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Research Article

Carbon capture, carbon storage and utilization

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Abstract

This aspect of Energy law prompts the Department of Energy to initiate a series of research and development endeavors aimed at assessing environmental suitability and safety, capacity. Additionally, it explores proposed geological storage sites. High-purity carbon dioxide finds primary application in the electronics sector, medical research, and clinical diagnostics. It serves as a calibration gas for carbon dioxide lasers, testing devices, and various mixed gases, besides being a regular component in polyethylene polymerization. The objective of this article is to shed light on theories that model the movement of stored carbon dioxide, aiding in the interpretation and anticipation of chemical alterations and the potential impact of increased pressure.

Introduction

Carbon Capture, Utilization, and Storage (CCUS) encompass techniques and technologies aimed at extracting CO$_2$ from flue gas and the atmosphere, then repurposing the CO$_2$ for various applications while identifying safe and lasting storage options. However, before delving into the advantages and disadvantages, it's essential to carefully consider the aforementioned energy terms (carbon capture, utilization, and storage). Carbon capture entails developing sorbents capable of effectively binding with CO$_2$ in flue gas or the atmosphere, albeit at a high cost. It stands as the primary large-scale approach to reducing emissions inexpensively while preserving the significance of fossil fuel resources and existing infrastructure in both the electricity and industrial sectors. Carbon storage serves to prevent widespread carbon dioxide emissions from further contributing to or worsening climate change. Although this process increases the energy demand of power plants, most experts acknowledge carbon storage as a transitional solution. Carbon utilization refers to the diverse ways in which captured carbon dioxide can be recycled to generate economically valuable products or services, primarily involving the conversion of carbon dioxide or carbon monoxide.

This diagram (Figure 1) illustrates the process of carbon capture, storage, and use (CCSU), which involves capturing carbon dioxide (CO$_2$) emissions from industrial sources such as power plants and factories. The captured CO$_2$ is then transported to storage sites, such as underground geological formations or deep ocean reservoirs, where it is securely stored to prevent its release into the atmosphere. Alternatively, captured CO$_2$ can be utilized in various applications such as enhanced oil recovery (EOR), carbon utilization in building materials, or even converted into synthetic fuels through processes like direct air capture (DAC) and power-to-gas (P2G). CCSU technologies play a crucial role in mitigating climate change by reducing greenhouse gas emissions and achieving net-zero carbon goals [1].

Moreover, understanding the three principles of Carbon Capture, Utilization, and Storage (CCUS), also known as carbon capture, utilization, and sequestration, involves a process of capturing carbon dioxide emissions from sources like coal-

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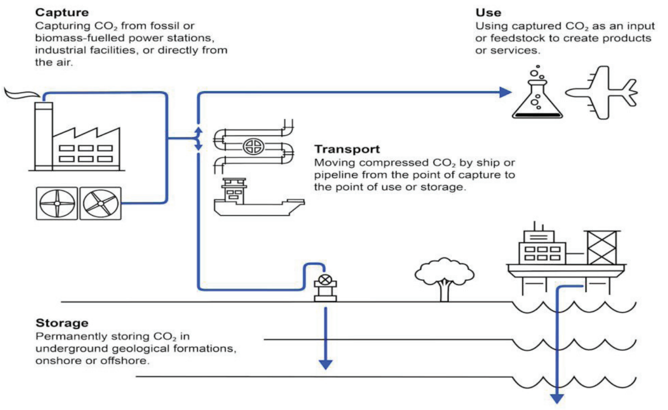

Figure 1: Carbon Capture, Storage, and Use (CCSU) [1].

fired power plants and either reusing or storing them to prevent their release into the atmosphere. Storage of carbon dioxide in geological formations encompasses oil and gas reservoirs, unmineable coal seams, and deep saline reservoirs—structures that have historically stored crude oil, natural gas, brine, and carbon dioxide over millions of years. CCUS is believed to have the potential to facilitate decarbonization and achieve carbon neutrality by capturing, transporting, and storing greenhouse gas emissions from fossil fuel power stations, energy-intensive industries, and gas fields through injection into the soil or underground. Although CCUS technologies have various applications, the primary focus is on fossil fuel energy infrastructure and reducing emissions at high-emitting facilities. Implementing CCUS technologies at such facilities involves three main stages: capture, transportation, and storage. Ideally, converting CO_2 into valuable chemicals or utilizing it for oil extraction or industrial waste remediation would enhance the economic value of this greenhouse gas. However, the demand for CO_2 is limited compared to the substantial amount that needs to be removed from the atmosphere to mitigate the adverse environmental impacts of climate change [2]. Therefore, various storage options for CO_2 have been proposed, including injection into geological formations and oceans, as well as promoting tree growth to enable biological CO_2 fixation through photosynthesis. The classification of carbon utilization and storage schemes depends on their storage capacity, permanence, environmental consequences, and implementation costs. Any effective carbon storage system must meet criteria such as cost competitiveness, long-term stability, and environmental friendliness. Given that CO_2 storage technologies may increase energy costs, their introduction is unlikely without regulatory pressure. Therefore, sustainable integrated systems that combine energy co-generation with CO_2 capture, such as chemical looping and sorption-enhanced water gas shift, require further investigation [3]. Addressing the technical aspects of CCUS is crucial, but it's also essential to consider the societal and economic costs of climate change [4,5]. Balancing the trade-offs between mitigating climate risks and investing in carbon-neutral energy infrastructure becomes more manageable if carbon management costs remain low. Another challenge in implementing CCUS is determining and communicating the social cost of carbon across diverse communities, including scientists, engineers, policymakers, and the general public. Thus, addressing various scientific, economic, and societal aspects is necessary to ensure the successful development and implementation of CCUS technologies.

This diagram (Figure 2) illustrates direct air capture technology that removes carbon dioxide (CO_2) from the air and stores it for reuse. However, this schematic diagram illustrates the Air Carbon Capture (ACC) system, focusing on the filtering and release process. Ambient air, containing carbon dioxide (CO_2), is drawn into the capture system, where it passes through filters or sorbents designed to selectively capture CO_2 molecules. The captured CO_2 is then stored within the sorbent material. To release the captured CO_2, the sorbent material is heated, causing the CO_2 to desorb and separate from the sorbent. Once released, the purified CO_2 can be stored, utilized in various applications, or converted into valuable products. This process plays a crucial role in mitigating climate change by removing CO_2 directly from the atmosphere.

According to Wilcox [6], it is crucial to differentiate between fixed sources like power plants and factories and mobile sources such as cars and airplanes when considering carbon capture [6]. Presently, there are no practical methods for directly capturing CO_2 from mobile sources onboard, so our focus remains on capturing CO_2 from stationary sources. While CO_2 is often viewed as a waste product in the context of flue gases, there are numerous applications where it is either utilized or considered a valuable commodity. Given the significant volumes of CO_2 being emitted, it's challenging to envision any storage method other than injecting it into geological formations. Suitable geological formations like deep saline aquifers, depleted oil and gas fields, unmineable coal seams, and silicate formations such as basalt can accommodate vast amounts of CO_2, estimated at up to 11,000 Gt (Dooley et al., 2006), significantly exceeding annual CO_2 emissions of around 30 Gt/year [7]. While we have experience in transporting and injecting CO_2 into geological formations, the main challenge lies in the scale of implementation. Currently, only around 50 Mt of CO_2 has been stored, with projections indicating 13 Mt of CO_2/year by 2016 [8] (Levina, et al. 2013). Ensuring the long-term safety of CO_2 storage sites is a scientific challenge. Developing technologies for monitoring, verification, and assessment (MVA) to ensure the continued containment of CO_2 underground is crucial. While the injection process is well understood, the cost of monitoring injected CO_2 over

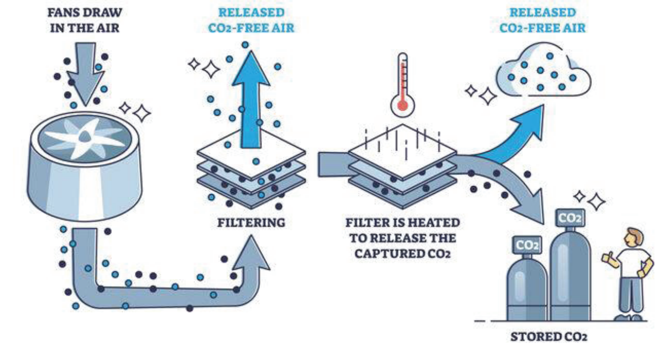

Figure 2: Air Carbon Capture works.
(Source: Climeworks, Climate Champions, The Guardian).

many years may be prohibitive unless the expenses associated with deploying MVA technologies are significantly reduced. Additionally, addressing key questions about long-term safety, such as induced seismicity and the potential for fractures, is essential for risk assessments of geologic storage.

This diagram (Figure 3) showcases the process of carbon utilization, where captured carbon dioxide (CO_2) is transformed into renewable low-carbon fuels and high-value products. Initially, CO_2 is captured from industrial emissions or directly from the atmosphere using carbon capture technologies. Subsequently, the captured CO_2 is utilized as a feedstock for the production of renewable fuels such as synthetic hydrocarbons, biofuels, or hydrogen through processes like carbon dioxide hydrogenation or Fischer-Tropsch synthesis [9,10]. Additionally, CO_2 can be converted into high-value products such as chemicals, polymers, or building materials through innovative carbon utilization pathways. These carbon utilization technologies contribute to reducing greenhouse gas emissions, fostering sustainable development, and creating economic opportunities in the transition towards a low-carbon economy.

Importances and demerits

The significance of CCUS cannot be overstated, particularly for the ecosystem, with several key points to consider:

CCUS has the potential to mitigate emissions at the source by directly capturing CO_2 and storing it in geological formations, potentially reducing up to 20% of total CO_2 emissions from industrial and energy production facilities [11].

Simultaneously, CCUS offers the opportunity to remove other pollutants. For instance, during oxy-fuel combustion, where fuel is burned in an oxygen-rich environment, there can be a substantial reduction in nitrogen oxide (NOx) and sulfur dioxide gases. Research conducted by the Argonne National Laboratory demonstrated a 50% decrease in NOx gases during oxy-fuel combustion [12].

Demerits

The substantial expense of implementation is a notable concern. In many regions, there is a lack of regulatory frameworks to drive or mandate the adoption of CCUS technology. The investment required for this technology is significant, encompassing high costs for equipment, materials needed for CO_2 storage, and the establishment of transportation infrastructure. Consequently, the overall expenses associated with deploying CCUS could be considerable.

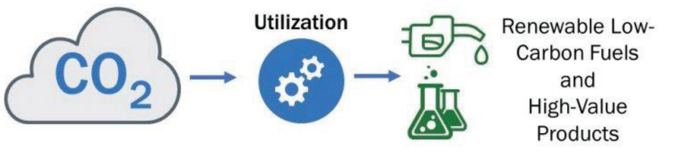

Figure 3: Carbon Utilization Pathways: Here's a caption for a figure depicting carbon utilization for renewable low-carbon fuel and high-value products. (Adapted from CO2, Office of Energy Efficiency & Renewable Energy, https://www.energy.gov/eere/bioenergy/co2-utilization).

- Uncertainty surrounds the storage capacity for CO_2. While geological storage availability isn't an immediate obstacle, long-term concerns persist regarding the ability of storage sites to effectively retain carbon without significant leakage. The injection of CO_2 underground may also trigger seismic activity [13]. Moreover, it's projected that not all nations will possess sufficient CO_2 storage capacity to effectively implement CCUS initiatives.

Transportation considerations present additional challenges. Although the risk of transportation accidents is relatively low, the potential for leaks remains. Transporting CO_2 to storage sites demands substantial energy for compression and maintaining high pressure throughout pipelines, which themselves require significant investment. The leakage of CO_2 in high concentrations could pose health risks. Each CO_2 source must be linked to a suitable storage site via pipeline, complicating CCUS implementation and adding to costs, particularly in areas lacking appropriate geological formations for storage.

Legal framework

The directive concerning the geological storage of CO_2, commonly known as the "CCS Directive," establishes a legal framework aimed at ensuring environmentally safe geological CO_2 storage to combat climate change. It encompasses all CO_2 storage activities in geological formations within the EU and throughout the entire lifespan of storage sites. While it primarily addresses CO_2 capture and transport, these aspects are also governed by existing EU environmental legislation, such as the Environmental Impact Assessment (EIA) Directive and the Industrial Emissions Directive, with amendments introduced by the CCS Directive [14].

In terms of risk prevention for health and the environment, the CCS Directive imposes stringent requirements for site selection for CO_2 storage. Sites can only be chosen if prior analysis demonstrates no significant risk of leakage or harm to human health or the environment under the proposed conditions of use. Geological CO_2 storage is contingent upon obtaining a storage permit. Additionally, to maintain the security of the transport network and storage sites, stored substances must predominantly consist of CO_2 to prevent adverse effects. Site operations must undergo close monitoring, with corrective measures promptly implemented in case of leakage. The directive also addresses closure and post-closure obligations, outlines criteria for transferring responsibility from operators to Member States, and mandates operators to establish financial security before CO_2 injection to meet the requirements of the CCS Directive and the Emissions Trading Directive.

To leverage existing legal frameworks and eliminate obstacles, operators are integrated into the Emissions Trading System, requiring them to surrender emission allowances in case of leakage. SST The Directive on Environmental Liability addresses liability for local environmental damage, while regulation at the Member State level governs liability for health and property damage [15]. Additionally, barriers to CCS in waste and water legislation are removed, and the Large Combustion Plants Directive is amended to mandate capture-readiness assessments for large plants [16]. The revised ETS Directive explicitly includes CCS in Annex I, considering emissions captured, transported, and stored following this directive as non-emitted.

Conclusion

Despite its potential benefits, CCUS struggles with a lack of public support and faces significant skepticism regarding its widespread adoption. A study conducted by Align CCUS E.U. revealed a lack of public awareness and understanding of CCUS globally. Many individuals are uncertain about CCUS, and its processes, and negative perceptions towards it are harbored. Concerns about perceived risks, potentially resulting from negligence by those involved in carbon capture, lead to opposition to the construction of large CCUS infrastructure near their communities. It is believed that precautionary measures should be rigorously implemented, with strict adherence to regulations. Any instances of gross misconduct must be met with severe penalties, and victims should have access to free, fair, and reasonable remedies.

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