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Mass Flow Analysis of Carbon Capture, Utilization, and Storage (CCUS) Potential in Thailand

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Abstract

This study analyzes the carbon dioxide flow in Thailand to assess the potential of Carbon Capture, Utilization, and Storage (CCUS) technologies. It utilizes data from academic literature and reports to conduct a qualitative analysis of CO_2 flow within Carbon Capture and Utilization (CCU) and Carbon Capture and Storage (CCS) processes. The mass flow analysis was performed using the e!Sankey Diagram software to simulate three scenarios: Scenario 1 involves utilizing captured CO_2 from industrial plants to produce various products such as beer, soft drinks, soda, urea fertilizer, and cement pellets. Scenario 2 focuses on storing all captured CO_2 from industrial plants in depleted natural gas or oil reservoirs within Thailand. Scenario 3 combines both CCU and CCS approaches to evaluate the overall CO_2 flow within the country's system. The main industries analyzed include power generation, cement production, and iron and steel manufacturing, which accounted for 107,498.98 ktCO_2 equivalent of greenhouse gas emissions in 2022. Post-combustion CO_2 capture using amine-based absorbents was identified as the most suitable method for these industries. The analysis highlighted the potential for CO_2 capture and utilization across various industrial sectors, as well as the feasibility of underground CO_2 storage in Thailand. The study found that CO_2 utilization and storage could reduce emissions by 25.07% under favorable conditions. In summary, CCUS technology can effectively reduce CO_2 emissions from power plants, cement, and steel industries while promoting a circular economy through the beneficial reuse of captured CO_2.

Keywords : Carbon Capture Utilization and Storage (CCUS); CO_2 Emission; Mass Flow Analysis; Climate Change Mitigation; Thailand

Introduction

Greenhouse gas (GHG) emissions significantly contribute to environmental degradation, climate change, sea-level rise, biodiversity loss, and adverse health effects, primarily resulting from human activities such as the combustion of fossil fuels, industrial processes, agriculture, and transportation [1]. Major sources of CO_2 emissions include electricity generation from coal and natural gas, manufacturing, and the use of fossil fuels in transportation, while methane (CH_4) and nitrous oxide (N_2O), predominantly from the agricultural sector and waste management, significantly exacerbate global warming, leading to the deterioration of ecosystems, economies, and overall quality of life without effective mitigation measures [2].

Carbon capture, utilization, and storage (CCUS) presents an effective strategy for reducing these GHG emissions through an integrated suite of technologies focused on capturing carbon dioxide (CO_2) from high-emission sources like power plants and industrial facilities to prevent atmospheric release and enable its conversion into valuable products. CCUS encompasses two main branches: carbon capture and utilization (CCU) and carbon capture and storage (CCS) [3].

Carbon Capture and Utilization (CCU) involves the reuse of captured CO_2 , with the capture process including several methods such as pre-combustion capture, which gasifies fossil fuels to produce hydrogen and CO_2 followed by CO_2 separation before combustion, primarily used in hydrogen or synthetic fuel production; post-combustion capture, which extracts CO_2 from flue gas after fossil fuel combustion using chemical solvents like amine-based absorption; oxy-fuel combustion, which burns fossil fuels in pure oxygen to produce flue gas mainly of CO_2 and water vapor for easier separation; and Direct Air Capture (DAC), which captures CO_2 directly from ambient air using solid sorbents or liquid solvents, offering potential for negative emissions despite being energy-intensive.

Wide range of technologies for CO_2 capture includes amines, organic compounds reacting with CO_2 to form carbamates like monoethanolamine (MEA) [4]; carbonate solutions that react with CO_2 to form bicarbonate; solid sorbents [5] like zeolites, activated carbon [6], and metal-organic frameworks (MOFs) [7] that adsorb CO_2 ; membranes made of polymers, ceramics, or composites that selectively permeate gases to separate CO_2 ; algae capture, which uses microalgae to fix CO_2 through photosynthesis; and cryogenics, employing very low temperatures to condense and separate CO_2. Captured CO_2 can be directly reused in Enhanced Oil Recovery (EOR) [8] by injecting it into oil or gas fields to enhance recovery and facilitate underground storage, and in the food and beverage industry [9] for carbonated drinks and as a refrigerant; indirect utilization [10] involves converting CO_2 into products like synthetic fuels and chemicals such as methanol, urea, and hydrocarbons through reactions with hydrogen from renewable sources. Carbon Capture and Storage (CCS) [3], on the other hand, involves the permanent storage of CO_2 in geological formations, ensuring it does not re-enter the atmosphere, thereby mitigating climate change impacts.

CCUS plays a vital role in mitigating climate change and achieving carbon neutrality by reducing emissions in hard-to-decarbonize sectors such as power generation, cement, and steel production. While globally recognized, CCUS research and implementation in Thailand remain limited, with notable gaps in emission data, economic feasibility studies, storage capacity assessments, and policy integration. Prior work by Zhang et al. (2022) [11] highlights Thailand's geological storage potential and concepts for CCS infrastructure but does not quantify CO_2 mass flows. This study builds upon previous research by employing Mass Flow Analysis to evaluate CO_2 capture, utilization, and storage pathways in Thailand. The central hypothesis of this study is whether Thailand possesses the capacity to utilize and store the CO_2 emissions generated annually. Despite significant advancements in CO_2 capture and storage technologies, there remains a critical gap in understanding the spatial and quantitative integration of these emissions within Thailand's infrastructure. This study addresses this gap by integrating quantitative emissions data with spatial planning, thereby enhancing the potential for effective CCUS deployment.

Materials and Methods

This research was conducted as a qualitative study through data collection from literature reviews and reports (Table 1). The study focused on analyzing CO_2 mass flow in the application of CCUS technology in Thailand, specifically in terms of CCU (Carbon Capture and Utilization) and CCS (Carbon Capture and Storage). The emission-generating industries considered in this study included all CO_2 emitters industries of Thailand that have capability for CCUS technology. The dataset is obtained from Thailand's 2024 Biennial Transparency Report (BTR), which contains CO_2 emission data for the year 2022, although the report was published in 2024. The criteria for selecting emission sources in combustion process industries were included four key criteria: (1) Emission Data Availability – ensuring that only sources with reliable and up-to-date data were considered to support accurate analysis and modeling; (2) Point Source Emission – focusing on concentrated emission points, such as industrial stacks, to enhance capture efficiency and cost-effectiveness; (3) Magnitude of Emissions – prioritizing large emitters to maximize overall GHG reduction and resource efficiency; and (4) Capture Potential – assessing the technical feasibility and practicality of applying CO_2 capture technologies to ensure successful and sustainable implementation.

There are many types of capture media and mechanisms. This research scope included amine-based solutions, adsorption using solid sorbents, membrane separation, and cryogenic techniques. However, each mechanism had its limitations, such as high energy consumption (particularly for solvent regeneration), solvent degradation, high capital investment, and limited scalability depending on industrial applications and geographical location. Therefore, the criteria for selecting the capture media were set included capture efficiency, cost, operation lifetime, TRLs, and number of existing full-scale applications.

Following a comprehensive criteria-based selection, data on CO_2 emissions, captured CO_2, and its utilization and storage were analyzed using mass flow analysis with e! Sankey Diagram software (version 5.2.1) to evaluate the CO_2 mass flows of CCUS technologies in Thailand. Three simulation scenarios were developed to examine the CO_2 flow pathways, with each process presenting a distinct CO_2 mass balance profile.

Scenario 1: CCU routes by captured CO_2 from industrial plants would be repurposed in products such as beer, soft drinks, soda, urea fertilizer, cement clinker, and for enhanced oil recovery (EOR). The goal was to support a circular economy by utilizing CO_2 as an industrial input. Utilization estimates were based on industry data as shown in Table 2.

Scenario 2: This scenario models CCS pathways by assuming that all CO_2 captured from industrial plants is stored in depleted natural gas fields or oil reservoirs within Thailand. The objective is to evaluate the CO_2 storage potential of the industrial sector in underground sites, using 10 years of historical data on utilized oil and gas fields. Preliminary estimates of underground CO_2 storage capacity were derived from national oil drilling records and proven oil reserve data.

Scenario 3: Combining CCU and CCS routes by considering the total mass flow of CCUS of Thailand. This is the evaluation of both utilization and storage potential through the following simulation scenarios.

Table 1 The sources of data for this study

Data	Sources
CO_2 capture technology	Available literature data from 2004 to 2024 [3]
CO_2 emission	Thailand 2024 Biennial Transparency Report (BTR) [11]
CO_2 usage	The market demand for CO_2 directly utilization (CCU) for the beverage and the CO_2 indirectly utilization for urea, and cement industries are identified based on the production of Thailand products using the data from Thailand statistic data during January - December 2022 by Office of Industrial Economics (OIE) [12]
CO_2 enhance oil recovery	Thailand CO_2 enhance oil recovery (CCU-EOR) from the report of petroleum procurement from both land and sea petroleum sources during January - December 2022 by Department of Mineral Fuels [13]
CO_2 storage capacity	Thailand oil reservoirs (CCS) from the report of petroleum procurement from both land and sea petroleum sources during 2012 - 2022 by Department of Mineral Fuels [13]

Table 2 The assumption for CO_2 utilization based on the CO_2 concentration in the products

Products	CO_2 concentration	References
Beer	3.5% W/V	[14]
Soft drinks and soda	4.5% W/V	[15]
Urea	5.5% W/W	[16]
Cement clinker	7.5% W/W	[17]

Results and Discussion

The selection of greenhouse gas (GHG) emission sources in combustion process industries was based on four key criteria: (1) Emission Data Availability – ensuring that only sources with reliable and up-to-date data were considered to support accurate analysis and modeling; (2) Point Source Emission – focusing on concentrated emission points, such as industrial stacks, to enhance capture efficiency and cost-effectiveness; (3) Magnitude of Emissions – prioritizing large emitters to maximize overall GHG reduction and resource efficiency; and (4) Capture Potential – assessing the technical feasibility and practicality of applying CO_2 capture technologies to ensure successful and sustainable implementation.

Table 3 Selection of industrial plants to be studied

Industry	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Total
	Emission Data Availability	Point source emission	Magnitude of Emissions	Capture Potential	
Energy Industries [18-20]	1	1	1	2	6
Cement Production [19, 21]	1	1	1	2	6
Lime Production [22, 23]	1	1	1	1	4
Glass Production [21, 23]	1	1	0	0	2
Chemical production [24, 25]	1	0			1
Iron and steel Production [24]	1	1	1	2	6
Pulp and Paper Industry [9, 26]	1	1	0	0	2
Food and Beverage Industry [9]	0				0

Note: Criteria details are provided below;

1) Emission data availability (1 = Availability of emission data, 0= No availability of emission data)

2) Point source emission (1 = Point source emission, 0 = Nonpoint source emission)

If any industries have the value of criteria 1 (emission data availability) and criteria 2 (point source emission) equal to 0, they were not further included for other criteria.

3) Magnitude (2 = emission ≤ 20%, 1 = 10% < emission < 20%, 0 = emission ≤10% of the total emission)

- 20% is used as the *upper threshold* because if an emission source accounts for more than one-fifth of total emissions, it is considered a major emitter, where actions targeting that single sector can have a significant impact at the national level.
- 10% is used as the *lower threshold* to distinguish small emission sources from those that are strategically important.

4) Capture Potential

- 2 = Good: High CO_2 concentration (>10–15%), continuous and centralized emissions, minimal process disruption, proven in similar industries.
- 1 = Fair: Moderate CO_2 concentration (5–10%), less consistent or multiple sources, more modifications needed, some cost/technical limits.
- 0 = Poor: Low CO_2 concentration (<5%), dispersed or intermittent emissions, inadequate infrastructure, high capture cost per CO_2 unit.

Table 3 presented a systematic approach for identifying priority industrial sectors for CCUS deployment in Thailand, emphasizing minimum requirements for emission data availability and point-source emissions to ensure accurate assessment and technical feasibility. The energy industry, cement production, and iron and steel production ranked highest, collectively emitting 107,498.98 ktCO$_2$eq in 2022—over one-quarter of the nation's total emissions—positioning them as strategic targets for large-scale emission reductions. These sectors possess favorable conditions for CCUS implementation, including continuous high-volume flue gas streams, centralized emission points, and high capture potential, which facilitate the adaptation of existing infrastructure with fewer technical barriers compared to smaller or more dispersed industries. Although no sensitivity analysis was conducted, a preliminary uncertainty assessment was carried out. The findings revealed a high degree of uncertainty, primarily due to limitations in data quality, as information was not collected continuously but obtained only from producers or national-level sources. Nevertheless, the researchers deemed the available data sufficiently reliable for the purposes of this analysis.

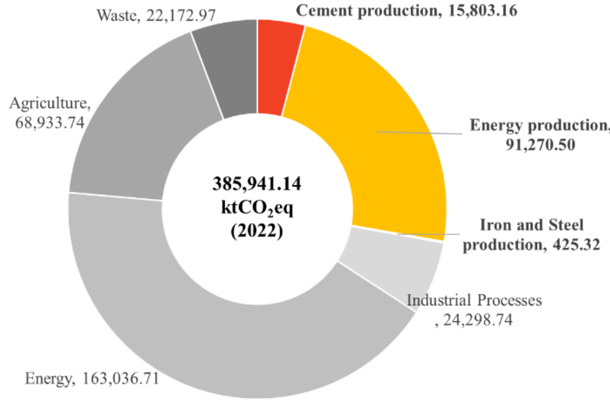

Figure 1 Total GHG emissions by sector 2022 (Adapted from [11])

Table 4 Selection of capture technology 2024 Biennial Transparency Report (BTR)

Criteria / Technology	**Post-combustion**	**Pre-combustion**	**Oxy-fuel combustion**	**Direct Air Capture (DAC)**
Compatibility with Existing Systems	Excellent – easy retrofit	Requires full system rebuild	Requires boiler modification	Installed separately from production
Cost	Medium to high	High – major system changes	High – needs pure CO_2 production	Very high – energy intensive
Suitable CO_2 Concentration Level	4–15% CO_2 (from flue gas)	High ~20–40% CO_2 (syngas)	High ~80% CO_2 (with O_2 combustion)	Very low (0.04% CO_2 in air)
Technology Readiness Level (TRL)	8–9	6–8	6–8	5–7
Space and Resource Requirements	Moderate space and water use	Requires more system management	High energy and O_2 demand	Extremely high energy usage
Industry Suitability	Power, cement, steel, Oil Refineries, Chemical Plants, Food & Beverage, Textile & Garment, Ceramics & Glass	Gasification-based industries	New power plant designs	Areas without point-source CO_2
Economic Feasibility	More feasible for retrofits	Not viable if building new	Too expensive currently	Not suitable for large-scale use
Reference	[27-29]	[28, 30]	[28, 31]	[32, 33]

Table 4 indicated that among the available capture technologies, post-combustion CO_2 capture is the most suitable option for retrofitting existing facilities in the selected industries. Since this method does not require modifications to the combustion process, it offers a practical and cost-effective solution with a medium to high-cost relative to other approaches. With a Technology Readiness Level (TRL) of 8-9, the technology is considered ready for integration into existing systems. Based on the available data sources.

The criteria presented in Table 5 indicated that amine-based solvents are the most suitable capture media due to their high selectivity, efficiency, and proven large-scale applicability in CO_2 capture. Compared with membrane and solid sorbent technologies, amine systems offer greater operational flexibility, higher capture rates (85-98%), and adaptability to a wide range of fuel types, including coal, natural gas, and biomass. These systems have been successfully implemented in industry for decades, and with a Technology Readiness Level (TRL) of 8-9, the technology is considered ready for deployment. The identical capture losses observed across all three scenarios can be attributed to the capture technology itself. However, the application of monoethanolamine (MEA) in Thailand is challenged by the country's hot and humid climate. Under such conditions, MEA alone may experience reduced absorption efficiency and increased solvent losses. Therefore, heat-tolerant blends, such as methyldiethanolamine (MDEA) combined with piperazine (PZ) or (AMP)-based solvents, are considered more suitable. The performance of these blends can be further enhanced through pre-cooling and impurity removal processes.

Then, all qualified data were analyzed using the e!Sankey Diagram software version 5.2.1, which applies Mass Flow Analysis and the Law of Conservation of Mass to track CO_2 flows from emission sources through capture processes to utilization (CCU) or storage (CCS). The software processes input data on CO_2 emissions, capture technology efficiencies, and utilization/storage capacities, performs mass balance calculations, and renders flows with widths proportional to actual quantities, enabling clear visualization of the overall system and potential bottlenecks. Three simulated scenarios were employed to observe the direction of CO_2 mass flow, each process exhibiting a distinct proportion of CO_2 mass balance, allowing multiple scenarios to be compared in a single view and facilitating communication of national-scale CCUS assessments.

In scenario 1, the total captured CO_2 in this scenario was 96,749.08 ktCO_2 eq. The gas was allocated across six applications, with the highest volume (24,091.47 kt CO_2eq) used in Enhanced Oil Recovery (EOR). Other sectors included beverage industries (beer, soft drinks, soda), urea fertilizer production, and cement clinker manufacturing. However, only 28.4% of the captured CO_2 could be utilized based on market demand and process limitations, leaving 69,269.44 ktCO_2 eq that required further handling, likely via geological storage.

Table 5 Capture Media Selection Criteria

Criteria	Amines	Carbonate Solutions	Solid Sorbents	Membranes	Algae-based Capture	Cryogenic
Capture Efficiency (%)	85-98	70-90	80-95	75-92	60-80	95-99
Cost (USD/tCO_2eq)	30-60	25-50	40-70	50-80	60-100	70-120
Operation lifetime (year)	2-5	3-7	5-10	5-10	1-3	10-20
Technology Readiness Level (TRL)	8-9	7-9	5-7	6-8	3-5	8-9
Number of full-scale applications (Plants)	>100	>50	<10	<20	<5	>30
Reference	[34-36]	[37, 38]	[5, 39, 40]	[5, 39, 40]	[41, 42]	[43, 44]

In scenario 2, all captured CO_2 (96,749.08 $ktCO_2$ eq) was assumed to be stored in geological formations such as depleted oil and gas reservoirs. Thailand's total estimated underground storage capacity was 345,226.43 $ktCO_2$, meaning that only 28.02% of this capacity would be used. This indicates that the country has ample geological potential to support future CCS operations.

In scenario 3, after evaluating the results from both utilization and storage pathways, it was confirmed through simulation and verification that all (100%) of the captured CO_2 could be either used or stored safely. This comprehensive approach ensures that no emissions escape into the atmosphere, supporting total emission management. The width of each flow corresponds to the volume of CO_2, making it clear that energy industries are the largest source, and storage in old oil and gas fields is the largest destination

Factors influencing the mass flow of CO_2 in CCUS systems, both currently and in the future, include the quantity and sources of CO_2 emissions which vary with production levels and energy use; the efficiency and technology of capture methods affected by environmental conditions and technical readiness; market demand and the capacity of underground storage sites; policies and regulations that either encourage or hinder investment incentives; the availability of infrastructure for CO_2 transportation; geographical and environmental factors impacting system design and safety; as well as social acceptance and economic impacts. These interrelated factors significantly determine the efficiency, scale, and long-term sustainability of CCUS implementation.

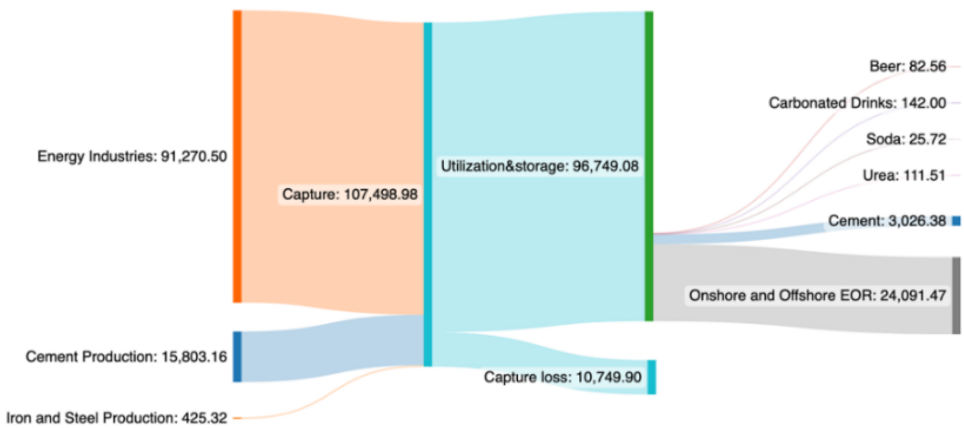

Figure 2 Mass balance of scenario 1

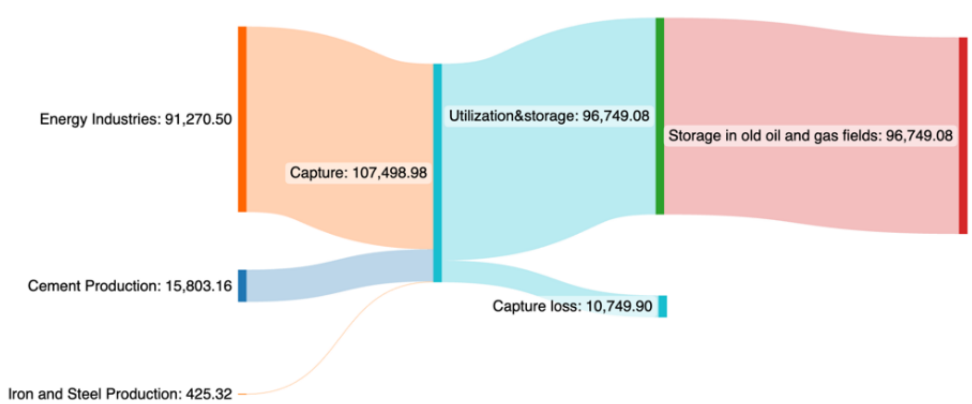

Figure 3 Mass balance of scenario 2

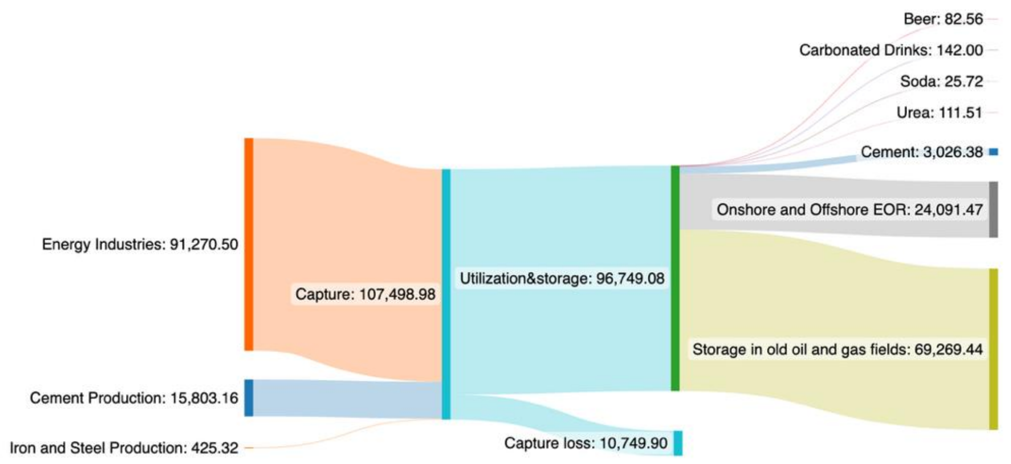

Figure 4 Mass balance of scenario 3

Conclusions

The study confirmed that CCUS technology is suitable for power plants, cement, and iron and steel industries, as it can effectively reduce CO_2 emissions directly at the source. Post-combustion capture technology using amines as absorbents was identified as particularly suitable for these selected industrial plants due to its high efficiency in capturing carbon dioxide (CO_2) directly from flue gas at the emission point and its compatibility with complex industrial environments. This technology has been proven commercially viable, and its widespread adoption demonstrates confidence in its practicality. In addition to reducing CO_2 emissions, the captured carbon can be reused across various sectors, contributing to the development of a circular economy. Examples of CO_2 utilization include its use in the production of beer and carbonated beverages, as a feedstock in fertilizer and clinker manufacturing, and for enhanced oil recovery (EOR). The study also found that the three largest CO_2 emission sources could collectively reduce total emissions by 25.07% if CCUS were implemented at full commercial scale.

While Thailand has considerable potential for CO_2 capture and storage, significant challenges remain, including investment uncertainties, technical constraints, high costs, and environmental considerations. This preliminary study produced encouraging results but also revealed several limitations. Future research should incorporate cost and economic analyses, assess emissions from the entire CCUS process, and explore policy measures such as pricing mechanisms, infrastructure development, and comprehensive CO_2 data management to better support effective utilization and storage.

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