Supplementary Materials to the article

An Integrated Comparative Assessment of Coal-Based Carbon Capture and Storage (CCS) vis-à-vis Renewable Energies in India's Low Carbon Electricity Transition Scenarios

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S1: Assumptions for estimating the CO_2 storage demand from all the coal-CCS plants built until 2050.

3 End Points of Coal-CCS capacity by 2050 are considered: 35/80/150 GW
CO_2 emissions per kwh-thermal: 344 gCO_2 / kWh-th
Average Efficiency of coal-CCS plants: 35%
CO_2 capture rate: 90%
Power plant capacity utilization factor (CUF): 80%
Lifetime of coal-CCS power plant: 40 years

S2: Levelized Costs

Table S2.1: Data and assumptions used for estimating the levelized costs of future coal power generation in India.

Parameters	Unit	2020 (2050)[#] Low/Mean/High			References & Comments
General cost parameters					
Capex (Overnight)	$/kW	1,044	1,200	1,200	[1–3] We assume that the increasing environmental norms will nullify the cost reductions achieved from coal technology's learning rate (if any) and moreover super-critical coal technologies can already be considered as mature technologies. So, the capex costs are assumed to remain same till 2050.
Cost Overruns	%Capex	5%	5%	20%	[4,5] It seems cost overruns for Indian coal power plants are on the higher side [5]; however, we keep the low and mean values same (5%; [4]).
Opex (Fixed)	$/kW-annum	42	48	50	[4,6] Opex (Fixed) are the annual fixed maintenance costs averaged across a time period of 25 years. Low/Mean – 4% Capex/annum High – 4.2% Capex/annum
Opex (Variable)	$/MWh	2.5 (5)			[4,7] Minimum value from [4]; assumed to increase from 2.5$ in 2020 to 3$ (2030) to 5$ (2050) [7] because of escalating water and oil prices, among others.
Fuel Costs	$/MWh	19 (60)	22 (55)	28 (50)	Authors' estimates based on the data in below section "Fuel Costs Assumptions".
Carbon Costs	$/ton	49	86	157	[8] Here we account for the social costs of carbon emissions indicating the climate damage associated with every additional tonne of carbon dioxide emitted into the atmosphere. Note these costs are independent of the

Parameters	Unit	2020 (2050)[#] Low/Mean/High			References & Comments
					carbon market prices and their future fluctuations or carbon penalties introduced by governmental regulations.
Systems Costs	$/MWh	5.6			[9] We account for the grid extension and reinforcement costs only; balancing costs for coal power plants are ignored.
Discounting					
Depreciation Period (N)	Years	25			We have kept 25 years depreciation period constant across all technologies.
Weighted Average Cost of Capital (WACC)	%	11%	13%	14%	[5,6,10] As investors increasingly perceive financing coal power plants to be more risky [10], we expect WACC to go further high in the next years. Hence, we assume 14% on the higher side.
Technical Parameters					
Efficiency	%	39% (40%)	40% (41%)	41% (42%)	[3,4,6] Efficiency values are assumed to rise by 1%-point by 2030 and then stabilize.
Capacity Utilization Factor (CUF)	%	80%	72%	60%	[1,5,6] Based on the projections and estimates in National Electricity Plan [1], we assume 60% as a lower value for supercritical coal power plants in India. However, [1] estimates that overall CUF for coal power plants in India may possibly come down to 56.5% by 2021-22 under the influence of renewable capacity additions in the country.
Fuel Costs Assumptions					
Import Share	%	0	30	100	
Net calorific value for Indian coal	MJ/kg	18			[5,11]

Parameters	Unit	2020 (2050)# Low/Mean/High			References & Comments
Net calorific value for Imported coal	MJ/kg	25			[6]
Price of hard coal	$/ton	36 (118)	50 (126)	80 (145)	[2,12] Three scenarios are assumed: (a) Low – 100% Domestic coal fuel; Domestic coal prices are escalated by 4%/year from 2020 till 2050 [13] (b) High – 100% Imported coal fuel; Imported coal prices are assumed to escalate at lower rate than domestic prices, that is, 2%/year from 2020 till 2050 (c) Mean – 70/30 mix of domestic (low) & imported (high) coal fuel.
Emission Factor	gCO_2/kWh-th	345	344	341	[14–16] Low – Domestic coal; High – Imported coal; Mean – 70/30 mix of domestic and imported coal fuel.

* The values from literature are inflation adjusted to 2018 US dollars (https://www.usinflationcalculator.com/); wherever applicable, a historic conversion rate of 1$ = 70 INR is assumed.

The figures in brackets are authors' estimates for 2050; mentioned only if the figures are changed.

Table S2.2: Data and assumptions used for estimating the levelized costs of future coal-CCS power generation in India.

Parameters	Unit	2020 (2050)# Low/Mean/High			References & Comments
General cost parameters					
Capex (Overnight)	$/kW	1,828 (1,383)	3,816 (2,421)	4,134 (3,084)	[3,6] Based on [3], it is assumed that Capex of coal-CCS will reduce from $3,816/$4,134 per kW in 2020 to $3,074/$3,763 per kW in 2030 for mean and high values. Low value ($1,828/kW) represents the Capex of retrofitting already existing super-critical coal power plants with CCS in India and is estimated based on [6]: 175% Capex without CCS. It is assumed that the commercialization of coal-CCS plants in India will start from 2030 onwards (best case scenario; see Section 3.1.3 in the paper for more details). From 2030 till 2050, a technology learning rate of 3.9% [6,17] is assumed for Capex and is applied according to 3 different endpoint scenarios in 2050 (150/80/35 GW), all starting with 1GW installed capacity in 2030 and straight line escalation until 2050.
Cost Overruns	%Capex	5%	5%	20%	[4,5] It seems cost overruns for coal based power plants in India are on the higher side [5]; however, we keep the low and mean values same (5%; [4]).
Opex (Fixed)	$/kW-annum	76 (50)	88 (61)	92 (68)	[6] 183% of Opex without CCS is assumed, and a learning rate of 5.8% is applied from 2030 till 2050 (similarly as indicated for Capex above).
Opex (Variable)	$/MWh	4.6 (9.2)			[6] Assumed to be 183% of Opex (variable) without CCS.
Fuel Costs		25 (72)	28 (63)	35 (56)	Authors' estimates based on the below mentioned coal fuel data and assumptions.

Parameters	Unit	2020 (2050)[#] Low/Mean/High			References & Comments
Carbon Costs	$/ton	49	86	157	[8] Here we account for the social costs of carbon emissions indicating the climate damage associated with every additional tonne of carbon dioxide emitted into the atmosphere. Note these costs are independent of the carbon market prices and their future fluctuations or carbon penalties introduced by governmental regulations.
Systems Costs	$/MWh	5.6			[9] We account for the grid extension and reinforcement costs only; balancing costs for coal-CCS power plants are ignored.
Discounting					
Depreciation Period (N)	Years	25			We have kept 25 years depreciation period constant across all technologies.
Weighted Average Cost of Capital (WACC)	%	11%	13%	14%	[5,6,10] As investors increasingly perceive financing coal based plants to be more risky [10], we expect WACC to go further high in the next years. Hence, we assume 14% on the higher side.
Technical Parameters					
Efficiency	%	29% (33.5%)	31.5% (36%)	32.5% (37%)	[6] The following efficiency penalty are assumed in comparison to supercritical coal power plants without CCS: 2020 – 8.5% points 2030 – 7% points 2040 – 6% points 2050 – 5% points Additional efficiency penalty for retrofits: 1.5% points.
Capacity Utilization	%	80%	80%	72%	[5,6] It is anticipated that coal-CCS plants are used more

Parameters	Unit	2020 (2050)# Low/Mean/High			References & Comments
Factor (CUF)					effectively than coal without CCS plants.
Fuel Costs Assumptions					
Import Share	%	0	30	100	
Net calorific value for Indian coal	MJ/kg	18			[5,11]
Net calorific value for Imported coal	MJ/kg	25			[6]
Price of hard coal	$/ton	36 (118)	50 (126)	80 (145)	[2,12] Three scenarios are assumed: (a) Low – 100% Domestic coal fuel; Domestic coal prices are escalated by 4%/year from 2020 till 2050 [13] (b) High – 100% Imported coal fuel; Imported coal prices are assumed to escalate at lower rate than domestic prices, that is, 2%/year from 2020 till 2050 (c) Mean – 70/30 mix of domestic (low) & imported (high) coal fuel.
Emission Factor	gCO_2/kWh-th	345	344	341	[14–16] Low – Domestic coal; High – Imported coal; Mean – 70/30 mix of domestic and imported coal fuel.
CCS Parameters					
CO_2 Capture Rate	%	90%			[6] The nominal capture rate (90%) is considered in this study throughout; however, the net capture rate is smaller than the nominal rate due to the penalty associated with adding CCS system to the coal power plant.
CO_2 transport distance	km	350	350	500	[6]
CO_2 leakage	%	Nil			

Parameters	Unit	2020 (2050)[#] Low/Mean/High	References & Comments
from storage sites			
CO_2 transportation costs	\$/ton-CO_2 (100km)	2.2	[6] CO_2 transportation costs via pipeline.
CO_2 Storage Costs	\$/ton-CO_2	5.3	[18]

* The values from literature are inflation adjusted to 2018 US dollars (https://www.usinflationcalculator.com/); wherever applicable, a historic conversion rate of 1$ = 70 INR is assumed.

The figures in brackets are authors' estimates for 2050; mentioned only if the figures are changed.

Table S2.3: Data and assumptions used for estimating the levelized costs of future solar PV power generation in India.

Parameters	Unit	2020 (2050)[#] Low/Mean/High			References & Comments
General cost parameters					
Capex (Overnight)	$/kW	479 (237)	486 (241)	600 (297)	[19,20] We assume solar-PV capacities will quadruple between 2020 and 2030, and hence we apply 2 times doubling for its Capex learning rate; During 2030 to 2050, we assume the installed capacities will double every decade. Further, we use short term learning rate of 20% between 2020-2030 and long term learning rate of 12% between 2030-2050 [21].
Cost Overruns	%Capex	1.5%	1.5%	3.5%	[4] Unlike conventional plants, renewable power plants have low cost overruns because of their modular nature and hence lower project installation lead time, among other reasons.
Opex	$/kW-annum	14 (7)	15 (7)	18 (9)	We estimate Opex = 3% of Capex: Based on the average operation and maintenance costs (escalated over 25 years) as per [19,20].
Systems Costs	$/MWh	13.5			[9] We account for the grid extension and reinforcement costs plus balancing costs incurred to maintain and operate reserves to tackle short-term electricity fluctuations in the grid due to integration of renewables.
Discounting					
Depreciation Period (N)	Years	25	25	25	We have kept 25 years depreciation period constant across all technologies.
Weighted Average Cost of Capital (WACC)	%	9%	10%	12%	[10,19,20,22] Renewables are perceived as low risky investment than coal power plants in the country, and hence have lower WACC [10].
Capacity Utilization Factor (CUF)	%	22%	19%	16%	[19,20]

Table S2.4: Data and assumptions used for estimating the levelized costs of future wind power generation in India.

Parameters	Unit	2020 (2050)[#] Low/Mean/High			References & Comments
General cost parameters					
Capex (Overnight)	$/kW	750 (643)	786 (674)	857 (735)	[23,24] We anticipate wind power installed capacities in India will double every decade. We use a constant learning rate of 5% between 2020-2050 [21].
Cost Overruns	%Capex	1.5%	1.5%	3.5%	[4]
Opex	$/kW-annum	15 (13)	20 (17)	26 (22)	[23,24] We assume Opex = 2%/2.5%/3% of Capex for low/mean/high estimates respectively; Based on the average operation and maintenance costs (escalated over 25 years) as per [23,24].
Systems Costs	$/MWh	14.6			[9] We account for the grid extension and reinforcement costs plus balancing costs incurred to maintain and operate reserves to tackle short-term electricity fluctuations in the grid due to integration of renewables.
Discounting					
Depreciation Period	Years	25	25	25	We have kept 25 years depreciation period constant across all technologies.
Weighted Average Cost of Capital (WACC)	%	9%	10%	12%	[23–25] Renewables are perceived as low risky investment than coal power plants in the country, and hence have lower WACC [10].
Capacity Utilization Factor (CUF)	%	32%	29%	20%	[23,24,26]

* The values from literature are inflation adjusted to 2018 US dollars (https://www.usinflationcalculator.com/); wherever applicable, a historic conversion rate of 1$ = 70 INR is assumed.

The figures in brackets are authors' estimates for 2050; mentioned only if the figures are changed.

Table S2.5: Data summary of Levelized Costs of Electricity Generation (LCOE) results.

a. **Simple LCOE Results (**$/MWh)

$/MWh	2010	2020			2030			2040			2050		
Coal	40	46	60	80	55	67	86	69	79	94	89	95	104
Coal-CCS	NA	88	136	185	97	128	179	103	127	169	125	142	175
Solar PV	307	33	41	69	21	26	44	19	23	39	16	21	34
Wind	84	33	42	79	31	40	75	30	38	72	28	36	68

b. **Comparison of Advanced and Simple LCOE Results for 2030 and 2050 (**$/MWh)

	2030		2050	
$/MWh	LCOE	aLCOE	LCOE	aLCOE
Coal	67	145	95	173
Coal-CCS	128	143	142	155
Solar PV	26	40	21	34
Wind	40	55	36	51

S3: Climate Footprint

Table S3.1: Data and assumptions used for estimating Life Cycle GHG emissions.

Source	Life Cycle GHG emissions $kgCO_2$eq./MWh Min/Mean/Max			Reference Details / Comments
Coal	**949**	**949**	**1020**	We assume the top quintile power plants from [27] represent the performances of India's newly built super-critical coal power plants.
Coal-CCS	**180**	**247**	**530**	Own estimations based on our meta-analysis on the percentage decrease in the GHG emissions of coal power plants after integrating with post-combustion CCS technologies [6,28–36]; We estimate the possible min/mean/max percentage GHG emission reductions for Indian coal-CCS power plants in future would be 48%/74%/81% [6,28,29].
Solar PV	**10**	**30**	**80**	[37]; Ground-Mounted Photovoltaic systems - Lower value for thin films at high radiation and higher value for C-Si PV at low radiation.
Wind	**2**	**16**	**81**	[38]; Life cycle performance values of Onshore, Large Wind Turbines.

Table S3.2: Meta-analysis on the percentage decrease in the GHG emissions of coal power plants after integrating with CCS.

Study	Percentage decrease in GHG emissions when equipped with CCS*
Viebahn et al. [6]	74%
Cuellar-Franca and Azapagic [28]	75-81%
Petrescu et al. [29]	48-59%
Pehnt and Henkel [30]	78%
Odeh and Cockerill [31]	71%
Viebahn at al. [32]	66%
Korre et al. [33]	79%
Koornneef et al. [34]	79%
Singh et al. [35]	74%
Viebahn [36]	67-72%

* Post combustion CCS with super-critical coal

S4: Water Footprint

Table S4.1: Data and assumptions used for estimating Life Cycle Water Consumption.

Source	Life Cycle Water Consumption L/MWh Min/Mean/Max			Reference Details / Comments
Coal	**2,215**	**2,575**	**2,904**	Own estimations based on [39] for fuel cycle and power plant life cycle data; Opencast mining is assumed for fuel cycle as it accounts for more than 93% of coal mining in India [40]; For power plant operations, water use data taken from [41,42]; Re-circulating type cooling systems are assumed for power plant operations as nearly 90% of Indian coal power plants use this cooling technology [42].
Coal-CCS	**3,799**	**5,098**	**5,746**	Own estimations based on our meta-analysis on the percentage increase in the life cycle water consumption of coal power plants after integrating with post-combustion CCS technologies [39,43–46]. Fuel cycle and power plant life cycle water use: 31% increase from conventional Coal power plants [39]; For power plant operations, we assume Min/Max of 72%/106% increase based on [43,44]; Mean is taken as 100% increase based on the argumentation of [43,45].
Wind	**1**	**6**	**42**	[39]
Solar PV	**23**	**244**	**892**	Lower value for thin films-flat panel [39]; Higher value for C-Si PV-flat panel from [39]; Mean value is own estimation: Power plant life cycle data – Average of C-Si and thin films median values from [39]; Operations – India specific data from [42] (80 L/MWh).

Table S4.2: Meta-analysis on the percentage increase in the operational water consumption of coal power plants after integrating with CCS.

Study	Percentage increase in the operational water consumption when equipped with CCS*
Meldrum et al. [39]	76%
Sharma and Mahapatra [43]	81% - 106%
Ou et al. [44]	72%
Zhai et al. [45]	83% (or 2x)
Jin et al. [46]	77%

* Post combustion CCS with super-critical coal and recirculating cooling tower

S5: What it takes to run 150 GW of coal-CCS for 40 years.

Assumptions

Deliverable Power Capacity of CCS: 150 GW

Capacity Factor: 80%

Time duration: 40 years

Annual GHG emissions of India = 3.3 Gt (approximate; [47])

Annual domestic water demand of India = 55 billion cubic-meters (approximate; [48])

Cumulative estimations for 40 years (approximate calculations based on mean values)

Electricity generated by 150 GW coal-CCS = 4.2E+10 MWh

GHG emissions: Coal-CCS = 10.4 Gt; Solar PV/Wind (70/30 mix) = 1.1 Gt

Water consumption: Coal-CCS = 214 billion cubic-meters; Solar PV/Wind (70/30 mix) = 7 billion cubic-meters

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