injection Project, Australia:** Operated by Chevron, the Gorgon CO2 Injection Project in Australia is one of the largest CCUS initiatives globally. This project aims to capture and store up to four million tons of CO2 annually from a liquefied natural gas (LNG) facility. By addressing emissions associated with natural gas production, the Gorgon Project demonstrates the potential

of CCUS in reducing carbon footprints within the energy sector on a significant scale (Chevron, n.d.).

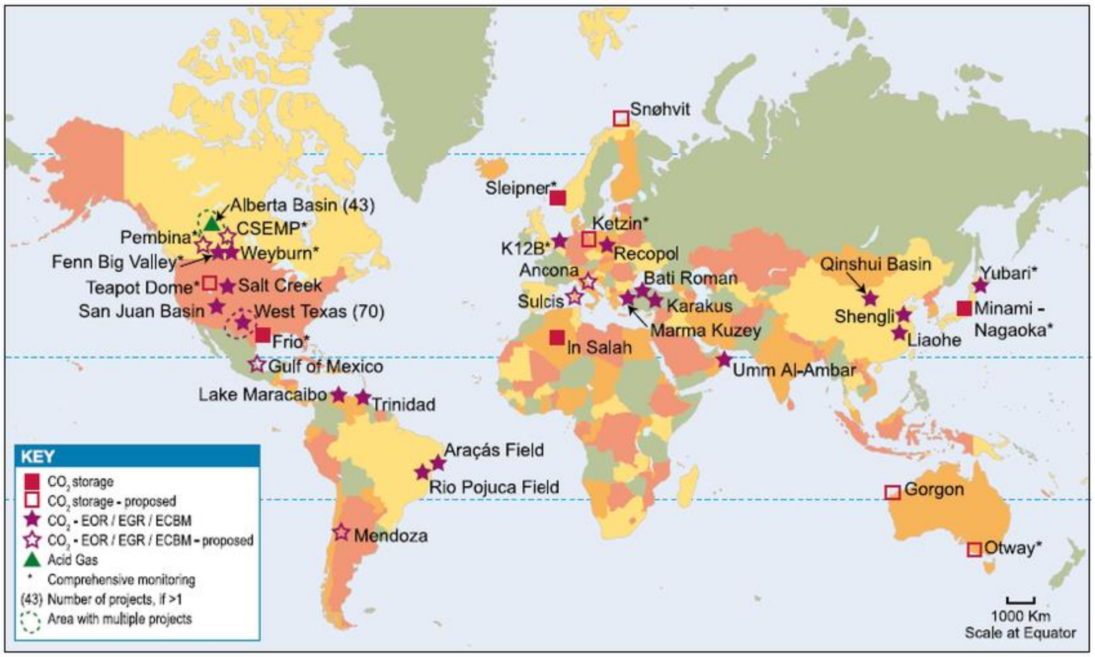

Figure 3.0: Location of major current and planned CCS projects worldwide

Credit: Uploaded by Steve Messner; Researchgate

Understanding CCUS

Imagine capturing the carbon dioxide (CO2) emissions from power plants and industrial processes, preventing them from entering the atmosphere, and then using or storing this CO2 in a way that benefits the environment. This is the essence of Carbon Capture, Utilization, and Storage (CCUS).

CCUS is an advanced process that not only reduces greenhouse gas emissions but also opens up new pathways for utilizing CO2 such as in enhanced oil recovery or the production of synthetic fuels. Think of it as turning a problem into an opportunity. Let's break down how this fascinating technology works

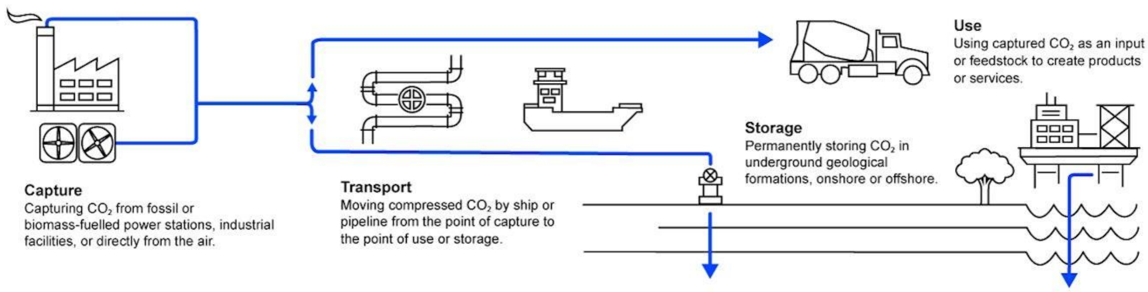

Figure 4.0: flowchart illustrating the CCUS process

Courtesy: https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage

How Does CCUS Work?

1. Capture: The first line of action

This begins with separating CO2 from other gases produced at large industrial facilities such as coal and natural gas-fired power plants, steel mills, cement factories, and refineries. The CO2 is then captured through various methods, including:

- **Pre-Combustion Capture**: Here, CO2 is removed from fossil fuels before they are burned, typically in gasification processes. This involves converting the fuel into a mixture of hydrogen and CO2, capturing the CO2, and then using the hydrogen for energy (IEA, 2021).
- **Post-Combustion Capture:** In this method, CO2 is captured from flue gases after the combustion of fossil fuels, using solvents, sorbents, or membranes (National Energy Technology Laboratory, 2021).
- **Oxy-Fuel Combustion**: Fossil fuels are burned in oxygen instead of air, producing flue gas that is mainly CO2 and water vapor, which simplifies the capture process (Global CCS Institute, 2021).

2. Transportation: Moving the Captured CO2

Once captured, the CO2 is then compressed and transported, typically via pipelines, to storage sites. In some cases, CO2 can be transported by ship or truck (IEA, 2021). Picture a vast network of pipelines, quietly and efficiently carrying CO2 to its next destination.

3. Storage and Utilization

The captured CO2 can be either stored underground in geological formations or put to good use in processes such as Enhanced Oil Recovery (EOR) or in the production of materials like concrete and biofuels.

- **Geological Storage**: CO2 is injected into underground rock formations, such as depleted oil and gas fields, deep saline aquifers, or un-mineable coal seams. These formations can securely store CO2 for thousands of years. This process is rigorously monitored to ensure the CO2 does not escape back into the atmosphere (IEA, 2021).
- **Utilization**: Here's where innovation shines. Captured CO2 can be used in Enhanced Oil Recovery (EOR), where it's injected into oil fields to boost production. It can also be used to manufacture building materials like concrete, or even as a feedstock for producing biofuels and chemicals (Global CCS Institute, 2021)

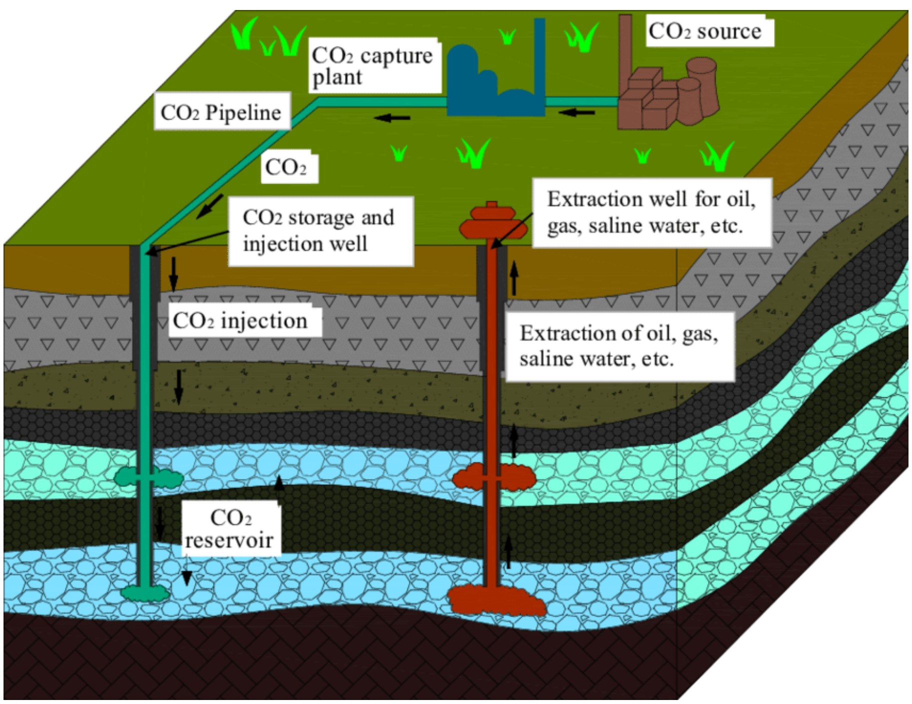

Figure 5.0: Overall schematic of carbon capture and storage concept.

Credit: Jiaquan Li et al. 2018

The Role of CCUS in Mitigating Climate Change

CCUS is a critical technology for achieving global climate goals. Its potential to reduce greenhouse gas emissions makes it a great tool in the effort against global warming. Let's explore how CCUS can help mitigate climate change and why it's so crucial for the future.

- **Reduction of Greenhouse Gases**: By capturing CO2 emissions from industrial sources and power plants, and storing them underground, CCUS can significantly reduce the amount of greenhouse gases released into the atmosphere, directly reducing the greenhouse effect (IEA, 2021). This reduction is vital for combating global warming and achieving the targets set by international climate agreements like the Paris Accord (IEA, 2021).

- **Enhanced Oil Recovery (EOR)**: Injecting captured CO2 into aging oil fields can boost oil extraction. This not only provides a valuable use for the captured CO2 but also makes oil extraction more efficient. By turning captured CO2 into an economic asset, EOR incentivizes industries to adopt CCUS technologies (Global CCS Institute, 2021). Utilizing captured CO2 in EOR creates a win-win scenario, enhanced oil production, and reduced atmospheric CO2. It's a practical example of how economic and environmental goals can align.

- **Sustainable Industrial Practices**: Decarbonizing heavy industries is a critical step in global climate strategies. Industries like cement, steel, and chemicals can be very difficult to decarbonize. CCUS technologies offer these sectors a way to significantly reduce their emissions. By integrating CCUS, these industries can continue to operate while shrinking their carbon footprint, thus bridging the gap toward a more sustainable future (IEA, 2021). In simple terms, CCUS provides a practical solution, enabling industries to maintain productivity and growth while committing to sustainability.

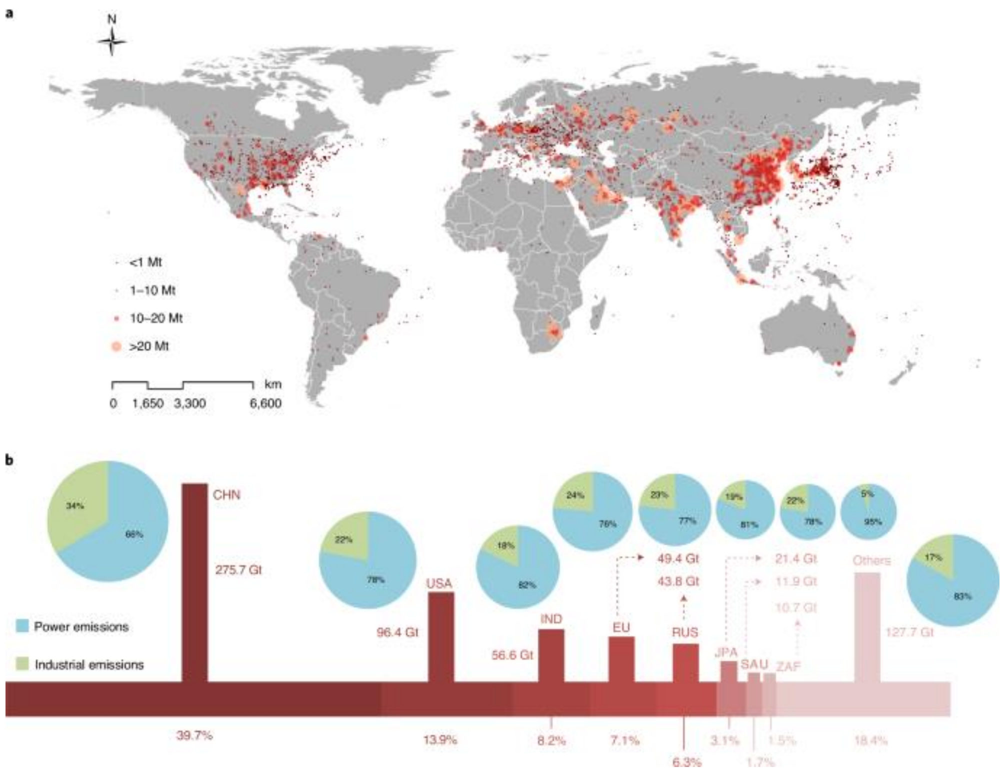

Figure 6.0: A proposed global layout of carbon capture and storage in line with a 2°C climate target

Credit: Nature.com

Industries and Adoption of CCUS

Carbon Capture, Utilization, and Storage (CCUS) is not just a theoretical solution, it's being adopted across various high-emission industries to make a tangible impact. Let's dive into how different sectors are leveraging CCUS to reduce their carbon footprints and contribute to a more sustainable future.

Key Industries Primed for CCUS Adoption

According to the Global CCS Institute and IEA (2021), several key industries are prime candidates for adopting CCUS technologies due to their high CO2 emissions:

1. **Power Generation:** Power plants fuelled by coal and natural gas are significant sources of CO2 emissions. By integrating CCUS, these plants can dramatically lower their carbon footprints, making energy production more sustainable and aligning with global climate goals. Power

generation is the pillar of modern society. Implementing CCUS in this sector not only helps meet energy demands sustainably but also sets a precedent for other industries to follow.

2. **Cement Production**: Cement is essential for construction, but its production is energy-intensive and emission-heavy, making it one of the largest industrial sources of CO2 emissions, and accounting for around 8% of global CO2 emissions. CCUS offers a way to continue building infrastructure while mitigating climate impact. CCUS can capture emissions produced during the calcination process, significantly reducing the industry's environmental impact.

3. **Steel Manufacturing:** Steel manufacturing is another major industrial emitter. CCUS can help reduce emissions from blast furnaces, a primary source of CO2 in steel production. As you know, steel is fundamental to countless industries, from construction to automotive. Reducing emissions in steel manufacturing is crucial for comprehensive climate action.

4. **Chemical Production**: The chemical industry produces essential products used in daily life and various industries. Industries involved in producing chemicals like ammonia and hydrogen are notable for their high CO2 emissions. Adopting CCUS can help these sectors minimize their environmental impact. Cleaner production processes mean a more sustainable supply chain and reduced global emissions.

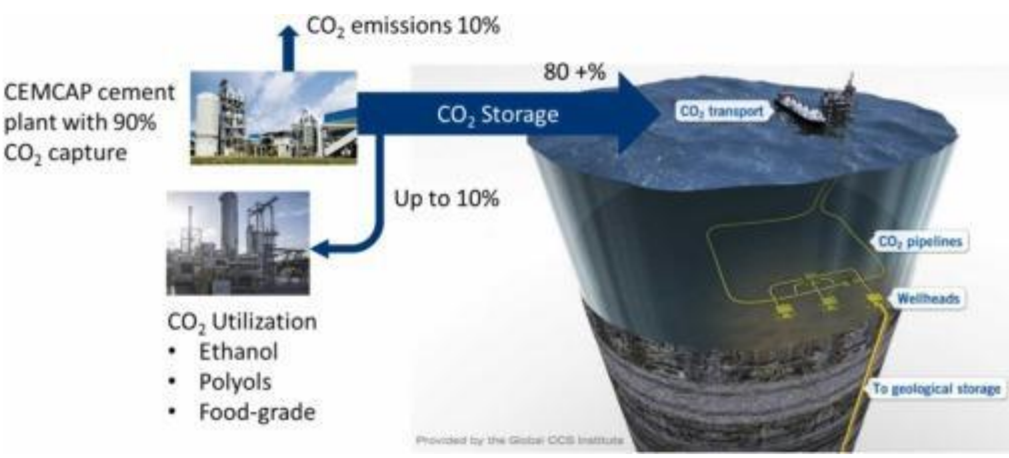

Figure 7.0: CCUS scenarios for the cement industry

Credit: Juliana Monteiro and Simon Roussanaly 2022.

Tools and Mechanisms Utilized in CCUS Operations

Advanced technologies and tools are essential for the efficient implementation of Carbon Capture, Utilization, and Storage (CCUS). Let's explore some of the key mechanisms that make CCUS possible.

1. **Solvent-Based Capture Systems:** Solvent-based capture systems use chemical solvents to absorb CO2 from flue gases. This method is widely used due to its effectiveness in separating CO2 from other gases emitted by industrial processes (National Energy Technology Laboratory, 2021). In this process, the flue gas is passed through a solvent that reacts with CO2, to capture it. The CO2-rich solvent is then heated to release the CO2, which is collected for storage or utilization.

2. **Membrane Technologies:** Membrane technologies employ selective membranes to separate CO2 from other gases. These membranes allow CO2 to pass through while blocking other gases, making the separation process efficient and scalable (Global CCS Institute, 2021). Membrane technologies are versatile and can be adapted for various industrial applications, enhancing the overall feasibility of CCUS.

3. **Compression and Transport Infrastructure:** Captured CO2 needs to be transported to storage or utilization sites. This requires robust compression and transport infrastructure, typically involving pipelines, but also ships and trucks in some cases (IEA, 2021). Efficient transportation systems ensure that captured CO2 is safely and reliably moved to where it can be stored or utilized, playing a critical role in the CCUS chain.

4. **Monitoring and Verification Technologies:** Ensuring the safe and effective storage of CO2 in geological formations requires advanced monitoring and verification technologies. Techniques such as seismic surveys, satellite monitoring, and chemical tracers are used to monitor CO2 storage sites (Global CCS Institute, 2021). These technologies track the CO2 in underground reservoirs, ensuring it remains securely stored and does not leak into the atmosphere.

5. **Simulation and Modelling:** Sophisticated software tools simulate CO2 behavior in underground reservoirs. These simulations help optimize storage strategies and predict long-term outcomes, enhancing the safety and efficiency of CCUS operations. Accurate modeling is crucial for understanding how CO2 will behave over time, ensuring that storage solutions are both effective and sustainable.

Author's View and Conclusion

Advancements and Feasibility of CCUS

Significant strides have been made in enhancing the efficiency and cost-effectiveness of CCUS technologies. Innovations in capture methods and storage techniques have rendered these solutions more accessible for broad implementation. Despite initial investment costs, the long-term advantages, including potential revenue from CO2 utilization and enhanced oil recovery, make CCUS a compelling and worthwhile investment for industries and economies alike.

Operational Flexibility and Adaptability

CCUS technologies offer substantial operational flexibility, enabling industries to adjust their CO2 capture rates in response to economic and environmental dynamics. This adaptability facilitates the seamless integration of CCUS into existing industrial infrastructures, driving sustainability efforts without compromising operational efficiency.

Future Prospects: Integration and Expansion

Looking ahead, the integration of CCUS with renewable energy sources and other low-carbon technologies holds immense promises for bolstering its environmental impact. By synergizing CCUS with these complementary technologies, we can amplify efforts to mitigate climate change on a global scale. Crucially, supportive policies and incentives will play a pivotal role in accelerating the adoption of CCUS technologies worldwide, fostering a conducive environment for sustainable development and climate resilience.

Conclusion

Carbon Capture, Utilization, and Storage (CCUS) stands at the forefront of the battle against climate change, offering a potent solution to reduce global greenhouse gas emissions. By capturing CO2 from industrial sources and either repurposing it beneficially or securely storing it underground, CCUS holds the key to achieving significant environmental benefits. As technology continues to advance and costs decline, the widespread adoption of CCUS across diverse industries promises to pave the way for a more sustainable and carbon-neutral future.

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