



Full length article

Understanding initial opportunities and key challenges for CCUS deployment in India at scale

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ABSTRACT

India's CO₂ emissions have risen at a compounded annual growth rate of 3.1% over the last three decades, primarily from an increase in consumption of fossil fuels. Carbon capture, utilization, and storage (CCUS) is considered one of the most effective strategies to counter these trends by reducing the carbon footprint of existing and upcoming infrastructure. Utilization of captured CO₂ (CCU) to produce valuable green chemicals is an economically viable proposition. On the other hand, storage of CO₂ (CCS) reduces the carbon footprint by sequestering the captured CO₂ in geological formations, which in some cases, facilitates hydrocarbon recovery. This paper showcases how a multifaceted approach of combining CCU and CCS in an economically viable manner is a key factor in the maintaining of sustainable development. We discuss at a systems level, the benefits of the implementation of CCUS for India's energy security, positive path dependency, and resiliency. This is followed by a bottom-up review of the symbiotic relationship between the capture and utilization/storage. We provide an assessment of sustainable CCUS implementation by pairing state-of-the-art technologies in the field of carbon storage/utilization with possible future directions in India. We also suggest pathways for the potential and the impact of India's carbon-intensive sources in different CCUS chains such as markets for large-scale utilization of CO₂ in emerging methanol economy. Finally, we provide research and policy recommendations that would facilitate a sustainable collaborative effort across sectors in mitigating the increasing carbon dioxide in the atmosphere.

1. Introduction

With the rapid advancement in science and technology over the last century, the world has undergone transformation at a large scale in all possible ways, which has enhanced our way of living. The development has been driven primarily by energy derived from fossil fuels. As a consequence, environmental degradation and climate change have resulted by the increasing concentration of greenhouse gases (GHGs) in the atmosphere. A dominant source of these GHGs is conventional energy resources, like coal, petroleum, and their derivatives. As of 2021, the amount of global CO₂ emissions crossed 33 Gt, mainly from burning conventional fossil fuels (IEA, 2021). EIA, 2016 The emissions will

continue to escalate if we follow the business as usual (BAU) scenario (Wagner et al., 2016). The production of steel, cement, chemicals, plastics, and paper contributes to about a third of the total annual GHG emission (Allwood et al., 2010; Philbert, 2017). Terminating the use of energy resources will halt the progress of the human race; the storage of CO₂ (CCS) was hence identified as the primary technology to mitigate the increasing carbon footprint (Hoegh-Guldberg et al., 2018; UNCCS, 2015). Considering the current situation, we need to not only attain net-zero but also negative GHG emissions by 2080 if we are to restrict the global temperature rise to 2°C above pre-industrial levels, as prescribed in the Paris Agreement (Fuss et al., 2014; Millar et al., 2017; Rogelj et al., 2018, 2015). In April 2021, we already crossed a global

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temperature rise of 1.25°C in comparison to the pre-industrial temperature (NOAA, 2021); there was also a simultaneous rise in the concentration of CO₂, which reached 419 ppm as of June, 2021 (www.co2.earth). Continued investment of time and money as well as support from government and industry stakeholders have enabled countries such as the USA, Canada, China and Australia to deploy a framework to facilitate the deployment of CCS. CCS is often paired with the transition to unconventional and renewable energy resources to keep the GHG emissions in check. The scope of CCS is rapidly expanding, with increasing number of research groups worldwide working on new technologies and process optimization including those by merging existing technologies. Aside from CCS, utilization of the captured carbon dioxide has been important in industrial environments. Although efforts are being made to reduce the use of elements with a high carbon footprint (such as, reducing the use of steel and cement in building materials), rapidly increasing industrial demand has necessitated the recycling of the captured CO₂. Although more challenging, retrofitting industries to operate in a low-carbon footprint mode may be considered.

Despite several challenges, the successful deployment of carbon capture, utilization, and storage (CCUS) has taken place across the world, which has been backed by closely linked legal and policy support, encouraging research communities worldwide to focus on CCUS (Xu et al., 2021). Developing a CCUS policy becomes challenging when the interests of climate, industries, and government regulations are weighed simultaneously. Uncompromising policy implementation with a substantial incentive to the partner industries will facilitate the commercial deployment of CCUS. However, since several sectors fall under the umbrella of CCUS, these kinds of policies have considerable uncertainties and need longer timeframes for implementation (Jaffe et al., 2005; Nesta et al., 2014). Since the technologies that are involved in CCUS evolve continuously, strict guidelines often fail to assess credit for new technologies; on the other hand, it also enables industries to follow a specific protocol in the adopting of new technologies along with substantial incentives and reduced initial expenses (Johnstone et al., 2009).

India is still in the nascent stages when compared to the forerunners in CCUS deployment, such as the USA, Norway, and China. India was one of the 190+ nations to have endorsed the Paris Agreement (Datta and Krishnamoorti, 2019). According to the commitments to the Paris Agreement, India targets to achieve the share for non-fossil power generation capacity to 40 %. Along with a focus on climate preservation programs and adaptation strategies, India pledged a reduction of up to 3 billion tons of carbon footprint by increasing its forest cover by 2030. Due to its large reserve of coal, India is able to produce affordable electricity from coal-fired power plants, and around 66 % of the total CO₂ that is emitted originates from the energy sector. Given India's energy distribution framework, a sudden shift from coal to natural gas or renewable energy resources will be cost-intensive. It requires massive retrofitting of the existing grid system, due to which electricity will become expensive for end-users. Hence, integrating CCS with existing thermal power plants can help mitigate a significant amount of CO₂ emission (Singh and Singh, 2016). The Intergovernmental Panel for Climate Change (IPCC) Special Report on Global Warming of 1.5°C (Hoegh-Guldberg et al., 2018) indicates that compared to other developed and highly populated countries, India is highly vulnerable to the adverse effects of climate change due to its peninsular geography combined with rapid development and still-growing economic infrastructure.

Moreover, most of the Indian population is directly or indirectly dependent on agriculture and fishery sectors, which are most sensitive to climate change (EIA, 2016). With over 1.3 billion people, India is in a dire need of sustained energy sources to cater to its large population. Although India fares well in terms of per capita GHG emissions, it is the third largest CO₂ emitter in the world. According to the nationally determined climate contributions for the period, 2021–2030, India pledged to attain a green and sustainable economic framework by

reducing the emission intensity of its GDP by 33–35 % by 2030 in comparison to the emission intensity in 2005. The proposed pathway aims to attain 40 % low-carbon energy in the total energy mix, and it proposes sequestration of 2.5–3 Gt CO₂ equivalent.

Keeping the current situations and the long-term targets in focus, this paper aims to determine India's progress in CCUS deployment, and suggest pathways for further development in technology optimization by engaging both government and private stakeholders. Ultimately, a set of recommendations is suggested to enable a smooth and fruitful transition of industries in different aspects of CCUS.

2. Role of CCUS in India at the systems level

This section makes a top-down case for the inclusion of CCUS in India's energy portfolio; this is followed by a discussion and an illustration about the manner in which this broad picture could be replicated through bottom-up concepts. We present the results of ensemble modeling that was compiled in the previous Integrated Assessment Modeling (IAM) consortium of Assessment of climate change Mitigation Pathways and Evaluation of the Robustness of mitigation cost Estimates (AMPERE) (Kriegler et al., 2015b; Riahi et al., 2015). The scenarios were extracted using the open-access scenario explorer of the AMPERE project. To understand the relevance of CCS in India's energy mix, we extracted different output parameters based on the 2°C constraints (450 ppm) examined in this exercise. First, only those scenarios were used in the exercise which had an emphasis on the Indian energy system, and also extended upto 2100. For the first analysis to understand the role of CCS in India's long-term energy security, we relied on scenarios involving the full technological portfolio as well as ones which inhibited any CCS deployment. By studying the coal-based electricity generation and carbon prices under these alternative scenarios, we were able to provide quantitative backing to the hypotheses of Garg and Shukla, (2009). We also extracted the generation capacity data from the aforementioned scenarios to compare the scale of stranded assets when CCS is not deployed. Additionally, within the range of scenarios which did deploy full technological portfolio, we compared the diversity of the generation mix using the Shannon-Wiener Index (SWI).

2.1. CCUS could help enhance India's energy security

The results of ensemble modeling indicate that the unceasing use of coal is incompatible with the 2°C climate target that is outlined in the Paris Agreement (Davidson et al., 2018). The current Indian power sector is heavily coal-dominated despite the recent plateau in coal production. Coal mining, power production, and auxiliary processes contribute to close to a million jobs (Spencer et al., 2018). Therefore, a complete and immediate phaseout would eliminate low-cost, indigenous fuel supply, and result in critical economic ramifications. It may also be noted that while renewable resources and land sinks from major thrusts of India's Intended Nationally Determined Contribution (INDC) have been created, a coal phaseout has not been committed to by the Government of India. Therefore, to decouple India's carbon emissions and energy security, CCS could be pivotal.

Prior work by Garg et al., (2017a) has shown the trends in CO₂ emissions at sectoral levels using qualitative arguments. We extend this by illustrations from the multi-model AMPERE dataset, as shown in Figure 1A. We find that the inclusion of CCS leads to continued coal use up to 2060, after which the phaseout is relatively smoother. When CCS technologies are explicitly excluded from the energy portfolio, coal phaseout and its associated effects on livelihoods are likely to be sharp. The cumulative power generation through coal reduces from 162 EJ to 14 EJ during the period, 2020–2100. Thus, contrary to the experience of developed countries, coal use with CCS could be largely consistent with the 2°C target due to India's historically low emissions and compatibility with the said target thus far. This would reduce gas imports, which is beneficial, because India's conventional gas resources have largely

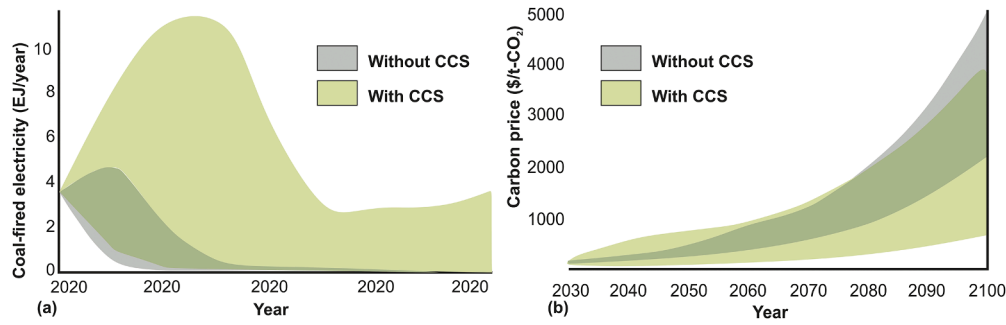


Fig. 1. Ensemble of trends in India's (A) coal-fired electricity and (B) carbon prices in multiple scenarios with (green) and without (grey) CCS, which are compatible with 2°C. Source: Data extracted from AMPERE database of IIASA

plateaued, and unconventional basins have not been fully explored due to various limitations (Singh et al., 2021).

Another way by which CCUS would help India's energy security is by

reducing the policy costs that are a result of the price of carbon.

Figure 1B shows the trends in CO₂ prices for multiple models with and without CCS. These prices are largely consistent with the *High Level*

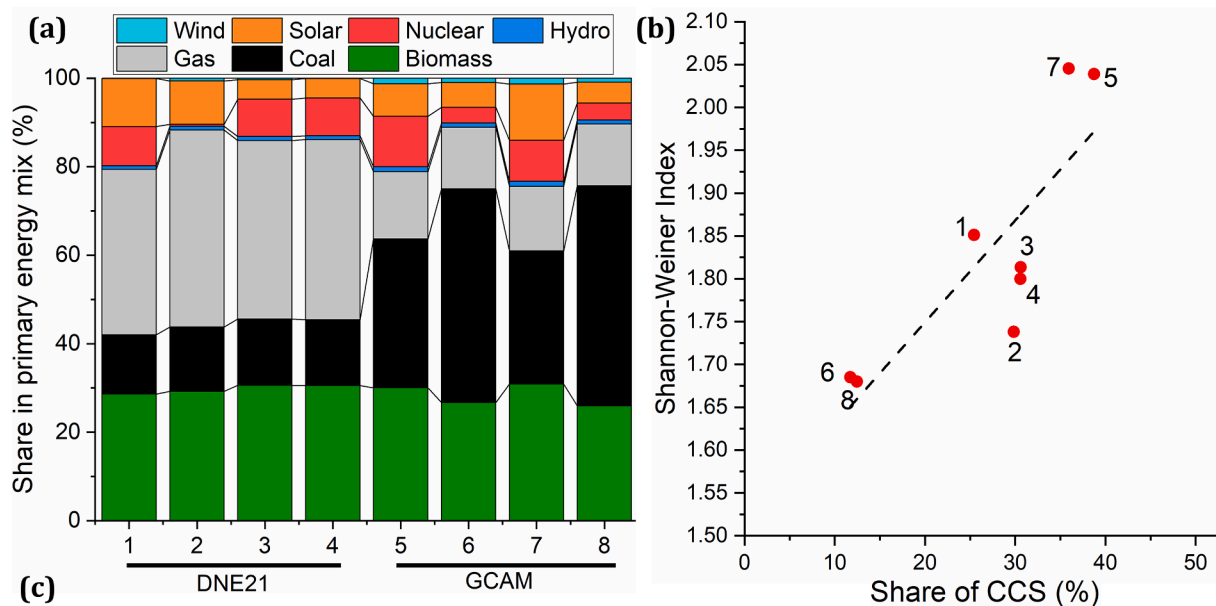


Fig. 2. (A) Share of different primary energy sources in illustrative scenarios (data extracted from AMPERE database of IIASA). (B) Shannon–Wiener Index (SWI) as a function of CCS's contribution to the energy mix in these scenarios and (C) brief description of these scenarios. More details about the scenarios may be found in the AMPERE publications (Crique et al., 2015; Kriegler et al., 2015a).

Commission on Carbon Prices which projects a carbon price close to \$200/t-CO₂ by the mid-century and increasing beyond \$1000/t-CO₂ by 2100. We observe that a gap of \$1600/t-CO₂, on an average, is seen by the end of the century. This has been echoed in global analyses (Muratori et al., 2016). Reliance on solar and wind resources as means to CO₂ mitigation can be cost-effective only in half of the country due to regional climatic constraints (Sharma, 2018). However, when CCS is included within the energy systems, most parts of the country show viable cost prospects for continued usage of coal.

2.2. CCUS and grid diversification

We have noted that in some parts of the country, solar/wind resources would be the cheapest resources, while in others, coal-fired electricity would be difficult to replace in a cost-effective manner. The inclusion of CCS can enable a diverse electricity grid, as discussed in the previous work (Gambhir et al., 2019). An added advantage of such diversification of the grid is enhanced resilience features that counter geopolitical and climatic risks. For a detailed description of this linkage, the reader may refer to the Global Energy Assessment (Cherap et al., 2012).

Essentially, a diverse energy grid exhibits higher resilience in two ways. First, it reduces the shock brought on due to geopolitical changes. For instance, within a diverse grid, even if international concerns accelerate coal phaseout in a country such as India, the presence of other low-carbon sources would facilitate the meeting of climate and energy objectives. Similarly, in the context of the oil and natural gas sectors, which are subject to important geopolitical factors, such substitutions are associated with enhanced resilience.

There exists a significant volume of literature on the impact of extreme weather on energy systems; for instance, it has been found that wide temperature and insolation changes could affect the operation of photovoltaic (PV) cells, and storms impact wind turbine maintenance. In conventional power systems, water shortages have routinely caused a shutdown of both thermal and hydropower. Having a diverse grid ensures that even in the case of such events that affect certain fuel sources, other sources can provide a reliable power supply. Prior works have used the Shannon–Wiener Index, which is an ecology-derived metric that serves as a proxy in the resilience of the energy sector. In Fig. 2B, we show how scenarios with and without CCS exhibit markedly different SWIs at comparable radiative forcing. This offers a distinct advantage in CCS with increased resilience through diversity. An additional point worth mentioning here is that while Fig. 2A reveals the IAM results within a specific set of assumptions (adherence to the 2°C target), CCS is also expected to spur further innovation in strategies in industrial sectors for the mitigation of emissions. These scenarios were selected from two different IAMs and were indicative of preferential technological changes in the energy sector. As such, they were diverse enough to show lack of favorability for different low-carbon technologies, e.g. solar, biofuels and wind. Therefore, the share of CCS in the power sector varied from 11–39%, which largely covers the range discussed by country-specific literature (Garg et al., 2017a; Vishwanathan et al., 2018). The detailed description of these scenarios may be found in the original AMPERE publications that were reviewed as part of this study (Criqui et al., 2015; Kriegler et al., 2015a). Note that the principle of enhanced resilience due to a more diverse energy mix occurs due to the reduced geopolitical risks of fuel availability. Accordingly, the diversity of fuel mix is evaluated based on the primary source of the electricity irrespective of the end-use technology adopted.

2.3. CCUS and stranded assets

Stranded assets refer to assets that are prematurely written-off due to physical or financial constraints. In the context of climate change mitigation, it relates to the infrastructure that may be subject to an early retirement or to operate at reduced capacity due to restrictions such as

an emissions limit or the carbon price. For instance, previous years have seen a considerable increase in the retirement of coal units in European and US power plants (Shearer et al., 2020). This could be extended on the demand side and into the fossil fuel supply side as well. For instance, around 80 % of the world's coal reserves would need to remain unused by 2050 for compatibility with 2°C scenarios (McGlade and Ekins, 2015).

Apart from such global analyses, there are also clearly demarcated regional trends in the scale of stranded assets. For instance, Mercure et al., (2018) projected an estimated financial burden of \$1–4 trillion along with greater stranding in countries with dependence on fossil fuels. Cui et al., (2019) indicated that stranding would take the form of reduced lifetimes to ~35 years in 2°C scenarios and 20 years in 1.5°C. This would entail capital costs at a higher level because amortization would need to occur within a constrained amount of time. More recently, Malik et al., (2020) have concluded that by early climate action and adherence to the NDCs, India could avoid stranding of 14–15 GW of power infrastructure. The timing of the climate policy should be strategic. It should not be too steep, which could cause exorbitantly high stranding; and not too low, which could result in large amounts of locked-in carbon (Seto et al., 2016).

To arrive at a first-order estimate of the manner in which CCS could help in the unstranding of power infrastructure in India, the AMPERE database can be used again. We use the metric of difference in power capacity in full technology and no-CCS scenarios as a proxy for this estimate, as proposed by Clark and Herzog, (2014). Fig. 3 shows that the mid-century capacity in full technology scenarios is 164 GW higher than when CCS is completely excluded.

By considering an average capital cost of \$1101/kW and reduced amortization for a year, we arrive at a first-order estimate of \$6 billion/year of economic damage that can be avoided by the inclusion of CCUS. It may be noted here that this is a conservative estimate, because it does not incorporate the additional financial burden of establishing substitute renewable technologies and grid stabilization. Similarly, Fig. 3 shows that a gas plant capacity of 70 GW could also be unstranded. Therefore, leveraging on the role of CCS can help avoid significant financial damages.

While demonstrating the necessity for CCUS in India by using these top-down results from a systems perspective, it is vital to understand if a bottom-up feasibility exists for this technology. Accordingly, the

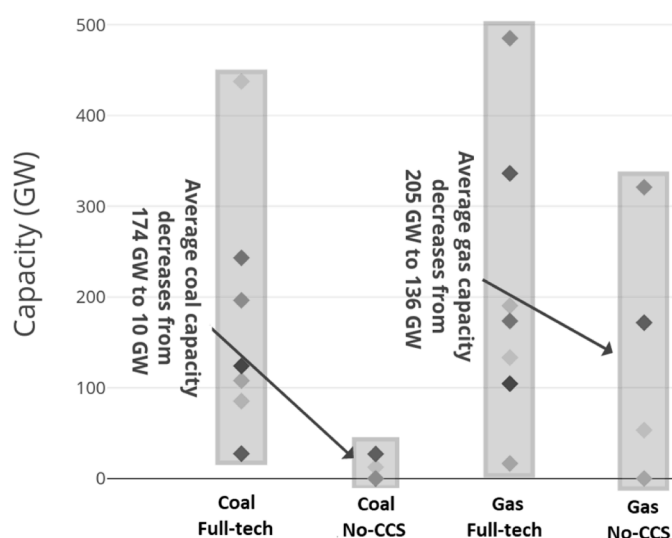


Fig. 3. The estimated amount of power plant assets unstranded by including CCS in the energy mix in India, based on the capacity in the year 2050. The data points correspond to results from different 2°C scenarios as projected by modeling consortia in the AMPERE exercise. Source: Data from AMPERE database from IIASA.

following sections discuss the system integration of the capture, and storage components of India's CCUS supply chains.

3. Sources of CO₂ in India

The use of fossil fuels in India is intricately bound to small and large energy systems, and the scope of usage spans from fundamental domestic use to large-scale power generation and operations in refineries. Based on the IPCC's methodology of characterizing GHG sources (IPCC, 2006), Garg et al., (2017a) classified large point sources of CO₂ and other GHGs in India based on their activity data and emission factors. In their study, they categorized the inventory methodology for electricity production and refineries as Tier III; iron and steel, and fertilizer plants as Tier II; and cement plants as Tier I. Emissions from transport activities are also estimated using Tier I methodology, but for the present, the scope of our study will be focused on large point sources only. The most commonly used energy resources for combustion activities in these large point sources are coal, crude oil, natural gases, and different petroleum by-products (naphtha, diesel). A comparison of the emission trends of the USA, China and India (Fig. 4a) between the period of 2000–2017 shows a steady decrease in emissions from electricity production and other industries in the USA (IEA, 2020). Although China shows a steady increase in emissions from electricity production, there is a dip in emissions from other industries since 2012. Although India is behind in terms of total emissions, there is a slow but steady increase in emissions from the energy sector and other industries. An integrated assessment modeling exercise that is based on the Low climate Impact scenarios and the Implication of required Tight emission control Strategies (LIMITS) database, which follows the IMAGE algorithm, shows a comparison between three scenarios: LIMITS 450, LIMITS Pledges, and LIMITS Baseline (Fig. 4b). LIMITS 450 refers to a scenario after implementation of a climate policy after 2020; its target is to achieve a concentration of 450 ppm of CO₂ by 2100, whereas LIMITS Pledges is an extrapolation of the Copenhagen climate pledges. LIMITS Baseline is a scenario in which no climate policies or restrictions in energy imports are in place (Jewell et al., 2016).

Capturing CO₂ from small and scattered sources is energy-intensive and expensive. However, with the recent advances and optimization of direct air capture (DAC), CO₂ capture from the air is becoming cheaper. Separation and capture of CO₂ from large point sources are affordable and consistent. Amine-based post-combustion separation of CO₂ from flue gases through chemical adsorption (Baburao et al., 2014;

Edvardsson and Chopin, 2012; EON, 2011; Kanniche et al., 2017, 2010; Knudsen et al., 2011; Telikapalli et al., 2011; Tensaka Trailblazer Partners, 2012; Yokoyama et al., 2011) has been widely implemented. This type of CO₂ separation is most preferred by thermal power industries due to its low cost and high efficiency (Dillon et al., 2005; Fu and Gundersen, 2013; Hagi et al., 2014; Stanger et al., 2015; Tranier et al., 2011). Although competitive technologies such as oxy-combustion with cryogenic air separation exist, it is less preferred due to a higher cost of investment and limited suitability to retrofitting (Kanniche et al., 2017). Among other processes, activated carbon adsorption (Krishnan et al., 2012; Merel et al., 2008; Radosz et al., 2008), solid CO₂ deposition (Balepin et al., 2014; Clocid et al., 2005; Hammer et al., 2014), chemical looping combustion (Authier and Le Moulec, 2013; Lyngfelt and Leckner, 2015; Lyngfelt and Linderholm, 2014), and pre-combustion with physical absorptions (Manzolini et al., 2013; Suomalainen et al., 2013) are also popular but not as widely accepted due to economic disadvantages.

3.1. Combustion-based electricity production sector

In 2017, out of India's total annual energy supply, around 390 Mte (million-ton equivalent) came from coal, which topped the charts along with oil and natural gas (223 Mte and 51 Mte, respectively). In the fossil fuel based power generation sector, coal-fired thermal power plants had a massive lead with a contribution of 11.33×10^5 GWh of energy, which was almost 80 % of India's total energy in 2017. In 2017, from the total annual CO₂ emissions in India, industries and electricity producers emitted around 1663 Mt CO₂ into the atmosphere, which was an all-time high in India. China has reduced CO₂ emissions from industries since 2013, and it currently shows a decreasing trend. The USA has decreased emissions from both electricity producers and industries since 2007. Nevertheless, from a capture point of view, India has a better prospect, because nearly 80 % of the CO₂ emissions come from large point sources (industries and power plants). In contrast, around 40 % of the total CO₂ emissions come from the transport sector in the USA, which is relatively difficult to capture. With the introduction of natural gas in thermal power plants, the CO₂ intensity of power has been decreasing since 2014. On the contrary, the CO₂ intensity of industries has been continuously increasing since 1990, which pushes the total carbon intensity upwards in comparison to China and the USA, who have decreased their carbon intensity over the years. However, in India, despite the massive pressure of population, the per capita CO₂ emissions are relatively low

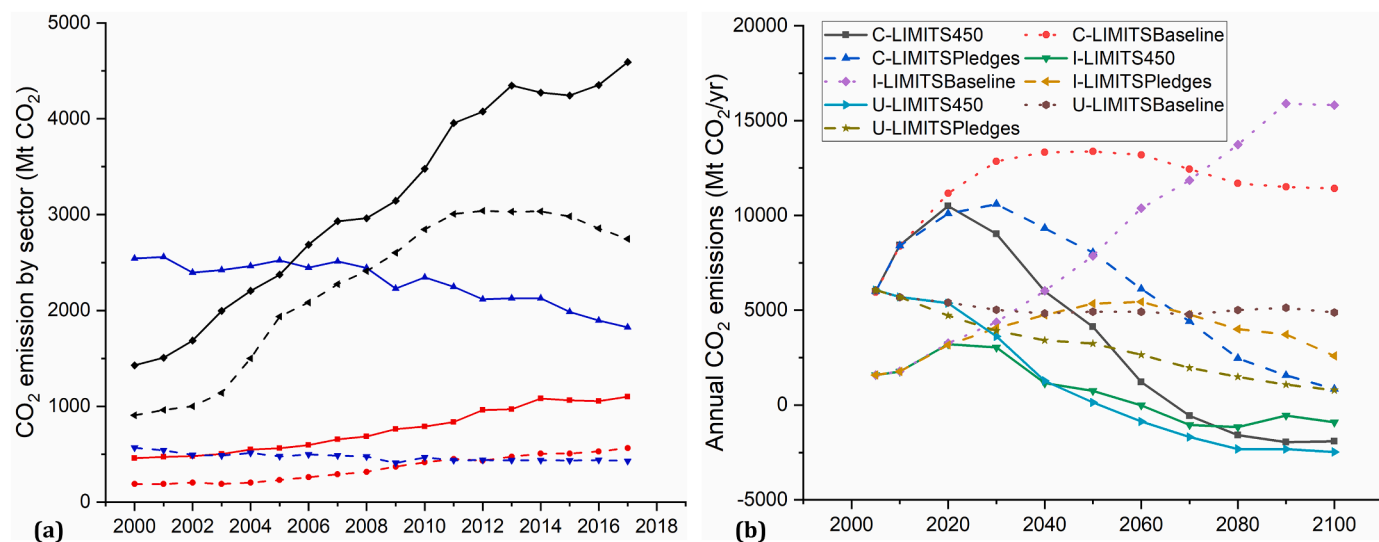


Fig. 4. (a) A comparison between CO₂ emission from electricity production (solid lines) and other industrial activities (dashed lines) in China (black), India (red), and the USA (blue) (IEA, 2020). (b) A forecast for CO₂ emissions until 2100, based on the LIMITS database. Solid, dashed, and dotted lines indicate LIMITS 450, LIMITS Pledges, and the LIMITS Baseline scenario, respectively. C, U and I indicate abbreviated form for China, USA and India respectively.

(1.6 t CO₂) when compared to China (6.7 t CO₂) and the USA (14.9 t CO₂). Nevertheless, the constant increase in the per capita emission in India needs attention.

An effective way to reduce global GHG emissions by 50–85 % by 2050 is the use of CCS. Emerging countries such as India can accelerate deployment and implementation of CCS due to the country's heavy reliance on fossil fuels. As discussed in the earlier section, around 50 % of the CO₂ emitted from large point sources in India comes from thermal power plants. The majority of these thermal power plants are coal operated, and a small fraction is operated by gas and oil (Adams et al., 2021). With a significant reserve of fossil fuels in India and inexpensive electricity, it is unlikely that India would completely phase out coal at a large-scale in immediate future. India is currently the third highest power-generating country. Considering that ~70 % of the power comes from fossil fuels, there is a great opportunity to neutralize the negative impact on the atmosphere by capturing CO₂ downstream. In commercial energy production, it is predicted that coal will comprise around 50 % of the total sources from which energy will be produced until 2040, if no stringent policy for reduced coal usage is in place (Niti Aayog, 2017).

Furthermore, to cope with the increasing energy demand, the annual energy production may increase by 2.3 % by 2050. To adhere to the Paris Agreement, India aims to reduce coal import significantly by 2030, which will lead to increased usage of indigenous coal, which has an average calorific value of 4000 kcal/kg. According to the report from INCCA (INCCA, 2010a) and the second biennial report to the UNFCCC (MoEFCC, 2018), the CO₂ emission factor for coal is the highest among all fossil fuels (93.68, 96.76, and 105.97 t/terajoule for coking, non-coking, and lignite, respectively,) whereas diesel and natural gases have far lesser CO₂ emission factors (74.1 and 56.1 t/TJ, respectively). As of 2019, Asian countries hold a massive 73.8 % of the global coal power-generation capacity, the main contributors being India and China (IEA, 2019b). CCUS retrofitting, or repurposing can bring the CO₂ emissions from coal-fired power plants down to almost zero by 2047. Due to rapidly increasing energy requirements and limited domestic supply, a significant amount of India's fossil-based energy resources (includes coal, oil, and natural gas) are imported. Since India has more reserve of coal in comparison to other fossil fuel resources, migration to oil or natural gas-based power plants will further increase India's energy dependence. India's unconventional natural gases have only started to receive due attention amidst sufficient reserves. Unlike India and China, the USA has successfully shifted most of their thermal power plants to gas-based operations (Fig. 5).

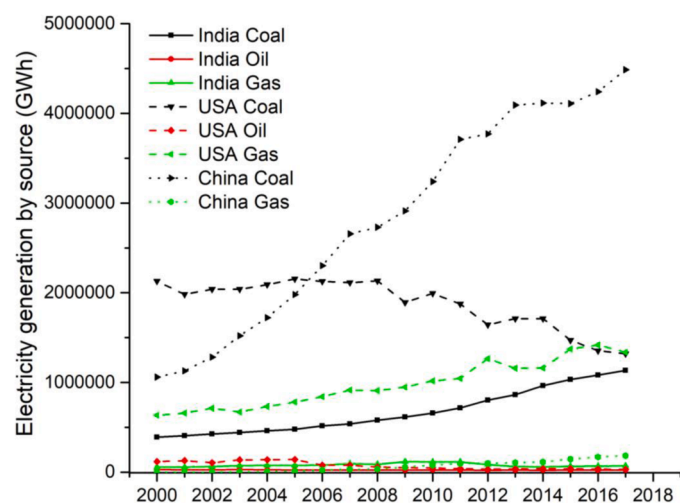


Fig. 5. A comparison of the source-wise electricity generation of India, the USA, and China. Black, green and red lines indicate electricity generated by coal, natural gas, and oil, respectively. Solid, dashed, and dotted lines represent statistics of India, the USA, and China, respectively (IEA, 2019a).

To adhere to the emission guidelines mentioned in the Kyoto Protocol (Grubb et al., 1999) and UNFCCC (UNFCCC, 2015), the Central Electricity Authority (CEA) of India has planned on utilizing the clean development mechanism (CDM) to improve the efficiency of high-capacity thermal power plants that operate at or above a load of 25 GWh. According to the annual data generated by the CEA (CEA, 2019), the older power plants, which have the prospect of reduction in the grid load, show an emission factor of 0.97 tCO₂/MWh. In contrast, the newer plants (established within five years) show an emission factor of 0.88 tCO₂/MWh, which signifies an improvement in the emission statistics. This improvement will be enhanced when CDM is implemented. The addition of new coal-fired plants has sharply declined since 2015–16, when around 22000 MW capacity of coal-fired plants were added compared to merely 5000 MW in 2018–19, despite 11.5 % growth in gross production in 2018–19 from 2015–16 (CEA, 2019). The emission factors of the power plants increase with their age; hence, retiring or retrofitting of older plants is crucial to keep the emission levels in check (Garg et al., 2017a).

3.2. Fuel production sector

The fossil fuel production industry is one of the most dominant CO₂ emitters in the world. According to the INCCA report on GHG emission in India (INCCA, 2010b), coal and oil extraction and handling activities emit a significant amount of CO₂ and methane into the atmosphere. Methane is a far more potent GHG than CO₂ with a global warming potential varying between 28–36 considering a time horizon of 100 years. According to the report by INCCA (INCCA, 2010b), on an average an underground coal mine has a methane emission factor (EF) of 23.64 m³/tonne, whereas an opencast mine produces far lesser methane during mining (EF of 1.18 m³/tonne) (Singh and Kumar, 2016; Gupta et al., 2019). Similarly, each oil well produces three tons of methane and an added 0.334 tons/1000 tons of crude. Methane release is a major drawback of natural gas production, in which 14.223 t of CH₄ is released into the atmosphere per MMCM (million cubic meter) of gas production and distribution (Gupta et al., 2019). Refinery throughput contributed to a cumulative 61 Mt CO₂e emission in 2015, which is around 10 % of the CO₂ that is emitted from industrial processes and product use (IPPU). The GHG emissions from Indian refineries between 2005 and 2015 show a 107 % increase (Fig. 6). In 2019, with a strength of 247.57 Mt per annum (MoPNG, 2019), India ranked fourth among the country-wise highest oil refining capacities, which is a growth of 5.81 % when compared to 2017–18. In the USA, 135 refineries operate with a capacity

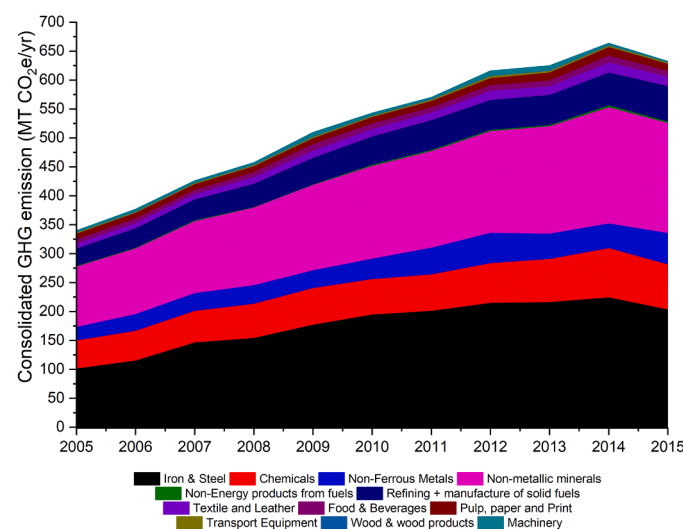


Fig. 6. GHG emission from the Indian industrial sector between 2005–15 (Gupta et al., 2019)

of 812 Mt per annum but with a lower cumulative CO₂ emission of 175 Mt CO₂e (EIA, 2019).

3.3. Metal production sector

India ranks second in crude steel production and first in Sponge Iron production. India had a cumulative production of 111.25 Mt crude steel and 36.86 Mt Sponge Iron in 2019. With a cumulative finished steel production (alloy + non-alloy) of 76.33 Mt, India is a net exporter of finished steel. Due to the rapid proliferation of the steel industry, it is responsible for 32 % of the CO₂ emissions from the IPPU sector. The primary source of fuel in the steel industry is coking coal. Around 56 Mt of coking coal is imported as fuel, of which, 90 % comes from Australia (MoS, 2020). Among the 977 steel plants in India, the steel industry's significant stakes are in the private sector (81 %). Since broilers have been regularly upgraded, the net CO₂ emission has steadily decreased and currently stands at 2.5 t/ton of crude steel (TCS). Other factors behind the low emission are improved waste-heat recovery, energy-efficient cooling systems, and increased use of pulverized coal instead of coking coal (MoS, 2020). The GHG emissions from steel industries expanded by 103 % between 2005 and 2015 (Gupta et al., 2019) but showed a decreasing trend in the emission statistics from 2015 onwards (MoS, 2020) (Fig. 6). In 2015, the total amount of CO₂ that was emitted from iron and steel industries was 194 Mt CO₂e, which is a decrease of 11.3 % from the emissions in 2014. The use of natural gas furnaces instead of coal-fired furnaces has also curbed emissions and increased the energy efficiency, which has benefited the industries. In 2019, 18 % of the steel plants used natural gas for combustion, with the prospect of further increase in each coming year.

3.4. Cement production sector

Cement production is one of India's strongest IPPUs, and with 337.32 Mt of cement production in 2018–19, India is currently the second-largest producer after China (2.2 Bt per annum). With a 13.3 % growth in production in 2018–19, the cement industry has a weightage of 5.4 % and ranks 7th among India's core industries (DPIIT, 2020). Three main variants of the cement produced in India are Ordinary Portland Cement (OPC) (25 %), Portland Pozzolana Cement (PPC) (66 %), and Portland Slag Cement (PSC) (8 %). The total installed capacity of the Indian cement industry stands at 537 Mt, with 144 integrated large cement plants as of 2020. In contrast, the domestic consumption of cement has fallen by 20 % since 2010 to 240 kg per capita against the global average of 530 kg per capita. The milling process and cooling system in the cement industry are the most power-hungry parts, and they comprise a total consumption of up to 54 kWh/t of production. In contrast, the calcination process emits the maximum amount of CO₂ directly from a cement plant (387 kg CO₂/Mt) out of a total emission of 697 kg CO₂/Mt (CII, 2010). The introduction of unconventional fossil fuels or alternate fuels, an increase in the blended cement production, and waste-heat recovery will significantly drop the power consumption and cumulative CO₂ emissions from the cement industry. The thermal substitution rate (TSR) in the Indian cement industry is currently at 4 %, which is lower than other countries (Switzerland: 83 %, USA: 25 %). However, TSR in the Indian cement industry is projected to become 25 % by 2025 and 30 % by 2030 (NCCBM, 2019). According to a study done in 2008–09, cumulative optimization at all fronts was projected to reduce the overall CO₂ emissions by up to 141.3 kg CO₂/Mt cement by 2020 (CII, 2010).

4. Advancements in capture and utilization

4.1. Capture technologies

The capture of CO₂ from large point sources is an important step in reducing the carbon footprint of the industry. Capture processes vary

based on the CO₂-generation method of the industry, and they often require retrofitting in the emission front to implement an optimal capture setup. Evolution in the capture processes is still going on to make the methods less expensive, robust, low maintenance, and highly efficient. Three of the main routes to implement CO₂ capture are pre-combustion capture, post-combustion capture, and oxy-fuel combustion (Figueroa et al., 2008). In post-combustion, CO₂ is separated from the flue gas that is generated due to combustion; in pre-combustion, the CO₂ is removed from the fuel before combustion; and in oxy-fuel combustion, fuel is burned in a pure oxygen stream, which avoids the separation of CO₂ from the flue gas after combustion. The capture process can be broadly divided into two segments: separation and condensation. Among these, separation is given more attention, because it governs the efficiency of the process. Advancements in the capture processes in different sectors will be discussed in further sections

4.1.1. Capture in thermal power plants

Thermal power plants generally implement the post-combustion capture process, because it has a low retrofitting cost. However, because of the low partial pressure of CO₂ in flue gas (<0.15 atm), significant pressurization requirement for storage, and the high flux of emissions, post-combustion capture can be challenging in thermal power plants (Figueroa et al., 2008; Wang et al., 2017). Several post-combustion technologies such as chemical absorption (Rochelle, 2009), adsorption (Harlick and Tezel, 2003), membrane separation (Zhao et al., 2008; Kian et al., 2021), Ca-looping (Martínez et al., 2016), and cryogenic fractionation (Hart and Gnanendran, 2009) have been developed and optimized over the years at a large scale and for economical capture. Among these methods, chemical absorption comprises the most number of financial benefits. It has shown a fair prospect of upscalability (Vega et al., 2020). Among other chemicals used for chemisorption, the alkanolamine family (triethanolamine, diethanolamine, monoethanolamine) has shown the best potential for large-scale capture (Chen et al., 2018; Muchan et al., 2017; Pilorgé et al., 2020; Psarras et al., 2020; Vega et al., 2020). These alkanolamines produce carbamate formations after interacting with CO₂ molecules, which has a high enthalpy of CO₂ solubility. This requires higher energy to release the CO₂ molecules before reuse (Liu et al., 2019; Wang et al., 2015). A simulation-based study to evaluate the economical prospect of CCS implementation in a thermal power plant in India by Akash et al., (2016) revealed that the addition of a capture system reduces the net power output by a significant amount (10 % in amine-based capture and 18 % in oxy-fuel combustion). The coal plant's capital cost also resulted in a 47 % and 55 % increase in amine-based and oxy-fuel captures, respectively. The increase in capital cost will essentially result in an increase of more than 2x in the unit price of electricity. Further, reduction in net power generation and efficiency was observed in other studies (Wang et al., 2017). Numerous works have been done on optimizing the temperature usage, chemical composition, and packing densities to obtain CO₂ that has a higher purity through chemical adsorption processes (Abu-Zahra et al., 2007; Amrollahi et al., 2012; Chang and Shih, 2005; Duan et al., 2012; Le Moullec et al., 2014; Oexmann et al., 2012; Shirmohammadi et al., 2018; Xu et al., 2013), membrane-based separation processes (Han et al., 2018; Hasan et al., 2012; Kotowicz and Bartela, 2012; Lee et al., 2018; Merkel et al., 2012; Shao et al., 2013), and oxy-fuel combustion techniques (Chen et al., 2019; Escudero et al., 2016; Rogalev et al., 2019; Yan et al., 2015; Zanganeh and Shafeen, 2007). Majoumerd et al., (2017) performed a comparative emissions and efficiency study of a model Indian integrated gasification combined cycle (IGCC) coal-fired power plant. Their results show that coals with lower ash content perform better in heat generation and reduction of CO₂ emissions. Singh et al., (2017) performed a simulation-based study of performance, emission, and cost optimization of seven major Indian power plants upon retrofitting with amine-based capture. The study reveals an energy penalty of 34–53 % upon implementing the capture framework, which can be mitigated by a higher carbon price and

implementation of ultra-supercritical boilers instead of circulation boilers, which have lower thermal efficiency (Chikkatur and Sagar, 2009; Karmakar et al., 2013a). An improvement of 0.8 % and 6.4 % energy points can be achieved simply by implementing supercritical and ultra-supercritical steam parameters, respectively, in coal-fired power plants that have a capacity of > 500 MW (Karmakar et al., 2013a). In India, NTPC and BHEL performed extensive studies to carry out pilot projects to implement a capture framework in existing large power plants (Kumar et al., 2019). Implementation of oxy-fuel was planned in India as pilot projects (Viebahn et al., 2011), and several studies identified CCS implementation in coal-fired power plants as a significant contributor to the reduction in India's carbon emission (Garg et al., 2017b; Kapila and Stuart Haszeldine, 2009; Sethi and Vyas, 2017; Sreedhar et al., 2017).

Recently, moving bed reactors with temperature or pressure swing adsorption (TSA/PSA), which is a combination of both (T/PSA) or vacuum swing adsorption (VSA), have been identified as a more effective process for post-combustion CO₂ stripping. The vapour pressure and the high temperature that are generated in boilers can be used to strip off the CO₂ molecules that are attached to reagents. The recycling of the adsorbent increases the efficiency of the separation process, although the adsorbents' longevity is still not understood well. Implementation of PSA with retrofitting is a feasible pathway. It can compete with chemical absorption processes, and multi-stage multi-layered PSA processes can reduce the energy requirement considerably (Gomes and Yee, 2002; Liu et al., 2011; Takamura et al., 2001). Hot PSA with potassium-promoted hydrotalcites have shown higher efficiency than chemical absorption, although cold PSA with activated carbon or a metal-organic framework (MOF) has a slightly lower efficiency (Na et al., 2002; Riboldi and Bolland, 2017; Wiheeb et al., 2016). Implementation of the elevated T/PSA process in a 540 MW IGCC power plant has shown that a combination of T/PSA can reduce the heat loss of the shifted gas and the adsorbent regeneration with only a minor decrease in the plant performance (Ho et al., 2008; Xiao et al., 2008; Zhu et al., 2014). A comparison of MOFs, chemisorbents, and physisorbents shows that mesoporous physisorbent solids with mesopores are more effective in TSA/VSA in power plants with a massive gas feed (Hedin et al., 2013; Ishibashi et al., 1996; Mondino et al., 2019; Plaza and Rubiera, 2019). Amine-based adsorbents can prove to be strong contenders to strip off CO₂ from feedstock through chemisorption; they have a low chance of being contaminated

by other gases, which results in a high concentration of CO₂ post-capture (Berger and Bhowan, 2011; Ghougassian et al., 2014; Mason et al., 2011; Pirngruber et al., 2013). Solar-assisted T/PSA can further reduce the energy requirement for adsorbent regeneration, albeit with a higher upfront cost (Zhao et al., 2019;).

4.1.2. CO₂ capture from non-power sources

Prior sections describe the possibility of establishing well-known CCS supply chains in which CO₂ is derived from the power sector. The literature indicates that for various reasons future work should significantly expand the scope in CCUS. First, decarbonization in the power sector may be achieved through several other mechanisms, and it is not impossible to reach near-zero emissions through renewables and nuclear in a large part of the country. India's NDC after ratification from Paris Agreement, along with some peer-reviewed literature indicates a good outlook for solar and wind energy. Second, geologic storage may be technologically reliable but needs wider acceptance. Third, while CCS has immense potential in the long run (as will be discussed in section 5), the power sector may not be the least-cost pathway to jumpstart initial deployment. Therefore, looking at industrial CO₂ corridors might be a useful complement to the CCUS supply chains discussed in sections 2 and 3.

Fig. 7 shows conceptually why visualizing such concepts might be useful from a life-cycle perspective; it also shows the parameters that would affect such pathways. For instance, higher purity sources may entail capture at a relatively lower cost. Similarly, government incentives may benefit a particular sequestration alternative. While no single pathway could be treated as a silver bullet, we discuss some opportunities for system integration in the following subsections. Throughout these pathways, it is important to note that CO₂ forms the links between the carbon supplier and consumer, which enables integrated analysis as a form of "currency" in the proposed carbon economy.

Industrial sources of CO₂ have been widely discussed in the literature. Future growth in India's carbon-intensive industries is considerable, with a likely increase of 40 % in the steel sector and 25 % in the cement and refinery sectors (Vishwanathan et al., 2018). Several of these sources may offer high purity CO₂, which reduces the separation energy. For instance, as the fraction of CO₂ in the flue gas increases from 10 % to 20 %, the energy of separation reduces by half. Thus, it is meaningful to consider some of these sources and their integration with

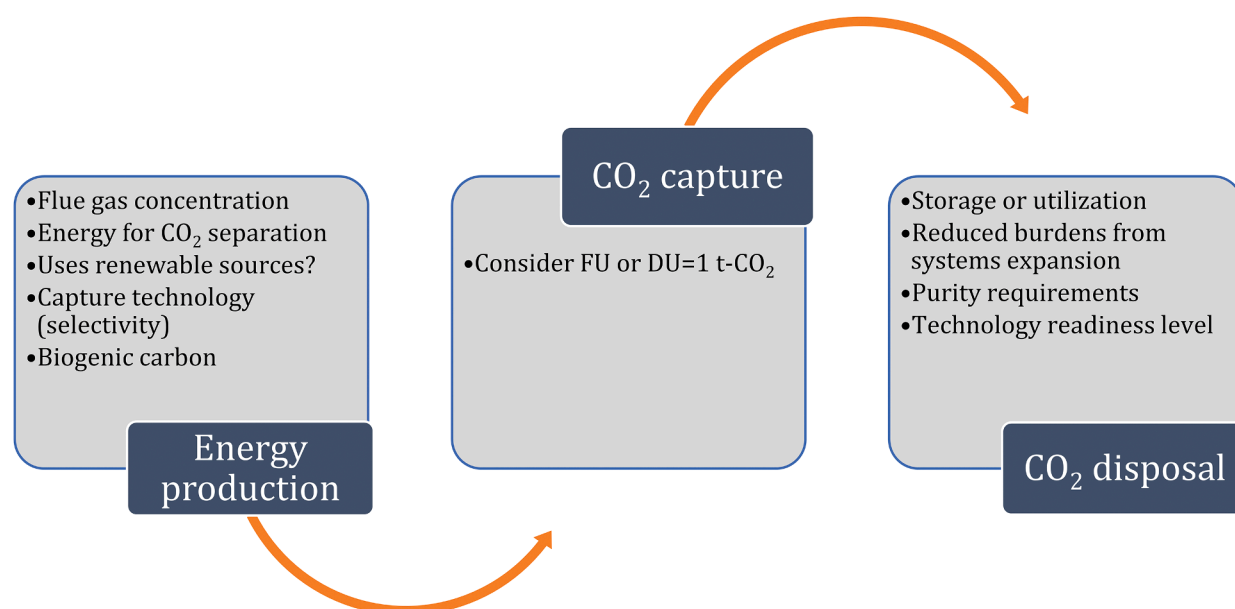


Fig. 7. Components and inventory flows for CO₂ producers and CO₂ consumers are very different from one another; therefore, scaling all quantities to a common CO₂ basis provides a convenient means to evaluate a hypothetical integrated system (Singh and Colosi, 2021). FU = Functional Unit; DU = Declared Unit.

the CCUS supply chain.

Meaningful opportunities may be illustrated here - such as, India's crude oil reserves are limited, and there is considerable import reliance, but India has a substantial number of petroleum refineries throughout the country. The refined hydrocarbon production in India already exceeds its demand, and the government has indicated its intent to double the refinery capacities over the next decade (Mukherjee, 2020). India already has the world's largest refinery in Jamnagar, and multinational collaboration is anticipated for future infrastructure. In the power sector, CO₂ emissions are largely derived from combustion. However, in refineries, a sufficient amount of CO₂ of high purity may be obtained from chemical separation in the catalytic cracker unit and through steam methane reforming (Yao et al., 2018). This creates CO₂ capture possible at around \$ 50/t-CO₂, which is considerably lower than the regional estimates for the power sector. Doing so also removes some of the barriers that are associated specifically with the Indian power sector such as high-ash coal and lower efficiencies. Relying on the modularity of refining processes may, therefore, yield the initial experience that is required to spur endogenous technological learning. Moreover, it will also create the initial infrastructure for CCUS in terms of well monitoring, transport pipelines, and so on. Similarly, the fertilizer production process enables CO₂ capture at <\$20/t-CO₂ with an increase of only 3–4 % in the selling price (Global CCS Institute, 2009). The Jagdishpur fertilizer plant has actively utilized this CO₂ with an annual capture rate of ~40,000 t CO₂ (Gupta and Paul, 2019).

Prior work by Garg et al., (2017b) also shows an additional advantage in capturing these industrial CO₂ streams. Due to the relative proximity of industrial and power sources, there are suitable prospects for the creation of CCUS "clusters," which are networks of sources and sinks that would reduce transportation costs by introducing economies of scale. Ten such clusters have been characterized, which would be sufficient for an avoidance of 800 Mt CO₂/y, which is compatible with the 2 °C constraints.

On the other end of the spectrum in the concentration of CO₂, the international literature on the capture of CO₂ from the ambient air has rapidly grown. While the earlier work on DAC indicated a large separation energy and accordingly capture costs of \$600–1000/t CO₂ (Chen and Tavoni, 2013), recent technological developments have reduced these costs to <\$150/tCO₂. This allows for a decoupling of the expansion of the energy sector with CO₂ emissions while requiring comparatively limited infrastructural coordination (Creutzig et al., 2019). Prior work has indicated that due to the involvement of multilateral stakeholders, CCUS development might be hindered (Viebahn et al., 2014) and DAC could help mitigate some of those concerns (Lackner, 2003, 2009). While IAM work does not specify large CO₂ removal goals for India due to historically low emissions (Pozo et al., 2020), this could be a realistic opportunity, especially when coupled with California's low-carbon fuel standards, which incentivize DAC deployment anywhere in the world at \$130–170/t CO₂. It may also help decarbonize hard-to-mitigate sectors such as buildings that are characterized by negative path dependencies and low energy efficiency (Yu et al., 2018).

With increasing interest in CCS and optimization in adsorbent technologies, retrofitting of old electricity plants will be cheaper with high volume of CO₂ capture with minimal reduction in plant efficiency. Cost of capture for high-purity CO₂ through optimum separation from emission feed is exponentially costly, especially with high feed flux. Currently India has several high capacity thermal power-plants, where capture and utilization techniques can be deployed in pilot scale based on previous simulation studies (Garg et al., 2017b; Kumar et al., 2019) for plant specific optimization, LCA and suitable adsorbent/method selection based on realtime operation.

4.2. CO₂ utilization pathways

4.2.1. CO₂ utilization in the energy sector

Coal-fired thermal power plants fulfill more than 50 % of India's

energy demand. In a scenario of retrofitting those power plants with a capture framework, the expenses will increase with a decrease in the performance of the plant. To mitigate this added cost and to provide cheap electricity to the end-user, different utilization techniques can be implemented, which will be used to generate a by-product of electricity. It will eliminate the complexity and cost of CO₂ transport and storage. Coal direct chemical looping (CDCL) on existing power plants can co-produce hydrogen and provide a higher concentration of H₂ with a lower coal feed (Gnanapragasam et al., 2009; Surywanshi et al., 2019). A comparative analysis of the performances of H₂ production from coal-fired and natural gas-fired power plants has shown better performance by coal-fired power plants with CDCL than by gas-fired power plants with chemical looping combustion (CLC) (Cormos and Cormos, 2014; Cormos, 2011). Although H₂ production when added to power generation can reduce the plant's efficiency by around 14 %, it is still lesser than many chemical absorption and T/PSA pathways (Ozcan and Dincer, 2014). Additionally, the produced H₂ can be also used as an energy source in the power plant to produce clean and efficient energy, increasing the net energy efficiency by 33 % (Surywanshi et al., 2019). The produced H₂ can also assist in converting syngas to methanol as another by-product. The syngas can also be transformed into methane through hydrogenation (Anwar et al., 2020). Lee et al., (2019) conducted a sensitivity and economic feasibility study of synthetic natural gas (SNG) production from CO₂ using a membrane reactor. All these by-products formed through CO₂ utilization (methane, methanol, H₂, SNG) will, in turn, boost the net energy production capacity of thermal power plants. Considering the growing energy demand in India and the late-blooming of renewable energy resources, CO₂ that is emitted from power plants can be processed and reused in situ for enhanced energy production with a low impact on the climate. As discussed in the last section, retrofitting costs of capturing CO₂ are gradually reducing, albeit with a decrease in plant efficiency and increase in electricity prices for customers. Suitable policy deployment from the government can help cut down the cost for consumers and aid the energy industry in migrating toward cleaner energy production. Indian economy depends a lot on agricultural production, and a considerable amount of urea is used every year as fertilizer. Green urea can also be produced by utilizing CO₂ that is captured/separated from flue gases. A multi-objective optimization study by Alfian and Purwanto, (2019) identifies the biomass gasification technology as a near-target optimum solution (2020–2035), combined biogas-PV electrolysis without a battery (2040–2050), which could be implemented in future. Koohestanian et al., (2018) performed a simulation-based study of the performance of urea production from flue gas through oxy-fuel combustion. They indicated a potential of 1.68 tons of urea production per ton of CO₂ that is separated from flue gas. The efficiency of the urea production process limits the CO₂ loss coefficient to almost zero, which denotes the lowest environmental impact when compared to other processes.

4.2.2. CO₂ utilization in the non-energy industrial sector

Although the technological reliability of geologic storage is high (Alcalde et al., 2018), research suggests a high public acceptability for the conversion of CO₂ into industrial products (Arning et al., 2019). This may be the case for government stakeholders as well. For example, India has placed a strong emphasis on the growth of the methanol sector with a planned expansion of ten times by 2025. This would create a CO₂ utilization potential of more than 10–12 Mt CO₂/year in the very short term. The life-cycle analysis of this pathway shows a good outlook for the production of methanol with near-zero emissions when coupled with power plant sources and negative emissions with DAC (Hoppe et al., 2018). Additionally, methanol may be further converted into methane to meet some of the demands for gas, which will be required to fuel the anticipated increase in combined cycle power plants. A comparable potential exists in the soda ash market, which has shown an annual growth of 6 % in India, where CO₂ capture costs could be completely offset at a market price of less than \$20/t of product. The

techno-economic feasibility of utilization pathways may be appealing as economies of scale are achieved. For instance, the cost of methanol production through CCU could be brought below the current market price of \$200/t CO₂ by 2035. This pathway's viability further improves because the geologic storage potential in India is still uncertain, as discussed in section 4.

As seen in Fig. 7, we reiterate that industrial sources across the purity spectrum may be suitable for CO₂ utilization. However, a critical challenge for CCU is achieving very high pressure and purity for certain pathways. Pathways such as enhanced gas recovery and urea production require a pressure of 120 bar and 99.9 % purity, which may place significant constraints on the sources that could be utilized with post-combustion capture (Ho et al., 2019). On the other hand, pathways for algae production may be utilized at atmospheric pressure and purity but may be unappealing on a life-cycle basis (Clarens et al., 2011). Table 1 shows the dominant utilization pathways, along with their current readiness levels and costs. Analogously, we may also consider the lowest purity source that may be compatible with that pathway. Under this wide uncertainty, visualizing the industrial “clusters” for CCU becomes considerably more challenging than in the case of geologic sequestration.

In summary, the CO₂ utilization pathways may have a prominent role to play in India in light of the increasing thrust on methanol generation and usage by the government. Similarly, in line with international energy outlooks, coal gasification for hydrogen production along with CCU may be an indigenous step for moving towards a blue hydrogen economy, i.e. hydrogen derived from fossil fuels but with CO₂ capture. While these pathways may be associated with considerable logistical benefits, their actual adoption is subject to technical and policy implications. For instance, insights into CO₂ purity and economic penalty considerations from actual flue gas of Indian power and other industrial facilities would need to be obtained to better evaluate low-hanging fruits in this sector.

5. Scope of CO₂ storage in geological formations

The technology of injecting CO₂ in depleted oil and gas fields for tertiary recovery has been utilized at a commercial scale since the 1970s. However, the pressure to mitigate climate change at a global scale has focused on the storage of CO₂ in the same geological formations that store large quantities of hydrocarbons. Global experience indicates that more than 95 % of the injected CO₂ is retained in the subsurface in enhanced oil recovery (EOR) projects (Azzolina et al., 2015). Moreover, decades of experience in CO₂ injection projects have provided the considerable advantage of in-depth technical knowledge and reduced the associated risks and costs. This has resulted in large storage projects such as Sleipner and Snøhvit in the North Sea (Cavanagh and Nazarian, 2014; White et al., 2018), and In Salah in Algeria (Eiken et al., 2011); and the conversion of CO₂ EOR to CO₂ storage projects (Brown et al.,

2017). India is similarly developing its storage infrastructure. In the CCUS Roadmap for India by the Technology Information, Forecasting and Assessment Council (TIFAC), the Government of India has highlighted CO₂ EOR and enhanced coalbed methane recovery (ECBM) as the first two recommendations for large-scale implementation of India's CCS strategy. However, sedimentary basins in India have not been explicitly explored for CO₂ storage. The primary source of in-depth information about exploration and production is the hydrocarbon industry. A few earlier studies have estimated India's total storage capacity (Holloway et al., 2009; Kearns et al., 2017) at 100–700 Gt of CO₂ by using publicly available data. The most recent study on CO₂ storage capacity in India demonstrates an advanced approach for systematic assessment, and estimates a total storage capacity at 395–614 Gt of CO₂ (Vishal et al., 2021).

5.1. Geological formations suitable for CO₂ sequestration in India

There are 26 sedimentary basins in India, which cover a total area of 3.4 million sq. km (Table 2). The area is spread across onland, shallow water up to a 400-meter water depth, and deepwater (Fig. 8) farther up to Exclusive Economic Zone (EEZ). Based on the conventional resource potential, seven basins are grouped under Category-I (GOI, 2020), and they cover 30 % of the total basinal area and hold 85 % of the total unrisked conventional in-place hydrocarbon (41.8 billion ton of oil and oil-equivalent gas). These seven basins are Krishna-Godavari (K.G.), Mumbai Offshore, Assam Shelf, Rajasthan, Cauvery, Assam–Arakan Fold Belt, and Cambay. Since later 2020, oil is being produced from the Bengal basin, making it the eight hydrocarbon producing basin in India (Business Standard, 2020). Many of the fields in Category-I basins have been producing hydrocarbons for decades, and have either been depleted or have reached their maximum secondary recovery capacity. Thus, they have a significant potential for CO₂ EOR (Srivastava and Mahli, 2012; Mishra et al., 2019). Initial feasibility studies on the Ankleshwar field in the Cambay basin indicate an almost 10 % tertiary recovery of oil and close to 150 Mt of potential CO₂ storage (Ganguli, 2017). Another field in the Cambay basin, Gandhar, has been identified in the CCUS Roadmap as a possible site for CO₂ EOR, and shows favorable reservoir conditions for the same (Mishra et al., 2021; Mishra et al., 2019). The Oil and Natural Gas Corporation (ONGC) has conducted preliminary feasibility analysis, and different research groups are also carrying out detailed studies related to CO₂-EOR and storage. Pilot/demonstration of a successful CO₂-EOR project can fast-track the development of the technology and the infrastructure that are needed to fulfill the CO₂ storage requirements. It may be noteworthy to mention that the total theoretical CO₂ storage capacity through EOR in the country has been estimated at 2.8 Gt of CO₂ (Vishal et al., 2021);.

Storing CO₂ in structural and stratigraphic traps in saline aquifers is similar to storing CO₂ in depleted oil and gas reservoirs. The difference is that the trap is initially saturated with water instead of hydrocarbons. Globally, deep saline aquifers have the potential to store 8000 to 55000 Gt of anthropogenic CO₂ because of their large pore volumes and spatial distribution (Kearns et al., 2017). Successful projects such as Sleipner in Norway (Furre et al., 2017), In Salah in Algeria (Bissell et al., 2011; Shi et al., 2019), Decatur in the USA (Bauer et al., 2016), and Aquistore in Canada (White et al., 2017) have boosted confidence in the technology. Several countries have also independently developed comprehensive estimates of storage capacities through quantitative and probabilistic assessments of their basins (Bachu et al., 2007; Brennan, 2014; Goodman et al., 2011; Heidug, 2013). In India, however, the level of detail in the data that is available for basins is highly skewed toward Category-I basins due to the country's hydrocarbon-focused exploration strategy. This does not necessarily imply that they are the best sinks for CO₂ storage; rather it implies that they are the most feasible due to infrastructure and comprehensive subsurface data (Fig. 8). The less-explored Category-II and III basins cover the remaining 70 % of the total basinal area and comprise almost half of the country's total

Table 1

Comparative cost of avoidance, technological readiness level (TRL) and purity requirements for different CCU pathways along with the potential sources that are compatible in terms of purity. The estimates for costs and TRL are adapted from Hepburn et al., 2019.

Utilization pathways	Cost of product with CO ₂ utilization (\$/t)	TRL	Purity requirement (%)	Potential sources
Methanol	510	6	99	PC
Methane	1740	5	99	PC
Fischer-Tropsch	4160	7	99.9	DAC
Microalgae	2680	4	0.04	Ambient Air
Cement curing	56	5	99	PC
Polymers	1440	5	95	IGCC

* PC=Pulverized Coal, DAC= Direct Air Capture, IGCC= Integrated Gasification Combined Cycle

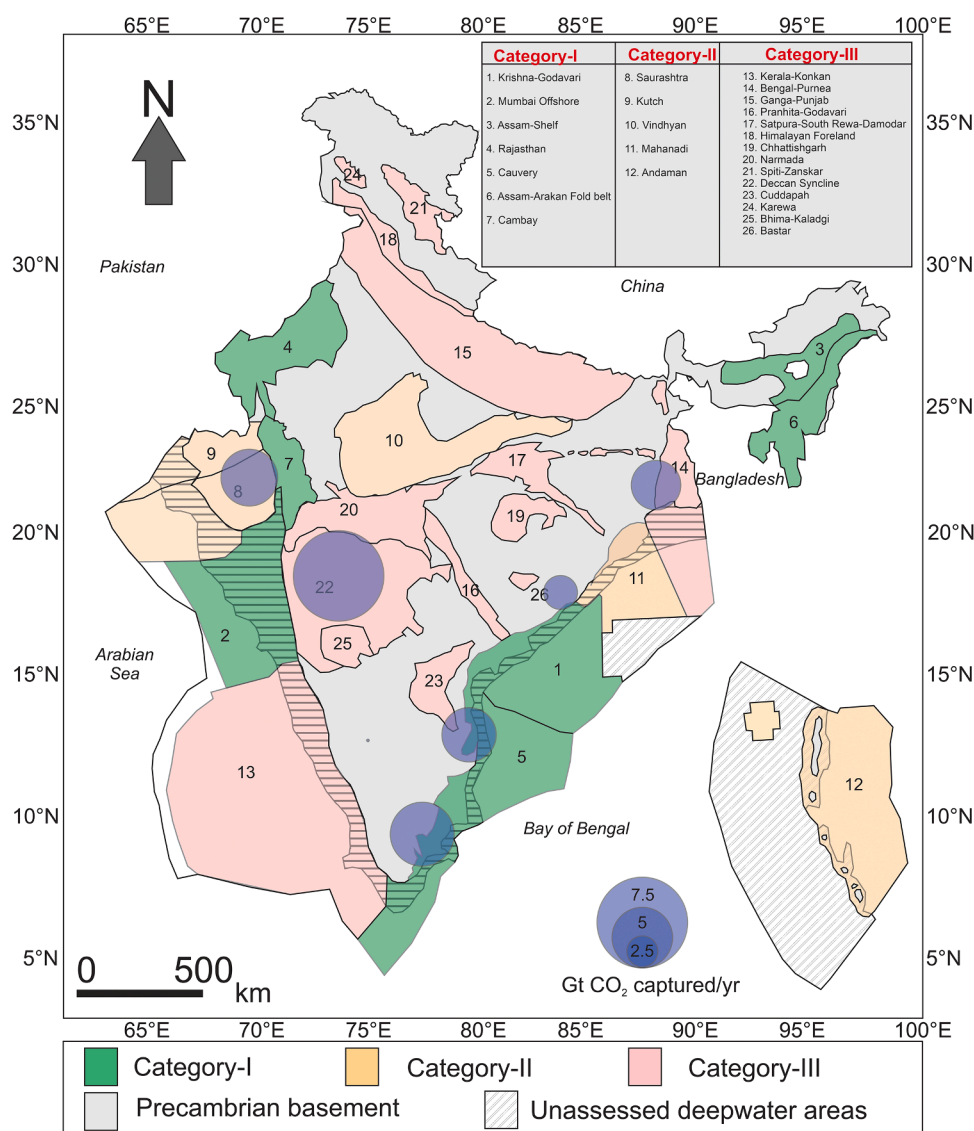


Fig. 8. Categorization of Indian sedimentary basins based on the maturity of conventional resources (after DGH, 2017). The CO₂ captured in each state within a range of 500 km from the sinks are marked as a blue circle (after Viebahn et al., 2014).

appraised area. The large area indicates a vast, untapped potential for CO₂ storage. The total CO₂ storage capacity in saline formations in Indian basins is estimated at 291 Gt of CO₂ (Vishal et al., 2021). If appropriately managed, this capacity is more than sufficient for India to fulfill its commitments toward reducing its cumulative emissions. Recent policy support for development of unconventional hydrocarbons necessitates further research for CO₂ storage in these formations (Chandra et al., 2020a,b; Chandra and Vishal, 2020; Singh et al., 2021). Further, CO₂ storage for enhancement of coalbed methane recovery (ECBMR) may be considered in select coal basins. Significant research works have been carried out on various aspects of CO₂ storage in Indian coal (Sharma et al., 2017; Varma et al., 2015; Vishal, 2017; Vishal et al., 2015b,c; Vishal and Singh, 2015; Singh et al., 2006; Vishal, 2017b; Vishal et al., 2013b). It may be worthwhile to mention that the CO₂ storage capacity is estimated at 2.8–5.3 Gt in coal allocated as CBM reserves. In addition, storage in unallocated coal account for another 0.8–1.3 Gt of CO₂ (Vishal et al., 2021).

Apart from sedimentary basins, storage in basalt formations is slowly emerging as another carbon storage solution. Injection of CO₂ into reactive basaltic rocks enables faster carbonate mineralization and ensures permanent storage of CO₂. A couple of projects are currently

underway worldwide to assess the feasibility of storing carbon in basalts (Gislason et al., 2018; Gislason and Oelkers, 2014). In India, the Deccan Volcanic Province (DVP) covers nearly 500,000 km² in the western-central area, and is one of the largest terrestrial flood basalt formations in the world (Eldholm and Coffin, 2000; Tiwari et al., 2001). The volume of the Deccan basalt is estimated to be 512,000 cubic km. In addition to the DVP, a smaller basalt formation exists in northeastern India, the Rajmahal trap, which consists of basalt that is 450 to 600 m thick and covers an area of approximately 18,000 km² (McGrail et al., 2006). Natural analogs have shown that up to 70 kg of CO₂ can be stored in a cubic meter of basaltic rock (Gislason and Oelkers, 2014), and it can go as high as 160 kg per cubic meter (Wiese et al., 2008). Singh et al., (2006) estimated 200 Gt of CO₂ storage capacity in basalt in India. However, Holloway et al., (2009) did not consider sequestration in basalt, because the technology had not matured enough at the time. The recently updated estimates for CO₂ storage in basalt formations report a theoretical storage capacity at 97–316 Gt (Vishal et al., 2021). Storage in basaltic rocks is still a developing technology, but it promises vast storage potential and guarantees rapid, permanent storage.

Table 2

Basin-wise area (including onland area, shallow water area up to 400m, and deepwater area beyond 400m isobath) of the 26 sedimentary basins in India, categorized by the hydrocarbon potential (DGH, 2017).

Category	Basins	Basin Area (Sq.km.)
Category-I	Cambay	53500
	Assam Shelf	56000
	Mumbai Offshore	212000
	Krishna–Godavari	230000
	Cauvery	240000
	Assam–Arakan Fold Belt	80825
Category-II	Rajasthan	126000
	Kutch	58554
	Mahanadi	99500
	Andaman	225918
	Vindhyan	202888
	Saurashtra	194114
Category III	Himalayan Foreland	30110
	Ganga	304000
	Kerala–Konkan–Lakshadweep	580000
	Bengal	121914
	Karewa	6671
	Spiti–Zaskar	32000
	Satpura–South Rewa–Damodar	57180
	Narmada	95215
	Deccan Syneclise	237500
	Bhima–Kaladgi	14100
	Cuddapah	40100
	Pranhita Godavari	30000
	Bastar	5360
	Chhattisgarh	32600

5.2. Feasibility of storage and possible impacts

The next step involved in making CCS a reality is the mapping of the storage sites with suitable sources of anthropogenic CO₂ (Lipponen et al., 2011). Viebahn et al., (2014), by using source-sink matching, calculated that 5–75 Gt of CO₂ could be stored in India, with 29 Gt being the most probable scenario (Fig. 8). Their analyses show significant storage potential in the western and south-eastern oil and gas fields, and the coal fields in the east. Garg et al., (2017b) estimated that India could mitigate 780 Mt CO₂/year at costs below USD 60/t CO₂ through 8 CCS source-sink grids that have a total capacity of 25 Gt of CO₂. The storage needed is divided into saline aquifers (4 Gt), depleted oil and gas reservoirs (6.8 Gt), and coal and basalt seams (12.2 Gt). Given that the estimated storage capacities are much larger than required, CCS could easily be viable through technology and infrastructure developments.

A significant reduction to India's cumulative CO₂ emissions can be made by CCS. However, several commercial-scale CCS projects will need to be executed in the next couple of decades. Considerable risks are always involved when large amounts of fluids are injected into the sub-surface. Induced seismicity has been detected at several enhanced geothermal and wastewater injection projects (Ellsworth, 2013; Grigoli et al., 2018; Grünthal, 2014; Guglielmi et al., 2015). India too has witnessed reservoir-triggered earthquakes (Gupta, 2002). Injection of CO₂ is similar to other large-volume fluid injection operations (Verdon, 2014), and the hazards and risks that are potentially associated with geological carbon sequestration must be assessed. The primary concern with induced seismicity is not the likelihood of large magnitude earthquakes but the risk of damage to caprock integrity, which can lead to CO₂ leakage, contaminating the environment (Zoback and Gorelick, 2012). Although felt seismic events have not been reported from CO₂ storage projects yet (Rutqvist et al., 2016), future CCS projects will require injection at much larger scales than the current capacity. The potential hazards have to be mitigated by effective modeling and better-quality monitoring networks. The IPCC special report on carbon capture and storage (Metz et al., 2005) has suggested that the health, safety, and environmental risks of geological storage can be managed through proper site selection, continuous monitoring techniques, and

contingencies to control CO₂ injection. Traffic monitoring systems, which have been effective in enhanced geothermal projects (McGarr et al., 2015), can also be adapted to CCS projects. Furthermore, increasing experience in managing CO₂ storage projects around the world is expediting development in mitigation and monitoring technologies. Assessment and management of the risks involved in CO₂ injection is the next crucial step. CO₂-EOR is not immune to the several risks associated with fluid-injection projects (Ellsworth, 2013). Even though the restoration of a depleted reservoir to its original pressure has limited risks, a number of critical geomechanical issues need to be taken care of in such an EOR project (Ferronato et al., 2010). Risks surrounding activation of major faults and induced seismicity, cap rock integrity, well bore instability, ground upliftment, etc. need to be investigated apriori (Verdon, 2014; Zoback and Gorelick, 2012; Verma et al., 2021).

Previous experience with other industries suggests that low levels of induced seismicity will be unavoidable. However, the risks associated with CO₂ storage are low compared to the risks of unchecked climate change. India can learn from the experience of different countries, and utilize developments in CCS technologies to plan and manage these risks that are associated with large-scale projects. With its geological diversity, India offers significant potential to reduce its cumulative emissions through CO₂ storage. Minimizing uncertainties through detailed geological studies and appropriate mitigation techniques can facilitate exploitation of its full storage potential. India currently does not have any commercial or pilot scale CO₂ sequestration projects. Further, mapping of CO₂ source-sink, sub-surface characterization, techno-economic analysis, uncertainty assessment, and development of suitable policies to drive CO₂ sequestration activities will be required. The way forward should encourage knowledge sharing for verification and validation of potential storage capacities, development of feasibility and engineering projects on CCS, suitable technology transfer, collaboration among relevant stakeholders, and capacity building for present and future endeavours to become better equipped for large-scale implementation.

6. Technological readiness in Indian context

India is in a nascent stage of deploying various CCUS initiatives. There are considerable investment barriers and perceived risks that restrict upscaling novel methods for capture, utilization, or storage unless it is efficient and economically viable. Progress of each mitigation component is universally represented as the Technological Readiness Level (TRL), which varies from concept (TRL 1) to commercial implementation (TRL 9). Global TRLs of CCUS pathways have been discussed in detail by Bui et al. (2018); however, the same for specifically Indian context has not been explored yet. There have been significant initiatives for CCUS implementation in India in the past few years. Based on the available literature, we have illustrated the current TRLs of different CO₂ mitigation pathways in India (Fig 9). We note that in most technological components, the Indian TRL is behind the global state-of-the-art. The most significant constraints exist in the capture process. That said, some novel post-combustion capture has been implemented between TRL 5 and TRL 8 specific to Indian conditions. As most of the capture methods reduce the efficiency of the plants, suitable optimization is of utmost importance. Facilitated by a collaboration between BHEL and NTPC, an oxy-fuel trial was conducted in a Fuel Evaluation Test Facility (FETF) in 2010 (Viebahn et al., 2011). Post-combustion (PC) amine-based CO₂ capture technology has been implemented in urea plants at Anola, Jagdishpur, and Phulpur with a 450, 150 and 450 TPD CO₂ absorption capacity, respectively (Gupta and Paul, 2019). Recently Dalmia Cement, India, also signed an MoU with Carbon Clean Solutions, UK to build a cement plant in Tamil Nadu to capture five megaton CO₂/yr through amine-based processes (CCSL, 2019).

It is noteworthy that several injection trials have been carried out

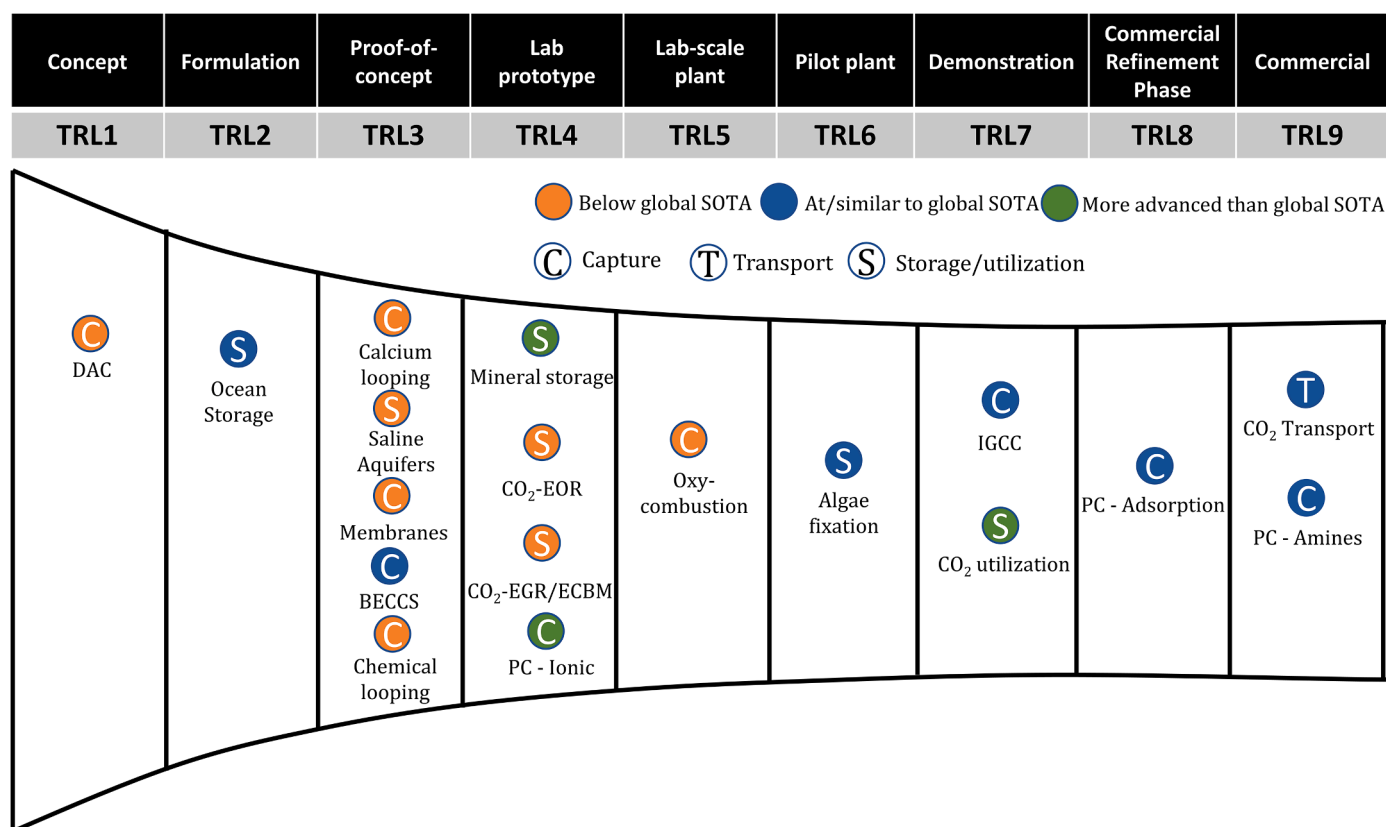


Fig. 9. TRLs of different CCUS technologies available in India. The color schemes illustrate the comparability of technology stages with the global state-of-the-art (SOTA) while the alphabets within the circle represent the component associated with the CCUS supply chain.

globally at a commercial scale, but they have primarily been incentivized through EOR. Similar progress could be replicated in India over the next two decades, but currently, they are at a lower TRL, i.e., TRL4, with the development of laboratory prototypes. A reservoir scale CO₂-EOR feasibility study was carried out in the Cambay Basin, considering its geophysical properties and their evolution over time was studied in detail (Ganguli, 2017). Alongside CO₂-ECBMR feasibility in Gondwana coals have also been explored in detail through field-scale simulation studies (Vishal et al., 2018; Vishal et al., 2015a; Vishal et al., 2013a).

The Indian TRL may be perceived as slightly more advanced in a few technology components than the global state-of-the-art. For example, in the area of mineral sequestration, considerable early work was carried out in Eastern Deccan Volcanic Province. The thermodynamics and mineral formation mechanism with respect to sequestration time and long-term storage behavior have also been explored (A. Kumar et al., 2017; Kumar and Shrivastava, 2019). Similarly, in post-combustion capture with ionic liquids, studies by P. Kumar et al., (2017) revealed good recycling ability, high selectivity, and high yield of products. Pilot-scale facilities have been established for algae-based CO₂ fixation at Hazira, India, representing a distinct technological advancement (Yadav et al., 2016). Additionally, theoretical estimations of carbon capture mediated by seagrass and algal productivity have been studied in Palk Bay and other places of Orissa (Behera et al., 2020; Ganguly et al., 2018). CO₂ utilization potential in India may also benefit considerably in the next couple of years with the development of the methanol plant in Dankuni in eastern India by Coal India Limited (TOI, 2020). Several other supply-chain components such as CO₂ transport could be considered at sufficiently high TRLs with a demonstrated history of natural gas transport and storage across national pipelines such as the Urja Ganga pipeline of GAIL India (PIB, 2019). NTPC has also expressed their interest to setup methanol production units in their thermal power plants as an utilization pathway (NTPC, 2021).

Notwithstanding some capture advancements discussed earlier, most of the work in this area remains at the proof-of-concept scale, i.e. TRL3 (Akash et al., 2016; Karmakar et al., 2013b; Karmakar and Kolar, 2013; Singh et al., 2017; Suresh et al., 2012). Burning profile of Indian high-ash coal in oxy-fuel environment, its optimization and CO₂ enrichment mechanism has been experimentally determined (Saravanan et al., 2009b, 2009a; Seepana and Jayanti, 2012) and its utility in underground coal gasification has also been explored (Kumari and Vairakannu, 2017). An integrated gasification combined cycle for Indian coal coupled with chemical looping was found to have a marginal reduction in efficiency (Shijaz et al., 2017). A simulation-based techno-economic assessment of an Indian coal-fired power plant in Sipat, Chattishgarh with calcite looping (CaL) and fluidized bed combustion (FBC) showed the energy penalty and cost benefits for the proposed retrofitting (Iyer et al., 2020). In some other technologies such as direct air capture (DAC), widespread global development has not translated into conceptualization in India. To our knowledge, this is the first paper to discuss any potential (albeit minor) for DAC in India.

Ultimately, developments in CO₂ capture will have to be accelerated in several ways. First, the technologies have to be conducive to higher-ash coal combustion or Indian lignite gasification. Second, they need to be developed with optimal water consumption as Indian power plants are the most vulnerable to closure due to cooling water shortages. Finally, country-specific technologies in the form of methanol economy and industrial CO₂ capture could place a thrust on CCUS with the co-benefit of reducing emissions in hard-to-decarbonize sectors. The gap between the current and desired TRLs for CCUS can be addressed through site-specific investigation, and development of pilot projects and demonstration facilities after detailed feasibility assessment thereby enhancing the storage readiness levels (Akhurst et al., 2021).

7. Conclusions and recommendations

Following the examples of the forerunners in CCUS and clean energy development, India is emerging as a global leader in climate change mitigation through rapid reforms in technical, economic, and policy dimensions. In the light of India's share in global CO₂ emissions, these reforms could lead the country toward a sustainable future, enhance its energy security, and aid economic growth.

This study explicitly portrays the current scenario in the Indian energy and industrial sectors, and it presents possible opportunities for CCUS development. Given India's economic stature, retrofitting of existing industries and power plants should be the first step in reducing emission levels. Mixing unconventional energy resources with conventional fossil fuels will also decrease the carbon footprint without a massive increase in costs for end-users. Lack of risk assessment and optimization studies has slowed CCUS deployment in India, which will eventually pick its pace upon favorable policy deployment by the government. Feasibility reviews done so far in the Indian context are mostly simulation-based, and they follow examples of pilot projects performed abroad. Continued carbon management initiatives by the government and financial aid for participating industries will eventually encourage field deployment of available technologies at a broader scale. With several opportunities for utilization and storage of captured CO₂ in India, an improvement in source-sink matching and comprehensive techno-economical assessments, and the development of optimization tools will greatly benefit the cost assessment of partnering industries, and oil and gas stakeholders. Studies that investigate the policy framework and legal outlines for CCUS in India are also crucial during the nascent stage of India's CCUS venture. Given India's good international standing, collaborative studies with industries and research groups in other countries that have gained experience in CCUS can aid quicker and sure-footed deployment of CCUS in India.

Our review of India's CCUS readiness demonstrates several key arguments for which a robust policy framework needs to be constructed. First, the degree of CCUS infrastructure would depend on the envisaged role of coal post-2040 and the Government of India's commitments to climate change. As the *Climate Action Tracker's* (CAT, 2020) analysis shows, India is the only country of its size (in terms of the GDP) whose emissions are consistent with the 2°C carbon budgets. However, some media reports (Chaudhary et al., 2021) and expert "op-eds" (Garg, 2021; Parikh and Parikh, 2021) have also pointed out that the government may be looking at higher climate targets of reaching net-zero emissions by 2050. Meeting these targets would likely require a focus on CCUS in existing facilities. Based on our first-order estimates of the stranded assets in the power sector, we recommend that the revisiting of this target should be met with appropriate revisions to India's INDC with some provisions on CCUS (which were not listed in the INDC submitted in 2015). Doing so would be beneficial in avoiding a large volume of stranded assets especially in case of supercritical power plants commissioned after 2010.

We also re-iterate the need for an integrated policy framework for CCUS in India. Currently, India's energy sector has key inputs from several ministries (coal, petroleum and natural gas, power, steel, cement, fertilizer). The anticipated levels of CCUS deployment would require a coordinated policy making across sectors. Moreover, the integration of these sectors on the supply and demand side brings in economic benefits of \$10-20/t-CO₂ due to economies of scale. It would also facilitate operation of infrastructure such as CO₂ pipelines as well as institutional measures such as life-cycle scrutiny (such as those introduced within US government's 45Q tax credits) that require uniform benchmarking of GHG emissions and sequestration.

Another key policy outlook is on the role of geographical appropriateness on CCUS development. For instance, coal-to-methanol opportunities are being actively pursued in India because of the need to decarbonize coal sector and promote domestic cleaner fuel. Therefore, ways in which CCUS could be incorporated within the methanol

economy could be studied. For instance, Coal India Limited has invited bids for construction of a \$800 million coal-to-methanol plant in Dankuni in eastern India. As discussed in sections 3 and 5, this region has the potential to emerge as a CCUS hub because of presence of large point sources and suitable geologic sinks. It would be useful for the Dankuni methanol plant to be considered for CO₂ capture opportunities. Conceptualization and development of geographical hubs/clusters has been a key component of CCUS infrastructure in Europe and North America since 2018 (Global CCS Institute, 2020). As these emerge, they are likely to reduce the risk perceptions associated with CCUS in India and would further spur technological innovation.

CRedit authorship contribution statement

Vikram Vishal: Conceptualization, Investigation, Methodology, Formal analysis, Validation, Project administration, Writing – review & editing. **Debanjan Chandra:** Data curation, Investigation, Formal analysis, Validation, Writing – original draft. **Udayan Singh:** Data curation, Formal analysis, Validation, Visualization, Writing – original draft. **Yashvardhan Verma:** Investigation, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare no conflicting interest.

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