

Comprehending the Significance of Carbon Capture, Utilization, & Sequestration (CCUS) & its necessity within the Context of India

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Keywords

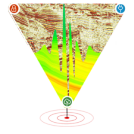
Carbon Capture, CCUS, Emissions, Enhanced Oil Recovery, Enhanced Coal Bed Methane Recovery, CO₂ sequestration, CO₂ storage potential

Abstract

For the past three decades, India's CO₂ emissions have risen at a compound annual growth rate of 3.1%, the source primarily being the consumption of fossil fuels. Carbon Capture, Utilization & Sequestration (CCUS) can be considered one of the most effective technologies for controlling the trends in this regard as well as in the achievement of net zero emissions. The carbon footprint resulting from various anthropological activities can be reduced by either using the captured CO₂ to produce certain green chemicals including aviation fuels or by sequestering large amounts of CO₂ in geological formations which in certain cases can also help in Enhanced Hydrocarbon Recovery (EHR). CCUS can reduce emissions from large, stationary sources like power stations & industrial sources as well as generate negative emissions by Direct Air Capture (DAC). Negative emissions refer to the process of removal of CO₂ from the atmosphere. The concept of CCUS isn't very new, but the advancements in the technology & its rate of deployment have fallen short of expectations due to commercial considerations & lack of proper policies. However, it has become a subject of renewed global attention in recent years, holding out to the promise of a rapid scaling-up of investment, wider deployment & accelerated innovation. Furthermore, the paper sheds light upon the state of emissions & potential for deployment of CCUS in India. This includes the capacities for utilization pathways such as Enhanced Oil Recovery (EOR), permanent storage options like Saline Aquifers & estimates of their capacity for storage of captured CO₂. Additionally, certain key steps which need to be funded and/or promoted by the Government of India have been discussed.

Introduction

India, after the US and China is the 3rd largest emitter of CO₂ in the world with estimated annual emissions summing up to about 2.6 gigatonnes per annum (gtpa). The Government of India is aiming to reduce CO₂ emissions by 50% by the year 2050 and thereby reach net zero by 2070. The advancements & growth in the renewable power sector have been a key success story for India in the context of the clean energy transition. However, only 1/3rd of the estimated total CO₂ emissions in India are a result of the power sector & and this will continue to abate as renewables increasingly replace fossil fuel-based power generation. The growing industrial economy results in another third of the aggregate emissions which are hard to abate and will continue to increase unless new carbon abatement technologies are deployed. Therefore, India's carbon footprint reduction pathway must embrace technologies that will ebb emissions from hard-to-abate industrial sectors as well as work in ebbing away emissions from the residual baseload power generation systems. CCUS has humungous potential for decarbonizing the hard-to-abate industrial sector as well as the power sector. CCUS (Carbon Capture, Utilization, and storage) refers to a suite of technologies that focus on the capture of CO₂, either from large point sources like power generation plants & large industries or directly from the air and its subsequent Storage and Utilization through various pathways. The decarbonization challenge for India is to identify scalable and economically sustainable solutions for the decarbonization of sectors that contribute to 70% of emissions. CCUS has an important and critical role to play, especially for India to accomplish net zero by 2070, as envisioned by the Hon'ble Prime Minister of India.



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What is CCUS and how does it work?

The International Energy Agency (IEA) defines Carbon Capture, Utilization, and Storage (CCUS) as a group of technologies for capturing CO₂ from large and stationary CO₂ emitting sources, such as fossil fuel-based power plants and other industries. The CO₂ can also be captured directly from the atmosphere. If not used on site, the captured CO₂ can be compressed and transported by pipeline, ship, rail or truck to be used in a range of applications. The CO₂ can also be injected into deep geological formations like depleted hydrocarbon reservoirs or saline formations which trap the CO₂ for permanent storage (*Figure 1*).

The use of CO₂ for industrial purposes can provide a potential revenue stream for CCUS facilities. The majority of CCUS facilities rely on revenue from the sale of CO₂ to oil companies for EOR (Enhanced Oil Recovery), but there are many other potential uses of CO₂, such as in the production of synthetic fuels, chemicals, and building materials.

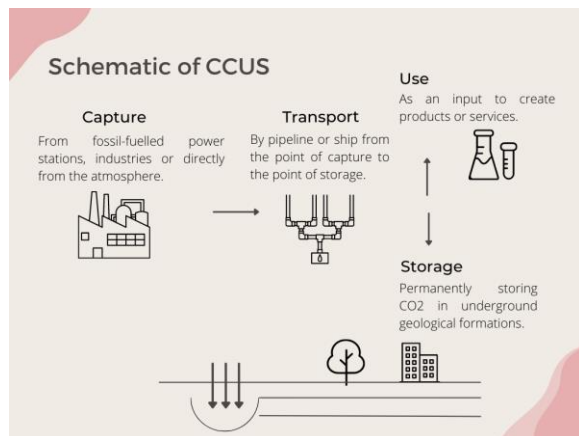


Figure 1: A schematic of the working of CCUS.

The technology can facilitate the removal of CO₂ directly from the atmosphere to counter emissions from sectors where reaching zero emissions is not feasible technically, or economically. The strategic value of CCUS lies as a climate mitigation option that can be applied to a variety of sectors in several ways to facilitate emissions reduction in almost every part of the global energy system. The four main ways in which CCUS can contribute to the transition of the global energy

system to net zero emissions – tackling emissions from the existing energy infrastructure, low carbon hydrogen production, a solution for sectors with hard-to-ebb emissions and removing carbon from the atmosphere- are mentioned below.

Abating emissions from the existing energy infrastructure

Tackling emissions from the existing power stations & industrial plants is crucial for the global clean energy transition. If these continue to operate as they currently do until the end of their technical lives, these assets will generate 600 Gt CO₂- virtually leaving no room for any other emissions-generating assets if the climate goals are to be met.

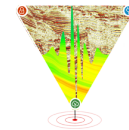
Coal-fired power generation accounted for approximately 1/3rd of the global CO₂ emissions. 60% of this carbon fleet could still be operating in 2050. Similarly, 40% of the current primary steel-making assets could still be operating in 2050 unless retired early. (Special Report on Carbon Capture, Utilisation, and Storage, Energy Technology Perspectives 2020, IEA).

The only alternative to retiring these plants early or remodelling them to work at lower capacities or with alternative fuels is CCUS. Retrofitting CO₂ capture equipment to existing plants can enable the continued operation of these plants and the associated infrastructure and supply chains but with significantly reduced emissions. This will also preserve employment & economic prosperity in regions that rely on emission-intensive industries.

A solution for sectors with hard-to-abate emissions

These sectors include heavy industry (which accounts for almost 20% of global CO₂ emissions) as well as long-distance modes of transport including, aviation, road freight, and maritime shipping. In these sectors, alternatives to fossil fuels are generally expensive or impractical. For example, using electricity to generate heat is more expensive than using fossil fuels for the same. Or using electricity to power aircraft is impractical.

For some sectors like the cement industry, it is practically impossible to achieve net zero emissions without CCUS. This is because cement production requires heating limestone (Calcium Carbonate) to



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produce calcium oxide and CO₂. This process is not dependent on the burning of fossil fuel, yet it accounts for about 2/3rd of the total emission from cement production. With no alternative to producing cement, capturing, and permanently storing the generated CO₂ is the only viable option along with using the captured CO₂ as inputs for other products or services.

CCUS can also facilitate the emissions from natural gas processing. Natural gas deposits can contain large amounts of CO₂ which must be removed before the gas can be sold for LNG (Liquified Natural Gas) production. This CO₂ is usually released into the atmosphere whereas it can be reinjected into geological formations or can be used for EOR.

Low carbon hydrogen production

Currently, the majority of hydrogen production relies on coal or natural gas gasification, a process that necessitates CO₂. By utilizing captured CO₂ from different sources, this approach enables the production of low-carbon hydrogen at an economical rate.

The expense of hydrogen production equipped with Carbon Capture, Utilization, and Storage (CCUS) can be approximately half that of electrolysis-based hydrogen production, which involves splitting water into hydrogen and oxygen. While the cost of electrolytic hydrogen production is expected to decrease over time, CCUS-equipped hydrogen production remains a viable choice, especially in regions where fossil fuels and CO₂ storage options are affordable.

Removing CO₂ from the atmosphere

There are various approaches to extracting carbon from the atmosphere, including nature-based solutions like afforestation and reforestation.

The significance of carbon removal in meeting ambitious climate targets was underscored by the Intergovernmental Panel on Climate Change (IPCC) in its Special Report on 1.5°C. Among the 90 scenarios evaluated by the IPCC, 88 assumed some degree of net-negative emissions to restrict future temperature rises to 1.5°C. Carbon removal offers the ability to neutralize or compensate for emissions in areas where direct mitigation is currently technologically challenging or excessively costly,

such as certain industrial processes and long-distance transportation.

Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture and Storage (DACS) represent contributions from the energy sector towards carbon removal. If effectively deployed, they can also help compensate for slower advancements in emissions reduction outside the energy sector. BECCS refers to the energy pathways where CO₂ is captured from a biogenic source and permanently stored. Unlike BECCS, the viability of DACS is determined not by the availability of sustainable biomass, but rather by the accessibility of low-cost energy sources.

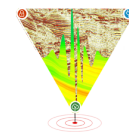
Current implementation of CCUS

Currently, there are 21 facilities worldwide dedicated to carbon capture, utilization, and storage (CCUS), with the capacity to capture up to 40 MtCO₂ annually. Some of these facilities have been operational since the 1970s and 1980s, when CO₂ capture began at natural gas processing plants in the Val Verde region of Texas. The captured CO₂ was then supplied to local oil producers for enhanced oil recovery (EOR) operations.

Over time, CCUS deployment has expanded to encompass more geographical areas and applications. The first significant project involving CO₂ capture, injection, and dedicated storage with monitoring was initiated in 1996 at the Sleipner offshore gas field in Norway. This project has successfully stored over 20 MtCO₂ in a deep saline aquifer. The commercial viability of the project was made possible by a CO₂ tax imposed on offshore oil and gas activities by the Norwegian government in 1991 (IEA, 2016).

The United States has been the primary hub for CCUS deployment, housing nearly half of all operational facilities. This is primarily due to the presence of an extensive CO₂ pipeline network, demand for CO₂ in EOR activities, and public funding programs implemented after the global financial crisis of 2008-09. In the past decade, other countries such as Australia, Brazil, Canada, China, Saudi Arabia, and the United Arab Emirates have also commissioned CCUS facilities.

Early CCUS projects often focused on industrial applications where capturing CO₂ incurred relatively low additional costs, approximately USD 15 per



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tonne of CO₂. For instance, in natural gas processing, separating CO₂ from the gas is typically necessary to meet market requirements or before liquefaction for LNG production to prevent damage to production facilities caused by CO₂ freezing.

Until the 2000s, the majority of globally captured CO₂ at large-scale facilities originated from gas processing plants. However, other sources now contribute approximately one-third of the total captured CO₂ (Figure 2).

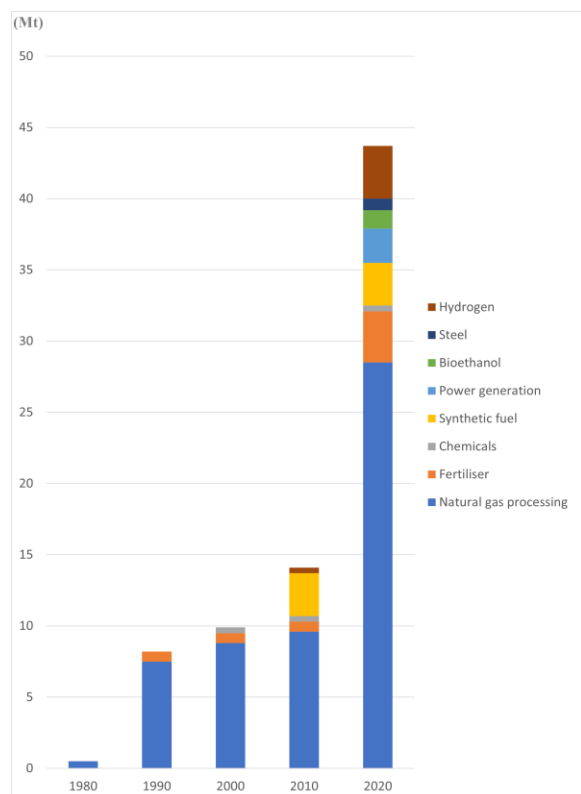


Figure 2: Operational CCUS facilities characterized by their respective applications, 1980-2020; Based on GCCSI (2020), Facilities Database, <https://co2re.co/FacilityData>.

CO₂ storage potential in India

Captured CO₂ can be utilized or stored permanently to achieve a net-zero outcome. Utilization options include urea manufacturing, conversion to other chemicals (methane, methanol, ethanol), and emerging applications like aggregates. Alternatively, captured CO₂ can be stored in underground geological reservoirs such as depleted oil and gas reservoirs (for enhanced oil production or EOR),

deep saline aquifers, and basaltic rock formations. This section will focus on the potential CO₂ storage capacities in India for utilization pathways like EOR and ECBMR, as well as permanent storage options like saline aquifers and basaltic storage.

Enhanced Oil Recovery (EOR)

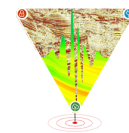
Oil recovery techniques can be classified into primary, secondary, and tertiary methods. Primary techniques rely on natural reservoir pressure and pumps to extract oil, but the recovery rate is only around 10%. Secondary techniques involve injecting water or gas into the reservoir to drive oil towards production wells, resulting in a recovery rate of 20-40% of the original oil in place. Tertiary techniques, such as thermal recovery (steam injection), gas injection (CO₂ injection), and chemical injection (polymer or surfactant use), are employed to further enhance production. These techniques can recover 30-60% of the original oil in place.

In CO₂ EOR, compressed CO₂ is injected into the reservoir, where it becomes miscible with oil at high densities. This causes oil to swell and reduces its viscosity, allowing it to move away from rock formations and towards production wells. A minimum pressure is required for CO₂ and oil to be miscible. To prevent the escape of low-viscosity CO₂ from the reservoir, water and CO₂ are injected alternately.

India in total has 26 sedimentary basins out of which 7 are category 1 basins (commercial oil & gas exploration is ongoing). The CO₂ storage capacities for these basins as estimated by Vishal et al. are given in Figure 3. Thus, as of now, a total of 3.4 Gt of storage capacity is available in the category 1 sedimentary basins of India.

Basin	Storage Capacity (mt CO ₂)
Krishna-Godavari	658.69
Mumbai	1597.24
Assam shelf	667.48
Rajasthan	312.52
Cauvery	99.5
Assam -Arakan	67.01
Cambay	657.25
Total	3402.43

Figure 3: CO₂ EOR capacity estimates for category 1 sedimentary basins. (CCUS Policy Framework & its Deployment Mechanism in India, NITI Aayog, November 2022).



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Enhanced Coal Bed Methane Recovery (ECBMR)

In Enhanced Coal Bed Methane Recovery (ECBMR), CO₂ is injected into unmineable coal seams under supercritical conditions. The injected CO₂ accumulates in the coal cleats, forming a dense gas phase. This CO₂ is absorbed in the coal, displacing coal bed methane (CBM) and improving its primary recovery. ECBMR, like CO₂ EOR, offers the potential for permanent CO₂ storage, while the recovered methane can help offset carbon capture costs. This approach can be particularly suitable for thermal power plants located near coalfields, making it a viable option.

Most Indian coal reserves consist of anthracite and bituminous coal, which are found throughout the Gondwana basin and in certain regions of northeastern India. These coalfields are abundant in coal bed methane (CBM), with CH₄ to CO₂ ratios ranging from 1:2 to 1:3. Given the proximity of numerous large-scale thermal power plants to these coalfields, ECBMR offers a promising opportunity for both CO₂ utilization and storage.

The current CO₂ storage capacity by ECBMR is estimated at **3.5 to 3.7 Gt** of CO₂ by Vishal et al.

Storage in deep saline aquifers

Captured CO₂ can be stored permanently in deep saline aquifers, although unlike EOR and ECBMR, there are no direct economic benefits associated with CO₂ injection in these aquifers. However, deep saline aquifers cover extensive areas, offering significant potential for storing large volumes of CO₂.

Deep saline aquifers are composed of porous rock formations containing abundant but unusable saltwater. The water in these aquifers, known as formation liquid or brine water, has a high salt/mineral content that makes it unsuitable for human use. The brine water is trapped by an impermeable rock layer called the caprock.

Supercritical CO₂ can be injected into these saline aquifers. Due to its higher density, the brine water displaces the injected CO₂, causing it to rise towards the caprock and become trapped within the saline aquifer. The total theoretical storage capacity is estimated at about **291.1 Gt** CO₂ by Vishal et al. This estimation will increase upon availability of data for seven category III basins for which calculations could not be done due to a lack of data.

CO₂ storage in basalts

Basaltic rock contains divalent cations such as Ca, Mg, and Fe. When CO₂ is dissolved in water, it can react with these cations to form stable carbonate minerals, making basaltic rock a viable and secure method for long-term CO₂ sequestration.

Compared to mineralization in saline aquifers, the reaction kinetics of CO₂ in basalt rocks are faster due to the higher presence of iron, calcium, and magnesium oxides. The widespread occurrence of basalts on Earth's surface has sparked growing interest in research and development programs focused on CO₂ storage in basaltic formations. The storage capacities of the two-basalt formations of India (Deccan Volcanic Province & Rajmahal traps) are estimated at **315.85 Gt** by McGrail et al. (2006) and at **97.38 - 252.27 Gt** by Sænbjörnsdóttir et al. (2014).

Overall CO₂ storage capacity in India

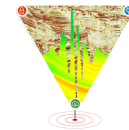
A summary of the CO₂ storage capacity assessment for the four options is presented in *Figure 4*.

Storage Pathways	Theoretical Storage Capacity (Gt)
EOR	3.4
ECBMR	3.5-3.7
Deep Saline Aquifers	291
Basalts	97-315
Total	395-614

Figure 4: A summary of the overall CO₂ storage capacity in India. (CCUS Policy Framework & its Deployment Mechanism in India, NITI Aayog, November 2022).

Conclusion & Discussion

Currently, carbon capture in India is primarily limited to specific industries and applications where it is integrated into the production process, such as urea manufacturing. India's annual urea production reaches approximately 24 million metric tons, and captured CO₂ is utilized in the conversion of ammonia to urea. Additionally, some CO₂ is captured during the gas conditioning process in the gasifiers of Reliance Industries Limited in Jamnagar (with a pet coke gasification capacity of 10 million metric tons per annum) and JSPL in Angul (with a coal gasification capacity of 2 million metric tons per annum). However, a significant portion of the



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captured CO₂ is currently released into the atmosphere rather than being utilized or stored.

Although there are a few pilot-scale carbon capture projects underway, such as the amine and biological enzyme-based carbon capture plant by IOCL R&D and Tata Steel's pilot-scale carbon capture plant in Jamshedpur, which captures 5 tonnes of CO₂ per day from blast furnace gases, there are no commercially operational large-scale CCUS projects in India.

Studies conducted thus far indicate a significant capacity for CO₂ storage in India. However, additional measures are required to translate the potential for geological storage of CO₂ into actual implementation within the country.

NITI Aayog's 'CCUS Policy Framework & its Deployment Mechanism in India, November 2022' suggests certain key steps which need to be funded and promoted by the Government of India:

1) Source-link mapping to prioritize regions and basins with the highest potential for CO₂ storage in terms of capacity and feasibility. This process involves mapping and analyzing the sources of CO₂ emissions and identifying suitable locations for storage based on their storage capacity and viability.

2) Conducting pore space mapping and characterization to identify the most promising regions and basins for CO₂ storage. This involves undertaking geological characterization and exploration activities specifically aimed at assessing the suitability of these areas for CO₂ storage.

3) To establish the necessary CO₂ storage infrastructure in the identified prospective regions in India, the following steps would be involved:

- **Characterization:** Characterization & geological mapping of the potential regions for assessing the potential to store CO₂ in different types of geological formations.

- **Validation:** To validate the potential CO₂ storage sites in each region, it is crucial to conduct lab-scale field projects in various types of storage fields, including Enhanced Oil Recovery (EOR), Enhanced Coal Bed Methane Recovery (ECBMR), saline aquifers, and basaltic formations. These field projects aim to gather essential information about CO₂ storage sites. By implementing these projects, it becomes possible to assess the feasibility, capacity, and effectiveness of each type of storage field, further

validating the most promising CO₂ storage sites within each region.

- **Commercial-scale development:** Undertaking commercial-scale (at least 1mtpa) CO₂ injection in selected sites would help in proving the permanence of CO₂ storage in the subsurface and monitoring the extent & movement of CO₂ plume.

A few other steps include engagement with relevant stakeholders to address their concerns related to the CCUS projects & providing training programs and fostering collaborations with international experts & organizations to enhance expertise & ensure the successful implementation of CO₂ storage projects.

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