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# Decarbonizing the Atmosphere Using Carbon Capture, Utilization, and Sequestration: Challenges, Opportunities, and Policy Implications in India

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**Abstract:** The IPCC's (Intergovernmental Panel on Climate Change) special report highlights the urgent necessity of limiting global warming to 1.5 °C, prompting a vital exploration of decarbonization methods. Carbon capture and sequestration (CCS) play a pivotal role in reducing carbon dioxide emissions from industrial processes and power generation, helping to combat climate change and meet global decarbonization goals. This article focuses on the economic prospects and market potential of carbon capture technologies in India, specifically in utilizing captured $CO_2$ in the power, petrochemicals, and fertilizer sectors. It also emphasizes decarbonization through carbon sequestration involving geological storage to extract carbon dioxide from the environment, ultimately reducing greenhouse gas emissions. This article stresses the need to develop new technologies for carbon capture, utilization, and sequestration to overcome technical and financial barriers. It highlights the importance of improving efficiency, reducing costs, and scaling up these technologies for widespread adoption. Additionally, this study delves into the essential policy and regulatory frameworks for CCUS implementation, emphasizing the need for standards and laws to ensure safety, environmental protection, and effective monitoring in the Indian context. The research findings and recommendations provide valuable insights for future CCUS implementation, advancing sustainable decarbonization efforts in India and globally.

**Keywords:** carbon capture and storage; atmosphere; global warming; human health; environment



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## 1. Introduction

The total annual global carbon dioxide ($CO_2$) emission was around 43.1 billion tons in 2019 from human activities, which was an all-time high, breaking the previous record from 2018 [1]. Hence, there is a need to shift the global emission control strategy from achieving 'carbon neutral' to 'carbon negative.' However, carbon-negative technologies are far more challenging and are still mostly in their developmental stage. It is expected that the carbon-negative technologies will be implemented between 2050 and 2100.

Carbon capture, utilization, and storage (CCUS) refer to techniques aimed at capturing and securely storing $CO_2$ that would otherwise be released into the atmosphere. The goal is to reduce $CO_2$ emissions and combat climate change. In India, opinions on CCUS are divided, with some supporting it as a means of achieving carbon-neutral industrialization and boost domestic production, potentially leading to cost savings and job creation. However, critics view CCUS as prolonging the use of fossil fuels, especially coal, which may impede India's transition to cleaner renewable energy sources. Various methods are used for capturing and storing $CO_2$, such as chemical absorption, physical separation, oxy-fuel separation, membrane separation, calcium and chemical looping, and direct separation. Each method carries its own energy and economic implications, with costs varying depending on the source of $CO_2$ and transportation and storage factors.

India is actively exploring CCUS initiatives, particularly in hard-to-abate heavy industries (thermal power, plants, steel, cement, aluminum, ammonia, petrochemical industries, etc.) and transport sectors where reducing emissions with low-carbon alternatives is challenging. India's power and industrial sectors generated over 1600 Mtpa of $CO_2$ in 2020, which is around 60% of the total annual emissions (Figure 1). For example, the cement industry generates 60% of $CO_2$ from its raw materials—limestone. With the economic growth anticipated in the present decade, the $CO_2$ emissions in these sectors are expected to touch 2300 Mtpa by 2030. Thus, the Indian government has launched the 'Mission Innovation Challenge' and partnered with other countries to foster research and development in $CO_2$ capture, separation, storage, and utilization technologies. Private initiatives, including large-scale carbon capture and utilization plants, are also underway. Supporters of CCUS in India believe it holds significant potential to reduce $CO_2$ emissions, lower oil imports, and bring economic benefits. They point to successful CCUS investments in Norway, China, and the USA, where integrated projects have been deployed on a commercial scale. Despite the promising aspects of CCUS, India faces the complexity of managing coal's role as a primary energy source, revenue generator, and social support mechanism while also pursuing decarbonization and cleaner energy alternatives. Integrating CCUS into the existing coal infrastructure may offer a practical solution for achieving emission reduction goals without causing major economic and social disruptions.

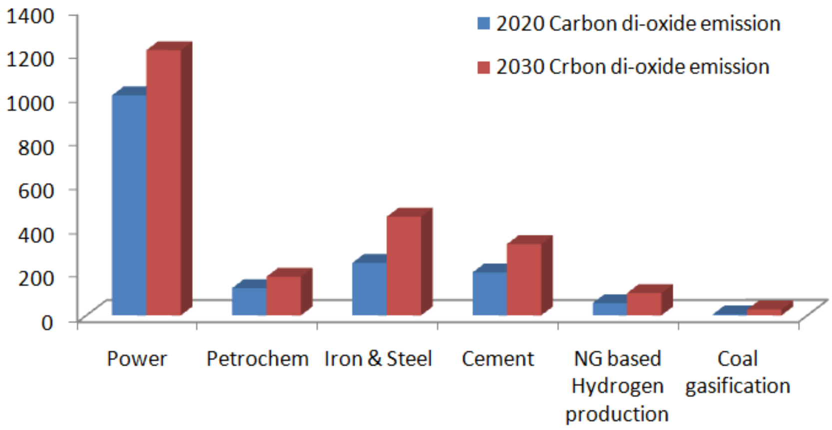


**Figure 1.** Sector-wise $CO_2$ emission (in Mtpa) in India [2].

Carbon capture, utilization, and storage are being debated as crucial for sustainable development in this context [2,3]. India's energy demand has risen significantly, and the transition to a green economy is a government priority, including focusing on electrification and renewable energy sources [4]. However, projections indicate that fossil fuels will still be part of India's energy economy, especially for power systems and industries [2,5]. Despite this, CCUS has not yet received much attention in India's climate discussions. The crucial role of CCUS in India's low-carbon future involves research and development, finance, and policy. Limited efforts have been made to understand CCUS's potential and geological assessments due to high capital and generation costs [6,7]. The technology's economic viability and political and economic aspects play vital roles in its adoption.

Apart from its contribution to climate change initiatives, CCS's potential in achieving long-term deep decarbonization is also debated. While currently economically unviable, long-term analysis stresses the need for CCS in the energy system [8]. CCS could significantly impact India's energy system transformation, reducing the share of non-hydro renewable energy and easing the pace of transition from fossil fuels. Studies suggest CCS has substantial mitigation potential in deep decarbonization scenarios in India [9].

India has committed to achieving a net-zero target by 2070, a goal that entails adopting various strategies. These strategies include diminishing the reliance on fossil fuel-based energy sources while increasing the incorporation of renewable energy. Moreover, they involve the integration of alternative energy carriers, such as hydrogen and biomass-derived fuels, and the process of decarbonizing challenging sectors, like thermal power generation, cement, steel, aluminum, ammonia, and petrochemical industries. However, India faces a pivotal juncture in its economic growth trajectory. As it pursues its ambition to become a USD 30 trillion economy by 2050, the per capita energy demand in the country is set to rise significantly. The transition from fossil fuels to renewables is expected to be gradual due to India's pressing energy requirements for its expanding population. Consequently, India's carbon emissions are likely to persist for a few more decades until the country achieves its economic aspirations.

The European Union's implementation of the Carbon Border Adjustment Mechanism (CABM) introduces a fair pricing system for carbon-intensive goods entering the EU market with the aim of discouraging carbon-intensive industrial processes outside the EU. This mechanism is anticipated to encompass products like cement, iron, steel, aluminum, fertilizers, electricity, and certain hydrogen imports. Consequently, India needs to proactively take measures to decrease its carbon emissions associated with the production of these goods. One way to achieve this is by adopting technologies like carbon capture, utilization, and storage (CCUS), which have the potential to capture substantial amounts of $CO_2$.

Given the prevailing conditions, it seems improbable for India to achieve its net-zero objectives or advance its economy without capturing and storing a substantial portion of its $CO_2$ emissions. An estimated 60% of the overall $CO_2$ output is recommended for capture and storage; approximately 20% could be transformed into chemicals, and the remaining portion should be addressed through biological means. The advancement and implementation of CCUS technologies hold the promise of notably curtailing greenhouse gas emissions, thereby facilitating the attainment of the goals set for Conference of parties (COP27). Nevertheless, there is a dearth of studies within the publicly accessible literature that specifically address the Indian context. Hence, this article takes on the task of delving into the challenges, prospects, and policy frameworks associated with CCUS in India.

## 2. Carbon Capture Technologies

Carbon capture technologies offer ways to capture $CO_2$ emissions from different sources and either store them safely or convert them into useful products. There are several methods to capture $CO_2$ [10,11].

- *Post-Combustion Capture:* This technique captures $CO_2$ from the exhaust gases of power plants and industries that burn fossil fuels. This method uses chemicals to absorb $CO_2$, but it can be energy-intensive. Post-combustion capture has a higher technological readiness level (TRL) than any pre-combustion technology.
- *Pre-Combustion Capture:* It focuses on capturing $CO_2$ before burning fossil fuels, particularly in power plants and hydrogen production facilities. This method separates $CO_2$ from the gas mixture before combustion.
- *Oxy-Fuel Combustion:* It involves burning fuels with pure oxygen, thereby creating a $CO_2$-rich gas that can be more easily captured.
- *Direct Air Capture (DAC):* It directly removes $CO_2$ from the air using various techniques. This can help reduce both ongoing and historical $CO_2$ emissions. However, it is important to note that the present article does not prioritize DAC, as it is still in its nascent stages, and the economics (current estimates suggest a cost range of approximately USD 400–800 per ton of $CO_2$) and operational scalability have not been firmly established.

Once captured, the $CO_2$ can be used in different ways. The captured $CO_2$ can be transformed into valuable products, such as fuels, chemicals, and building materials, offering economic benefits while reducing emissions. Carbon sequestration involves storing $CO_2$ underground in places like empty oil and gas reservoirs or deep aquifers. Proper site selection and monitoring are vital to prevent leakage.

A diagram explaining the carbon capture technologies in fossil-fuel-powered power plants is shown in Figure 2, and various methods and techniques for $CO_2$ capture are shown in Figure 3. There are many $CO_2$ separation technologies for $CO_2$ capture. Chemical absorption and physical absorption are used to mitigate emissions. Chemical absorption involves reacting $CO_2$ with solvents like Monoethanolamine (MEA), Diethanolamine (DEA), Methyldiethanolamine (MDEA), or Diisopropanolamine (DIPA), thereby creating compounds that are later separated during regeneration. It efficiently removes low-concentration $CO_2$ at low pressures but demands flue gas purification and has high energy consumption. In contrast, physical absorption dissolves $CO_2$ in inert solvents, such as Rectisol or Selexol [12,13]. It is effective at higher $CO_2$ pressures but less profitable with low concentrations. Regeneration is energy-efficient, and solvents are less corrosive. This method is common in ammonia production, methanol synthesis, and valuable chemical processes, offering a range of $CO_2$ capture solutions [14].

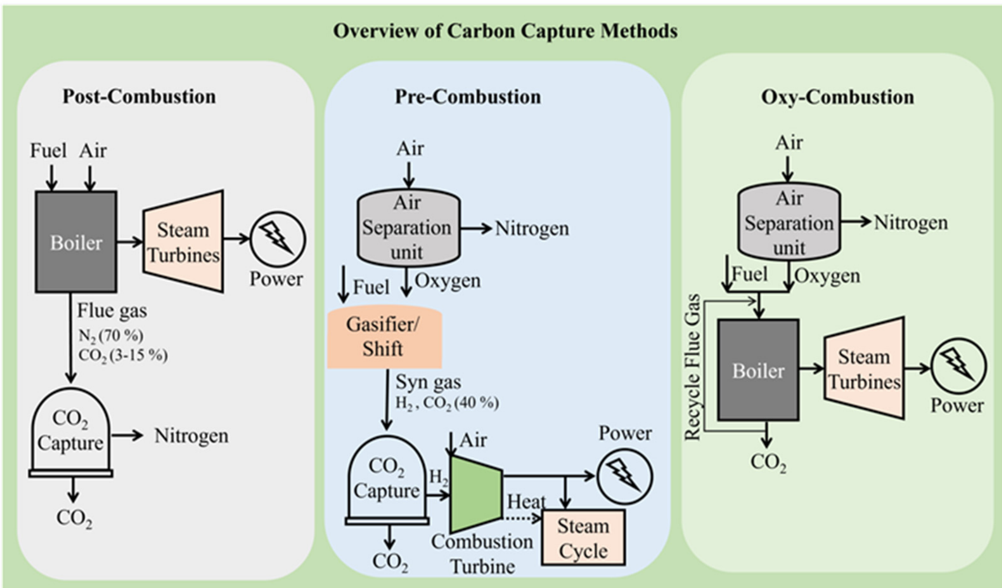


**Figure 2.** Overview of carbon capture configuration.

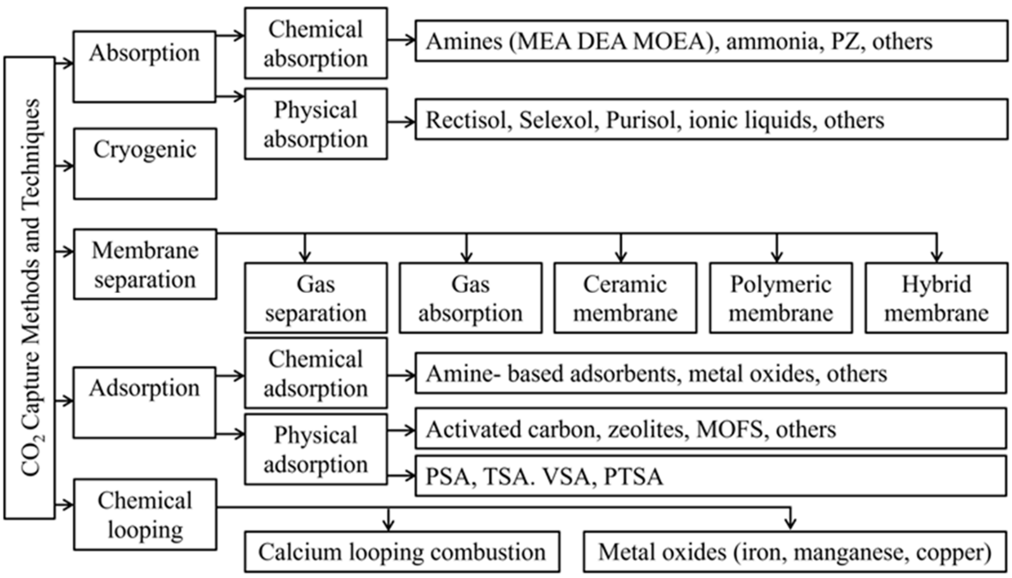


**Figure 3.** $CO_2$ separation technologies. [MEA: Monoethanolamine, DEA: Diethanolamine, PZ: Piperazine, PSA: Pressure swing adsorption, TSA: Thermal swing adsorption, VSA: Vacuum swing adsorption, PTSA: Pressure temperature swing adsorption].

Cryogenic carbon capture (CCC) is a method for separating $CO_2$ from gas by cooling and compressing it to induce phase changes. CCC achieves high $CO_2$ recovery and purity, which is especially effective for gases rich in $CO_2$. However, it is not cost-effective for low $CO_2$ concentrations, like boiler exhaust gas, due to high energy requirements. Cryogenic carbon capture involves multiple compression and cooling stages, and its efficiency depends on different dew/sublimation points of gas components, which can lead to corrosion and fouling issues. Benefits include no need for chemicals and easy $CO_2$ transport, but high energy consumption is a drawback due to water removal processes [15–17].

Membrane techniques offer an innovative way to separate $CO_2$ from flue gas mixtures. They employ thin, semi-permeable membranes that divide gases into permeate and retained streams using pressure, temperature, or electric forces [18,19]. These membranes come in various types, categorized by their source, structure, and characteristics. Organic membranes, especially polymeric ones, are widely used due to their durability and excellent gas separation properties. Inorganic membranes made from materials like carbons, zeolites, ceramics, and metals also show promise. Membranes can be classified by their structure, including porous, homogeneous solids, those with electric charges, or those containing selective carriers. Membrane separation offers benefits, such as avoiding common issues seen in packed columns and better gas flow control. However, it becomes less efficient at low $CO_2$ concentrations, high temperatures, and in the presence of corrosive gases, especially for long-term use. There are two main types of membrane separation methods: gas separation membranes operate through dissolution and diffusion, while gas absorption membranes rely on transferring $CO_2$ through pores into an absorbing liquid. Commercial applications are primarily found in gas separation membranes for natural gas processing [20].

Chemical looping combustion (CLC) is a $CO_2$ reduction method that divides combustion into oxidation and reduction phases [21,22]. Two reactors, an air reactor and a fuel reactor, are connected internally, with a solid oxygen carrier (OC) moving between them. Transition metal oxides like copper, cobalt, iron, manganese, and nickel serve as OCs, requiring specific properties like high oxygen capacity, reactivity, stability, and more. CLC offers benefits, such as cleaner air reactor exhaust and easy $CO_2$ separation, thereby reducing energy and separation costs. Yet, it has challenges like OC instability and slow reactions. Calcium looping (CaL) is another $CO_2$ capture method for sectors like coal power and biomass plants. CaL uses CaO-based sorbents and reversible carbonation and calcination reactions. Calcium looping has minimal impact on plant efficiency and can potentially improve it. However, sorbent deactivation issues increase costs and waste removal challenges [23,24].

Adsorption is a promising method for $CO_2$ separation in flue gas due to its high capacity, potential for purity, automation, and simplicity. However, challenges include cost-effective adsorbent production, handling impurities, temperature control, and adsorbent replacement costs. The process is cyclical, involving adsorption where $CO_2$ is captured and desorption for regeneration. Adsorption efficiency depends on the adsorbent's structure and chemical properties, as influenced by flue gas temperature. There are two types: physical (used in cement, chemical, and iron and steel industries) and chemical (used in research phases) [25].

However, there are challenges and opportunities, particularly in India. The energy-intensive nature of capture methods could strain India's power infrastructure. Public awareness, laws, regulations, and incentives are crucial for successful implementation. India's unique industrial landscape and energy mix need to be considered for effective application. They can be a win–win, reducing $CO_2$ while enabling economic growth through carbon utilization. Yet, a united effort involving government, industry, and public support is essential to overcome challenges and make CCUS a success in India's sustainable journey.

## 3. Utilization Applications of Captured $CO_2$

Captured carbon dioxide can be turned into useful products through carbon utilization, offering a sustainable approach to combat climate change and promote economic growth [11,26,27].

- *Industries and Energy:* Industries can use captured $CO_2$ to create synthetic fuels, replacing conventional fossil fuels and reducing emissions. $CO_2$ can also be integrated into making cement, concrete, and construction materials, lowering their carbon impact. Concrete can embody carbon (around 45–55%) in the form of concrete mixing and solid wastes. Sequestering $CO_2$ in the form of concrete is relatively easy, and there is market potential for it. Furthermore, RKDF University (Bhopal, India) has collaborated with CSIR India on initiatives related to CCUS and green hydrogen.
- *Chemicals and Materials:* $CO_2$ can be used to make chemicals like methanol, which is a building block for plastics and other products. It can also be turned into sustainable materials like polymers and composites, conversion of CO, catalytic hydrogeneration of $CO_2$, hydrogen rich syngas, synthesis of olefins and aromatic compounds, and other value-added goods. One plant built in Singrauli, Madhya Pradesh (India) utilizes $CO_2$ of the steel mill gases to produce methanol. Breathe Applied Sciences Pvt. Ltd., based in Bangalore, has achieved significant advancements by converting carbon dioxide emissions into methanol at an exceptional value. Basaltic soil helps in converting sequestered $CO_2$ into crystallized minerals in a few years.
- *Agriculture and Food:* Captured $CO_2$ can improve crop growth in greenhouses and serve as a base for fertilizers, enhancing agricultural productivity. In the food industry, it can carbonate beverages and extend product shelf life.
- *Algae and Biofuels:* $CO_2$ can help grow microalgae, which can be converted into biofuels, animal feed, or valuable chemicals, reducing reliance on traditional fuels. The National Aluminum Company (NALCO) has setup a bio-CCS-based pilot plant in Angul, Odisha (India). Flocculation-based $CO_2$ capture from wastewater is also an emerging area.
- *Oil Recovery:* $CO_2$ can aid in enhanced oil recovery, increasing oil production while storing $CO_2$ underground. However, the pros and cons of this approach need careful consideration.

India can benefit from utilizing captured $CO_2$ across sectors. This not only reduces emissions but also supports the transition to a circular economy. By integrating carbon utilization into climate and industrial policies, India can contribute to global climate efforts while reaping economic and environmental rewards. The adoption of new carbon-capture technologies could help reduce industrial emissions further, particularly for hard-to-abate sectors like cement, oil, and gas and chemicals. There could also be potential for utilizing the captured carbon in applications like chemical production, artificial limestone, and construction blocks. There are some private initiatives as well. Since October 2016, Tuticorin Alkali Chemicals and Fertilisers Limited (TACFL, Tuticorin, India), in partnership with Carbon Clean (London, UK), have been operating the world's first industrial-scale carbon capture and utilization (CCU) plant near Chennai. Installed on a coal-fed boiler, the plant is designed to capture 60,000 tons of $CO_2$ per year and convert it to soda ash. The project is privately financed, and the cost is estimated to be just USD 30/t$CO_2$, which is much lower than the USD 60–90/t$CO_2$ typically observed in the global power sector [7]. A start-up incubated at IIT Bombay-Urjanovac enables facile conversion of $CO_2$ to commercially high-value products, like pharmaceutical-grade calcium carbonate. If the technology to create solid carbon from $CO_2$ gas can be developed in the future, the potential uses of $CO_2$ would be diverse, and the value chain would also be improved.

## 4. Carbon Sequestration Methods

$CO_2$ capture and storage are considered some of the most potentially scalable technologies for mitigating greenhouse gases emissions, contributing 19% of the required reduction of GHG emissions by 2050 [28]. They can play a significant role in carbon handling, which is required for the transition of the global low-carbon energy economy. The primary benefit of these technologies is their ability to retrofit existing thermal power plants. This reduces around 90% of $CO_2$ emissions from flue gases. $CO_2$ storage in geological formations is an important part of CCUS. Geological storage of $CO_2$ simply means storing $CO_2$ permanently beneath the earth's surface through any method. It includes underground injection of captured $CO_2$ for storage or utilization of liquid $CO_2$ in industries from emission sources. Various oil and natural gas reservoirs have already been tested and used for storing $CO_2$ for expanding fuel recovery. The other benefit includes enhanced recovery of methane from coal seams and shale gas. The selection of a geological reservoir and method is crucial to assure the success of any activity and also to get the most out of the capacity of $CO_2$ to be stored. Furthermore, $CO_2$ in the subsurface reacts geochemically with the rock and water, which further affects the storage capacity and effectiveness [29].

### *4.1. Depleted Oil and Gas Reservoirs*

Geological sequestration can be performed in oil and gas fields, which are now unutilized due to the uneconomical production of hydrocarbons. Basin characteristics that are essential for a geologic $CO_2$ storage site are already present in these formations. Fuel production wells can be utilized for $CO_2$ injection. However, $CO_2$ storage capacity becomes notably low due to excess basin pressure, which damages the caprock, and the considerable leakage risk due to the abandoned wells [30,31]. $CO_2$ storage in depleted oil and gas reservoirs is taken as a valuable storage alternative with several benefits. There also exist infrastructures, such as injection wells and pipelines. These reservoirs have been comprehensively studied before and during the hydrocarbon exploration stage. The technique of injection of gases to enhance production has been widely used within the oil and gas industry and, therefore, such experience could be useful for the storage process [32].

### *4.2. Deep Unmineable Coal Beds*

$CO_2$ can also be sequestered with the enhanced coal bed methane (ECBM) process for the recovery of methane from coal seams. Produced methane is used as an energy source. $CO_2$ can raise methane recovery to about 90% from 50% compared to other conventional methods. $CO_2$ is then stored in the coal bed after the recovery of methane. However, its technical feasibility mainly depends on the coal's permeability because of its depth variation with the influence of effective stress on coal fractures [33,34].

Cleats present within the coal matrix provide some permeability to the system. In the coal matrix, large numbers of micro-pores are present, due to which it becomes capable of adsorbing significant amounts of gases. The affinity of coal is higher towards $CO_2$ in comparison with methane. Therefore, the injected $CO_2$ can replace previously adsorbed methane and be permanently stored while enhancing methane production [35]. Another advantage of this method is its location in the vicinity of many coal-fired power plants. Thus, this reduces $CO_2$ transportation costs.

### *4.3. $CO_2$ Storage during Enhanced Oil Recovery*

$CO_2$ can be utilized for enhanced oil recovery (EOR) from mature oil fields. $CO_2$ sequestration with this method has the additional benefit of EOR. Over the last decade, $CO_2$ has been used in over 70 EOR operations around the world. This technology may help to extract 30–60% more of the crude oil that is initially available in the well but could not be extracted using the conventional method [36]. EOR has been performed using various techniques, including gas, thermal, chemical, or plasma-pulse injection, the most common being the gas injection.$CO_2$ is considered the most suitable option as it could reduce the oil viscosity, and it is also cheap compared to other gases [37]. The injected $CO_2$ mixes with the oil, causing it to swell, thereby reducing its viscosity. The injection of $CO_2$ increases the pressure in the oil reservoir, allowing the oil to flow towards the production well, thereby increasing the production rate.

Globally, $CO_2$-EOR can produce 470 billion barrels of additional oil and store 140 billion metric tons of $CO_2$, which is equivalent to the GHG emissions from 750 sizeable 1 GW size coal-fired power plants over 30 years [38].

### 4.4. Ocean Storage of $CO_2$

$CO_2$ can be stored in deep oceans with a minimum depth of 1000 m below sea level. As deep ocean water is unsaturated with $CO_2$ and can dissolve it, this technology may be feasible. Ocean storage of $CO_2$ includes injection of $CO_2$ to form hydrates either on land or at great depths in the ocean to dissolve at suitable conditions. Various models have predicted that over the next several centuries, the oceans will eventually take up most of the $CO_2$ released to the atmosphere as $CO_2$ is dissolved at the ocean surface and subsequently mixed with deep ocean waters. $CO_2$ can be injected and stored in the deep ocean at an estimated rate of 2 GtC/year. The major challenge of this technology lies in its environmental threats [39,40].

### 4.5. $CO_2$ Storage in Saline Aquifers

Large, deep formations of porous sand and limestone rocks, which have a large amount of saltwater in their pore spaces, are known as saline aquifers. Dumping of $CO_2$ from emission sources into saline aquifers is recommended as an important and beneficial method to reduce greenhouse gas emissions into the atmosphere. In this method, the $CO_2$ captured from the source is compressed to an enormously large pressure of nearly 95 bar or more. The brine is then displaced by the injected $CO_2$ occupying the porous area in the saline aquifers [41]. Deep saline aquifers can be outlined by their extended structural quality. Some attributes, like thickness, porosity, absolute permeability, permeability, anisotropy, and heterogeneity, have much influence in determining the amount of $CO_2$ to be injected, which aquifers can sustain. The low permeable caprock prevents the migration of $CO_2$ vertically to the top of the aquifer through pore spaces, and, thus, $CO_2$ is trapped for the long term. Caprocks are generally shales, mudstones, or evaporate layers. The caprock should ideally be un-faulted. The role of caprock in the storage of $CO_2$ has been investigated by several authors [42,43].

It has been established that several saline aquifers in the world with a depth greater than 1 km are found within sedimentary basins, which can store a large amount of $CO_2$ because of their large pore quantity and steep permeability, which minimize the quantity of significant injectors and encourage the dissipation of pressure [44]. According to De Silva et al. [45], worldwide, there is sufficient capacity in deep saline aquifers, with almost 10,000 billion tons, which is around 20–500% of the emissions predicated from large stationary sources by 2050. The process of $CO_2$ injection into these aquifers has already been initiated by some countries.

### 4.6. $CO_2$ Trapping Mechanisms

The injected $CO_2$ is securely trapped in the reservoir by four trapping mechanisms, which are named structural trapping, residual trapping, solubility trapping, and mineral dissolution trapping. The effectiveness of the storage system depends on the combination of the same [46]. Broadly, trapping mechanisms in a saline aquifer can be classified into three categories: geological trapping, hydrodynamic trapping, and geochemical trapping [47].

Regarding geological trapping, the injected $CO_2$ can be trapped beneath the caprock (structural trapping); it corresponds to the containment of $CO_2$ initially and its safe storage. Meanwhile, $CO_2$ plume migration and its circulation in the reservoir is governed by residual and solubility trapping. Hydrodynamic trapping can be described as the migration of dissolved $CO_2$ in the reservoir at low velocities with the regional flow or at higher rates by processes like dispersion and diffusion. As the $CO_2$ plume migrates in the reservoir, it increasingly contacts rock minerals, which helps in faster trapping geochemically, thus becoming more and more stable in the mineralization trapping by reacting with rock minerals to form stable minerals. With this, $CO_2$ storage becomes more secure, with minimal leakage risks [48].

### 4.7. $CO_2$ Storage Site Evaluation Criteria

Three criteria have been defined for selecting the geological site for $CO_2$ storage: $CO_2$ storage capacity, $CO_2$ injectivity, and the containment of $CO_2$ in the site. The storage capacity indicates sufficient porous volumes for the enormous sum of $CO_2$ storage. $CO_2$ injectivity can be guaranteed with high permeability of the reservoirs and lower wellhead pressures to keep up preferred injection rates. Capable non-permeable caprocks are essential for the containment of $CO_2$ from escaping to the surface or leaking into groundwater, as $CO_2$ is less dense compared to brine. Secure $CO_2$ storage for a long time depends on various physical and geochemical mechanisms. The proper locations of plants, infrastructure, and pipelines are essential for optimum use of the capital invested and subsurface capacity to store carbon dioxide. The sedimentary basins, which are located near the emission source or power plants, are the most suitable site for $CO_2$ storage [49]. Sandstones are considered the most perfect rocks to satisfy this criterion, and these are also available abundantly at desirable depths containing saline water [50,51].

Mature basins, such as existing oil and gas production sites, have infrastructures, such as transport pipelines, injection/production wells, and access roads, that make them economical. Immature basins, such as saline aquifers, do not have such existing infrastructure. In developing countries like India, the priority is to increase per capita GDP and living standards, which may be given higher priority than the deployment of GHG-mitigating technologies, such as CCS. Also, land access for these projects might be a challenge. These scenarios must be considered before site evaluation. There should be awareness campaigns to highlight the importance of global climate change and the effects of these storage projects for the local as well as the global public. These projects should be promoted as a measure to address the environmental challenges of the communities, not as some corporate projects.

### 4.8. Challenges in $CO_2$ Storage

CCS application in the energy industry has some noteworthy impediments. CCS may help in diminishing the absolute expense of battling environmental change by almost 30% without any carbon capture technology. However, the high capital cost of this technology causes a challenge towards its progression. The total expense of the CCS technology is controlled by the carbon capture cost, which is 75% of the total expense. This may bring about an increase in the prices of electricity between 30 and 90%. This is because of the higher energy requirement in capturing as well as compressing the $CO_2$. This significantly reduces the overall energy conversion efficiency from 48% to 36%. For example, if 50% of domestic thermal power has CCS integrated into it, the energy sector will utilize an extra 65.27–261.10 million tons of standard coal. The costs of electricity prices from an old thermal plant retrofitted with CCS technology are cheaper than those of a new plant with CCS [52,53].

To gain confidence in the technology, larger field demonstration projects are needed worldwide. Various scientific experiments and industrial experiences strongly suggest that sequestration is safe when practiced in an appropriate site. Carbon sequestration is successfully implemented in Norway on a pilot scale and a massive geo-engineering scale. Equinor, a Norwegian company, runs Northern Lights, which is the most successful CCS project to date. However, managing hundreds of sources injecting $CO_2$ into a single sedimentary basin requires a high level of knowledge sharing and project coordination, as well as research and development support. Also, for environmental protection, monitoring and long-term care programs must be developed. A robust public policy framework must support the development of these institutions [54,55].

#### 4.8.1. Challenges in $CO_2$ Leakage

There might be a possibility for leakage of the injected $CO_2$ from the reservoir to the upper rocks or aquifer or to the surface. Various circumstances may cause this leakage, such as (a) $CO_2$ leaking into the upper aquifer via faults present in the lower aquifer, (b) the pressure of injected $CO_2$ exceeding the capillary pressure, causing it to pass through pores, (c) the risk of $CO_2$ migrating through a gap or any abandoned well in the caprock into an elevated aquifer, and (d) the risk of dissolved $CO_2$ escaping into the atmosphere or the ocean. Mechanical integrity, either internal or external, plays an essential role in the injection well performance and in the avoidance of $CO_2$ leakage from an active or abandoned well. It is suggested that, generally, leakage rates should not be more than 0.01%/year for all scenarios of leakage rates [56]. This rate can be set as a performance indicator for any $CO_2$ sequestration project. Also, in $CO_2$ transportation in pipelines, flow behavior and impurities present in $CO_2$ could cause accidental leakage or bursting out. A quantitative risk assessment is performed to assess the $CO_2$ leakage amount, $CO_2$ dispersion dynamics, and its impact on pipelines, human health, and the environment [57]. Several authors have identified two significant processes in the scenario of $CO_2$ leakage. First is the vertical free phase migration of $CO_2$ through fractures. Second is buoyancy-governed flow via the caprock's permeable zones. The leakage occurs due to gravity override together with viscous instability, causing the carbon dioxide to move to the top of the injection layer and bypassing large quantities of brine [58–60].

Leakage of $CO_2$ into the atmosphere could cause incompetence of the project, destruction to the $CO_2$-susceptible habitation, and health distress from exposure to $CO_2$ where humans can be exposed to an accumulation of elevated $CO_2$ concentrations. $CO_2$ leakage into the groundwater could cause acidification and probable dissolution of contaminated minerals. Induced seismicity due to CCS projects can cause potentially felt ground motion and structural damage. Effective site selection and monitoring, administrative controls over leakage pathways, and regulatory limits on pressure buildup and, consequently, induced seismicity can be management approaches to solve these problems.

#### 4.8.2. Challenges in $CO_2$ Monitoring

It is essential to monitor the injection facilities, storage reservoir, and the surrounding environment to assess the overall risk of geological $CO_2$ storage. A suitable monitoring plan should be set up to observe key features and risk assessment, manage the injection process, describe and identify leakage risk and surface escapes, provide early warnings of failure near the reservoir, and verify the storage for accounting and crediting. Also, the monitoring plan should comprise continuous monitoring of (1) fugitive emissions of $CO_2$ at the injection facility; (2) $CO_2$ pressure, temperature, and volumetric flow at injection wellheads; (3) reservoir temperature and pressure; and (4) chemical analysis of the injected material. The monitoring techniques utilized at CCS project sites depend on the information to be procured and the ecological state of the storage area. These monitoring procedures incorporate seismic imaging monitoring, geoelectrical methods, temperature logs, gravimetry methods, remote sensing, eco-chemical sampling, atmospheric monitoring, tracers, soil gas, and microbiological analysis. The monitoring of $CO_2$ at storage sites gives early warning in the case of leakage, and the information gained can be utilized in calibrating and approving predictive models [61–63].

#### 4.8.3. Geological Assessment of $CO_2$ Storage Potential

In India, an initial assessment of carbon dioxide ($CO_2$) storage is currently underway. This assessment primarily focuses on the potential for $CO_2$-enhanced oil recovery (EOR) through seismic, geomechanical, and reservoir studies, building upon preliminary surveys conducted by ONGC. Some researchers have also explored the feasibility of storing $CO_2$ in saline aquifers and basalt formations, as well as the prediction and monitoring of $CO_2$ movement using seismic methods. India possesses a geological storage capacity for carbon dioxide ($CO_2$) that spans from 500 to 1000 gigatons (GT), rendering carbon capture and storage a viable prospect. The Government of India has identified $CO_2$ EOR (enhanced oil recovery) and ECBMR (Enhanced Coal Bed Methane Recovery) as immediate strategies for $CO_2$ sequestration in the country. However, for the practical implementation of geological $CO_2$ storage, additional efforts must be backed by the Indian government. This support is particularly crucial in the areas of source-sink mapping, pore space assessment, geological characterization of the most promising $CO_2$ storage regions and basins, and the establishment of $CO_2$ storage infrastructure. This involves the validation and development of commercial-scale $CO_2$ injection programs (at least 1 million tons per annum) at selected sites. Nonetheless, the effective utilization of this potential necessitates the development of a comprehensive, long-term strategy for mapping and realization. Substantial investment in infrastructure and the formulation of initial incentives would be essential to implement widespread CCS.

## 5. CCUS Implementation in the Indian Context

With India revising its NDC (nationally determined contributions) targets, aiming for a 50% share of non-fossil-based energy sources in total installed capacity, a 45% reduction in emission intensity by 2030, and a net-zero status by 2070, the significance of carbon capture, utilization, and storage (CCUS) as a decarbonization strategy for challenging sectors becomes pronounced. CCUS plays a vital role in facilitating the production of environmentally friendly goods while harnessing our coal resources, thereby reducing imports and fostering self-reliance in the Indian economy. Notably, CCUS initiatives are poised to yield substantial employment opportunities. It is projected that capturing approximately 750 million metric tons per annum of carbon by 2050 could generate around 8–10 million full-time-equivalent (FTE) jobs in a phased manner [64]. The versatility of CCUS extends to its potential to convert captured $CO_2$ into an array of value-added products, including green urea, applications in the food and beverage industry, construction materials, like concrete and aggregates, a spectrum of chemicals encompassing methanol and ethanol, polymers (including bio-plastics), and enhanced oil recovery (EOR). These avenues offer significant market prospects within India, thereby contributing significantly to the concept of a circular economy.

Carbon capture is currently in progress at the Vindhyachal Super Thermal Power Station in Madhya Pradesh (India)—a 500 MW coal-fired power plant operated by NTPC with help from Carbon Clean and Green Power International Pvt. Ltd. This facility is specifically designed to capture 20 tons of $CO_2$ daily, employing a modified tertiary amine for the capture of $CO_2$ from the power plant's flue gas. Subsequently, the captured $CO_2$ will be combined with hydrogen to generate 10 tons of methanol per day using a catalytic hydrogenation process. In addition, the Aonla urea plant and Phulpur urea plant under IFFCO (Indian Farmers Fertiliser Cooperative Limited) use amine-based post-combustion capture with a capacity of 450 tons per day of $CO_2$ absorption. Indo-Gulf Fertilizers Ltd. (Jagdishpur, Uttar Pradesh, India) run urea plant also uses similar capture technology, with a capacity of 150 tons per day.

CCUS is a widely adopted strategy among the leading players in India's oil and gas industry. India's state-owned Oil and Natural Gas Corporation (ONGC), an enterprise engaged in oil and gas exploration and production, recently formalized a Memorandum of Understanding (MoU) with the Norwegian energy firm Equinoroto explore prospects within the low-carbon and renewable sectors, with a particular emphasis on CCUS initiatives. ONGC, in collaboration with the Indian Oil Corporation (IOCL), another Indian public-sector oil producer, is actively involved in realizing India's inaugural large-scale carbon capture project situated at the Koyali refinery, Vadodara (Gujarat). This endeavor entails capturing $CO_2$ emissions generated by the refinery and transporting them via pipelines to ONGC's Gandhar oil field (Mumbai), where the captured carbon will be stored. The integration of CCUS technology is also integral to the transitional strategies of Bharat Petroleum Corporation Limited (BPCL). BPCL is aiming to implement innovative CCUS technology in its refinery by 2026. Furthermore, Hindustan Petroleum Corporation Limited

(HPCL) has devised plans to establish a carbon capture unit within the Visakh refinery (Andhra Pradesh) by December 2023. The Gas Authority of India Limited (GAIL) has also embarked on a pilot initiative centred around utilizing microalgae to capture $CO_2$. This pioneering effort takes place in an artificial pond within GAIL's Patapetrochemical complex (Uttar Pradesh). The technology aims to convert inorganic carbon into organic compounds through the cultivation of microalgae.

Two National Centres of Excellence in Carbon Capture and Utilization (NCoE-CCU and NCCCU) are established in India with support from the Department of Science &Technology (DST), Government of India. These centers, located at IIT Bombay in Mumbai and JNCASR in Bengaluru, respectively, serve as hubs for research and innovation in carbon capture and utilization (CCU) [65]. They will map existing R&D and innovation activities, foster networks among researchers, industries, and stakeholders, and facilitate collaboration and synergy. However, it is essential to establish a value chain for the product for a sustained utilization of carbon/$CO_2$-based products/processes. IIT Bombay has established a laboratory for studying deformation in $CO_2$ flow storage due to sequestration. NTPC Energy Technology Research Alliance (NETRA) and IIT Bombay have undertaken a project to study geological carbon sequestration (GCS) potential in India.

## 6. Challenges and Opportunities

The use of carbon capture and storage/sequestration in the energy industry faces significant challenges. While CCS could potentially reduce the overall cost of addressing climate change by up to 30%, its high initial investment cost poses a major hurdle to its widespread adoption. The primary cost of CCS technology lies in carbon capture, accounting for 75% of the total expenses. Primary challenges faced by all CCS technologies revolve around the energy needed for absorption and desorption, the overall expense of $CO_2$ capture, the intricacies of transporting compressed $CO_2$ to sequestration sites, and ensuring the safety and stability of these sites. This could lead to a considerable increase in electricity prices, ranging from 30% to 90%, due to the substantial energy needed for capturing and compressing $CO_2$. This reduction in energy efficiency from 48% to 36% means that if half of the domestic thermal power plants adopted CCS, the energy sector would require an additional 65.27–261.10 million tons of standard coal. Retrofitting old thermal plants with CCS is cheaper than constructing new plants with CCS technology.

Additionally, as large-scale implementation of storage in natural systems becomes a reality, the matter of social acceptance tied to risk and safety factors will also need to evolve gradually through ongoing discussions. To build confidence in CCS, larger field demonstration projects are necessary globally. While scientific experiments and industrial experiences suggest the safety of sequestration in suitable sites, managing numerous sources injecting $CO_2$ into a single sedimentary basin demands extensive knowledge sharing, project coordination, research, and development support. One needs to be careful of fault-bound reservoirs while selecting the storage site for geological carbon sequestration. Robust public policies are needed to establish monitoring and long-term care programs for environmental protection. There are challenges associated with the cost of developing sorbents for effective $CO_2$ capture and limited demand for recycled $CO_2$ compared to the amount requiring removal from the atmosphere to combat climate change.

In India, specific challenges regarding CCUS include developing competitive CCUS technologies tailored for challenging sectors in India, addressing current technological hurdles to enhance economic viability, creating novel minerals and methods to facilitate carbon capture, investigating $CO_2$ utilization technologies for value creation, evaluating $CO_2$ storage potential through geological and biological sequestration, utilizing advanced simulation tools for efficiency and economic predictions, establishing a central/natural CCUS facility via public–private partnership, and testing global CCUS technologies under India-specific conditions for validation.

## 7. Policy and Regulatory Frameworks

A successful strategy for CCUS policy in India hinges on establishing a framework that fosters the development of viable and sustainable markets for CCUS projects. This framework must acknowledge that the private sector's involvement in CCUS is contingent on ample incentives or, conversely, penalties for inaction. Alternatively, private sector engagement could be driven by the potential for revenue through $CO_2$ sales or by earning credits for curbing emissions within carbon pricing systems. To materialize CCUS initiatives in India, a range of policy measures is essential, including direct financial grants, tax incentives, carbon pricing initiatives, operational subsidies, regulatory mandates, and public sector preferences for low-carbon goods.

Various factors rooted in local market dynamics and institutional considerations, encompassing the present state of CCUS infrastructure advancement, emission targets, domestic energy composition, and the accessibility and expense of alternative emissions reduction methods, collectively mould the most suitable selection or combination of tools for each nation. The appropriateness of each policy instrument varies based on the specific CCUS application. Certain applications of carbon capture, like the processing of natural gas, have firmly taken root and entail only minor policy adjustments due to their established nature and relatively modest costs. Conversely, other applications, such as CCUS implementation in heavy industries, like steel production, remain nascent in their developmental journey. The significant costs associated with $CO_2$ capture, particularly their influence on overall expenses, pricing, and the competitiveness of end products, present notable barriers to embracing CCUS. Government backing for project developers becomes pivotal in managing these expenses and risks associated with CCUS undertakings across the entire value chain, spanning capture, transportation, storage, and the meaningful establishment and expansion of CCUS ventures in India. After evaluating existing policy mechanisms worldwide, it is evident that India has two distinct policy avenues to consider: (a) a policy centred on carbon credits and incentives, and (b) a policy founded on carbon taxation. The fundamental elements of a policy based on carbon credits involve stimulating the adoption of CCUS and reducing capture expenses, setting up markets for products derived from carbon, and countering capture costs through financial tools and future tax prospects, making it particularly well-suited for decarbonizing current industrial infrastructure. Conversely, a policy centred on carbon tax might not provide direct impetus for CCUS, especially considering its absence in India, and the acceptance and affordability of such a tax remain uncertain. Although it might eventually become necessary in the long run, potential short-term issues could lead to industries relocating and reduced competitiveness. Moreover, the effectiveness of this approach in the short term might also raise questions.

A policy that relies on carbon credits and incentives is better suited for a developing economy like India in the short term [66]. This approach aims to initiate and foster the CCUS sector in India by providing tax breaks and monetary incentives. As time progresses, likely beyond 2050, a shift towards implementing carbon taxes becomes necessary to facilitate India's achievement of net-zero goals by 2070. This policy should also establish early-stage funding mechanisms to support CCUS projects.

The European Union has taken a hub-based, large-capacity CCS approach instead of localized sequestration at a smaller capacity at multiple locations, as the former is cost effective. It is, therefore, essential to establish regional hub and cluster models to enhance the promotion of CCUS that capitalize on economies of scale within India. This involves defining the roles of various stakeholders, such as emitters, aggregators, hub operators, disposers, and conversion agents. An industrial cluster denotes a geographical concentration of interconnected businesses, suppliers, and associated entities. In the context of CCUS, such clusters can prove beneficial for emissions-intensive facilities, encompassing both industrial units and power plants, situated in close proximity. These clusters should offer incentives for $CO_2$ emitters to come together and form a capture cluster, which can then link to a large-scale $CO_2$ storage site using a well-proportioned shared transportation system. Additionally, opportunities should be explored for utilizing captured $CO_2$ to generate low-carbon downstream products.

The components along the CCUS value chain, including $CO_2$ sources, capture, transport, injection, and storage, are united through a network of CCUS hubs and clusters. These clusters consist of multiple co-located source capture facilities, which may involve the same or different types of sources, all supplying $CO_2$ to a shared oversized transportation and storage infrastructure. As the number of $CO_2$ suppliers or emitters grows, the transport and storage framework must expand, incorporating multiple transport pipelines, injection sites, and storage formations based on the specific geological attributes of the region. The effectiveness and cost-efficiency of the CCUS infrastructure are bolstered by the presence of numerous high-concentration $CO_2$ sources located in close proximity to ample storage capacity.

The policy framework also involves granting preference to low-carbon or carbon-reduced products in government procurement bids. Additionally, it aims to stimulate innovation in low-carbon products by offering incentives through various initiatives, such as policy-linked incentives (PLI). The policy extends to ensuring that the economic benefits generated are distributed to communities that are most impacted by environmental and climate changes. Moreover, it focuses on safeguarding communities and preserving employment, particularly in sectors influenced by regulations related to clean energy.

The accounting and regulatory structure encompasses establishing controlled emission thresholds and allocations for different sectors. It also entails adopting Life Cycle Analysis/Assessment (LCA) to consider Scope-2 and Scope-3 emissions, thereby facilitating effective carbon reduction. Given that CCUS is still in its developmental phase, the policy and regulatory framework places significant emphasis on mitigating risks. This involves constraining $CO_2$ liability and clarifying ownership responsibilities among participants throughout the CCUS value chain. A comprehensive Monitoring, Verification, and Accounting (MVA) framework is also imperative to manage potential risks effectively.

## 8. Conclusions

Lifeforms on Earth encompass diverse manifestations of carbon. Carbon is ingrained in our daily routines through consumption, hydration, and utilization in various forms. However, the interference of human activities and natural processes generate carbon dioxide and other harmful greenhouse gases. According to the recent IPCC report [66], it has been determined that global net anthropogenic greenhouse gas (GHG) emissions in 2019 were estimated to be 60 gigatons of $CO_2$-equivalent (GtCO2-eq). This figure represents a 12% increase compared to the emissions in 2010 and a substantial 54% increase when compared to the levels observed in 1990. The majority of these emissions, both in terms of the overall quantity and the growth rate, were attributed to carbon dioxide ($CO_2$) emissions resulting from the combustion of fossil fuels and industrial processes. A prominent impediment to the implementation of CCUS technologies revolves around the substantial energy requirements, commonly known as parasitic energy demand. Rather than focusing solely on capturing $CO_2$, a more effective approach is to curtail its generation at the source.

The world is witnessing a surge in hydrogen generation technologies. A pivotal inquiry is how hydrogen can be harnessed to fulfill the energy requirement of CCUS. Forecasts indicate that by 2033, blue hydrogen is poised to become a predominant energy source for driving all CCUS initiatives. On a global scale, approximately 26 start-ups are engaged in developing $CO_2$ capture technologies. However, the evaluation of these technologies poses a challenge. Many CCS technologies worldwide find themselves at Technology Readiness Levels (TRL) 6 and 7. In India, CCS technologies are positioned at TRL 4 and 5. Because science and technology are integral to public policy, increased collaboration between government bodies and industries is imperative to advance the TRL of CCS technologies within the Indian context.

CCUS presents not only technological complexities but also systemic challenges. It is crucial to recognize CCUS technologies as public goods rather than exclusive patentable entities. A significant question remains: can carbon capture and storage (CCS) be economically integrated into the heart of human civilization? In contrast, the rapid adoption of hydrogen production technologies and their economic implications have garnered substantial traction. Unveiling the prerequisites for transitioning CCS into a viable technology requires thorough exploration. Addressing these queries necessitates further comprehensive research in the areas of CCUS.

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