APPLICATION OF CARBON CAPTURE, UTILIZATION, AND STORAGE (CCUS) FOR CLEANER ENERGY- A REVIEW

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ABSTRACT

The increasing level of carbon dioxide (CO_2) in the atmosphere, primarily caused by burning fossil fuels, presents us with a significant challenge in the fight against climate change. Carbon Capture, Utilization, and Storage (CCUS) technology has emerged, aiding us in dealing with this issue (though not to maximum potential). This review paper addresses the role of CCUS in the energy sector, detailing its role in producing cleaner energy. It examines the current status of CCUS technology, highlighting its potential and challenges on a global scale, with particular attention to the vital contributions of geoscience in ensuring adequate carbon storage. The methodology involves a systematic literature review of peer-reviewed articles, conference papers, and authoritative reports, synthesising critical information to understand CCUS comprehensively. Despite economic and policy hurdles, recent advancements and a growing commitment to climate goals foster renewed interest and investment in CCUS. This paper underscores the crucial need for continued research, policy support, and investment to harness the full potential of carbon capture, utilisation, and storage in mitigating climate change and transitioning to a sustainable energy future, motivating the audience to contribute to this vital field.

Keywords: *CCUS, Green house gases, CO_2, Cleaner Energy, Geosciences*

1. INTRODUCTION

Carbon dioxide is a vital greenhouse gas essential for sustaining life on Earth. It traps heat and contributes to the greenhouse effect, necessary for maintaining Earth's temperature at a level that supports life. It is integral to photosynthesis, where plants use it to produce oxygen and glucose, forming the basis of the food chain. Although it plays an indispensable role in sustaining life on Earth, there is an increasing concern that its concentration in the atmosphere is rising due to the increased dependence on fossil fuels worldwide. Based on the annual report from NOAA's Global Monitoring Lab, the global average atmospheric carbon dioxide was 419.3 parts per million ("ppm" for short) in 2023, setting a new record high (Fig. 1). This increasing accumulation of CO_2 in the atmosphere causes global warming and shifts in climatic patterns, which threaten the very survival of humans. Though other greenhouse gases contribute to global warming and climate change, attention is shifted to carbon dioxide as it is the primary source and remains in the atmosphere far longer than other significant GHGs. When a tonne of CO_2 enters the atmosphere, 40% will stay in the atmosphere for 100 years and 20% for 1000 years, while 10,000 years will elapse before the final 10% is removed (Awadh, 2023).

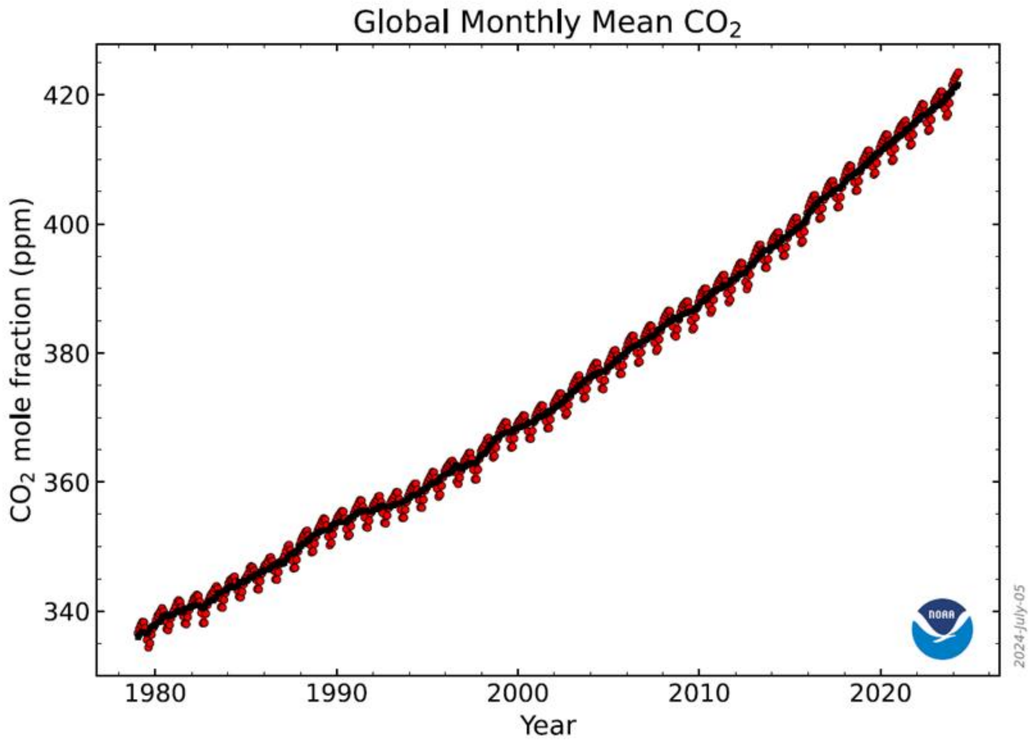

Fig. 1: Carbon dioxide emission trend (1980-2024) (NOAA, 2024)

Climate change presents an urgent and unprecedented threat to the stability of our planet, primarily driven by the relentless increase in carbon dioxide emissions. Understanding this and embracing innovative strategies is imperative to mitigate the impact of these emissions on the environment. Carbon Capture, Utilization, and storage (CCUS) has emerged as a pivotal technology, offering a multifaceted approach to address the challenges associated with carbon emissions. Carbon capture, utilisation, and storage are integral components of efforts to mitigate carbon dioxide (CO_2) emissions and combat climate change. Carbon capture refers to capturing CO_2 emissions from various sources utilising various technologies, including post-carbon capture, pre-carbon capture, and oxy-fuel combustion, to prevent their release into the atmosphere (Metz *et al.,* 2005). Carbon utilisation involves using captured carbon dioxide for beneficial purposes rather than releasing it into the atmosphere. Captured carbon can be utilised in several ways: enhanced oil recovery (EOR), production of chemicals, building, etc. Carbon storage involves capturing CO_2 emissions and storing them underground or in long-term geological formations to prevent their release into the air (Fig. 2).

This review paper focuses on the crucial role of geoscience in CCUS. It digests the application of CCUS in the energy sector for cleaner energy. It addresses the current status of carbon capture, utilisation, and storage, as well as its opportunity on a global scale and challenges.

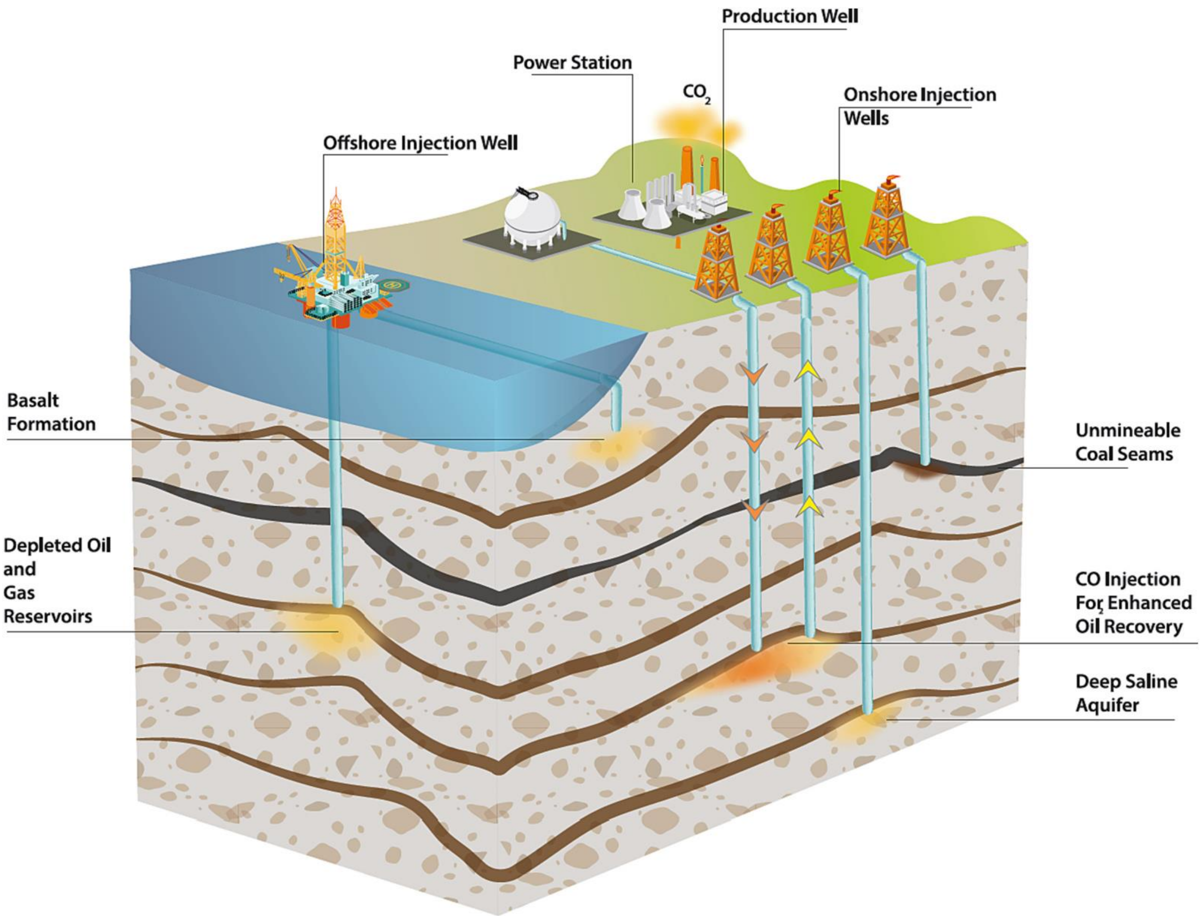

Fig. 2: CO_2 geo-storage methods (Ali *et al.,* 2022a).

2. METHODOLOGY

Systematic and comprehensive approaches were employed for this review paper; literature was sourced from research databases, including Google Scholar and Research gate, and authoritative sources such as the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) websites. The literature utilised consists of conference papers, peer-reviewed journal articles, and relevant thesis which focused on CCUS technology, its application in cleaner energy production, the role of geosciences, opportunities, and challenges. Critical information was collected from selected articles, and the extracted data was organised and synthesised topically to create a rational review. The review has limitations, including potential biases in the literature search, data extraction, synthesis process, and variability in contexts that may affect the generalisation of findings.

3. DISCUSSION

STATUS OF CARBON CAPTURE, UTILIZATION, AND STORAGE (CCUS)

The status of Carbon Capture, Utilization, and Storage (CCUS) reflects both unmet expectations and renewed momentum. Despite its long-recognized potential to mitigate climate change, CCUS technologies have seen slow deployment, leading to a limited impact on global CO_2 emissions. However, the untapped potential of CCUS to significantly reduce emissions and contribute to achieving global net-zero targets is a reason for hope. Several factors have contributed to the sluggish advancement of CCUS. The potential of Storing CO_2 underground is also a critical parameter that is uncertain worldwide but potentially very large. The potential of CO_2 storage worldwide approximately is shown in Fig. 3. (IEA, 2020)

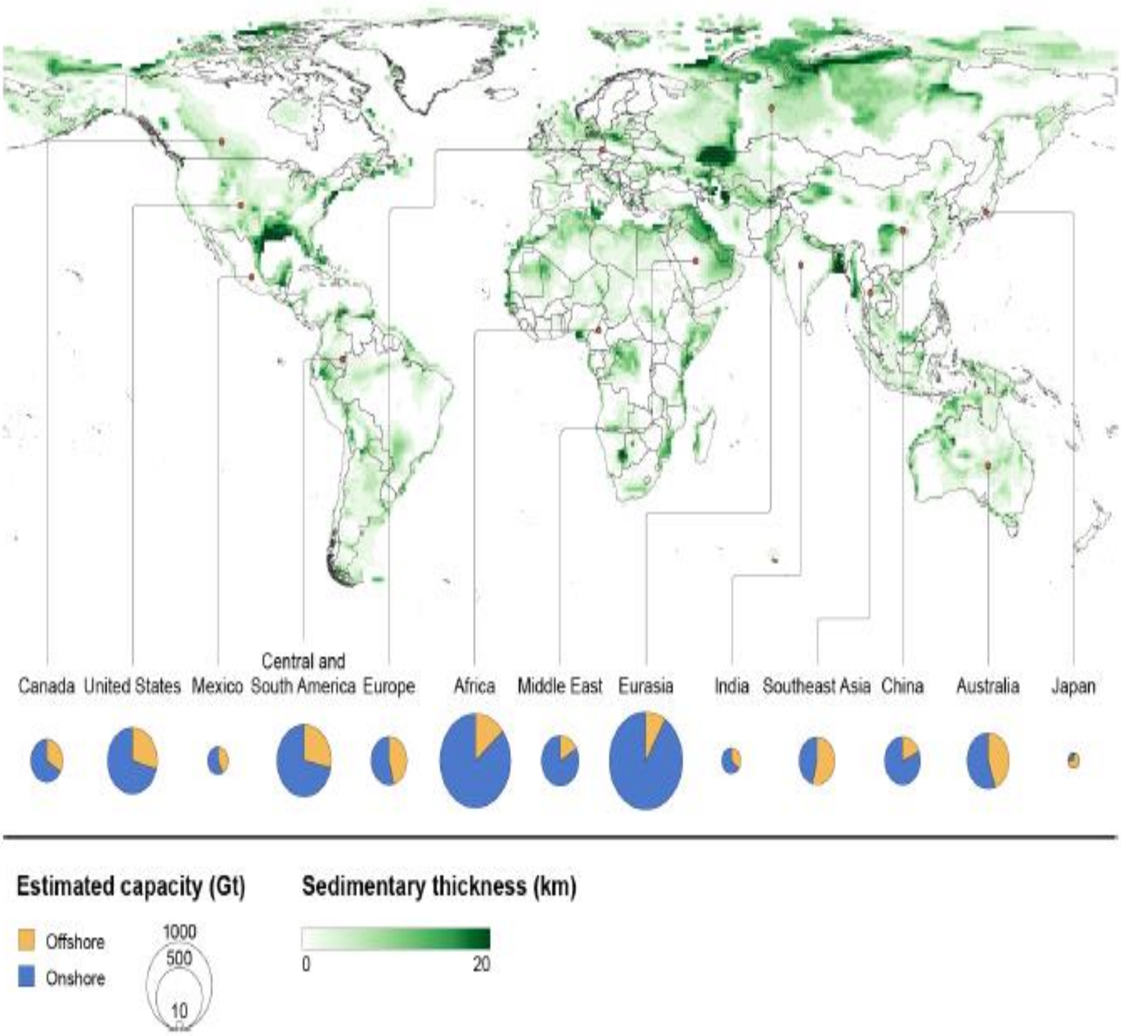

Fig. 3: The potential of CO_2 storage worldwide (IEA, 2020)

Many planned projects have stalled due to commercial considerations and a need for consistent policy support. However, recent developments show that CCUS is gaining traction despite economic uncertainties. The number of large-scale CCUS facilities has been steadily increasing, a promising sign for the future and a testament to the growing global commitment to combat climate change. In 2019 and 2020, there were approximately 51 and 65 facilities, with maximum CO_2 capture capacities of around 96 million tons and 114.3 million tons per year, respectively. By 2021, the number of commercial CCUS facilities worldwide had risen to 135, with a total mean capture capacity of 149.3 million tons per annum. The Global CCS Institute's September 2021 report reported that these advancements are a reason for optimism. Despite its established nature, CCUS is experiencing renewed global interest, with a growing pipeline of new projects driven by strengthened national climate targets and new policy incentives. CCUS costs are declining, new business models are emerging, and technologies related to CO_2 use and carbon removal are advancing and attracting interest from policy makers and investors. This trend towards cost reduction is a positive development, making CCUS more economically viable and attractive to potential investors.

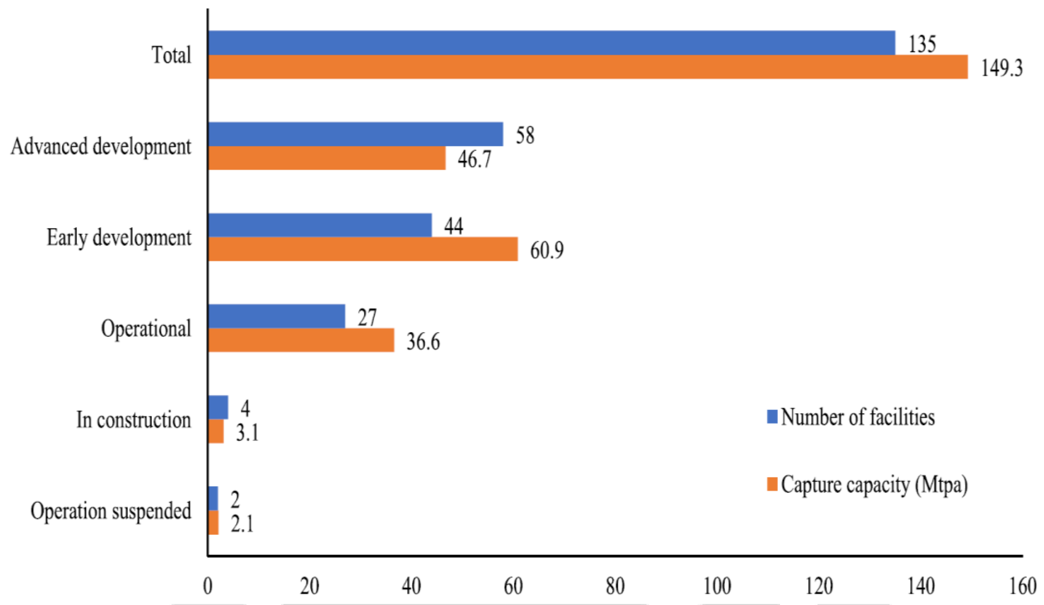

Fig. 4. Numbers of global CCUS facilities and their mean CO_2 capacity by different stages of development in 2021 (Global CCS Institute, 2021).

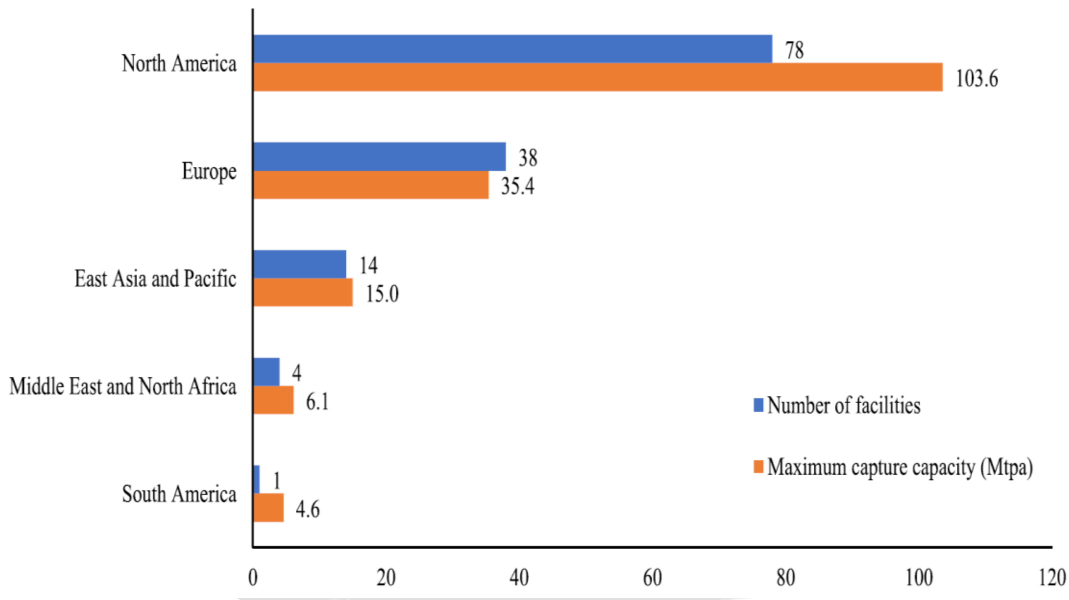

Fig. 5: The number of global commercial CCUS facilities and their maximum CO_2 capture capacity by world region in 2021 (Global CCS Institute, 2021).

	Relative deployment of CCUS by application					
	Power (coal)	Power (gas)	Industry(cement, steel and chemicals)	Low-carbon hydrogen production	Other fuel transformation	Carbon removal (BECCS and DAC)
China	Large	Limited	Large	Large	Moderate	Moderate
Europe	Limited	Limited	Large	Moderate	Moderate	Large
India	Large	Limited	Large	Moderate	Limited	Large
Middle East	Limited	Large	Limited	Large	Large	Large
North America	Moderate	Large	Moderate	Large	Large	Large
Rest of World	Limited	Limited	Large	Moderate	Moderate	Large

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Fig. 6: Deployment of CCUS by application in different countries (IEA, 2020)

THE CRUCIAL ROLE OF GEOSCIENCE IN CARBON CAPTURE, UTILIZATION, AND STORAGE

The International Panel on Climate Change (IPCC) has established a goal of reaching net-zero emissions by 2050 (IPCC, 2023). The 2015 United Nations International Climate Change Conference in Paris (COP21) was a watershed moment, with 197 national parties committing to keeping global warming well below 2°C. They discussed various de-carbonization technologies, including carbon capture, utilisation, and storage. Geoscience plays a crucial role in these processes, particularly in monitoring and storage. Recent research has validated five methods of geologic carbon storage through several demonstration and pilot projects worldwide. These methods include storage in depleted oil and gas fields, use of CO_2 in enhanced hydrocarbon recovery, storage in saline formations and aquifers, injection into deep unmineable coal seams, and in-situ/ex-situ carbon mineralisation (Albertz *et al.,* 2023).

This points out geoscience's role in securely sequestering carbon dioxide (CO_2) without posing environmental risks. Geoscientists' roles in storing CO_2 underground encompass the following: selection and characterisation of storage sites, evaluation of caprock integrity, site monitoring and verification, and risk assessment and management. Geoscientists are responsible for identifying potential risks associated with CO_2 storage, such as leakage or induced seismicity, and developing strategies to mitigate these risks.

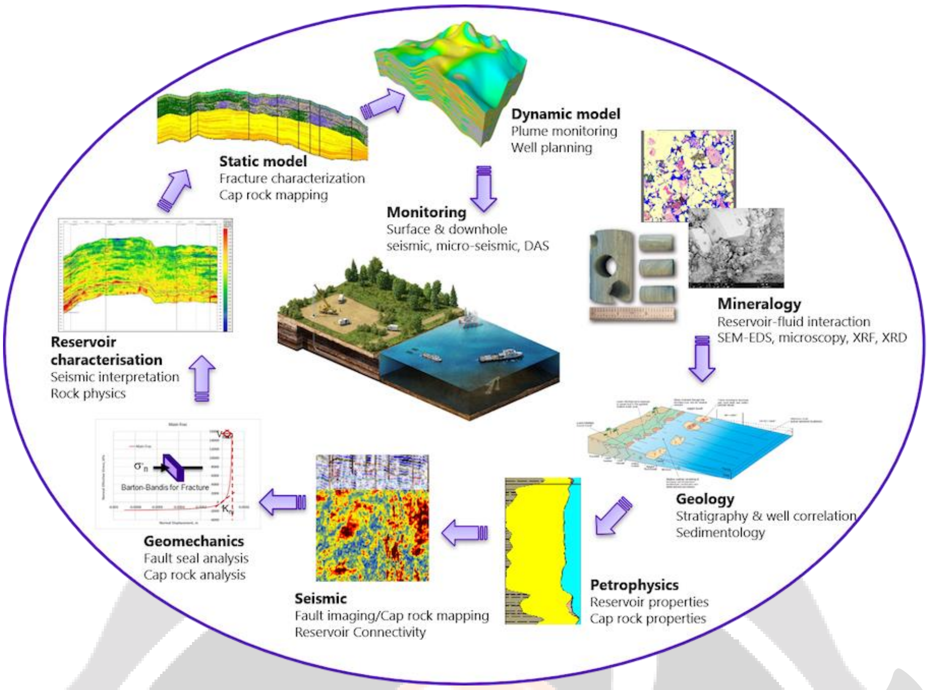


Fig. 7. This schematic integrated workflow for CCUS reservoir characterisation outlines the essential steps and the disciplines involved. (Source: CGG)

Detailed geological surveys such as studying rock types, structures, and subsurface geology, identify suitable formations for CO_2 storage. Geophysical surveys are initiated to locate suitable basins, depleted oil and gas fields, deep saline aquifers, and unmineable coal seams, and geological data are analysed to understand subsurface structures and suitability for CO_2 sequestration. Once a potential site is identified, geoscientists focus on reservoir identification, evaluating the critical properties of the rock formations. They assess porosity to determine the rock's capacity to hold CO_2 and permeability, which affects how easily CO_2 can flow through the rocks. Adequate storage of CO_2 underground requires that the integrity of the storage site be evaluated as well. Geoscientists assess the integrity of impermeable rock that acts as a seal to prevent CO_2 escape to the surface. To prevent the escape of sequestered carbon dioxide, caprock in the storage site must be continuous and without fractures. Geomechanical analysis is also conducted to understand the mechanical properties of the storage site, predicting how the injection of CO_2 will affect the rock formations and prevent issues such as induced seismicity.

Furthermore, geoscientists carry out detailed site characterisation through advanced techniques such as 3D seismic imaging, core sampling, and fluid flow modelling. These techniques help create a detailed geological model of the storage site, which is used to simulate CO_2 injection and predict its behaviour over time. This modelling is essential for understanding the long-term stability of the stored CO_2 and ensuring the site's safety and effectiveness.

Geoscientists play a pivotal role in selecting and characterising storage sites for CCUS. Their work involves detailed geological surveys, reservoir identification, ensuring storage integrity, and advanced site characterisation. These efforts ensure that selected sites can safely and effectively store CO_2, significantly mitigating climate change. Their expertise and dedication are crucial in this global effort.

APPLICATION OF CCUS IN THE ENERGY SECTOR FOR CLEANER ENERGY

The International Energy Agency (IEA) Energy Technology Perspectives report highlights the central role CCUS must play as one of four key pillars of global energy transitions alongside renewables-based electrification, bioenergy, and hydrogen (IEA, 2020a). CCUS applications in the energy sector include decarbonising fossil fuel power plants, Bioenergy with Carbon Capture and Storage (BECCS), hydrogen production, hydrogen from biomass, geothermal energy integration, synthetic fuels, and energy storage (Fig. 8).

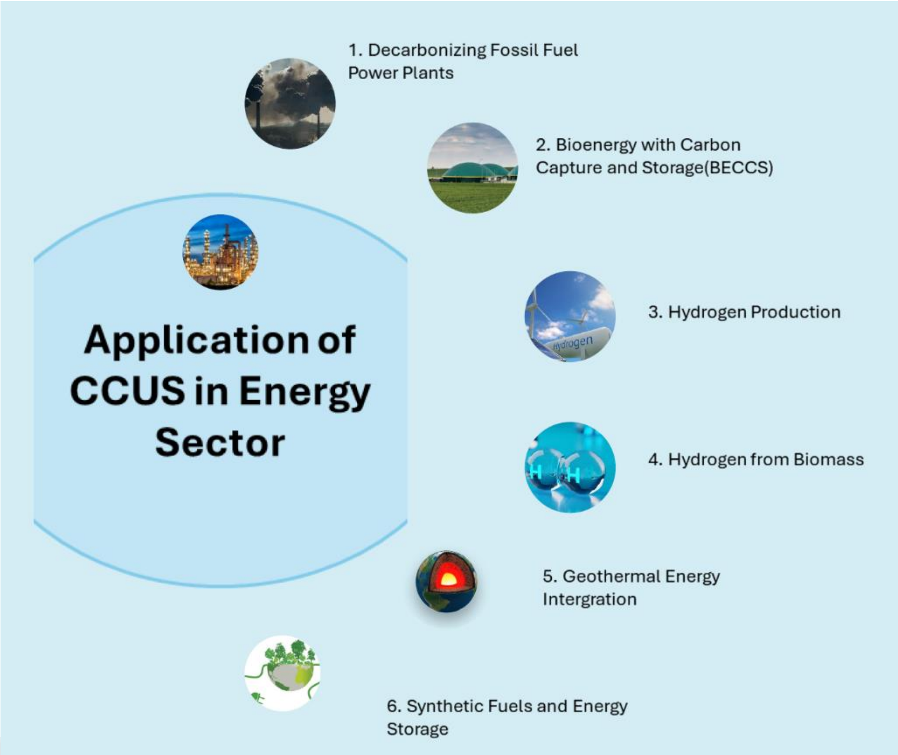


Fig. 8: Application of CCUS in energy sector

The world's increasing energy demand is met mainly by burning fossil fuels, e.g. coal, oil, and natural gas. The burning of fossil fuels releases CO_2. Fossil fuel combustion and coal mining liberate greenhouse gases (GHGs) into the atmosphere, which are linked to climate change responses (IPCC, 2007). These gases present in the atmosphere pose a significant threat to life on Earth. Therefore, decarbonising fossil fuels from coal-fired or natural gas-fired power plants is a critical application of CCUS technology. Retrofitting existing facilities with CCUS technology in coal-fired power plants can significantly cut CO_2 emissions. This mainly involves post-combustion capture, where CO_2 is captured from the flue gases after combustion using solvents, solid sorbents, or membranes. Natural gas-fired power plants can also benefit from CCUS. Pre-combustion capture in integrated gasification combined cycle (IGCC) plants allows CO_2 to be captured before combustion by converting natural gas into hydrogen and CO_2. Additionally, oxy-fuel combustion, which uses pure oxygen instead of air, produces flue gas, mostly CO_2 and water vapour, simplifying the capture process.

BECCS (Bioenergy with Carbon Capture and Storage) is another application of CCUS, which involves capturing and permanently storing CO_2 emissions generated from processes where biomass is utilised to produce energy or materials. Examples include biomass-based power plants, pulp mills for paper production, cement kilns, and biofuel production plants. Waste-to-energy facilities can also produce harmful emissions when biogenic fuels are utilised. BECCS can be considered carbon-neutral if biomass is sustainably grown and processed into fuel, which is then combusted, releasing CO_2 recently captured from the atmosphere by the biomass. Practical evaluation through life cycle assessments is essential to determine if a specific BECCS technology and application genuinely achieves harmful emissions. Factors such as biomass sustainability, land management practices, emission timing, and the scope of application influence the overall carbon balance (IEA Bioenergy, 2013).

Globally, more than ten facilities actively capture CO_2 from bioenergy production (Table 1). The Illinois Industrial CCS Project stands out as the largest, with a capacity to capture 1 million tons of CO_2 annually and dedicated CO_2 storage. Other projects, predominantly pilots, utilise captured CO_2 for Enhanced Oil Recovery (EOR) or other purposes (IEA, 2020).

Table 1. Leading bioenergy with CCS/CCU projects currently operating worldwide (IEA,2020)

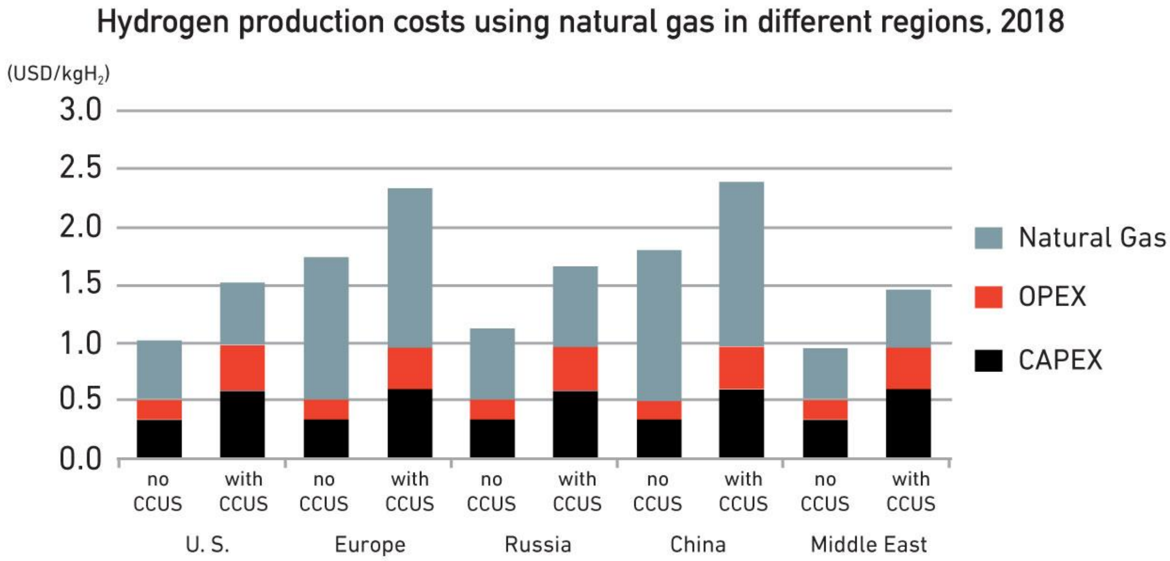
Plant	**Country**	**Sector**	**CO_2 storage or use**	**Startup year**	**CO_2 capture capacity (kt/year)**
Stockholm Exergi AB	Sweden	Combined heat and power	-	2019	Pilot

Arkalon CO_2 Compression Facility	United State	Ethanol production	Storage	2009	290
OCAP	Netherland	Ethanol production	USE	2011	<400*
Bonanza BioEnergy CCUS EOR	United State	Ethanol production	Storage (EOR)	2012	100
Husky Energy CO_2 injection	Canada	Ethanol production	Storage (EOR)	2012	90
Calgren Renewable Fuels CO_2 recovery plant	United State	Ethanol production	Use	2015	150
Lantmannen Agroetanol	Sweden	Ethanol production	Use	2015	200
AlcoBio-refinery CO_2 recovery plant	Belgium	Ethanol production	Use	2016	100
Cargil wheat processing CO_2 purification plant	United Kingdom	Ethanol production	Use	2016	100
IIinois industrial Carbon Capture and Storage	United State	Ethanol production	Dedicated storage	2017	1000
Drax BECCS plant**	United Kingdom	Power generation	-	2019	Pilot
Mikawa post combustion capture plant	Japan	Power generation	-	2020	180
Saga City waste Incineration plant	Japan	Waste to Energy	Use	2016	3

Hydrogen offers tremendous promise as a clean energy solution, yet current production methods commonly called 'grey hydrogen' rely almost entirely on coal and natural gas. The technology used for hydrogen production from natural gas is Steam Methane Reforming (SRM). It is likely to remain the dominant production technology due to favourable economics. Adding Carbon Capture, Utilization, and Storage (CCUS) technology to SMR plants can effectively neutralise emissions from hydrogen production. The result is blue hydrogen. Applied to hydrogen production, the proven CCUS technology can turn grey hydrogen into blue hydrogen for a greener future.

While producing hydrogen from low-carbon energy is costly, there is hope. The declining costs of renewable energy could reduce the cost of producing hydrogen from renewable electricity – 'green hydrogen', i.e. approximately 30% or more by 2030. As production costs decline, the potential exists for hydrogen to play a significant role as a clean energy source. On the other hand, when pure hydrogen is used as a fuel, the only byproducts are heat and water. When hydrogen is combined with carbon-reliant energy sources to create industrial feedstocks, it lowers the emissions of those feedstocks. Adopted hydrogen as clean energy at that scale could put countries on course to achieve the zero-emissions future outlined in the 2015 Paris Agreement on climate change.

A recent study by the IEA has highlighted that hydrogen production from natural gas with CCUS is more expensive than grey hydrogen. However, as the price of CO_2 emissions increases and CCUS technology becomes cheaper, the price gap will narrow in the coming years, making blue hydrogen ever more competitive. In different regions, costs vary for Hydrogen production by using natural gas (see Fig. 9).



Notes: kgH_2 = Kilogram of hydrogen; OPEX = Operational expenditure; CAPEX in 2018; SMR without CCUS = USD 500 – 900 per kilowatt hydrogen (KWH_2); SMR with CCUS = USD 900 – 1600 kWH_2, with a range due to regional differences. Gas price = USD 3-11 per million British thermal units (MBtu) depending on the region

Fig. 9: Cost of Hydrogen production in different regions (IEA,2019)

Combining Geothermal energy production with Carbon Capture, utilisation and storage (CCUS) is an innovative approach that enhances energy sustainability and contributes to climate change mitigation goals. Geothermal energy production has seen innovative applications, mainly through enhanced geothermal systems (EGS), evolving to use captured CO_2 rather than water as the primary working fluid. This adaptation not only improves the efficiency of heat extraction but also provides a dual benefit of storing CO_2 underground. Traditional geothermal systems inject water into hot rock formations to extract heat and generate electricity. However, using captured CO_2 instead of water offers several advantages. CO_2 can operate at higher temperatures and pressures than water, potentially increasing the efficiency and output of geothermal plants. Moreover, injecting CO_2 into underground formations can aid in its long-term storage, contributing to carbon sequestration efforts and helping mitigate greenhouse gas emissions. This approach aligns with advancements in Carbon Capture, Utilization and storage (CCUS) technologies, where CO_2 captured from industrial processes or directly from the atmosphere is repurposed in geothermal applications.

Synthetic fuels and energy storage offer promising applications for CCUS. Synthetic fuels provide an alternative pathway from low-carbon electricity to energy-dense fuel applications. The Fischer-Tropsch process is pivotal in producing synthetic fuels to substitute traditional fossil fuels used in long-distance transportation. Using carbon monoxide (CO) as its primary carbon source enables the creation of various synthetic fuels, including kerosene, diesel, and heavy fuel oil. These synthetic fuels are crucial in addressing energy security concerns and reducing dependence on conventional petroleum sources. Moreover, they offer potential environmental benefits by reducing particulate matter and greenhouse gas emissions compared to their fossil fuel counterparts. The versatility of the Fischer-Tropsch process in generating a range of fuels underscores its significance in advancing sustainable energy solutions for the future. Synthetic hydrocarbon fuels and BTL with CCUS start to make inroads in the late 2020s. By 2070, synthetic hydrocarbon fuels make up 10% (254 Mtoe) (IEA, 2020). Synthetic hydrocarbon fuels make the most significant contribution in aviation, accounting for almost all synthetic fuel use and 40% of the total demand for kerosene in 2070 (biofuels account for 35%) (Fig. 10). Presently, only about 40% of the energy input results in the final liquid synthetic fuel product, though process optimisations hold promise for improving overall conversion efficiency beyond 45%. Recent initiatives like the Norsk e-Fuel project aim to establish European commercial plants utilising these technologies. For instance, their first plant is slated to commence operations in 2023 with an annual production capacity of 10 million litres (Norsk e-Fuel, 2020).

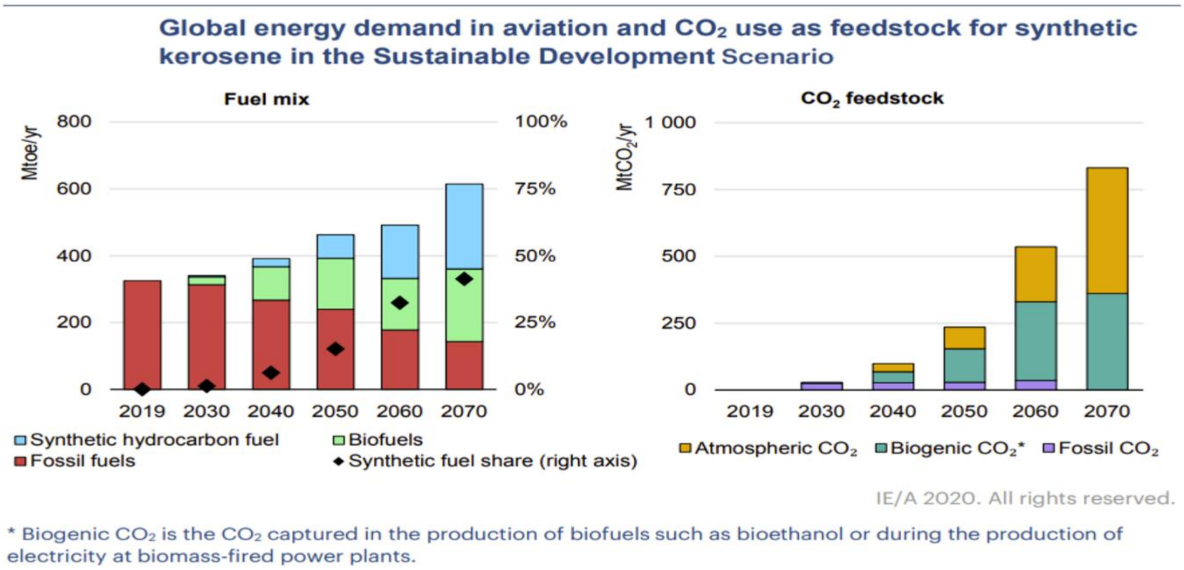


Fig. 10. Graph for Expected Demand for Synthetic Fuels by 2070. (IEA, 2020)

Captured CO_2 offers a transformative opportunity to produce chemicals that serve as a viable form of energy storage. Through advanced carbon capture utilisation and storage (CCUS) technologies, CO_2 can be converted into valuable chemicals such as methane, methanol, and formic acid. These chemicals can be stored effectively and, when required, converted back into energy through combustion, chemical reactions, or as fuel for various applications. Integrating CO_2-derived chemicals into energy storage systems enhances grid stability, supports intermittent renewable energy sources, and contributes to the global transition towards a more sustainable and resilient energy infrastructure.

OPPORTUNITIES AND CHALLENGES ON A GLOBAL SCALE

Carbon capture, utilisation, and storage (CCUS) present diverse opportunities for advancing global clean energy transitions. Carbon capture, utilisation, and storage (CCUS) present significant opportunities beyond reducing emissions; they also transform captured CO_2 into valuable products and clean energy sources. One key opportunity is converting CO_2 into hydrogen fuel through processes like steam methane reforming (SMR) coupled with CCUS. Another promising avenue is Enhanced Coal Bed Methane (ECBM), where CO_2 is injected into coal seams to enhance methane recovery. This process increases the recovery of natural gas and sequesters CO_2 underground, effectively reducing greenhouse gas emissions. ECBM can leverage existing coal mining and natural gas infrastructure, making it a practical and economically viable option in regions with extensive coal reserves. CCUS technologies facilitate the production of synthetic fuels such as methanol and synthetic natural gas (SNG) from captured CO_2. Moreover, CCUS supports the development of carbon-negative technologies by enabling the direct capture of CO_2 from the atmosphere or bioenergy facilities. These captured emissions can then be permanently stored underground or utilised in industrial processes, contributing to net-negative emissions and enhancing climate resilience. Overall, CCUS mitigates greenhouse gas emissions and catalyses the transition towards a sustainable energy future by enabling the production of clean energy carriers and fostering innovation in carbon management technologies.

However, despite these opportunities, CCUS faces significant challenges that hinder its widespread adoption. The application of CCUS depends on complex factors such as the size and age of existing power plants and industrial facilities, which may vary significantly across different countries and regions. The availability and proximity of suitable CO_2 storage sites are critical considerations, as they affect the feasibility and cost-effectiveness of CCUS projects. Furthermore, the cost and availability of alternative low-carbon technologies, such as renewable energy sources and energy efficiency improvements, pose competition to CCUS as a preferred emissions reduction option. Public acceptance and regulatory frameworks also play pivotal roles in determining the success of CCUS deployments, as concerns over safety, environmental impacts, and long-term liability associated with CO_2 storage must be addressed. Overcoming these challenges requires coordinated efforts among governments, industries, and communities to develop robust policies, infrastructure, and investment frameworks that support the sustainable deployment of CCUS technologies globally. The level of climate ambition and the strength of associated policy measures will also be critical factors in determining CCUS's role in each country (Table 2).

Table 2. National and regional factors favourable to CCUS deployment(IEA, 2020)

Factor	Potential role of CCUS where:
Existing energy assets	❖ Large fleet and low average age of fossil-based power. ❖ Station and industrial plants. ❖ High economic and/or social cost of retiring assets early.
Current and future energy needs	❖ Heavy reliance on fossil fuels in current power generation and industrial energy mix. ❖ Strong projected growth in electricity demand, industrial output and aviation. ❖ Limited availability of alternative (non-fossil) energy sources. ❖ Large planned role for low carbon hydrogen in energy system.
Domestic energy resources	❖ Abundant low-cost coal and gas resources. ❖ Abundant and low-cost renewable (for BECCS and DAC)
Industrial profile	❖ Large cement, steel or chemical industry, where availability of alternative decarbonization option is currently limited. ❖ Good potential availability of low-cost CO_2 to produce low carbon materials.
Climate policies	❖ Ambitious climate target including for net zero emissions that require deep emissions cut across all sectors and/or carbon removal technologies. ❖ Comprehensive climate plan and supportive measures for low carbon technologies.
CCUS readiness	❖ Availability of CO_2 storage resources within reasonable proximity to emission sources. ❖ Easy access to CO_2 transport infrastructure and/or the possibility to repurpose existing assets. ❖ Legal and regulatory frameworks that enable and encourage CCUS deployment. ❖ Public acceptance of CCUS as an emission abatement option.

4. CONCLUSION

CCUS technology is a promising avenue for mitigating the adverse effects of increased atmospheric carbon dioxide, a critical driver of climate change. Carbon capture, utilisation, and storage technology are crucial in reducing emissions from various sectors, particularly energy production. The integration of CCUS with coal and natural gas power plants and bioenergy and hydrogen production demonstrates its versatile application in transitioning towards cleaner energy systems.

Though CCUS has demonstrated great potential, its deployment faces several challenges, including policy support, public acceptance, and economic viability. However, increasing global commitment to climate goals and recent advancements drive renewed interest and investments in CCUS technologies. CCUS represents a critical component of the international strategy to combat climate change. By capturing, utilising, and storing carbon emissions, this technology not only helps in reducing atmospheric CO2 levels but also facilitates the transition to a more sustainable and cleaner energy future. Continued research, investment, and policy support are essential to overcoming the challenges and maximising the potential of CCUS globally.

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