Perspectives on Carbon Capture and Geologic Storage in the Indian Power Sector

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ABSTRACT

India is a major developing country with ambitious developmental goals. Future development is expected to increase energy demands and subsequently greenhouse gas (GHG) emissions. Carbon capture and storage (CCS) is one of the GHG mitigation strategies that might be adopted in this context. This article summarizes the scope of deployment of CCS in India's power sector. It also offers perspectives with regard to CO_2 capture technologies vis-à-vis Indian power plants. The potential geologic CO_2 storage sites and their resulting storage capabilities are discussed with references to the Indian research work being performed.

This article reviews the scope of CO_2 capture and storage in India's power sector which is largely dominated by coal. It considers how coal-based power generation is expected to rise in the near future, the potential role of CCS, and various perspectives of capture and storage strategies. This is followed by a discussion of the economic and regulatory aspects of the CCS technology, the two largest non-technical deterrents to implementing CCS. Finally, recommendations are offered regarding improving CCS technologies and policies in India. The major theme of this paper is CO_2 capture from the power sector. Applications in other sectors, such as the fertilizer industry are similar. The Jagdishpur fertilizer plant, as one example, has been performing CO_2 capture for a considerable time.

This article considers the Indian perspective, summarizes and re-

views past CCS work in India and provides suggestions for the future. Suggestions include progressive ideas on the technologies and policies that can advance CCS in India. We conclude that CCS is an important transition technology to minimize GHG emissions while technologies develop that will enable future deployment of renewable energy sources.

INTRODUCTION

India is a major developing economy and ranks fourth in the world in terms of energy consumption [1]. India must produce more energy to meet its growing demands since no country has increased its Human Development Index without a corresponding increase in per-capita energy consumption [2]. However, a large portion of India's primary energy supply is reliant upon fossil fuels which are sources of atmospheric greenhouse gases. India's CO_2 emissions are expected to increase in the future in order to meet its developmental challenges.

The problem of climate change is a major concern for India considering its developmental ambitions and natural climatic vulnerabilities. These include a long coastline, tropical rainforests, assorted biodiversity and the Himalayan mountain range. Thus, climate change mitigation is one of the key issues faced by India [3]. The Maplecroft Index [4] suggests that India is the second most vulnerable country with regards to climate change. In a recent review by Sathaye and Shukla [5], it has been predicted that regions growing demographically and economically will need to play a major role in climatic change mitigation. Economic growth in India is strongly linked to energy consumption. If we consider the economic growth trajectory of India from 2001 to 2007, we find that this period's increase in the growth rate of the real gross domestic product from 5.2% to 9.6% was accompanied by an increase in the growth rate of CO_2 emissions from 0.7% to 8.6% [6]. While the relationships are not strongly linear, there is certainly a strong co-relation between GHG emissions and growth rate.

India has a history of environmental protection policies, beginning with the Water Act of 1974 [7] to the National Action Plan on Climate Change announced in 2008 [8,9]. India is a signatory to the Kyoto Protocol and has ratified the United Nations Framework Convention on Climate Change (UNFCCC). India is a founding member of the Carbon

Sequestration Leadership Forum (CSLF) organized by the U.S. Department of Energy and is a past vice chair for this group [9]. Thus, India has played a proactive role in the formulation and implementation of policies related to climatic change mitigation.

India's total GHG emissions in 2007 were 1,831,647 giga tons of CO_2-equivalent of which 1,388,307 (~75%) giga tons of CO_2-equivalent were from the energy sector [10]. A large portion of India's GHG emissions come from large point sources (LPSs) such as thermal power plants, the steel industry, the cement industry and petroleum refining. Figure 1 provides a graphical representation of projected trends and contributions of all-India CO_2 emissions and the contributions of LPSs. As shown, CO_2 emissions will continue to increase and the contribution of LPSs will be roughly 70% [11]. LPSs offer a manageable way to control CO_2 emissions as a large amount of emissions can be mitigated while controlling a smaller number of sources.

Of the LPSs, coal-fired power plants are the most prominent contributors. In 2020, roughly 47% of India's CO_2 emissions are projected to be from coal-fired power plants [11]. The rate of CO_2 emitted per unit of electricity is much higher for coal-based power generation than for oil

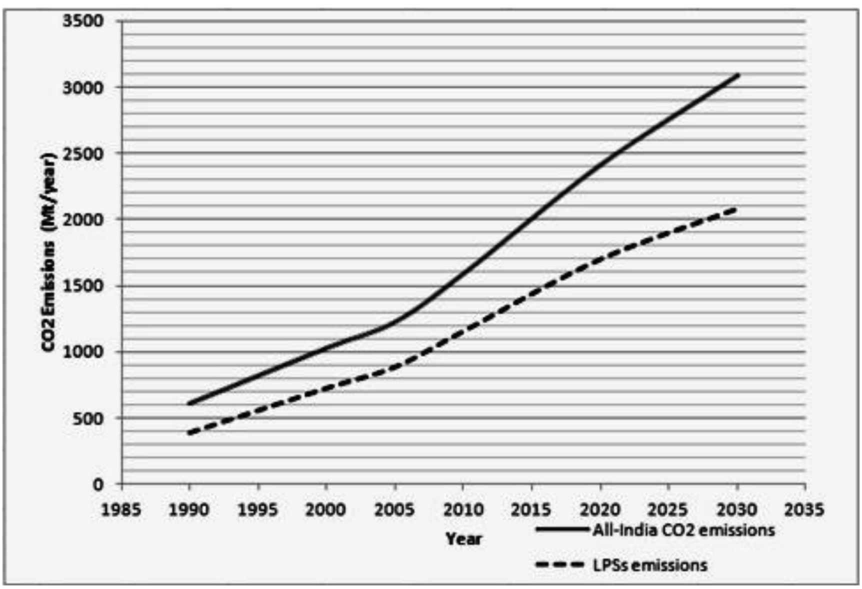


Figure 1. All-India CO_2 emissions and CO_2 emissions from large point sources (past and projected trend). Graph plotted from referenced data [11].

and natural gas based ones [12,13]. This includes emissions from both pulverized coal (PC) and integrated gasification combined cycle (IGCC) plants. For these reasons, coal-fired power plants are the most important sources from the perspective of CO_2 emission reductions.

Carbon capture and storage, also referred to as carbon capture storage and utilization (CCSU) encompassing industrial utilization of CO_2 along with geologic storage, is a technology involving capture of CO_2 from LPSs flue gases, its compression, transport and subsequent storage in geologic reservoirs. These reservoirs might include coal seams, saline aquifers, basalt formations and depleted hydrocarbon reservoirs. The reader may refer to IPCC (2005), DOE (1999) and Haszeldine (2009) for excellent reviews on this subject. Since coal-fired power plants are the largest emitters of CO_2 among all the other LPSs, it is imperative to judge the prospects of CCS in such plants. The government of India is taking steps towards energy security with the development of ultra mega power plants (UMPPs) with generation capacities on orders of giga watts [17]. Government expenditures on climate change adaptation in India already exceed 2.6% of GDP, indicating that the government intends to work towards greenhouse gas (GHG) emission mitigation [8]. Development of renewable energy sources have been hampered as they are location dependent, have high establishment costs and non-competitive pricing [13]. To mitigate rising GHG emissions, CCS is considered to be a tool for India's power sector.

India's Power Sector and CCS Deployment

India's power sector is currently dominated by coal. At 210 GW, India has the world's fifth largest electricity generation sector, with plans to add 76 GW from 2012 to 2017 and 93 GW more from 2017 to 2022 [18]. Coal accounts for more than 50% of total electrical power generation. It is predicted that this domination of coal will increase in the future [19,20]. Integrated economic, energy and environmental modeling for India suggests that roughly 150,000 MW of coal-based power could be added by 2030.This is a factor in the projected increase in CO_2 emissions by 2.5 times during this period [21]. Given the increase in coal-based power generation, it is likely that CCS technologies will be used by power plants [11]. If renewable power becomes less expensive in the future, yet remains costlier than the conventional fossil fuel power generation, CCS could allow India to continue using coal in a more climate friendly manner. CCS will thus be a form of energy security for India

[11]. For instance, the current predicted cost of concentrated solar power in India is about $230(US)/MWh [22], compared to the $110(US)/MWh cost of coal-fired power with CCS [23].

Thus, we must determine by what margins CCS will increase given the planned increases in coal-based power generation. The India Energy Security Scenarios 2047 model, developed by the Planning Commission, Government of India, provided estimates in this regard [24]. Their model indicated four levels of deployment of CCS technology in Indian power plants:

- Least effort scenario (Level 1)—Involves a capacity addition of 10 GW to the year 2052. In this scenario, the installation of CCS-based plants will begin in approximately 2030, after which the growth of such plants will be very slow.
- Determined effort scenario (Level 2)—CCS-based capacity additions will reach roughly 40 GW by the year 2052. For this scenario, CO_2 capture based plants must begin functioning by 2022.
- Aggressive effort scenario (Level 3)—Involves CCS-based capacity additions of 88 GW by 2052 and requires such plants to be operational by 2017. This is the same level of CCS deployment found in the International Energy Agency (IEA) roadmap on CCS [25].
- Heroic effort scenario (Level 4)—Results in cumulative capacity additions of 100 GW of CCS-based power in India. This scenario occurs if the IEA Global Vision on CCS technology is followed [25].

Based on the previous data and the study by Singh and Rao [26], we can predict the extent of resulting CO_2 reductions from CCS. Assuming a super-critical boiler of 660 MW as characterized in this study, there will be a reduction of 0.78 kg/kWh using CO_2 capture. Using this data, we obtain results as shown in Figure 2.

The role that CCS will play in India will be determined by several factors. This includes cost of the technology, the attitude of the government and other stakeholders, and the development and pricing of other low carbon energy initiatives. As indicated in Figure 2, almost 200 million tonnes could be mitigated in the Indian power sector assuming a Level 3 scenario and nearly 230 million tonnes could be mitigated assuming a Level 4 scenario by 2052. Since the current CO_2 emissions are 665.4 million tons [27], this technology can serve as a useful tool to mitigate CO_2 from the largest emission source. This is in accordance with

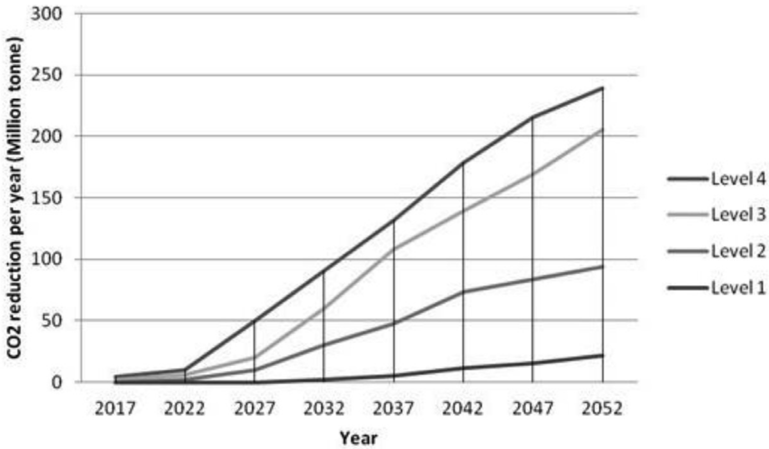


Figure 2. Projected annual CO_2 reductions through CCS in Indian power plants from 2017 to 2052. This graph has been plotted by multiplying the projected CCS installations in India [24] with the data on CO_2 reductions from Indian coal-fired power plants [26].

an IEA assessment [28], which suggests that CCS may be instrumental in meeting the 19% CO_2 reduction necessary to achieve the less than 2ºC climate change mitigation.

CO_2 Capture Perspectives for India

The first major step in the CCS technology is to capture CO_2 from LPSs, or in this case, thermal power plants. There are two basic considerations that need to be studied. The first is the type of capture technology to be used and the second is the implications of base plant power generation or those lacking CO_2 capture. For a plant with CO_2 capture, the two factors are related (i.e., the plant conditions govern which capture technology should be used). For capture, one assessment studied energy, exergy, and environmental (3E) aspects for a plant with CCS compared to the same plant without CCS. Hasan et al [29] have suggested a modeling framework for the CCS chain to arrive at the most cost-effective configuration while dealing with several sensitivities. These sensitivities include the type of material for carbon capture, process optimization, capture technologies and deployment of CO_2 utilization. A similar framework may be applied to India to suggest an optimized CCS chain for cost-effective CCS and CCUS deployment.

The first consideration in the base plant or the plant without

CO_2 capture is the type of plant. Does it use combustion (pulverized coal plant) or gasification (IGCC)? When dealing with pulverized coal (PC) plants, the type of boiler plays a crucial role. It must initially be determined whether it is sub-critical (SubC), super-critical (SuperC) or ultra-super-critical (USC). For carbon capture, the capture technology can be post-combustion, pre-combustion or oxyfuel based capture. Post-combustion capture has several sub-divisions including sorbent based (amine and ammonia) and non-sorbent based (membrane).

Only a few studies have been performed for thermodynamic as well as environmental comparisons of Indian PC plants with and without CCS. Numerous studies report that supercritical technology is well-suited for power plants with CCS [30]. A 2007 study of the risks of moving to more advanced steam conditions for the UMPPs being commissioned by the Indian government was undertaken by Mott MacDonald [17] with funding from the UK Foreign and Commonwealth Office. It considered factors such as environmental conditions in India, limited local manufacturing capability and a lack of experience with deploying the technology.

If CCS is to be tested on a reasonable scale, it is expected that the future UMPPs would be carbon capture and storage ready (CCSR). According to Kapila and Gibbins [31], a CCSR facility is a large-scale industrial or power source of CO_2 which is intended to be retrofitted with CCS technology when the necessary regulatory and economic drivers are in place. Designing a plant to be carbon capture ready could lead to CCS implementation at a minimal cost. The factors to consider if it is economically feasible to make an older power plant CCSR include installed capacity, remaining lifetime, load factors, cost of retrofitting and the required rate of return. For a new power plant factors include cost of CCSR investment and expected plant lifetime [32].

Karmakar and Kolar [33] simulated a 500 MW sub-critical plant operated by the National Thermal Power Corporation (NTPC). They concluded that the net plant efficiency drops by 8.3% to 11.2%, while the net plant exergy drops by 7.6% to 10.7%. They also suggested that the net plant efficiency improves when using low ash coal instead of high ash coal (most Indian coals are high ash). They also stated that the amount of CO_2 avoided varies between 0.68 and 0.70 kg per kilowatt-hour of electricity generated.

In a similar study, Singh and Rao [34] simulated a 500 MW sub-critical and a 660 MW super-critical PC plant. While Karmakar and

Kolar [33] studied only amine based capture, this study analyzed amine, ammonia, membrane and oxyfuel based capture. They also studied the implications of using an auxiliary natural gas boiler. They calculated the energy penalty to be between 39% and 46% using CCS for the super-critical plant. They also predicted that using an auxiliary natural gas boiler would not be beneficial in India. Singh and Rao [26], in another paper, studied the implications of CCS on power plant emissions and resource use. They concluded that CO_2 emissions would be reduced by 0.78 kg/kWh for a 660 MW super-critical plant. They also stated that for the sub-critical unit, the increase in coal use is between 46% and 52% while for the super-critical unit the increase is between 40% and 48%. Water consumption almost doubles for amine and membrane-based capture. The increase is more than 150% using ammonia-based capture and approximately 50% using oxyfuel technology.

These studies suggest a clear energy penalty as well as penalties on the use of resources. Plants with higher boiler efficiencies using better quality coals are more suited to CO_2 capture. This is not beneficial for Indian plants as they have lower efficiencies [35]. Furthermore, Indian coals generally have lower heating values and higher ash contents [36].

International studies, such as Rubin et al [37] suggest that IGCC plants are more suited to CO_2 capture than PC plants. However, India currently lags in IGCC technology. Initial studies of the economics of power generation with CO_2 capture have suggested that the costs of producing electricity from coal with CO_2 capture could be similar for IGCC and state-of-the-art pulverized coal-fired power plants with CO_2 capture [38]. The Indian company Bharat Heavy Electricals, Limited (BHEL) held research trials in 1989 on IGCC in a pilot plant with a capacity of 6.2 MW [39].

While a few experimental and modeling initiatives have been performed with IGCC, none has dealt with CCS. In 1991 Iyengar and Haque [40] studied performance of high-ash Indian coals gasified by a fluidized bed reactor (FBR) at the Central Fuel Research Institute (CFRI) in Dhanbad. Similarly, Krishnudu [41] studied the performance of moving-bed gasification on Indian coals at the Indian Institute of Chemical Technology in Hyderabad (IICT). Some Indian indigenous coal samples were also tested for IGCC at the Gas Research Institute, in the U.S. [39]. Goel [42] made a comparative study of the IGCC and oxyfuel options in the Indian context. More recently, Singh et al [43] and Ajilkumar et al [44] developed mathematical models for gasification of Indian coals in a moving bed and tubular gasifiers respectively. However, despite discussions concerning IGCC for over three decades, it has not yet come to fruition in India [45].

Lessons for CO_2 capture from power plants may be drawn from industrial CO_2 sources. The Jagdishpur fertilizer plant operated by the Indo Gulf Corporation has had success with CO_2 capture. This plant has been instrumental in capturing 9,131 Mt CO_2 and establishing a precedent for the power sector [46].

CO_2 STORAGE SITES

After capturing CO_2, the question arises as to whether there are adequate storage sites. India is a large country with varied landforms. Options for potential geological storage for CO_2 include basalt formations, saline aquifers, hydrocarbon reserves, coal seams and use in enhanced oil recovery. We next consider each of these in a detail.

Basalt Formations

Basalt is a volcanic rock composed of metal silicates. Deccan Basalts in Southern and Central India are composed of 48 flows, covering 5,000 km^2 (1,930 m^2) and are one of the world's largest flood eruptions [47,48]. The Rajmahal traps which are smaller than the Deccan traps also have substantial storage potential [49]. Tectonically, these traps are considered to be stable (see Figure 3). These provide solid storage for CO_2 with long-term integrity as they form mineral carbonates upon reaction with CO_2. Basalt formations have high storage capacities but have not been widely researched, perhaps because the IPCC Special Report on CCS has stated that this technology is not yet mature [14]. Nevertheless, if storage in basalt formations is developed, it might be a highly attractive option for India. McGrail et al [50] mapped the locations of India's power plants and their proximity to basalt formations and concluded that 26% of the former lay in proximity to the latter. They also compared India's Deccan basalts spectroscopically with Columbia River basalts and identified similarities. Thus, international experience in CO_2 storage in basalt formations may help India obtain a suitable understanding of this alternative.

India's Hyderabad based National Geophysical Research Institute in collaboration with U.S. Pacific Northwest National Laboratory

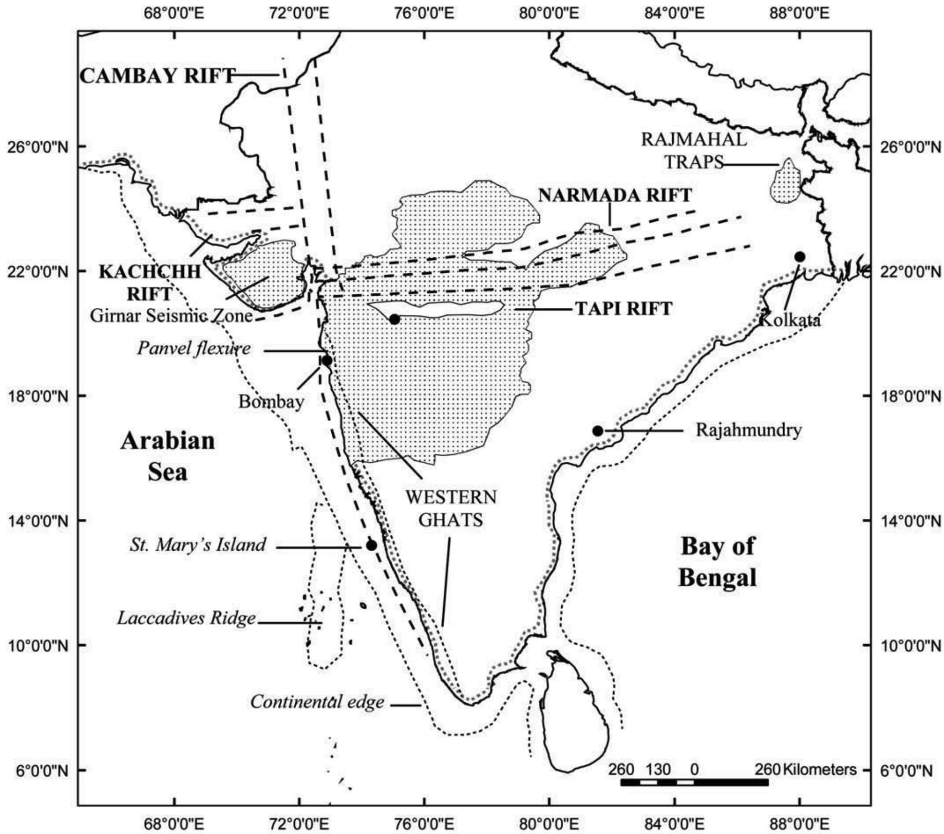


Figure 3. Map of the Indian sub-continent showing Deccan and Rajmahal Trap province [11].

(PNNL) are involved in a joint project entitled "Demonstration of Capture, Injection and Geologic Sequestration of CO_2 in Basalt Formations of India" [51]. This is both a research and demonstration initiative endorsed by the CSLF. It involves assessing selected basalt storage areas and injecting 2,000 tons of CO_2.

Saline Aquifers

Saline aquifers are also a very good storage option due to their ubiquity [52]. Many locations in Rajasthan and southern Haryana have EC values of ground water greater than 10,000 mS/cm at 25°C, making the water non-potable [53]. The Central Ground Water Board and the Geological Survey of India have established that saline aquifers exist at depths greater than 300 meters (984 ft) in the Ganga river basin. These are in the states of Rajasthan, Uttar Pradesh, Haryana and Punjab [53]. Research under the IEAGHG program [54] divided these basins into three parts:

- Good potential basins—Assam Basin, Assam-Arakan fold belt, Mahanadi basin (deep water part), Krishna-Godavari Basin, Cauvery Basin, Mumbai Basin, Cambay Basin, Barmer Basin and Jaisalmer Basin.
- Fair potential basins—Mahanadi Basin, Bikaner-Nagaur Basin and Kutch Basin.
- Limited potential basins (areas with uncertain storage potential)—Ganga Basin (and Punjab Shelf), Bengal Basin (Indian part), Vindhyan Basin, Cuddapah Basin, Chhatisgarh Basin, Konkan-Kerala Basin, Narmada Basin, Saurashtra Basin, Rajmahal Basin, Pranhita-Godavari Basin, South Rewa Basin, Satpura Basin and Damodar Valley Basins.

Coal Seams

Coal has a porous structure which contains adsorbed methane. When CO_2 is injected into coal, methane is displaced since coal has a higher affinity for CO_2 than for methane. Enhanced coalbed methane recovery (CO_2-ECBM) expedites the conventional coalbed methane recovery process. Methane is a fuel source that can supplement India's natural gas reserves.

The coal seams which have a good potential for CO_2 storage are divided into three categories, unmineable coal beds in well-delineated coalfields, grey area coal beds and concealed coal beds [55]. Table 1 provides a detailed categorization of coal beds.

ECBM is considered to be a good prospect for initial plants as the high costs of CCS are supplemented by the methane extraction. Vishal et al have considered numerical modeling for CO_2 storage in India coalbeds. They initially studied the permeability of Indian coal seams and identified subsequent implications for CO_2 storage [56]. They also modeled Gondwana coal seams in India as CBM reservoirs substituted for CO_2 sequestration [57]. In a more recent study, they have analyzed the influence of sorption time in the CO_2-ECBM process in Indian coals using coupled numerical simulation [58]. Researchers from the state funded CSIR-Central Institute of Mining and Fuel Research based at Dhanbad have studied CBM and ECBM [59,60].

Table 1. Categories of coal beds in India [55].

Category of coal beds	*Grade of coal*	*Candidates /Basins*
Unmineable Coalbeds in explored areas	Power Grade coal	Singrauli MandRaigarh Talcher Godavari
Grey Areas Coalbeds	Coking coal	Jharia East Bokaro Sohagpur South Karanpura
	Superior non coking coal	Raniganj South Karanpura
	Power grade coal	Talcher
Concealed Coalfields	Tertiary age coal	Cambay basin Barmer Sanchor basin
	Power grade coal	West Bengal Gangetic Plain Birbhum DomraPanagarh Wardha Valley Extension Kamptee basin Extension

Oil and Gas reservoirs

India is heavily dependent on imported oil and natural gas. As only 27% of oil-in-place is normally recovered, recovering the balance would boost India's energy sector. The Oil and Natural Gas Corporation Limited, India's petroleum giant is exploring the possibilities of enhanced oil recovery (CO_2-EOR), which is the acceleration of oil recovery using CO_2 injection. EOR projects have been approved in both the Ankaleshwar (Gujarat) and Rajasthan oilfields. The possibility of CCS for disposal of acid gas at Uran is also being explored [61].

CO_2 Storage Potential

A major issue for implementation of the CCS technology is accurate assessment of CO_2 storage potential in various geological formations. A first order estimate by Singh et al suggested a storage potential of 360 Gt CO_2 in saline aquifers, 200 Gt CO_2 in basalt formations, 5 Gt in coal seams and 7 Gt in oil and gas fields [55]. These total 572 Gt CO_2. While encouraging, another study by the IEAGHG [63] regards this total as highly exaggerated and estimates total storage potential to be only 142 Gt CO_2 for good, fair and limited quality areas. The major differences are that the latter study excluded basalt formations and included only 0.345 Gt CO_2 storage potential for coal seams. This is due to an assumption that much of India's coal would be mined instead of being used for CO_2 storage. Table 2 compiles the results of these two studies and another by Dooley et al [64,65].

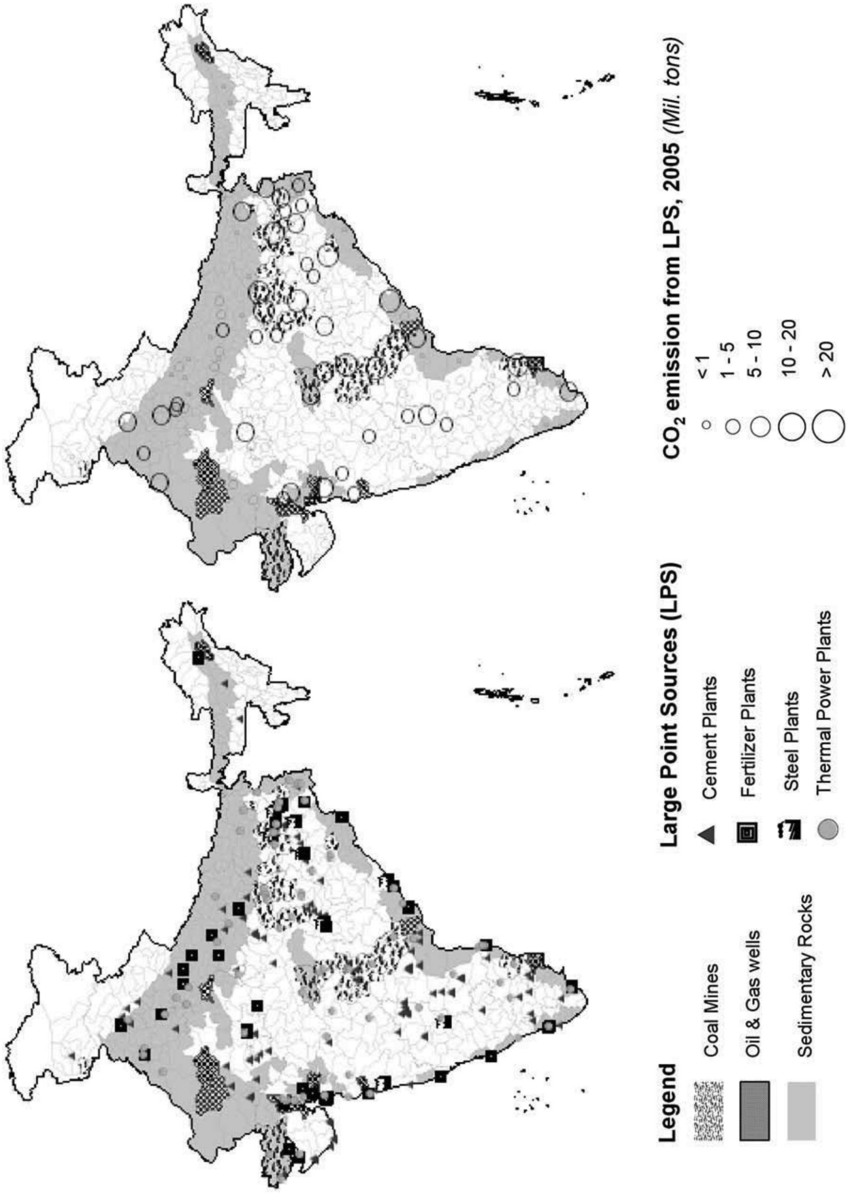
Interestingly, Narain [66] states that CO_2 storage sites are not constrained by geography or geology. Doig [67] meanwhile suggests that Indian geologic formations offer inadequate CO_2 sequestration capability. It is clear that estimates of CO_2 storage potential vary widely and that progress will be hindered until reliable estimates of storage capacities are available. To reduce discrepancies, a standard methodology needs to be used to estimate storage potential, such as one suggested by Bachu et al [68]. Figure 4 provides locations of India's CO_2 emission sources and potential storage area.

The data calculated by the researchers mentioned above consider theoretical storage capacity, which is based on the physical limits of

Table 2. Overview of existing estimates for theoretical storage capacity in India [65].

	Dooley et al, 2005[64]	*Singh et al, 2006[62]*	*Holloway et al 2008[63]*		
			Good, fair and limited quality	*Good and fair quality*	*Good quality*
Oil fields	-	7		10.0 – 1.1	
Gas fields	2			2.7 – 3.5	
Aquifers	102	360	138	59	43
Coal Seams	2	5		0.345	
Basalts	-	200		-	
Total	104	572	142	63	47

Figure 4. Districts with CO_2 storage potential in India [11].



what the geological systems can accept [68]. When a range of technical and geological cut-offs are applied to the theoretical storage limit, it provides a more realistic storage limit [69,70]. Technical, legal, regulatory, economic and geological barriers [68] limit the practical CO_2 storage capacity. By matching the three CO_2 sources with the sinks, we can define the matched storage capacity. Source sink matching by Beck et al [71] mapped a number of industrial sector LPSs to CO_2 sinks. Specific to the power sector, Jain et al [72] used a graphical information system (GIS) for source sink matching for eastern India considering seven major power plants and four sinks.

ECONOMIC AND POLICY CONSIDERATIONS

Reducing GHG emissions by any means is costly. Carbon capture and storage is often criticized as an expensive technology. Based on expert assessments, the cost for the total chain of capture, transportation and compression for India is expected to be roughly $50-60(US)/t CO_2. The various components of the costs are capture (45%), compression (20%), transportation, injection and monitoring (35%) [11]. Reliable economic estimates are not available for CCS in India [69]. This hampers policy-making.

Attempts have been made to quantify the economic penalty for Indian power plants. Mott Macdonald estimated the cost of CO_2 abatement by CCS to be between $35 and $42 (US) for each tonne of CO_2 avoided [17]. The TERI scooping study on CCS stated that the cost of electricity with CCS will increase by 47% for the UMPPs [61]. Viebahn et al estimated that the cost of electricity would increase by 45-51% for CCS in India [65]. A recent study by Rao and Kumar, estimated the incremental cost of electricity due to CCS between $39(US)/MWh and $47(US)/MWh and the cost of CO_2 avoidance between $48 and $58 (US) per tonne of CO_2 avoided [23]. This study was based on retrofit installation of CCS in four Indian power plants. This is substantially less than the estimated cost in the international power sector, which ranges from $72 to $114 (US) for each tonne of CO_2 avoided [73-76]. One reason why the cost of avoidance in India could be lower is due to the lower price of coal which is regulated domestically.

The studies referenced have not followed the standard costing methodology suggested by the Global CCS Institute. In this methodology, guidelines have been established to avoid ambiguity in the results as CCS cost estimates have several pitfalls [77]. The assumptions made for the study must be clearly specified per the Global CCS Institute guidelines [78, 79]. Future studies should follow a probabilistic methodology rather than a deterministic methodology based only on studying nominal values of just a few plants. Also, our belief is that some of the assumptions made in the aforesaid studies are not appropriate. In the study by Rao and Kumar [23], the reduction in gross size due to solvent regeneration was not considered. Such improvements are needed in future studies to obtain more reliable estimates of CCS implementation costs in India.

CO_2-ECBM and CO_2-EOR are expected to be tested earlier due to their greater cost benefits compared to storage in basalt formations and saline aquifers. Initially, it is expected that CCS will be implemented for thermal power plants which are near storage areas as this offers lower transportation costs [11]. It is also envisaged that capture from coal-fired thermal power plants will be initiated before oil and natural gas fired ones. Tax incentives for emission reductions implemented by the Norwegian Sleipner project will help in the progress of CCS projects [13]. Factors that are likely to play a role in determining the economics of CCS in India include the price of fuel and imposition of carbon taxes. The policies of India's government and support by financial and regulatory agencies will be key determinants for the success of CCS technology in India. This includes issues such as the debt-to-equity ratio for the power plants and interest rates on loans which lead to differences in the costs of the plants. Technical parameters and new developments in CO_2 capture mechanisms also affect the CCS costs substantially [80, 81].

The Indian government's policies toward CCS can be either major enablers or deterrents to implementing this technology. India's government has been very pro-active in mitigating climatic change. However, whether or not the mitigation will include CCS depends on future policies and governmental regulations.

In India research on carbon sequestration began with the support of the industry and the government [42]. The Indian government continues to look favorably upon carbon sequestration technologies including biological and terrestrial storage. The Department of Science and Technology, initiated a national program on carbon sequestration with one of its thrusts being carbon capture process development [9]. However, programs like these remain restricted to research and development

(R&D). There is a consensus in developing nations that they should test this technology and then it can later be adopted in emerging economies [82]. It is desirable to develop local technical, economic and regulatory capabilities, so that CCS technologies can be more easily adopted in India. One assessment states that the Indian Government has adopted a cautious stance towards CCS for the following reasons [83]:

- CCS leads to substantial energy penalties, whereas the principal aim of the government is to ensure maximum power generation.
- CCS leads to a higher economic penalty, whereas the government wants a low electricity price.
- CCS is not yet commercially viable.

Public sector industries have shown a positive approach towards CCS with two of the largest companies in the Indian power sector, NTPC and BHEL, being involved in R&D projects. This contradicts Kapila and Haszeldine [32] who state that CCS in India may progress in the same way as the information technology (IT) sector, which benefited from investments made by private enterprises. There is a consensus among several stakeholders that developed countries will have to demonstrate CCS at a commercial scale prior to commercial–scale development in India [84].

For development of CCS in India, there are also national and international laws that need to be considered. These relate to long-term monitoring of stored CO_2, ownership issues, site-selection and remedial responsibilities in case of accidents [85]. The reader may refer to TERI [61] who mentioned specific laws that need to be considered when proposing CCS-specific legislation in India.

CONCLUSIONS AND RECOMMENDATIONS

There is a strong agreement that India needs to focus on climatic change mitigation. India's government has already provided a strong mandate towards mitigation efforts. Since coal is expected to dominate India's energy mix, there is a need for "clean coal" development. The prime minister of India recently stated that there are vast opportunities for development of clean coal technology (CCT) in India and invited foreign investments [86]. Yet the question remains whether the thrust on CCT will focus on improving power generation efficiency or radical reductions in emissions when CCS deployed.

CCS will require additional research before implementation. While work has been successful in determining plant level results and storage capacity, there is a need for less ambiguity. This may be achieved using standard assessment methodologies. Adoption of CCS in India would create major challenges including reductions in energy efficiency and higher electricity costs. Reductions in efficiency may be offset (at least partially) by the following means:

- Development of IGCC technology in India as IGCC plants are more suited to CO_2 capture than PC plants.
- Higher capacity installations of super-critical and ultra-super-critical boilers.
- A major breakthrough may be achieved by research and development of membrane based capture in India. Singh and Rao [26] state that the energy penalty for membrane-based capture is less at lower capture efficiency. Research can focus upon making membrane-based capture more economically feasible and efficient. Improved blending and beneficiation of coal as better coal quality leads to more economic and efficient CO_2 capture. Plants which use imported coal should be among the first ones to employ CCS [26].
- Indigenous development of capture and compression equipment would lower costs. Current estimates are based on using equipment found in developed countries. Since Indian boilers are less expensive than their western counterparts, radically lower capital costs are possible if similar R&D is undertaken for capture and compression equipment.

The following must be considered regarding economic policies towards CCS:

- Currently, CCS is not part of the Clean Development Mechanism (CDM). If CCS can be brought within the ambit of CDM, India could benefit from its use [87].
- Financial and regulatory bodies need to support the technology for it to be successful. If lower taxes or lower interest rates are imposed on plants with CCS than the plants lacking CCS, then such favorable regulation would help CCS become established. Also, the availability of higher loans guarantees, production credits, purchasing agreements or other policy instruments, through

government interventions [37] would help create a positive investment opportunity for CCS in India.

- Long-term carbon pricing will enhance the feasibility of CCS. However, the Indian government has not shown interest in placing a tax on CO_2.
- Additional revenues from CCS, such as ECBM and EOR, will help reduce incremental electricity costs due to CCS. However, India's ECBM and EOR prospects are not favorable.
- Foreign funding should be attracted for R&D in CCS. Such funding can be from other governments or international institutions such as the Asian Development Bank.

There is also the need to strengthen the CCS knowledge base by organizing workshops and courses for college students, as public perception plays a major role in CCS deployment [13]. The political will and bureaucratic acceptance for the technology is crucial. At least two foreign studies [35,89] on CCS in India have deemed that the Indian governmental bureaucracy has too many roadblocks to innovations in technology and financing. Kapila and Haszeldine stated that the coalition structure of the Indian government was a deterrent towards innovation [35]. The recent parliamentary elections have given a majority to the ruling party yet it remains uncertain whether CCS will become an important policy area for the new government.

While considerable research has been carried out in various areas for CCS in India, there is a need for the studies to be integrated. Singh [13] and Jayanthu et al [85] have vouched for a national mission project on CCS involving academic institutions (IITs, IIMs, NITs and other universities), research laboratories (NGRI, CIMFR, IIP, NCL) and industries (NTPC, CIL, BHEL, private sector industries). Funding for such a project might be financed by industry or foreign sources. Interdisciplinary research is the key to lowering the costs of CCS. As Rubin et al have indicated, there has been a considerable decrease in costs from lessons learned for all the power-plant based technologies for emission controls [90,91].

We conclude by reiterating the tone of Maroto-Valer that CCS is an important transition technology to minimize GHG emissions while developing technologies for deployment of renewable energy sources [92]. A larger number of abatement options will help ensure fewer difficulties in the mitigation of climate change [88].

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