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Coal based CCS in India's Low Carbon Electricity Transition: Prospects and Challenges

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SusPoT - Center for Sustainability is a non-profit Think-&-Do Tank incorporated with a mission to assist governments, civil society organisations, industries and general public in developing inclusive sustainability strategies and implementing action plans towards achieving climate-neutral India by 2050. SusPoT intends to bridge the gap between scientific research and policy design and implementation in India's clean energy space by conducting multi-disciplinary system analytics based policy research and developing inclusive strategies for a just transition towards sustainable energy future. SusPoT was incubated by the Clean Energy Lab in 2018 – an initiative by Shakti Foundation and Indian School of Business to support early stage civil society organizations with big innovative ideas that can create research and evidence based policy impact in India's clean energy space.

Since it was founded in 1991, the Wuppertal Institute for Climate, Environment and Energy has been an integral part of the national and international research landscape and a key player in shaping the debate on transitions to a sustainable development at local, national and international level. The Wuppertal Institute sees itself as a leading international think tank for sustainability research focused on impacts and practical application, being among the top ten environmental policy institutes for several years. The organisation's activities are centred on developing transformation processes aimed at shaping a climate-friendly and resource-efficient world. The overriding goal of the Institute's work is to help to ensure that the planetary boundaries are respected. The Wuppertal Institute has put this goal into concrete terms with its guiding vision of a "climate-neutral and resource light society" by 2050.

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Key Messages

Roadmaps for India's energy future foresee that coal power will continue to play a considerable role until the middle of the 21st century. Among other options, carbon capture and storage (CCS) is being considered as a potential technology for decarbonising the power sector. Consequently, it is important to quantify the relative benefits and trade-offs of coal-CCS in comparison to its competing renewable power sources from multiple sustainability perspectives. In this study, we assessed coal-CCS pathways in India up to 2050 and compared coal-CCS with conventional coal, solar PV and wind power sources through an integrated assessment approach coupled with a nexus perspective (energy-cost-climate-water nexus).

Our findings highlight that coal-CCS in India not only suffers from typical new technology development related challenges—such as a lack of technical potential assessments and necessary support infrastructure, and high costs—but also from severe resource constraints (especially water) and the competition from outperforming renewables in an era of global warming. We recommend that these challenges would have to be comprehensively addressed if coal-CCS should play a significant role in low carbon electricity transition in India. (Coal) CCS should, however, be developed as a backstop technology because, even if it is not available on a large scale until 2030 (or later) in India, it could be used to retrofit existing coal power plants in future and could also become integrated with energy-intensive industries where there are often no alternative low-carbon options. Our study, therefore, adds a considerable level of techno-economic and environmental nexus specificity to the current debate about coal-based large-scale CCS and the low carbon energy transition in India.

Major Findings

- Assessment of India's future electricity scenarios shows that coal-CCS capacity projections are very conservative or the technology is ignored altogether.
- It is still too early to predict the year of commercial availability of large-scale CCS for India's coal power sector, even though we optimistically assumed 2030 as the base year in this study.
- Systematic quantification and in-depth assessments of potential CO_2 storage capacity available across geological reservoirs in the Indian subcontinent are not yet available, but high confidence CO_2 storage capacity data is a prerequisite for charting long-term strategic CCS roadmaps for the country.
- Levelized costs assessment reveals that coal-CCS is expensive and significant cost reductions would be needed for CCS to compete in the Indian power market by 2030.
- Although carbon pricing could make coal-CCS competitive in relation to conventional coal power plants, it cannot influence the lack of competitiveness of coal-CCS with respect to renewables. Moreover, there still remains a levelized cost gap of $98 per MWh electricity between coal-CCS and a 70/30 solar PV/wind mix in 2030.
- From a climate perspective, coal-CCS could eventually act as a technology intervention if India follows a coal-dominant future pathway, but renewables are better positioned than coal-CCS if the goal is ambitious climate change mitigation.
- Water footprint assessment reveals that coal-CCS consumes an enormous volume of water resources in comparison to conventional coal and, in particular, to renewables.

1. Introduction

Largely as a consequence of economic development driven by fossil fuel use—with coal-based energy sources at its core—India's share of global annual greenhouse gas emissions (GHGs) is rising steadily [1]; India currently ranks third after China and the USA for annual GHG emissions [2,3].[1] Based on the current economic growth trajectories, it is anticipated that India's GHG emissions will continue to rise substantially until 2050. Hence, to tackle climate change and decouple economic growth from GHG emissions, the Indian government has already introduced a series of initiatives and national taskforces [4]. For instance, at the 2015 UN climate change conference (COP21) India pledged to reduce its GDP emission intensity by 33% to 35% by 2030 (in comparison to 2005 levels). Although one major pillar of the climate change mitigation strategy is to meet the country's power demand via non-fossil fuel sources—especially solar and wind renewable energy sources—more radical interventions may be needed for deep decarbonisation of the power sector [5]. Among other options, carbon capture and storage (CCS) is being considered as a potential technology to decarbonise the Indian coal fleet and hence the power sector at large. However, the proponents of renewable energies have called for strategies focused on a complete coal exit or for coal phase-out strategies that include very high shares of renewables in the future power system [6–8]. Although this might be a reasonable transition pathway because of the phenomenal rates of technological learning of renewable energies and the corresponding cost reductions in recent years, coal-CCS as a competing technological option should not be disregarded as well. In order to fully assess its role in India's future power market, however, a consistent comparative levelized costs assessment of coal-CCS vis-à-vis renewables is necessary, complemented by analysing other relevant dimensions of a sustainable energy transition.

Hence, our scientific study [1] here referred to had two objectives:

a. To conduct a detailed, transparent, India-specific futuristic levelized costs assessment of coal-CCS and renewables up to 2050 using a learning curve approach;

b. To harmonize the literature data and quantify the relative benefits and trade-offs of coal-CCS vis-à-vis renewables through an integrated assessment approach coupled with a nexus perspective (energy-cost-climate-water nexus); thus accounting for multiple sustainability perspectives within a single methodological framework (see Figure 1).

Our work thus adds a considerable level of techno-economic and environmental nexus specificity to the current debate on coal-based large-scale CCS and the low carbon energy transition in India in particular, and emerging economies in the Global South in general. The results of our study can: (1) guide the CCS and coal industry by identifying the key challenges and benefits of coal-based carbon capture and storage in India in future; (2) assist India's decision makers to promote low carbon energy technologies as a basis for India's future energy system with a comprehensive understanding of their pros and cons from multiple sustainability perspectives; and (3) pave the way for a sustainability assessment of CCS in other fields of application (like the energy intensive industries).

2. Coal-CCS Pathways 2050

Our future coal-CCS pathways' assessment for India up to 2050 allows us to make several observations. Firstly, our scrutiny of India's future energy scenarios indicates that most energy scenario studies either ignore the CCS option or call for a complete coal-exit, except for a few that provide conservative estimates for coal-CCS capacity projections. Based on the limited number of studies that predict coal-CCS pathways for India, we adopted three end point scenarios as the likely range of total capacity

[1] Nevertheless, it should be noted that India has GHG emissions of around 2.4 tCO2-eq/capita, which is far below the world average (6.8 tCO2-eq/capita) [2,3].

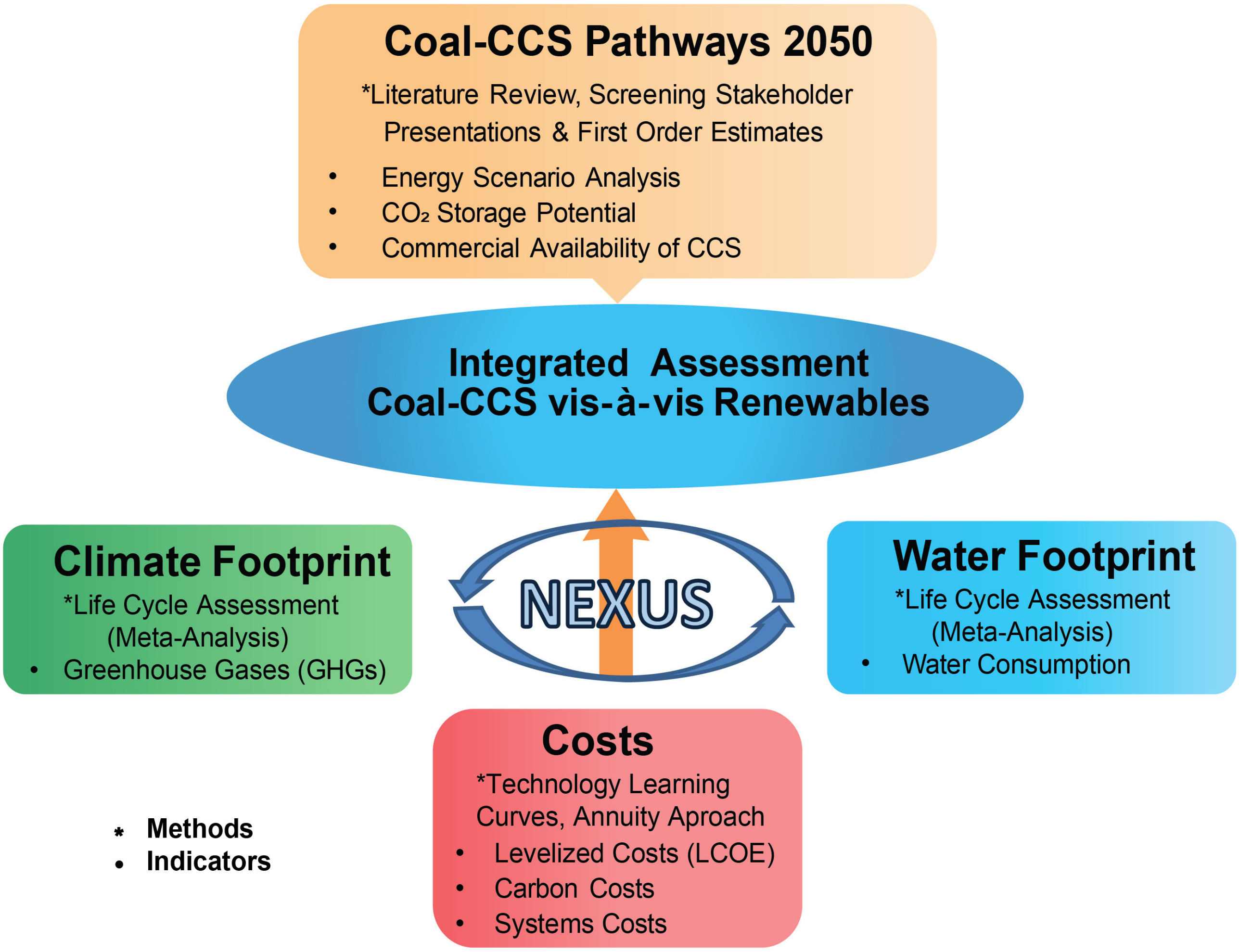

Figure 1: **Integrated Assessment methodology encompassing multiple energy sustainability assessment dimensions, including the methods and indicators used in our study [1].**

of coal-CCS by 2050: 35 GW (low), 80 GW (mean) and 150 GW (high).

Secondly, the CO_2 storage potential estimates for India range from 45 Gt to 572 Gt in the literature, with a very low confidence level. As a result, the available data should be treated with caution [9,10]. Moreover, we note that the CO_2 storage potential assessment studies carried out for India to date are preliminary in nature. Therefore, we strongly recommend for a systematic quantification and in-depth assessment of potential CO_2 storage capacity available across geological reservoirs in the Indian subcontinent, taking into account reductions in the theoretical storage potential due to technical, economic and social implications [9,11]. It will only then be possible to develop strategic long-term CCS roadmaps for the country. Moreover, a systematic potential storage capacity assessment is a prerequisite for investors and the industry to enter the Indian CCS market on a large scale, if feasible.

Thirdly, our cumulative CO_2 storage demand estimates for the three end point coal-CCS scenarios up to 2050 indicate that the estimated storage demands (9 Gt/20 Gt/37 Gt) are well within the lower bound of the good quality estimate available for India's CO_2 storage capacity (45 Gt; [12]). However, we underline that our demand estimations are based on conservative coal-CCS capacity projections and further do not take into account the storage demands from large-scale industrial CCS applications, among others. Therefore, these estimates should be treated with caution and further research in this direction is certainly recommended.

Lastly, we see clear signs in the literature and stakeholder presentations that the large-scale adoption of coal-CCS in India depends on how fast CCS technologies mature and are implemented at scale in industrial countries. As the coal-CCS landscape is still nascent even in industrialized countries and the prerequisites for the commercial availability predictions have not yet been met in the Indian context—for example, high confidence data on the CO_2 storage capacity in Indian geological reservoirs is not yet available— we believe that it is still too early to predict the commercial availability of large-scale CCS for India's coal power sector, despite optimistically assuming 2030 as the base year in this study. Furthermore, we also assert that commercial availability will greatly depend on the political-will and backing of the Indian government towards developing CCS support infrastructure in the country in the years to come.

3. Costs

We conducted a detailed, transparent, India-specific futuristic levelized costs assessment (LCOE) of coal-CCS and renewables up to 2050. For better comparison and adaptability with the existing literature, we provided our LCOE results in two steps: (1) Simple LCOE – representing the prevalent methodology used in the literature; and (2) Advanced aLCOE – wherein the carbon costs and systems costs are added to simple LCOE results. In addition, we used the learning curve approach to predict the development of the capital costs and, therefore, the levelized costs over time (up to 2050).

Our levelized costs assessment points out that coal-CCS is very expensive in comparison to both conventional coal power plants and successful renewables; hence, significant enhancement in its technology learning rate is crucial if CCS is to enter the Indian power market in future. For instance, the integration of CCS with coal power plants doubles their LCOE, and the mean LCOE of coal-CCS plants are 5 times and 3 times higher than solar

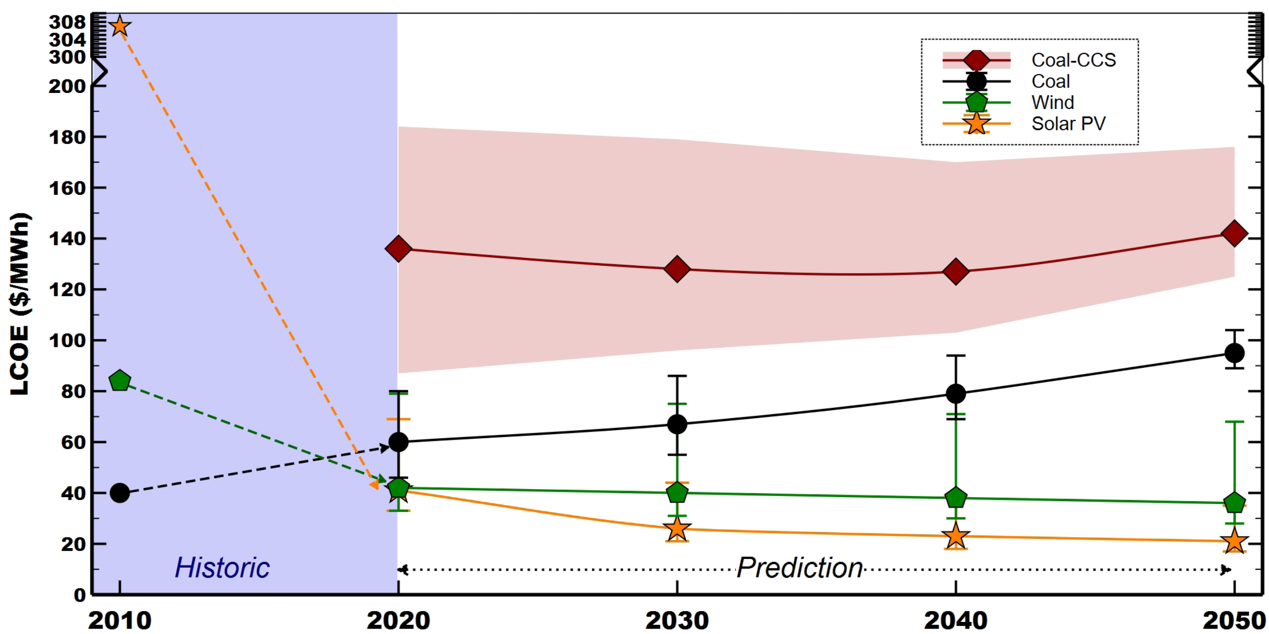

Figure 2: Simple LCOE for coal-CCS, coal, solar PV and wind power sources from 2010 to 2050. The area-fill and bars show the low and high LCOE range [1].

PV and wind power plants in 2030, respectively. This price difference could increase steadily until 2050 due to the possible escalation in coal fuel prices in the coming decades and the relatively higher learning rates of renewables in comparison with coal-CCS (see Figure 2). Furthermore, we note that the inclusion of carbon costs and systems costs in the advanced aLCOE scenario does not considerably affect the relative cost differences between coal-CCS and renewables, since the increase in the levelized costs of renewables (due to their higher systems costs) is partly compensated for by the proportionate increase in coal-CCS levelized costs (due to carbon costing). However, in the aLCOE scenario, coal-CCS does compete in terms of costs in comparison to conventional coal power plants (see Figure 3).

Further, generally the studies on future prospects of coal-CCS argue that carbon pricing favours the deployment of coal-CCS in India. Although this seems evident in comparison to conventional coal power plants, we underscore that carbon pricing will not reduce the levelized costs of coal-CCS but will instead make conventional coal power furthermore expensive—and conventional coal power is already expensive when compared to successful renewables. The obvious lack of competitiveness of conventional coal power plants in future energy markets (with and without carbon pricing) should not be interpreted as a favourable sign only for coal-CCS, especially when there are other promising competitors in the market. We emphasise the possibility that carbon pricing might also strongly favour the deployment of energy storage technologies and, therefore, support a much stronger setup of renewables-based energy system, since there is a large "operating space" in the difference of $98 per MWh between the mean LCOE (aLCOE) estimates for coal-CCS and a 70/30 RE mix (solar PV/wind) by 2030 (see Figure 3).

While the complete costs resulting from a high penetration of renewables in future are yet to be estimated for India, the cost difference estimate from this study ($98/MWh) can give a rule of thumb for the upper cap of energy storage

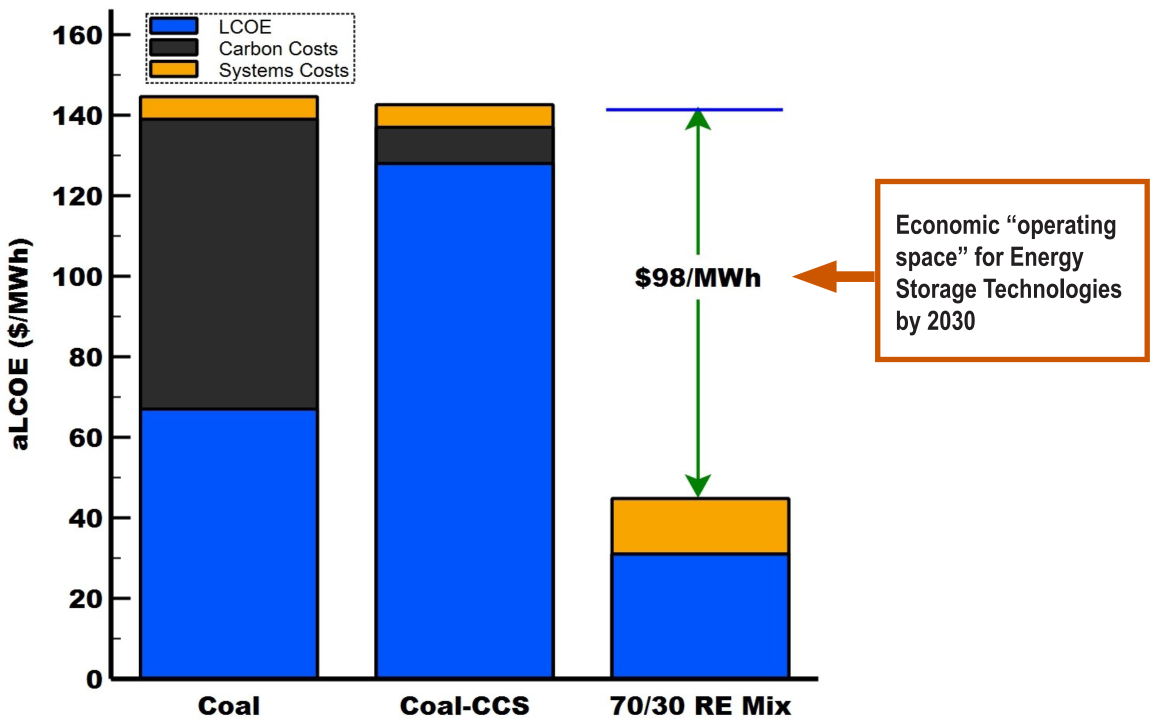

Figure 3: Economic "operating space" for additional energy storage technologies by 2030; 70/30 RE Mix represents 70% solar PV and 30% wind hybrid renewable energy mix [1].

and ancillary service costs to maintain a high penetration of renewables in the future grid; so that the overall costs of renewables, storage and ancillary services will still be competitive in relation to coal-CCS in 2030. In addition, we note that the gap between the levelized costs of coal-CCS and renewables might further widen depending on rising carbon prices and coal fuel prices post 2030. Moreover, the capacity utilisation (CUF) of coal-CCS plants could decrease significantly in the future (compared to the optimistic 80% CUF assumed in our study) due to the higher penetration of renewables, which would significantly increase the LCOE of coal-CCS. These possible future scenarios could further increase the competitiveness of high renewables-storage integrated future energy systems. In addition, the small-scale nature of renewables and many storage systems makes it more likely that a large-scale expansion could be achieved in a relatively short timeframe compared to the large-scale and infrastructure-heavy nature of coal-CCS. Summarising, our findings show that the cost reductions of storage technologies up to 2030, given coal-CCS is expected to become commercially available only after 2030 even in the best-case scenario, strongly determine the practical relevance of coal-CCS in future Indian power market.

4. Climate Footprint

Our climate footprint assessment suggests that coal-CCS plants could make a significant contribution to the decarbonisation of coal power fleet if India follows a coal-dominant future pathway, as CCS technologies could potentially lower the coal-based life cycle GHG emissions in the country by almost 74% net (Figure 4a). However, although favorable compared to conventional coal plants, coal-CCS life cycle GHG emissions are still 8 to 15 times higher in comparison to renewables. Hence, we underscore that renewables are better positioned than coal-CCS if the goal is ambitious climate change mitigation and long-term sustainable development.

5. Water Footprint

Our water footprint assessment reveals that the life cycle water consumption of Indian coal power plants doubles when equipped with CCS technologies. Coal-CCS would consume huge volumes of water resources during its life cycle in comparison to renewables: over 20 times more than solar PV and 900 times more than wind power plants (Figure 4b). We underscore here that coal power plants already

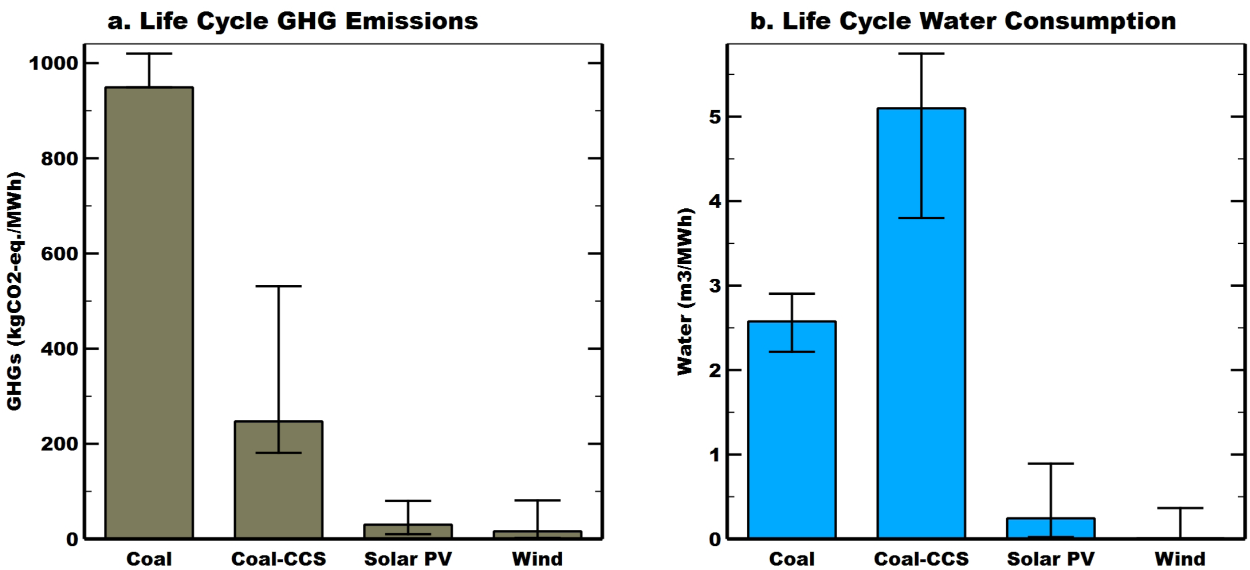

Figure 4: Life cycle GHG emissions and Life cycle water consumption of coal, coal-CCS, solar PV and wind [1].

consume significant freshwater resources in the country; for instance, it is estimated that nearly 88% of industrial water demand in India comes from thermal power plants. Furthermore, more than 44% of India's existing coal power plants and 45% of newly-proposed plants are sited in high to extremely high water-scarce regions and the establishment of coal power plants is often the primary cause of water stress in the regions of their placement [13]. This shows that the conventional coal power plants are already competing with water demands from other essential services in the country. In addition, climate change impacts are expected to further exacerbate the water issues in the country [14,15]. These issues, combined with exponentially rising water demands [16,17], will mean that the availability of water resources in India will have a strong influence on the fate of water-intensive coal-CCS technologies.

6. Energy-Cost-Climate-Water Nexus

Our study reveals that coal-CCS underperforms considerably in comparison to renewables from a cost-climate-water nexus perspective (see Figure 5). A simple first order estimate shows that 150 GW of coal-CCS cumulatively emits 10 Gt of GHG emissions and consumes 214 billion cubic metres of water throughout its life cycle over a period of 40 years. If the same amount of electricity is generated from a 70/30 mix of solar PV/wind power, 9 Gt of GHG emissions can be avoided (roughly equivalent to the total GHG emissions of whole India for three years [3]) and 207 billion cubic metres of water can be conserved (roughly equivalent to the total domestic water demand of whole India for four years [18] (see [1] for assumptions). However, it should be noted here that the additional impacts of energy storage and ancillary power sources necessary to sustain the high renewable energy scenarios are not taken into account in the above simplistic comparison. Although we accounted for systems costs in our aLCOE estimates—including grid integration and reinforcement costs plus balancing costs to operate short-

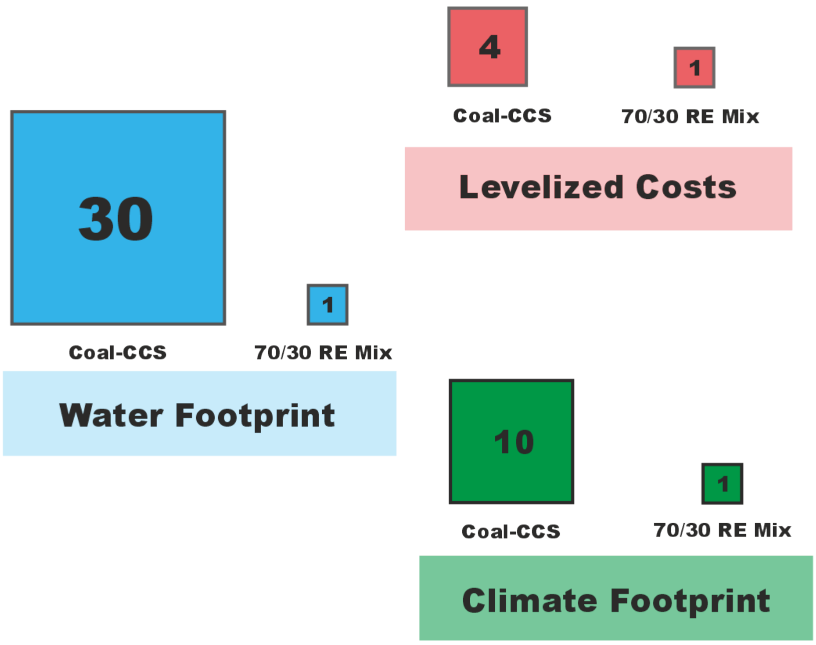

Figure 5: Comparative ratios between coal-CCS and a 70/30 RE Mix (solar PV/wind renewable energy mix) for water-climate-cost indicators [1].

term reserves—we did not account for all the costs that could arise from the operation of energy storage units and ancillary services across the entire grid system to maintain a high penetration of renewables in future energy scenarios. Consequently, further research in this direction is recommended.

Furthermore, although it is fairly apparent that coal-CCS could make a significant contribution to reducing GHG emissions if India follows a coal-dominant future energy pathway, the major drawbacks are that coal-CCS consumes nearly twice the water resources and costs twice as much as conventional coal power. Given that climate change impacts are likely to intensify water and environmental issues significantly in India in the coming decades [19], we envisage strong positive feedback loops between global warming, water scarcity issues and stricter environmental norms that, in turn, impact negatively on the levelized costs of coal-CCS—making its practical feasibility tremendously challenging. Therefore, it is crucial that climate-friendly technologies must also have low water footprints and be cost competitive in order to become sustainable and effective large-scale solutions for power generation in India in an era of global warming and resource scarcity.

7. Conclusion

To conclude, our study indicates that coal-CCS in India suffers not only from typical new technology development related challenges—such as the lack of technical potential assessments and necessary support infrastructure, and high costs—but also from severe resource constraints (especially water resources) in an era of global warming and simultaneously the competition from outperforming renewable power sources. We recommend that these challenges would have to be comprehensively addressed if coal-CCS should play a significant role in low carbon electricity transition not only in India, but in the Global South in general. (Coal) CCS should, however, be further developed as a backstop technology because, even if it is not available on a large scale until 2030 (or later) in India, it could be used to retrofit existing coal power plants in future and could also become integrated with energy-intensive industries where there are often no alternative low-carbon options.

A comprehensive overview of our integrated assessment results with respect to the chosen seven indicators are summarized below (see also Figure 6):

1. Our scrutiny of India's future energy scenarios indicates that most energy scenario studies either ignore the CCS option or call for a complete coal-exit, except for a few that provide conservative estimates for coal-CCS capacity projections.

2. We note that the CO_2 storage potential in India has not yet been quantified systematically and there is a low confidence in the available data. As a result, we highlight that the systematic quantification and in-depth assessment of potential CO_2 storage capacity available across geological reservoirs in the Indian subcontinent—accounting for reductions in the theoretical storage potential due to technical, economic and social implications—is a prerequisite for charting long-term strategic CCS roadmaps for the country. Furthermore, although our cumulative CO_2 storage demand estimates for coal-CCS scenarios up to 2050 (9 Gt/20 Gt/37 Gt) fall within the good quality storage potential estimate (45 Gt), we underline that our demand estimations are based on conservative coal-CCS capacity projections and do not take into account the simultaneous storage demands from large-scale industrial CCS applications, among others. Therefore, these estimates should be treated with caution and further research in this direction is certainly recommended.

3. We see clear signs in the literature and stakeholder presentations that the adoption of coal-CCS in India depends on how fast

CCS technologies get matured and are implemented at scale in industrial countries. This leads us to believe that it is still too early to predict the year of commercial availability of large-scale CCS for India's coal power sector (although we optimistically assume 2030 as the base year in our assessments).

4. Our levelized costs assessment points out that coal-CCS is very expensive in comparison to conventional coal power plants and successful renewables; hence, significant enhancement in its technology learning rate is crucial if CCS is to enter the Indian power market in future.

5. Even though carbon pricing can make coal-CCS competitive in relation to conventional coal power plants by nearly doubling the levelized costs of the latter in 2030, it does not influence the lack of competitiveness of coal-CCS with respect to renewables. For instance, there still remains a levelized costs (LCOE/aLCOE) gap of $98 per MWh between coal-CCS and 70/30 solar PV/wind mix in 2030. However, the full impact of socio-environmental costs, storage and ancillary services costs on the relative competitiveness of these power sources needs to be evaluated in future studies.

No.	Indicator	Assessment	Notes—See Text for Explanations
1	Future Energy Scenarios	Negative	Coal-CCS capacity projections in India's future electricity scenarios are very conservative or the technology is ignored altogether.
2	Carbon Storage Potential	Depends	Systematic quantification and in-depth assessments of potential CO_2 storage capacity available across geological reservoirs in the Indian subcontinent are not yet available.
	Carbon Storage Demand (for Coal-CCS)	Positive	Our cumulative CO_2 storage demand estimates for coal-CCS scenarios up to 2050 fall within the good quality storage potential estimate quoted in the literature.
3	Commercial Availability	Depends	We think it is still too early to predict the year of commercial availability of large-scale CCS for India's coal power sector, even though we optimistically assume 2030 as the base year in our assessment.
4	Levelized Costs (LCOE)	Negative	Coal-CCS is very expensive in comparison to conventional coal and successful renewables; its LCOE is higher by a factor of 3 to 5 in comparison to renewables in 2030.
5	Advanced Levelized Costs (aLCOE)	Depends	Even though carbon pricing makes coal-CCS competitive in relation to conventional coal power plants, it does not influence the lack of competitiveness of coal-CCS with respect to renewables. For instance, there still remains a levelized costs gap of $98 per MWh between coal-CCS and 70/30 RE mix in 2030.
6	Climate Footprint	Depends	Coal-CCS might eventually act as a technology intervention to decarbonise the power sector if India follows a coal-dominant future pathway; however, its life cycle GHG emissions will still be higher by a factor of 8 to 15 in comparison to renewables.
7	Water Footprint	Negative	Coal-CCS has nearly twice the water footprint of conventional coal plants and consumes enormous amounts of water in comparison to renewables: 20 to 900 times more.

Figure 6: Summarised results of our integrated assessment with respect to the chosen seven indicators [1].

6. From a climate change mitigation perspective, our results show that coal-CCS could eventually act as a technology intervention to decarbonise the power sector if India follows a coal-dominant future pathway, as CCS technologies can significantly reduce the life cycle GHG emissions of conventional coal power plants (by about 74% net). However, we note that renewables are better positioned than coal-CCS if the goal is ambitious climate change mitigation and long-term sustainable development.
7. Our water footprint assessment reveals that coal-CCS is a water-intensive technology and consumes twice as much water resources as conventional coal plants. India may well struggle to retain its conventional coal power plants over the next decades because of their large water footprints, which raises doubt about the potential acceptance in India of the introduction of additional water-intensive technologies such as coal-CCS—especially when extremely water-efficient renewables are available with water consumption rates nearly 30 times (70/30 solar PV/wind mix) lower than coal-CCS.

Abbreviations

Coal / Conventional Coal: Conventional supercritical coal power plants (without CCS)
Coal-CCS: CCS-equipped supercritical coal power plants
Solar PV: Utility-scale solar photovoltaic power plants
Wind: Large onshore wind power plants
GHGs: Greenhouse gases
LCOE: Levelized Cost of Electricity Generation
aLCOE: Advanced LCOE (LCOE + Carbon Costs + Systems Costs)
Carbon Costs: We account for the social costs of carbon, indicating the climate damage associated with every additional tonne of carbon dioxide emitted into the atmosphere. Note that these costs are independent of carbon market prices, their future fluctuations and carbon penalties that may be introduced by governmental regulations.
Systems Costs: These are the additional costs incurred due to the integration of a particular type of power plant in the overall electricity system; here we account for the grid extension / reinforcement costs and balancing costs incurred to maintain and operate reserves to tackle short-term electricity fluctuations.

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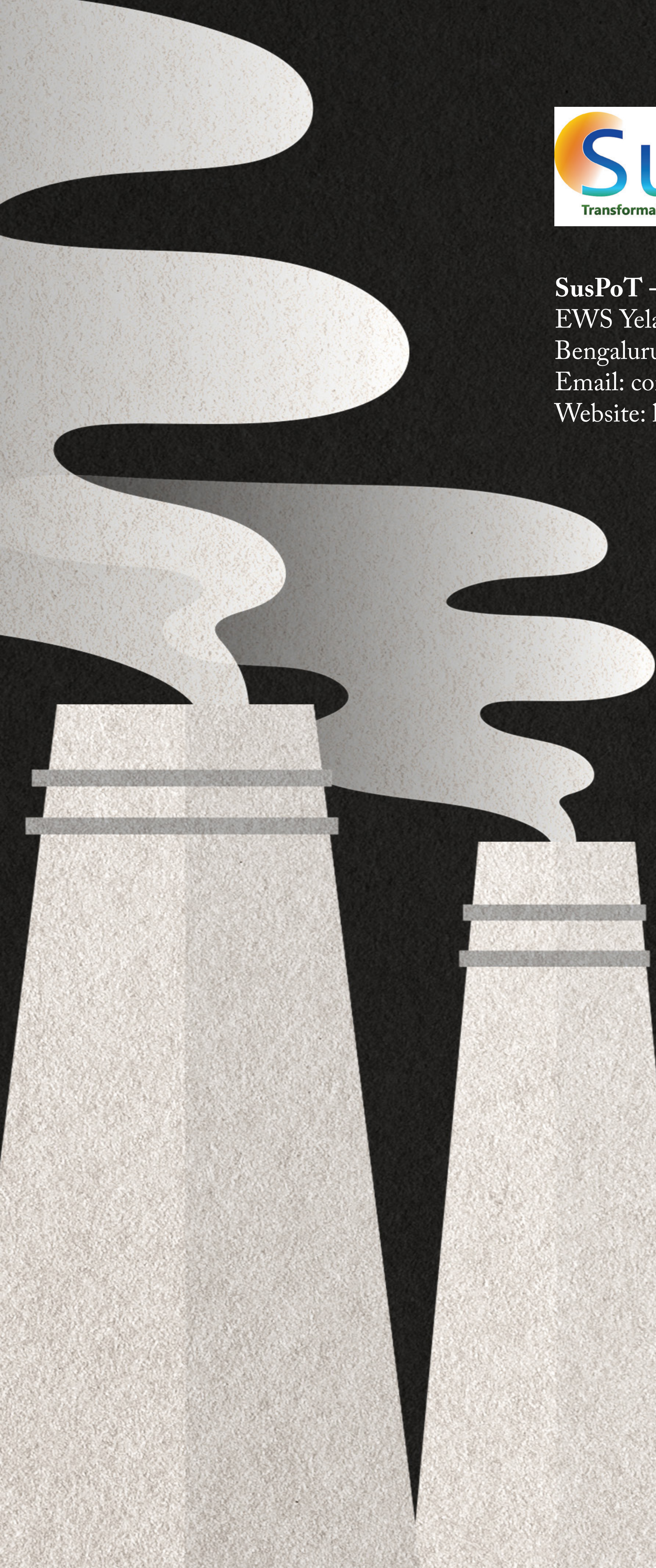

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