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Prospects of carbon capture and storage (CCS) in India's power sector – An integrated assessment

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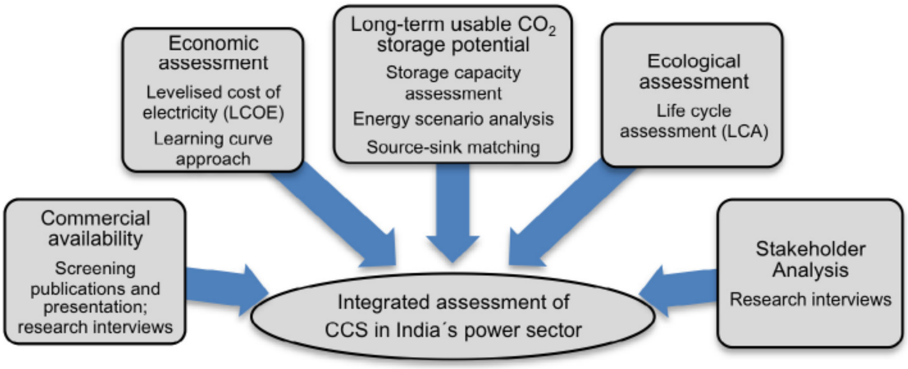
HIGHLIGHTS

- In this study an integrated approach is chosen to assess CCS in India.
- Five different assessment dimensions are covered.
- Several conditions need to be fulfilled if CCS is to play a future role in India.
- The most crucial requirement is a reliable storage capacity assessment for India.
- Further requirements are economic viability, ecological impacts and public support.

GRAPHICAL ABSTRACT



Set of methods used for the integrated assessment

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ABSTRACT

Objective: The aim of the present article is to conduct an integrated assessment in order to explore whether CCS could be a viable technological option for significantly reducing future CO_2 emissions in India.

Methods: In this paper, an integrated approach covering five assessment dimensions is chosen. However, each dimension is investigated using specific methods (graphical abstract).

Results: The most crucial precondition that must be met is a reliable storage capacity assessment based on site-specific geological data since only rough figures concerning the theoretical capacity exist at present. Our projection of different trends of coal-based power plant capacities up to 2050 ranges between 13 and 111 Gt of CO_2 that may be captured from coal-fired power plants to be built by 2050. If very optimistic assumptions about the country's CO_2 storage potential are applied, 75 Gt of CO_2 could theoretically be stored as a result of matching these sources with suitable sinks. If a cautious approach is taken by considering the country's effective storage potential, only a fraction may potentially be sequestered. In practice, this potential will decrease further with the impact of technical, legal, economic and social acceptance factors. Further constraints may be the delayed commercial availability of CCS in India, a significant barrier to achieving the economic viability of CCS, an expected net maximum reduction rate of the power plant's greenhouse gas emissions of 71–74%, an increase of most other environmental and social impacts, and a lack of governmental, industrial or societal CCS advocates.

Conclusion and practice implications: Several preconditions need to be fulfilled if CCS is to play a future role in reducing CO_2 emissions in India, the most crucial one being to determine reliable storage capacity

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figures. In order to overcome these barriers, the industrialised world would need to make a stronger commitment in terms of CCS technology demonstration, cooperation and transfer to emerging economies like India. The integrated assessment might also be extended by a comparison with other low-carbon technology options to draw fully valid conclusions on the most suitable solution for a sustainable future energy supply in India.

Nomenclature

Acronym

E1	high coal development pathway
E2	middle coal development pathway
E3	low coal development pathway
S1	high storage scenario
S2	intermediate storage scenario
S3	low storage scenario

Abbreviations

CCS	carbon dioxide capture and storage of CO_2
GDR	Greenhouse Development Rights
GHG	greenhouse gas
GWP	global-warming potential
IGCC	Integrated Gasification Combined Cycle
LCA	life cycle assessment
LCOE	levelised cost of electricity
NGO	non-governmental organisation
O&M	operation and maintenance
PC	pulverised coal
PLF	plant load factor
SC	supercritical

1. Introduction

Carbon capture and storage (CCS)[1] for reducing carbon dioxide emissions from fossil fuel-fired power plants and industrial sources is the subject of intensive global debate. CCS is considered a technology option that could contribute significantly to achieving the objective of decreasing greenhouse gas (GHG) emissions by 50–85% by 2050 [1]. This radical reduction is imperative in order to prevent the rise in global average temperature from exceeding a threshold of 2 °C above preindustrial times by 2100 [2]. For the time being, however, unabated use of coal is on the rise. This development is mainly driven by coal-consuming emerging economies that experience a rapidly growing demand for energy. The aim of the present article is to explore whether CCS could be a viable low-carbon option for India, which is one of these key countries. Respective analyses for China and South Africa will be presented in upcoming articles.

The main objective of the analysis is to estimate how much CO_2 can potentially be stored securely for the long term in geological formations in India. Based on source-sink matching, this CO_2 storage potential is compared with the quantity of CO_2 that could potentially be separated from power plants according to a long-term analysis up to 2050. This analysis is framed by an assessment of the commercial availability of CCS technology, an evaluation of levelised costs of electricity, ecological implications and stakeholder positions.

It is not the aim of the article to elaborate the role, CCS might play in a future sustainable energy system in India in comparison to other low-carbon technology options like renewable energies. Although this question is most challenging, this article focuses on a sound analysis of CCS by itself providing the basis for a future comparative assessment.

To our knowledge, no assessment with a comparable comprehensive scope has been published before. CCS in India started gaining interest in 2008, when publications first mentioned CCS as a possible mitigation measure in coal-using countries.[2] Several later publications explored the challenges of CCS with a direct focus on India [3–7], and a few applied a holistic view rather than considering single issues [8–10]. However no source developed long-term energy scenarios by 2050 including CCS and evaluating the possible impact through an integrated assessment. Our article therefore aims to close this gap by providing a holistic, long-term analysis of the potential role of CCS in India.

The presented paper first describes the methodologies applied in the individual assessment aspects of the study (Section 2). The outcome of each assessment step is given in Section 3. Subsequently, the authors combine the assessment dimensions to present an overall result from an integrative perspective (Section 4). The paper closes with an outlook on the needs for further research (Section 5).

2. Methodology

In this paper, an integrated approach covering five assessment dimensions is chosen. However, each dimension is investigated using specific methods.

(1) The assessment of the *commercial availability of CCS technology* is based on screening publications and presentations by international CCS experts on the current state and expected course of development of CCS in the years ahead. The term *commercial availability* refers to the time when the complete CCS chain could be in commercial operation, incorporating large-scale CCS-based power plants, transportation and storage.

(2) The derivation of India's *long-term usable CO_2 storage potential* consists of three different methods:

(2.1) The aim of the *storage capacity assessment* is to systematically analyse and compare existing capacity estimates for India with regard to their assumptions, the methodologies applied, the chosen parameters and the data sources. The concept of the "techno-economic resource-reserve pyramid for CO_2 storage capacity" [11] is applied to classify the different capacity categories. Finally, three storage scenarios (S1–S3) are developed representing a range between a high and a low estimate of India's storage potential by taking into account different levels of uncertainty in storage capacity figures.

(2.2) An *energy scenario analysis* is used to estimate the amount of CO_2 emissions that could potentially be captured from power plants. Based on existing long-term energy scenarios for India,

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[1] Also: Carbon dioxide capture and storage of CO_2.

[2] According to an analysis of peer-reviewed literature based on Scopus.

three long-term coal development pathways for power plants (E1–E3) are derived. These project different trends of coal-based power plant capacities up to 2050. In the next step, assumptions are drawn on how many of these power plants could be built or retrofitted with CO_2 capture. Finally, the quantity of CO_2 that could be separated is calculated for the pathways assuming different parameters such as the CO_2 capture rate and the efficiency penalty. CO_2 emissions are cumulated over the life time of all power plants newly built up to 2050.

(2.3) To achieve the *source-sink match*, each storage scenario is combined with each coal development pathway. The emission data from each pathway is divided amongst the states where they occur. An investigation is made into whether the emissions located the closest to the storage formations of S1–S3 could be stored there. Thus the match is at the *state-to-basin level*. The selected aquifer basins extend several hundred kilometres; the exact position of subbasins is not known. The maximum distance between sources and sinks is therefore defined as roughly 500 km, a transport distance that has been estimated to be economically viable [12]. The matching process is as follows: first *oil and gas fields* are filled, as they provide the most secure potential, followed by *aquifer basins*, depending on their quality. The following rules are applied:

(1) Each sink can only be filled up to its maximum storage capacity.
(2) Any remaining emissions from the state concerned cannot be sequestered unless other basins within the estimated maximum transport distance provide additional space, either in the same state or in neighbouring ones.
(3) If a basin's capacity exceeds the total emissions of these states, this storage site is not completely filled.

Finally, a total matched capacity is derived for each combination of S1–S3 and E1–E3. Due to missing data and the consequential heuristic approach, matching is performed manually without using a geographic information system.

(3) The aim of the *economic assessment* is to conduct a comparative analysis of the long-term development of the levelised cost of electricity (LCOE) of coal-fired power plants with and without CCS. The analysis is built upon three main methodological principles: firstly, cost calculations are based on the capacity development of power plants up to 2050 given in E1–E3. Secondly, data from existing studies and the knowledge of numerous experts interviewed during the course of this study are used to define and quantify important cost parameters, such as capital costs and operation and maintenance (O&M) costs. Whenever possible, country-specific conditions and data are taken into account. This is particularly true for plant capital costs. Thirdly, the assessment uses learning rates to project a long-term cost development. All cost data and parameters are fed into the general equation to calculate the development of the LCOE (see Supplementary information).

(4) To assess the possible *environmental impacts of CCS*, a life cycle assessment (LCA) of potential future CCS-based coal-fired power plants in India is performed according to the international standard ISO 14 040/44. Since no commercial CCS-based power plants exist yet, a *prospective LCA* following a threefold approach has to be performed: firstly, a generic future coal-fired power plant is balanced by updating an LCA of an existing coal-fired power plant to future conditions. Secondly, this power plant is equipped with CO_2 capture facilities, and the transportation and storage of CO_2 is added. Thirdly, the environmental impacts of the CCS power plant are compared with the power plant without CCS. The life cycle impact assessment (LCIA) is performed by applying the method *CML 2001* [13].

(5) *Stakeholders* are key players in implementing and deploying new and innovative technologies. Hence, analysing their *positions* regarding the prospects of CCS is an important assessment element. The overall aim of the analysis is to reflect the current state of the CCS debate in India and to draw up a map of key stakeholders and their respective positions. The analysis is based mainly on 18 research interviews conducted with CCS and energy experts from the national government, science, industry and societal organisations in October 2010. The interviews were guided by a questionnaire containing open questions, giving interviewees the opportunity to freely unfold their positions and to identify parameters affecting the prospects of CCS in India (see Supplementary information). If necessary, the questionnaire was supplemented with questions tailored to the individual expertise of each respondent.

3. Analyses and outcomes of the individual assessment aspects

3.1. Commercial availability of CCS technology

Commercial availability of CCS before 2030 seems improbable for India. At the international level, experts from scientific institutions and non-governmental organisations (NGOs) expect a later large-scale availability than previously assumed due to delayed demonstration projects and a lack of public acceptance in the potential storage regions [14–18]. Although there is substantial development ongoing in the field of CO_2 capture (see for example, the expected declining efficiency losses as assumed in Table 3), a lack of business cases slows down the launching of commercial technology). As such, the Indian government is unlikely to adopt CCS before the technology has been demonstrated by industrialised nations (see Section 3.5). The year 2030 as the start of operation of the first large-scale CCS projects is therefore chosen as the "base case" of the presented analysis. To consider further possible delays in both industrialised countries and in India, 2035 and 2040 are regarded as two sensitivity cases. However, the main assessment presented here is conducted for the base case only.

3.2. Long-term usable CO_2 storage potential for India's power sector

3.2.1. Analysis of storage potential for India

The storage capacity assessment is presented in two steps. (1) *In the first step*, the few existing studies are reviewed. These indicate a wide range of possible storage capacities in India from 47 to 572 Gt of CO_2 (Table 1). All estimates need to be classified as theoretical capacity (see Fig. 3) since no efficiency factors are included in the studies. The first study conducted a first-order assessment based on a global integrated assessment model [19]. It results in a total storage capacity of 105 Gt of CO_2, mainly in deep saline aquifers. A second study assessed a huge storage capacity based essentially on storage in deep saline aquifers (360 Gt) and basalt formations (200 Gt) [20]. Neither of the assessments provides a regional split-up of the potential sinks.

The most detailed assessment conducted by [21] characterised the oil and gas fields and aquifer reservoirs regionally as areas, and categorised the aquifers qualitatively as either *good*, *fair* or *limited* as defined by [22]. A reservoir is considered *good* if hydrocarbons are produced there, which leads to the assumption of an intact sealing rock. It is categorised as *fair* if hydrocarbons are expected but not yet produced; and as *limited* if no hydrocarbons have been found and the geology does not look promising for CO_2 injection. Most of these basins, especially those with a good quality, are situated offshore surrounding the sub-continent (Fig. 4). The volume of deep saline aquifers and basalts was not quantified in detail due to the lack of adequate geological information [21]. Nonetheless, a rough method developed for saline aquifers in the EU [23] was applied on "good and fair" reservoirs with an average storage density of 0.2 Mt/km^2. Although [21] emphasise the limitations of this method, it is extended here to the other two

Table 1
Overview of existing estimates for theoretical storage capacity in India.

Formation	Dooley et al. [19]	Singh et al. [20]	Holloway et al. [21]		
	Gt of CO_2				
Oil fields	–	7		1.0–1.1	
Gas fields	2			2.7–3.5	
Coal seams	2	5[a]		0.345	
Basalts	–	200		–	
			Good, fair & limited quality	*Good & fair* quality	*Good* quality
Deep saline aquifers	102	360	138[b]	59	43[b]
Total	105	572	142–143[b]	63–64	47–48[b]

[a] The more recent estimate by [80] reduces this capacity by 10% to 4.5 Gt of CO_2.
[b] Own calculation as described in the text.

Table 2
Three scenarios of theoretical CO_2 storage capacity in India.

Formation	S1: high		S2: intermediate		S3: low	
	Gt of CO_2	Source	Gt of CO_2	Source	Gt of CO_2	Source
Oil and gas fields	4.5	High value in [21]	4	Low value in [21]	2	[19]
Aquifers	138	*Good, fair & limited* quality	59	*Good & fair* quality	43	*Good* quality
Total	142.5		63		45	

quality categories of deep saline aquifers ("good" and "good, fair & limited") to show a possible range for the following storage scenario development.

(2) Confronted with the numbers of existing estimates, most of the experts consulted agreed that, for now, it is difficult or even impossible to determine a reliable figure for the total storage capacity. *In the second step*, therefore, an "if ... then" approach is applied to show the implications of different storage capacity prospects. To this end, three storage scenarios *S1: high*, *S2: intermediate* and *S3: low* are developed (Table 2), based on figures from Table 1, mainly from [20]. This study is preferred over [21] due to methodological issues. It provides a comprehensive and reasonable argumentation of storage capacity assessment which is lacking in [20]. In contrast to [20], it gives a basin-specific resolution, which is needed for the source-sink match. Hence the higher capacity for aquifers in [20] compared to the highest value in [21] is disregarded in favour of the higher quality of our assessment.

Furthermore, storage capacities in coalfields and basalt formations are excluded. Although CO_2 sequestration in *coal seams* is currently being discussed and researched in India to enhance the production of coal bed methane [24], this storage option is not included due to the high level of technical uncertainties. Especially the swelling of coal by CO_2 injection is a major obstacle [25]. Since considerable further research is needed in the case of *basalts* [7,21] and there is a lack of both laboratory and in situ test results, it may not be a very promising solution for the period considered here.

3.2.2. Deriving the amount of CO_2 that may be captured in India's power sector

Both the literature review and the interviews conducted in India revealed that no suitable[3] long-term energy scenarios including CCS existed for India.[4] Instead, the capacity of coal-fired power plants that could theoretically be operated with carbon capture is derived from coal development pathways E1–E3.

(1) *Pathway E1: high* is based on the World Energy Outlook (WEO) 2009 Reference Scenario for India [30]. Since WEO scenarios extend only to 2035, the scenario is extrapolated to 2050 as given in [31].
(2) *Pathway E2: middle* is based on the Advanced Technology Scenario [32]. It covers a time frame up to 2045, which is extrapolated to 2050 for this study. The scenario foresees the deployment of Integrated Gasification Combined Cycle (IGCC) as "clean coal" technology as well as a massive increase in both conventional and advanced nuclear energy technologies. This makes it possible to reduce CO_2 emissions from the power sector by 16% in 2045, compared to the reference scenario of that study.
(3) *Pathway E3: low* is based on the Sustainable India Energy Outlook [33] as a country analysis of the global Energy [R]evolution Scenario 2010 [31,34]. The target of the global scenario is to reduce worldwide energy-related carbon dioxide emissions by 50% up to 2050, from their 1990 levels. Applying the Greenhouse Development Rights (GDR) framework, an Indian share of global greenhouse gas obligations is calculated. As a result, the CO_2 emissions in India may increase from 1074 million tonnes in 2005 to 1689 million tonnes in 2050, peaking at 2235 million tonnes in 2030. Annual per capita emissions will remain at nearly the same level, rising from 0.9 to 1.0 tonnes/capita. Whilst the scenario is based on a massive increase in renewables and energy efficiency, both newly built coal and nuclear power plants are excluded from 2030.

Fig. 1 compares the development of coal-fired power plant capacity in the resulting pathways E1–E3. In addition, the installed power plant capacity as of 2010, its decommissioning curve and the power plants expected to be built by 2020 are given, derived from public governmental and commercial databases [35–38]. The figure illustrates that all three pathways reflect relatively well the 2010 installed capacity, but show divergent paths to the number of announced new power plants and governmental planning

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[3] The preconditions for selecting a study were that scenarios must cover a period up to 2050 and the installed capacity of coal-fired power plants must be provided at least in decadal resolution.

[4] After our research had been completed, long-term energy scenarios for Asia, which also include CCS in India, were published [26–29]. However, these do not provide any detailed figures on power plant capacities in India, which are required here.

figures for 2030. Whilst the National Energy Map for India [39,40] envisages a similar development as in our pathways E1–E3 up to 2020, 2030 targets vary by more than 500 GW [41]. Since official planning targets were often only realised in part in the past in India, this difference is neglected in the following.

Our assumptions behind the application of CCS in the pathways are as follows:

- In *E1: high* the deployment of CCS will have to be as high as possible to decrease the high CO_2 emissions resulting from this pathway.
- In both *E2: middle* and *E3: low* the deployment of CCS could be a "fall back" option which may have to be used if other measures to reduce power sector CO_2 emissions cannot be realised as envisaged in the respective scenarios (usually the considerable use of nuclear energy in *E2: middle* and energy efficiency improvements and renewable energy deployment in *E3: low*).

In order to calculate the possible *capacity* of CCS-based power plants, the following assumptions are made for all three pathways: only supercritical (from 2020), IGCC (from 2030) and ultra supercritical (from 2040) power plants will be built, fuelled by hard coal. New plants are distributed proportionately to currently operating power plants, since no plans for any future regional allocation are known. From 2030, all new plants will be built as CCS-based power plants. Earlier-built power plants are only retrofitted if they are no older than 12 years [42]. One third of the power plants built between 2020 and 2030 will be retrofitted from 2030 in the base case of the three pathways (CCS available from 2030). In sensitivity case two (CCS available only from 2040), 50% of power plants built between 2030 and 2040 and 10% of those built between 2020 and 2030 are retrofitted. Fig. 2 shows the resulting CCS-based power plant capacity in the base case. This figure also illustrates the penalty load caused by efficiency losses introduced by the use of carbon capture technology. The penalty load has to be installed additionally to the load given in the coal development pathways (black line), and will increase the total load of coal-fired power plants in 2050 by 9% (*E3: low*) to 16% (*E1: high*).

Further assumptions are required to calculate the *quantity of CO_2* that could be separated (Table 3 and Supplementary information): the maximum *efficiency* for newly-built non-CCS power plants in 2050 is set at 40% for supercritical and 42.5% for ultra supercritical power plants. The efficiency of IGCC is assumed to exceed the efficiency of supercritical power plants by 6 percentage points. For CO_2 capture and compression, an *efficiency loss* declining over time from 8.5 to 5 percentage points for the period from 2020 to 2050 is assumed for post-combustion, whilst loss due to pre-combustion ranges from 6.5 to 6 percentage points [43–52]. Retrofitting power plants with CCS technology would cause an additional efficiency loss of 1.5 percentage points [53].

The technical lifetime, and hence the time available for capturing CO_2 from new power plants, is assumed to be 40 years [54–56]. A CO_2 capture rate of 90% is assumed and a net calorific value for medium-quality Indian coal of 19.6 MJ/kg [57] is applied. A plant load factor (PLF) of 80% (7000 full load hours) is chosen, which seems to be the most realistic value for India. Although several experts regard a PLF of 90–100% [54], 95% [55] or 91% [56] for India as realistic, a cautious approach is chosen here since in industrialised countries such as Germany, around 85% is usually reported for coal-fired stations [58].

The cumulated amount of CO_2 separated per power plant is calculated by adding the annual CO_2 emissions captured by each power plant over its lifetime. This means, for example, for power plants built in 2050 that their annual emissions up to 2090 are included. In the base case, between 13 and 111 Gt of CO_2 could be available for sequestration in total (Table 4). Considering only the annual figures, between 0.3 and 3.3 Gt/a would have to be sequestered in 2050. In the sensitivity cases, the range falls to 9–91 Gt (CCS from 2035) and 4–71 Gt (CCS from 2040).

3.2.3. Deriving India's CCS potential as a result of matching sources and sinks

Finally, the range of CO_2 storage capacity is compared with the cumulated quantity of CO_2 emissions. Methodologically, it would be preferable to use effective capacities as the storage pyramid concept assumes that every time a source-sink match is conducted, an effective capacity has already been derived. Since only theoretical capacities are available, the authors introduce *theoretically matched* capacity (Fig. 3).

In the *first* step, a regional match is performed as described in the methodological section. As an example, Fig. 4 shows storage scenario S2 with *good-quality* and *fair-quality* basins. In addition,

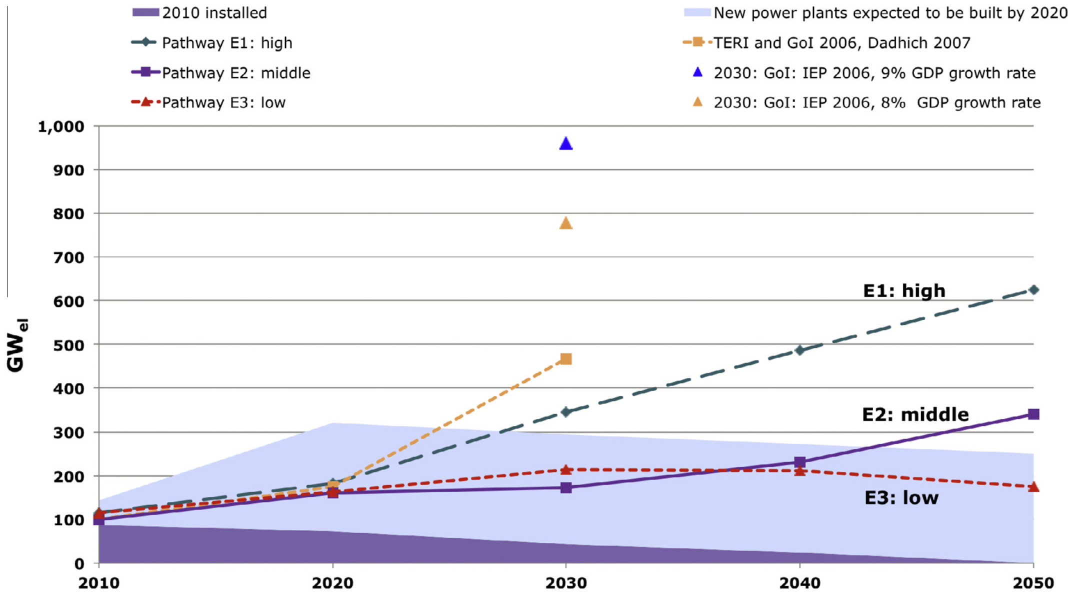

Fig. 1. Coal-fired power plant capacity in India (2010 installed, decommissioning curve, expected to be built by 2020, governmental planning figures, and envisaged according to coal development pathways E1–E3).

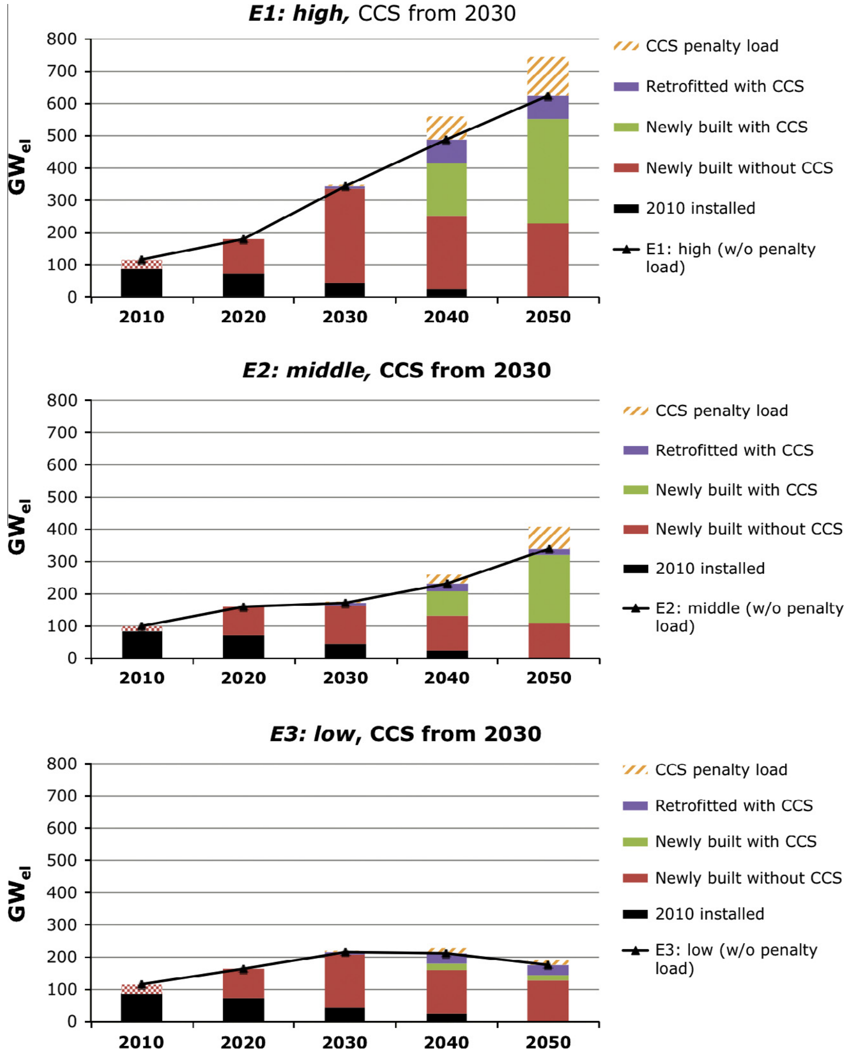

Fig. 2. Conventional and CCS-based coal-fired power plant capacity installed in India in the three pathways E1–E3 for the base case (CCS from 2030).

Table 3
Efficiencies and efficiency losses through CCS assumed for future newly built coal-fired power plants in India.

		2010	2020	2030	2040	2050
Subcritical	%	37				
Supercritical	%	39	39	39	40	40
Ultra supercritical	%				42	42.5
IGCC	%			45	46	46.5
Efficiency penalty post-combustion	%-pt	12	8.5	7	6	5
Efficiency penalty pre-combustion	%-pt	8	6.5	6	6	6
Additional efficiency penalty for retrofitting	%-pt	1.5	1.5	1.5	1.5	1.5

Table 4
Separated CO_2 emissions in India according to coal development pathways E1–E3, cumulated over the life time of all power plants newly built until 2050.

Availability of CCS	E1: high	E2: middle	E3: low
	Gt of CO_2		
CCS from 2030 (base case)	111	66	13
CCS from 2035 (sensitivity case 1)	91	57	9
CCS from 2040 (sensitivity case 2)	71	49	4

the cumulative emissions of the states adjacent to the selected basins from pathway *E2: middle* are displayed, resulting in a total matched capacity of 29 Gt (see Supplementary information for the detailed match of each scenario combination).

Second, values from the regional breakdown are aggregated, leading to the theoretically matched capacity for the whole of India for each scenario combination. This figure ranges from 5 to 75 Gt of CO_2, as shown in the upper third of Table 5. The central third indicates that the storage potential is exploited by less than 66%, and therefore never fully used. Less than 60% of the storage potential is used in 7 out of 9 combinations, even in the low storage scenario S3. This is due to the long distances between most sources and sinks considered. The lower third presents the share of emissions that can be stored in the respective scenario combination. For the high storage scenario, 68–96% of the emissions that can potentially be captured from coal-fired CCS power plants are sequestered whereas this share is 60% or lower for the other storage scenarios. In four out of nine scenario combinations, over half of these emissions can be stored.

The sensitivity cases (CCS from 2035 or from 2040) have not been analysed in detail. However, since only 69–80% or 31–64% of the power plant emissions of the base case are available, respectively (Table 4), a higher share of these emissions than in the base case could become sequestered while, on the other hand, the exploitation rate of the storage potential will decrease further.

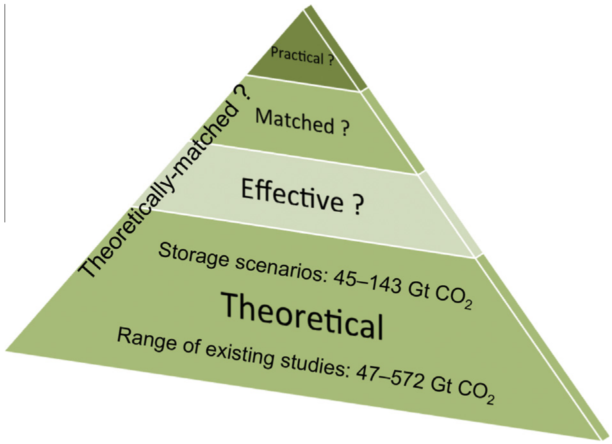

Fig. 3. Modified and extended version of the storage potential pyramid suggested by [11] and values derived for India.

3.3. Economic assessment of CCS in India's power sector

The assessment of LCOE of coal-fired power plants in India is based on a comprehensive set of assumptions. The analysis focuses on hard coal-fired, supercritical (SC) pulverised coal (PC) plants, since the deployment of these plants is expected to take off in 2020 and therefore earlier than assumed for IGCC and ultra supercritical PC plants. Due to a lack of technology- and country-specific cost data for both IGCC and ultra supercritical PC plants, these are not considered here.

The basic plant parameters for SC plants with and without CCS are for the most part consistent with those presented for the base case in Section 3.2.2. These parameters include the assumed commercial availability of CCS, the capture rate, the technical lifetime of power plants and the PLF (see also the Supplementary information).

With regard to thermal efficiency, the cost calculation uses slightly more optimistic figures, which enables a "best case" analysis for CCS due to the lower resulting LCOE. All newly built SC units without CCS are assumed to operate at thermal efficiencies of 40% before 2020 and 41.1% from 2020, which, due to the climate conditions, is the maximum achievable efficiency in India [59]. Applying post-combustion capture leads to an efficiency loss of 6 percentage points on average as a mean of the figures estimated in Section 3.2.2 for 2030 to 2050. Since the commercial availability and construction of full-scale CCS plants is assumed to begin no earlier than 2030, with capacities being installed gradually in the following years, the cost assessment only gives figures for CCS plants for 2040 and 2050.

Current capital costs ($\$_{2011}$ 1550/kW) are based on reference SC plants from [60–62] with capacities ranging from 510 to 800 MW. O&M costs are assumed to be 4% of capital expenditures [63]. Capital costs of post-combustion equipment are estimated to be equivalent to 75% of non-CCS plant capital costs; O&M costs are assumed to increase by 83% (both figures represent an average value

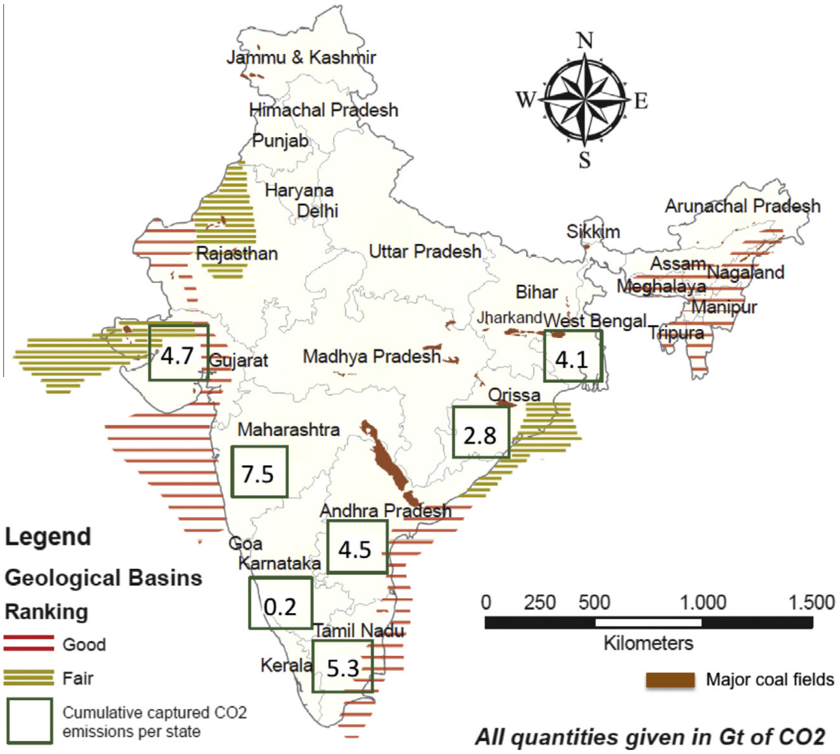

Fig. 4. Geological basins and cumulative CO_2 emissions in India as a result of source-sink matching using the example of storage scenario S2: intermediate and coal development pathway E2: middle (base case) with a distance range of up to 500 km (geological information by [21]).

Table 5
Theoretically-matched capacities for India and their share in total storage capacity and supply in the base case (CCS from 2030).

Theoretical storage capacity scenarios	Power plant emissions from coal development pathways		
	E1: high (111 Gt of CO_2)	E2: middle (66 Gt of CO_2)	E3: low (13 Gt of CO_2)
Theoretically-matched capacity (Gt of CO_2)			
S1: high (143 Gt of CO_2)	75	51	13
S2: intermediate (63 Gt of CO_2)	39	29	8
S3: low (45 Gt of CO_2)	29	22	5
Share of theoretical storage capacity used (%)			
S1: high (143 Gt of CO_2)	53	36	9
S2: intermediate (63 Gt of CO_2)	61	46	13
S3: low (45 Gt of CO_2)	65	49	12
Share of emissions that can be stored (%)			
S1: high (143 Gt of CO_2)	68	77	96
S2: intermediate (63 Gt of CO_2)	35	44	60
S3: low (45 Gt of CO_2)	26	33	40

of figures from [14,17,64]). The total capital costs for the power plants considered are allocated to individual years on an annuity basis and related to a kilowatt hour. An interest rate of 13% and a depreciation period of 25 years according to [54] yield an annuity factor of 13.6% per annum.

The cost development of power plants is derived by applying learning rates, taking into account newly installed capacities of SC units with and without CCS at the global level. As projected in the Blue Map scenario of the IEA [1], it is assumed that a total of 663 GW CCS-based coal-fired power plants will be installed by 2050. The learning rates for power plants without and with CCS are derived from [65], resulting in rates of 1.7% and 3.9% for capital costs and 2.5% and 5.8% for O&M costs, respectively. For CCS-based power plants, these are lower than one might expect. The reason for this is that only the additional expenditure for CO_2 capture follows the learning curve, whilst the actual SC plant is a widely mature and deployed technology. The learning rates are then applied to the capacity additions projected in the coal development pathways E1–E3 for India. Only India's capacity deployment is taken into account because the quality parameters of Indian coal require a highly specialised boiler design, which is not available on the world market.

Due to the limited quantity of India's high-quality hard coal reserves, domestic coal prices are an important parameter of this cost assessment. It is assumed that 30% of the coal feedstock is imported as hard coal because the Indian government requires new coal plants to be designed for a 30% share of imported coal [54]. Also under mitigation scenario aspects, India's coal imports are projected to increase steadily due to its lower emission intensity [26]. Another constraint is the proven recoverable reserves in India, which were reduced by nearly 40% in 2005 by [66] based on surveys of the World Energy Council.[5]

Based on historic price data, the price of Indian hard coal is estimated to be 30–40% below the price of internationally traded hard coal. The international hard coal price is assumed to grow in line with the international oil price. Based on these assumptions, the cost of the envisaged hard coal mix is estimated to start at $\$_{2011}$ 81/t coal in 2010, reach $\$_{2011}$ 108/t coal in 2030 and rise to $\$_{2011}$ 124/t coal in 2050.

Estimates for CO_2 transportation costs via pipeline are based on [14,64,68]. These average at just over $\$_{2011}$ 2/tonne over a distance of 100 km. Assuming an average transport distance of 350 km in India, transportation costs of CO_2 are approximately $\$_{2011}$ 7.5/tonne.

Due to the relatively low learning rates of CCS power plants, only minor technology cost reductions occur over time, which are overcompensated by increasing fuel costs, leading to an overall increase in LCOE up to 2050 (Fig. 5).

Although CCS plants pass through a learning process, they indicate clearly higher LCOE than conventional PC plants. By 2050, they supersede the LCOE of plants without CCS by about 45–51%. Fig. 6 illustrates this for pathway E2, specified by cost category. It becomes clear that increasing fuel costs and capital expenditures are the most important cost factor.

The outlined results suggest that there is a substantial barrier towards the economic viability of CCS in India, making policy incentives a crucial precondition for the technology's commercialisation. Furthermore, this barrier is clearly higher in India than in other emerging economies, such as China, or even industrialised countries, as Indian plant investment costs tend to be higher due to complex ambient conditions and low feedstock quality. Since introducing a carbon price could significantly improve the competitiveness of CCS plants towards non-CCS plants, it is investigated how a CO_2 price pathway up to 2050 as assumed for the EU in energy scenarios of the German government [69] would outweigh the technology's cost penalty. CO_2 costs start at $\$_{2011}$ 42/t CO_2 in 2020, reach $\$_{2011}$ 56/t CO_2 in 2040 and rise to $\$_{2011}$ 63/t CO_2 in 2050. Fig. 7 illustrates a comparison of the LCOE of power plants with and without CCS in India for pathway E2, both with the existence and in the absence of a CO_2 cost. Although the assumed CO_2 price pathway would bring the LCOE of CCS plants close to those of non-CCS plants, it would be insufficient for making India's CCS plants significantly more competitive than supercritical PC plants without CCS. The slight cost advantage of CCS plants in 2040 and 2050 might be insufficient to compensate for the higher risks associated with investing in CCS power plants. [70] point out that variable generation profiles of power plants need to be taken into account when calculating the CO_2 price needed in order to make mitigation technologies economically viable. The presented calculation does not consider variations in plant operation on a daily basis and is, thus, simplified. Nonetheless, it allows to conclude that even a substantial carbon price does not create sufficient economic certainty to function as a strong incentive for CCS.

3.4. Environmental impacts of CCS-based power plants from a life cycle assessment perspective

The following LCA refers to the year 2030 and is performed for both supercritical PC power plants (post-combustion capture using the solvent monoethanolamine, MEA) and IGCC power plants (pre-combustion capture using the solvent methyl diethanolamine, MDEA). Saline aquifers without any leakage of CO_2 are assumed

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[5] A detailed examination of how downgrading occurred and was reported is given in the project report [67] on which this article is based.

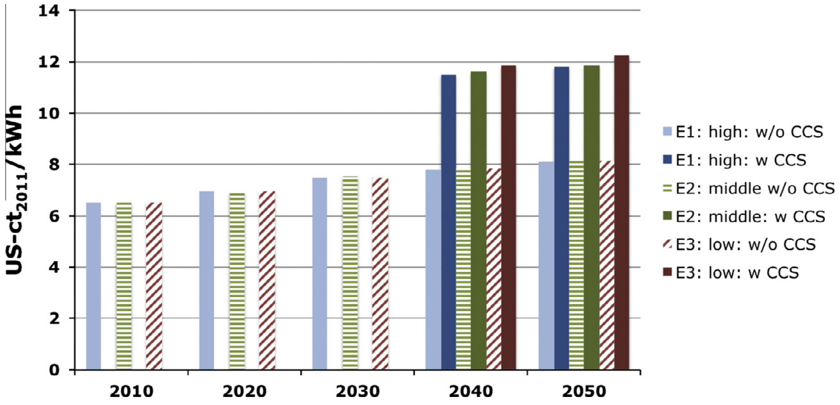

Fig. 5. Levelised costs of electricity production in India with and without CCS in coal development pathways E1: high – E3: low up to 2050 without CO_2 costs.

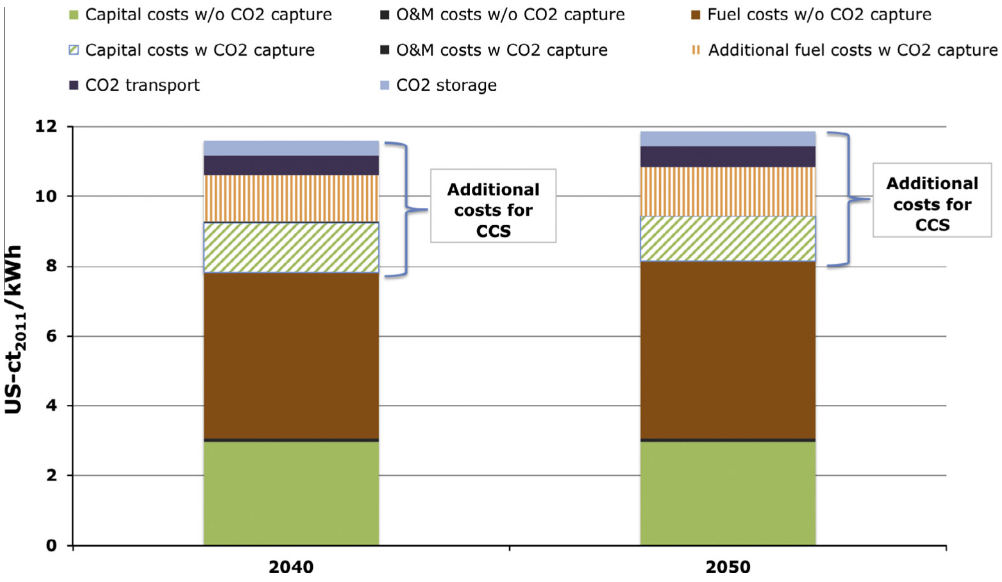

Fig. 6. Elements of levelised costs of electricity in India resulting from coal-fired CCS power plants by cost category in coal development pathway E2: middle up to 2050 without CO_2 costs.

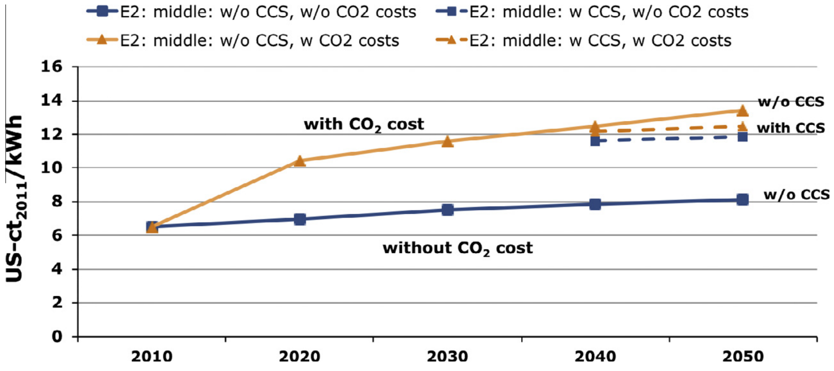

Fig. 7. Levelised costs of electricity in India for coal-fired supercritical power plants with and without CCS and with and without CO_2 costs in coal development pathway E2: middle up to 2050.

to be the storage medium; the average transport distance is set to 350 km. It is assumed that 50% of the coal will be imported from South Africa in 2030 [71]. This is higher than assumed in the economic part, but enables a “best case” analysis to be made due to the lower emission factor of imported coal.

Most of the basic LCA datasets (mining, transport, generation, etc.) are taken from the international LCA database ecoinvent 2.2 and adapted to the conditions considered (for example, the transport distance of CO_2, the calorific value of coal, etc.). Efficiencies and efficiency losses in the year 2030 are taken from Table 3. Since no specific data is available for India, the dataset of CPA (Central Plant Asia and China) has to be taken as the basis and modified, where necessary. In particular, the ratio of open cast to deep mining has to be adapted since opencast mines make up only 3% of total coal production in East Asia while open cast mining accounts for 70–90% in India [72,73]. According to predicted trends of increasing open cast mines in India [73], the coefficients of the mine infrastructures are altered to 3% deep and 97% open cast mining in 2030 for the purpose of this LCA.

Despite the fact that India has large uncontrolled coal fires that emit substantial amounts of carbon dioxide and other greenhouse gases, these emissions are disregarded in our analysis. Since coal fires are not only ignited naturally, but usually through human influence [74], they cannot essentially be connected to coal mining activities caused by power production, although this context has not yet been fully discussed.

Methane emissions from coal mining are included based on the aforementioned ratio of deep to open cast mining and indigenous to imported coal. Applying specific emission data from India [57] and South Africa (ecoinvent 2.2 dataset), the total methane emissions of India's coal mix is assumed to be 0.0011 kg CH_4/kg coal in 2030.

Fig. 8 illustrates the impact category *global-warming potential* (*GWP*), which comprises the impact of all greenhouse gases, and the CO_2 emissions as part of the GWP.

The overall reduction rates of both CO_2 and GHG emissions are lower than one would expect, when focusing only on the CO_2 separation rate of 90%. The reasons behind this are the life cycle perspective and coalbed methane emissions. Focusing only on the CO_2 capture rate excludes:

- The excess consumption of fuels (energy penalty) required by the use of CCS technology. It causes more CO_2 emissions, with the consequence that the *separated* CO_2 emissions are higher than the *avoided* CO_2 emissions.
- The CO_2 emissions released into the upstream and downstream parts of the system which are the provision of additional fuels and further processes such as the production of solvents or the transportation and storage of CO_2.
- Other GHG emissions that are released in upstream and downstream processes, the most relevant of which is methane emitted during coal mining.

In contrast to GHG emissions, most other environmental impact factors increase per kilowatt hour of electricity in the case of CCS for both PC and IGCC (eutrophication, human toxicity, terrestrial ecotoxicity, freshwater and marine aquatic ecotoxicity and stratospheric ozone depletion), whilst acidification and summer smog decrease in the case of PC. Fig. 9 illustrates the results for the most commonly discussed categories.

Similar to the case of GHG emissions, two issues are responsible for these results: firstly, the energy penalty leads to higher emissions per unit of electricity generation at the power plant itself. Only CO_2, NO_x and SO_2 can be removed during the CO_2 scrubbing process. Secondly, the upstream and downstream processes cause an increase in several emissions. The net result depends on the extent to which the decrease in emissions at the power plant's stack is outweighed by an increase in the upstream and downstream processes.

With regard to the CCS-induced relative change in performance of emissions, in most cases PC power plants outperform IGCC power plants. The stronger increase in the case of IGCC depends on the emissions released during the upstream and downstream processes, which cannot be balanced by decreasing direct emissions. However, the absolute values also need to be considered, which are usually lower or equal in the case of IGCC power plants compared to PC power plants. The reasons for this are the greater efficiency of IGCC and the lower energy penalty for capture processes.

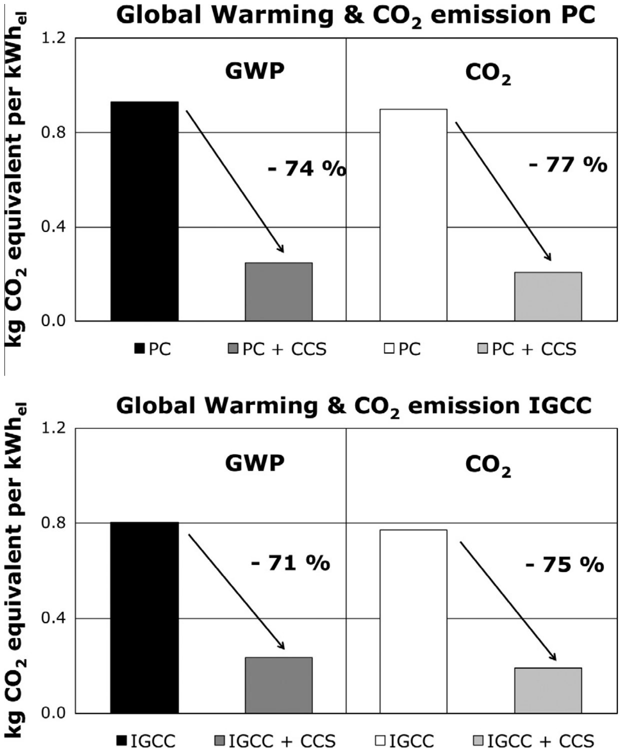

Fig. 8. Specific global-warming potential and specific CO_2 emissions for PC and IGCC power plants with and without CCS in India in 2030 from a life cycle perspective.

3.5. Analysis of stakeholder positions

During the interviews conducted within this study it became clear that although CCS is the subject of considerable internal assessments and strategic planning within the Indian government, it is perceived to be of limited relevance for India by the relevant ministries. Amongst the ministries involved in the Indian CCS debate, the Ministry of Power and (to a more limited extent) the Ministry of Environment and Forests are considered key governmental players. The Department of Science and Technology as well as the Ministry of Coal, which oversees the planning, exploration and development of coal and lignite resources in India, also shape the CCS debate, although in a less leading role than the aforementioned ministries.

All ministries share a cautious stance on the commercialisation of CCS. India's foremost energy policy priority is a massive addition of new power-generating capacity to provide all citizens with access to electricity. Since CCS leads to substantial efficiency losses, applying this technology impedes achieving this aim. Furthermore, the high LCOE of CCS plants would be in conflict with the high priority that affordable electricity rates enjoy in the national government's energy policy agenda. For this reason, the capability of new power technologies to be developed and applied at reasonable costs is a major prerequisite for their adoption. All respondents confirmed that there is a great degree of scepticism within the Indian government towards CCS as the technology is not yet commercially viable and is currently very expensive. Instead, the political focus with regard to fossil-fired power capacities is on increasing the thermal efficiency of individual plants.

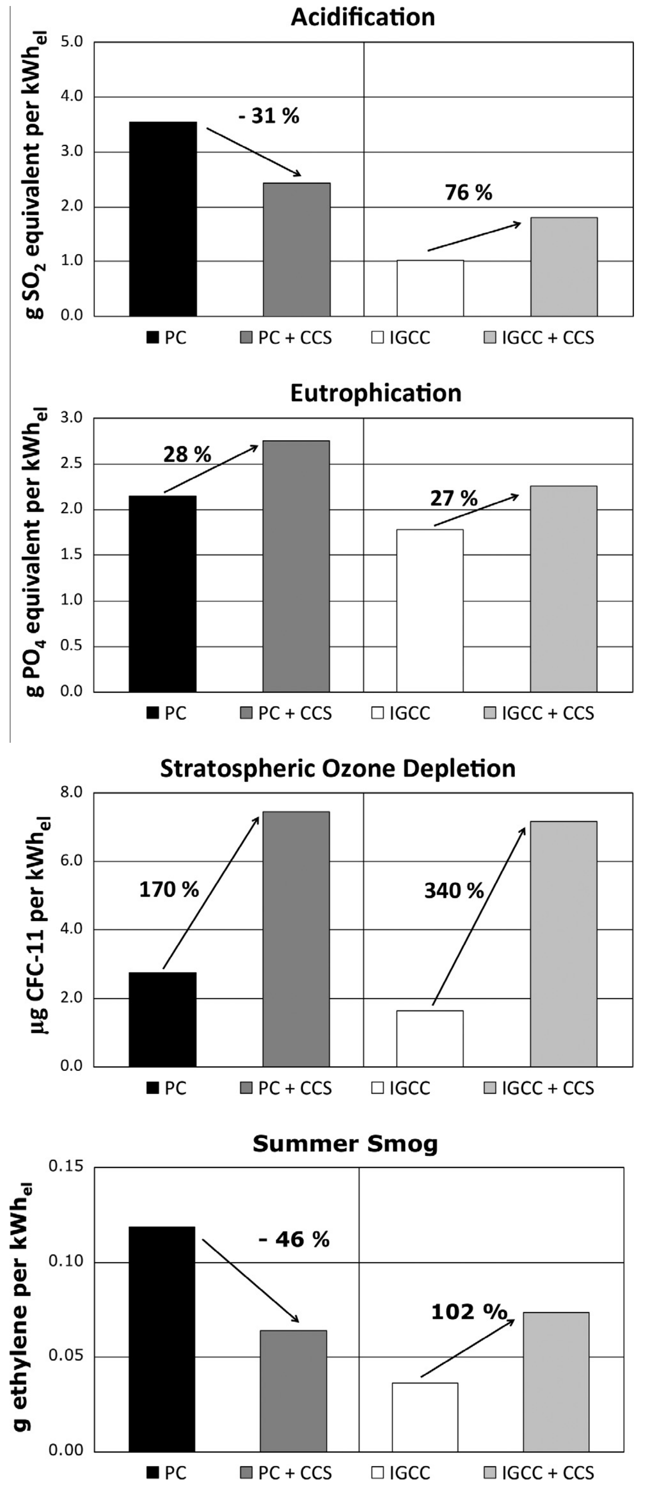

Fig. 9. Results of selected non-GHG impact categories for PC and IGCC power plants with and without CCS in India in 2030 from a life cycle perspective.

Mainly due to the government's cautious approach towards CCS and the technology's current techno-economic drawbacks, those representatives of major industrial players interviewed, such as the National Thermal Power Corporation (NTPC), Bharat Heavy Electricals Ltd. (BHEL) and Oil and Natural Gas Corporation (ONGC), do not perceive CCS as a very promising technology option. Nonetheless, NTPC and BHEL are developing and testing CO_2 capture technologies and ONGC is demonstrating enhanced oil recovery based on CO_2. Most stakeholders with more positive views on CCS are from the science sector and have an interest in intensifying or acquiring CCS-related R&D projects or have a perspective focused on their specific (CCS-related) research fields. However, their capability to act as powerful drivers of CCS is very limited because they depend on R&D funding from the government or industry. Amongst the civil society representatives interviewed, WWF India had a positive stance towards CCS whereas Greenpeace India is opposed to it (Fig. 10).

4. Overall results and discussion

The previous sections indicated that a successful implementation of CCS in India is affected by a broad variety of aspects even if looking only at CCS without assuming a competition with other low-carbon technology options. Looking at the findings from the five assessment dimensions leads to the overall conclusion that several preconditions need to be fulfilled if CCS is to play a future role in reducing CO_2 emissions in India:

- The time of the *commercial availability* of CCS in India depends strongly on the successful implementation of CCS technology in industrialised countries, which confirms earlier findings by [8]. If this does not occur, the hope that the need for upgrading and extending India's power plant capacities between 2010 and 2025 "may bring CCS into the equation" [3] may fail. However, CCS is not expected to be applied in India before 2030 in current global and regional modelling studies either [29].
- From our point of view, the most crucial requirement for being able to derive a long-term CCS strategy for India is a reliable *storage capacity assessment* for the country. Whilst several publications on CCS in India refer to literature sources that suggest a large theoretical storage capacity and fail to consider the fact that the practical capacity will be much lower [4,5,9,10,29], the present analysis shows the high uncertainty inherent in existing storage capacity assessments. As a general rule, due to the lack of geological data, any calculations of storage capacity quantity in India can only be highly speculative and should therefore be treated with caution. If very optimistic assumptions are applied, 75 Gt of CO_2 could *theoretically* be stored as a result of matching emissions captured from coal-fired power plants to be built up to 2050 with suitable sinks. If a cautious approach is taken into account by considering the country's *effective* storage potential, only a fraction may potentially be sequestered. In practice, this potential will decrease further with the impact of technical, legal, economic and social acceptance factors.
- Hence, in the future, more in-depth assessments of the country's effective and matched storage potentials are required, as also suggested by [7,8,75]. Based on such assessments, an optimisation model could be applied to identify cost-optimal sites for CCS power plants, taking into account the transportation costs of electricity, coal, the separated CO_2 emissions and even the cooling water. The lack of cooling water is projected to become an increasingly severe problem in the operation of coal-fired steam power plants in water-scarce regions, even without the use of CCS [76].
- The *economic assessment* reveals a significant barrier to achieving the economic viability of CCS in India under current conditions and even under the assumed CO_2 price development. Although the latter would compensate the cost penalty of CCS, it would be unlikely to suffice in order

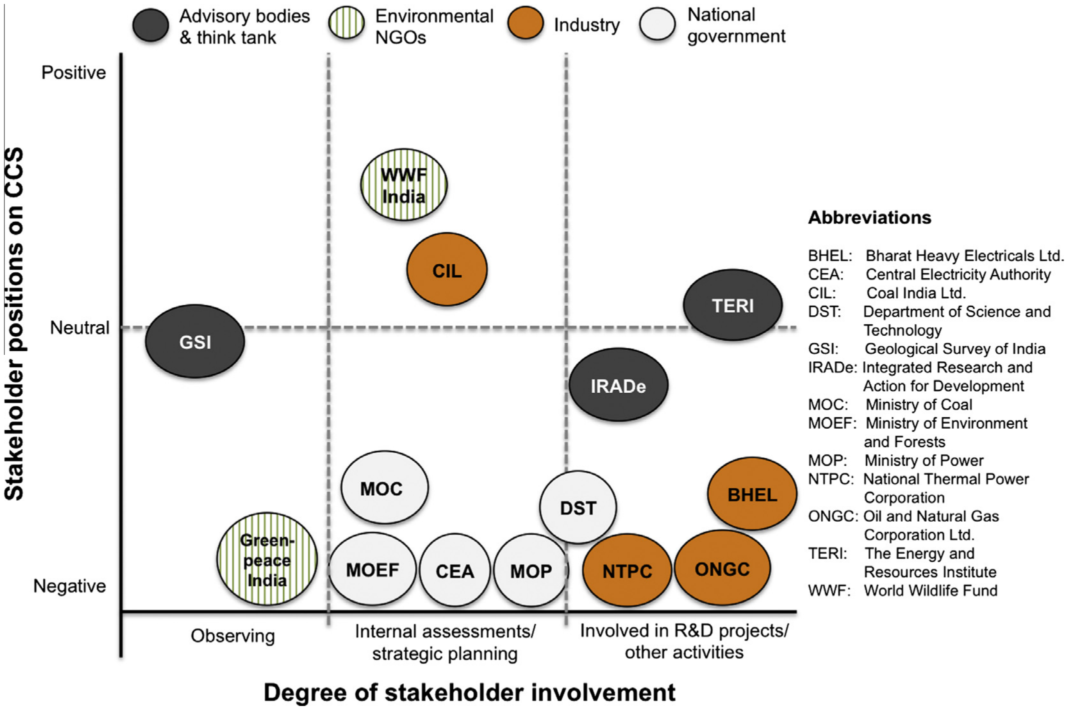

Fig. 10. Constellation of key CCS stakeholders in India.

to provide a strong and clear cost advantage of CCS plants over supercritical PC plants without CCS. Hence, a higher carbon price would be required in order to function as a clear economic driver for CCS deployment.

- The findings of the *prospective LCA* comply with results of former studies by [49,77,78] but yields conflicting results. Firstly, and most importantly, the total GHG emissions per unit of electricity output are considerably reduced. However, the reduction rate over the whole life cycle of only 71–74% may call into question the benefits of the huge investments that would be required for the deployment of a comprehensive CCS infrastructure in India. Furthermore, it is presumed here – somewhat optimistically – that there would be no leakages at the storage sites. Assuming some leakage over time could significantly change the balance of CO_2 emissions. Secondly, most other environmental and social impacts of coal-fired power plants would increase with the use of CCS. Due to the additional primary energy demands of CCS, further environmental and social issues that were not included in the LCA will also increase (for example, air quality, noise, mine waste, health risks, displacement and resettlement). Thirdly, scrubbing technology development has only been considered in terms of decreasing efficiency losses. If more environmentally benign technologies would enter the market, the results of the prospective LCA might change significantly.
- Last but not least, *public support* would be necessary to establish conditions for a prominent development of CCS in India. The interviews conducted within this study lead to the conclusion that the substantial energy penalty and high costs of electricity negatively affect the perception of CCS amongst potential key stakeholders. Hence the lack of governmental, industrial and societal CCS advocates strongly hampers the promotion of CCS in India, although adequate long-term strategies may over time reverse this situation.
- Furthermore, it should be pointed out that a long-term roadmap of CCS in India's *industry* could refine our source-sink match by including CO_2 emissions from industry. Since even in pathway *E1: high* the theoretical storage capacities are used by less than 65% (Table 5), a considerable amount of industrial CO_2 emissions could additionally be stored. However, a rough calculation has already revealed that additional CO_2 emissions from industry would slightly increase the share of theoretical storage capacity used, but would not change the results fundamentally [67].
- Finally, it needs to be taken into account that CCS plants will face strong competition from other low carbon technologies, especially renewable energy technologies, most of which have much higher learning rates than supercritical PC plants with CCS and show a better environmental performance [17]. Thus, CCS plants would need to be compared with other low carbon technology options to draw fully valid conclusions on the economic, ecologic and social viability of CCS in a low carbon policy environment. One could also assume to combine CCS plants with renewable power plants for solar-assistance of the energy intensive scrubbing process [79] as India has significant potential areas for solar thermal power plants.

5. Conclusions and outlook

Existing scenario studies for India show varying strategies for reducing CO_2 emissions in the electricity sector: *one option* is to make a considerable effort to achieve drastic improvements in energy efficiency together with an ambitious increase in the use of all forms of renewable energy. The Energy [R]evolution Scenarios [33], for example, show that such pathways would still rely on the use of conventional coal-fired power plants in order to satisfy energy needs over the next two or three decades but, nonetheless, ambitious climate targets could be met without using any new CCS or nuclear energy plants. However, such a scenario poses a significant challenge in that renewable energies would have to be systematically integrated into the current energy system.

Another option is to pursue a fossil fuel-based pathway, supplemented by varying shares of nuclear energy or renewable energies as it is assumed, for example, in the BLUE Map Scenario of the IEA [1]. Due to the striking dominance of coal-fired power generation in the country's electricity sector, this option would require the introduction of CCS and it would have to cope with the related challenges highlighted above. Without CCS, a coal-dominated path would be unable to reduce fossil fuel-related CO_2 emissions towards a level that would be consistent with the long-term target of the international community. However, a precondition for opting for CCS would be finding robust solutions to the constraints highlighted in this article.

In order to overcome the aforementioned barriers, experts and decision-makers from India made it very clear in the interviews conducted during the course of this study that the industrialised world would need to make a stronger commitment in terms of technology demonstration, cooperation and transfer to developing countries and emerging economies. In the authors' opinion the presented analysis should be extended by a similar integrated assessment of other low-carbon technology options like renewable energies and a weighting of all considered options, for example, by applying a multi-criteria analysis. Such an approach would allow to find the most suitable solution for a sustainable future energy supply in India.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2013.11.054.

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