Chapter 58
Impact of Coal Quality on Post-combustion, Amine-Based CO_2 Capture in Indian Coal Power Plants

Pranav C. Phadke, Anand B. Rao and Munish K. Chandel

Abstract India has substantial reserves of low sulfur, low grade (high ash) coal, which provides a reliable, cheap baseload power, and hence, it is expected to continue to be a major energy source for the next few decades. But, the combustion of coal emits a huge amount of carbon dioxide (CO_2), the most prominent greenhouse gas (GHG) which is responsible for climate change. Various CO_2 mitigation techniques including carbon capture and sequestration (CCS) may be required in the future to reduce the greenhouse gas emission to the atmosphere. The quality of coal used in power plants could play an important role in the overall performance of CCS. The focus of this study is to investigate the impact of coal quality while implementing carbon capture (CC) system in the new supercritical coal-fired power plants in India. Supercritical pulverized coal (PC) plants with and without carbon capture (CC) and with different coal characteristics were simulated using integrated environmental control model (IECM). The impact of variation in the cost of coal and plant capacity factor on the viability of CC has also been assessed along with different policy strategies required toward the implementation of CCS in the country.

Keywords Indian coal power plants · Coal quality · Emission control technologies · Post-combustion amine-based CO_2 capture

58.1 Introduction

About one-third of the population in India has no access to reliable electricity. The per capita annual electricity consumption in India is 1075 kWh/cap [1] which is about one-third of the global average [2]. This electricity is presently being supplied by

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coal, natural gas, hydro, nuclear power, and renewable energy, with coal having about 60% share in the total installed capacity in the country [1]. Projections show that coal will continue to be a major energy source in India for the next few decades due to the increase in electricity demand and adequate availability of coal [3]. India has substantial reserves of low sulfur, low grade (high ash) coal, which provides a reliable, cheap baseload power; however, the coal-based thermal power industry is responsible for significant share of emissions of the industrial sector. Major pollutants from coal-fired thermal power plants are particulate matter (PM), sulfur dioxide (SO_2), and oxides of nitrogen (NO_x). Recognizing the central role that coal power plants play in worsening the air quality in India, the Ministry of Environment, Forest and Climate Change (MoEFCC) announced in December 2015 more stringent emission control standards for coal-based thermal power plants [4]. The new standards aim to drastically reduce emissions of NO_x, SO_2, PM, and mercury.

In addition to the aforementioned pollutants, coal-fired power plants also emit carbon dioxide (CO_2), a prominent greenhouse gas (GHG) responsible for climate change. Efforts on several fronts are being carried out to limit the CO_2 buildup in the atmosphere and to keep global average temperature rise well below 2 °C [5]. One such solution toward reducing CO_2 emissions is carbon capture and storage/sequestration (CCS). CCS can effectively reduce 80–90% of CO_2 emissions from large point sources (LPS) by separating CO_2 from flue gas of these sources, compressing it, and subsequently storing the compressed CO_2 such that it can be isolated from the atmosphere [6]. The CCS system comprises of three major stages: CO_2 capture, transport, and storage. However, the entire CCS process is energy-intensive with CO_2 capture being the most energy-intensive of the three and represents ~75–80% of total cost of CCS [6]. Efforts are being made globally to improve this technology and make it commercially viable for thermal power plants [7]. Separation of CO_2 from flue gas stream can be achieved using either post-combustion capture technology, pre-combustion capture technology, or oxy-fuel combustion technology [7].

The coal-based total installed capacity in India is about 188.5 GW [1] and generates large amount of CO_2 emissions from a single-point source making CCS a potential CO_2 mitigation strategy for Indian coal power plants. Also, the per capita CO_2 emissions in India is around 1.9 t CO_2/cap which is about 60% less than global average of 4.9 t CO_2/cap [8] but contributes to about 6.24% of total CO_2 emissions globally only behind China (28.21%) and USA (15.99%) [9]. Due to the heavy reliance on monsoon-dependent agriculture and a limited technical, financial and institutional capacity, a large fraction of the population in the country is vulnerable to the impacts of climate change. As per the commitments made at the Paris Agreement (Nationally Determined Contribution, NDC), India is supposed to reduce the CO_2 emission intensity by 33–35% by 2030 from 2005 level by pursuing different mitigation strategies such as renewable energy programs, enhancing energy efficiency, and improved coal policies [10]. Although CCS technology is not a current priority for the country, it could provide a potential option for carbon mitigation.

58.2 Objectives and Scope

The quality of coal used in power plants affects the energy output, plant efficiency, choice of suitable emission control technology, and cost of electricity. This study assesses the impact of coal quality (domestic and imported coal) on emission control technologies and CCS in the Indian context.

Supercritical pulverized coal (PC) base plants using different coal characteristics were simulated using the Integrated Environmental Control Model (IECM) [11] in two categories, viz. base plant with emission control technologies (reference plant) and base plant with emission control technologies and amine-based post-combustion CO_2 capture system (CC Plant). This study only focuses on amine-based post-combustion CO_2 capture which seems a promising option in an Indian context, considering the large existing pulverized coal (PC) fleet that is available in the country and the ease with which it can be retrofitted, compared to other capture technologies. Also, there have been large-scale post-combustion CCS-based demonstration projects in Canada and the USA with more upcoming projects planned globally [12]. Oxy-fuel combustion capture is another promising technological approach; however, it is still in early stages of development. Pre-combustion capture technology through integrated gasification combined cycle (IGCC) is an attractive option as it also reduces SO_2 and NO_x emissions significantly and imposes (relatively) lower energy penalty for separation and capture of CO_2, as compared to PC plants; however, in the last few decades, total capital cost of IGCC plants (without CCS) has increased significantly more than the capital cost of supercritical PC plants (without CCS) resulting in increased levelized cost of electricity (LCOE) even after CCS [13]. Also, gasification using the high ash Indian coals is another challenge and is still under research and development [14]. Thus, considering all these factors and since supercritical PC plants with post-combustion CCS is a more mature technology compared to the other two, it was considered for modeling simulations. This work only focuses on capture and compression of CO_2 (CC) and does not take into account technical and economic viability of transportation and long-term storage (T&S) of the captured CO_2.

58.3 Methodology

For this study, coal from different parts of the country was considered, each with different calorific values and pricings. To make the power plants more economical, plants were assumed to be situated near these coal fields, thereby not considering the transportation costs. In addition to domestic coal, plants were also simulated using Indonesian coals since 55% of all imported coal in India comes from Indonesia [15]. In this case, plants were assumed to be situated near the ports. For all conversions from INR to USD, the conversion rate is assumed at 1 USD = 67.17 INR. The detailed coal characteristics considered for modeling are provided in Table 58.1.

Table 58.1 Coal characteristics considered for modeling

Coal	C (% wt)	H (% wt)	N (% wt)	S (% wt)	O (% wt)	Moisture (% wt)	Ash (% wt)	GCV (MJ/kg)	Delivered cost of coal [16]	
									($/tonne)	$/GJ
Rajmahal, [17] Jharkhand	25.1	2.95	0.5	0.17	6.7	18.5	46	10.24	18.10	1.76
Bilaspur, [18] Chhattisgarh	31	2.60	1.3	0.60	11.2	5.5	47.7	11.74	20.55	1.75
Talcher [17] Orissa	40.5	2.76	0.9	0.40	9	6.4	40	16.34	23.57	1.45
Raniganj [17] West Bengal	60.2	4.20	1.8	0.30	7.1	3.5	22.9	17.89	24.52	1.37
Indonesian [19]	58.5	4.80	1.0	0.70	12	9	14	22.99	74.44 [20]	3.23

Table 58.2 Efficiencies of emission control technologies considered for the reference plants and the carbon capture plants using various coals

Parameters	Rajmahal	Bilaspur	Talcher	Raniganj	Indonesian
Efficiencies of emission control technologies for reference plants					
ESP Efficiency (%)	99.91	99.92	99.88	99.63	99.47
SCR Efficiency (%)	89.90	89.40	86.65	80.00	79.60
FGD Efficiency (%)	82.50	95.20	91.10	80.10	92.30
Efficiencies of emission control technologies for carbon capture plants					
ESP Efficiency (%)	99.84	99.86	99.78	99.35	99.10
SCR Efficiency (%)	90.30	90.00	87.00	80.50	80.50
FGD Efficiency (%)	82.50	95.20	91.10	80.10	92.30

The cost of coal to the power plant includes the base price of coal [16], royalty rate, stowing duty, taxes and other duties and clean energy cess for the domestic coal [21], while it comprises of coal price, freight charges, taxes, and custom duty for imported coal. The reference plants and CCS plants were simulated using Integrated Environmental Control Model (IECM) [11] using the above-mentioned coal characteristics. The reference plant is assumed to be a new supercritical unit with a nominal gross capacity of 500 MW, in compliance with all the revised emission control norms for the coal plants installed after 2016 [4]. So, the reference plants were assumed to include electrostatic precipitators (ESP) to control particulate matter emissions, limestone-based flue gas desulfurization (wet FGD) to control SO_2 emissions and selective catalytic reduction (SCR) to control NO_x emissions. The efficiencies of these emission control technologies, as mentioned in Table 58.2, were adjusted such that they just meet the emission control norms of 100 mg/Nm^3 for SO_2 and NO_x emissions and 30 mg/Nm^3 for particulate matter [4] for new plants. For all plant simulations, 20% excess air is considered for complete combustion. The capacity factor of the reference plant is considered to be 75%, and plant life is considered at 30 years and debt–equity ratio of 70:30 [22]. A benchmark capital cost for supercritical PC base plant is considered at Rs. 60 million/MW [22]. The interest rate is considered at 8% and average labor rate at 1.85 $/hr [23].

The reference plants were then installed with post-combustion Econamine (FG+)^{SM}-based CO_2 capture unit with CO_2 removal efficiency assumed at 90%. In addition to CO_2 capture, pollutant removal technologies are also added to the configurations. SO_2 and NO_2 react with amine solvents to form heat-stable corrosive salts. The SO_2 concentrations therefore need to be restricted between 3 and 30 mg/Nm^3 at the inlet of the carbon capture system in order to minimize amine degradation and thus enable long-term solvent usage [24]. Wet FGD along with SO_2 polisher is used to restrict SO_2 outlet concentration to 10 ppmv (~20 mg/Nm^3) [25] before amine-based absorber.

58.4 Results

The results from simulation studies performed for both reference (ref.) plants (base plant with ESP, FGD, and SCR) and post-combustion carbon capture (CC) plants (base plant with ESP, FGD, SCR and Fluor's Econamine FG+^{SM}-based capture system) using five different coals are summarized in Table 58.3. All cost parameters are reported excluding transport and storage of captured CO_2 (excl. T&S).

The results indicate that, out of the five coals analyzed, it seems most cost-effective to install carbon capture (CC) system in plants using Talcher coal. This is because the reference plant using Talcher coal has the highest efficiency and generates the least amount of flue gas by volume compared to other plants, thereby reducing the energy consumption of the capture system. Bilaspur and Rajmahal coals have high incombustible material content (ash and moisture) in coal and thus require less amount of air for complete combustion per kg of coal as seen in Fig. 58.1, but it affects the boiler efficiency and increases the energy consumption by emission control devices, thereby reducing the overall plant efficiency. Raniganj coal has high C/O ratio and thus requires more amount of air for complete combustion, thereby increasing the volume of flue gas generated. This results in high energy consumption by emission control technologies, resulting in much larger energy penalty after CC. However, it removes the highest amount of CO_2 emissions annually. Indonesian coal has the least amount of incombustible material, which increases the amount of air required for complete combustion but incurs the least amount of auxiliary energy penalty on the plant even with and without CC which is evident from its highest net capacity generation. Though the plant has highest net electricity generation amongst the coal types analysed, its high coal price results in higher LCOE and cost of CO_2 avoided than Talcher coal.

Sensitivity analysis was also performed between Talcher coal and Indonesian coal for supercritical PC plant with CC. The variation in capacity factor of plant compared to the LCOE with and without CC and cost of CO_2 avoided is shown in Figs. 58.2 and 58.3, respectively.

The percentage variation in delivered cost of coal compared to LCOE of plant with and without CC and cost of CO_2 avoided is shown in Figs. 58.4 and 58.5, respectively.

58.5 Conclusions and Discussions

Coal selection for power generation plays a critical role toward achieving high plant efficiency, selection of appropriate emission control technologies, maximizing net electricity generation, and minimizing the cost of electricity generation. The study presented here helps us to understand the impact of coal quality while implementing carbon capture (CC) system in the new supercritical coal-fired power plants in India. The suitability of Indian coal and imported coal for implementation of CC in the

Table 58.3 Summary of simulation results for the reference plants and CC plants

Parameters	Rajmahal	Bilaspur	Talcher	Raniganj	Indonesian
Gross Capacity (MW)	500	500	500	500	500
Net Capacity ref. plant (MW)	445.1	449.2	458.6	455.8	463.1
Net Capacity CC plant (MW)	376.5	380.8	397.7	367.2	400.7
Boiler Efficiency (%)	81.57	86.76	88.61	85.30	87.31
Flue Gas flow in ref. plant (tonne/hr)	2277	2044	1857	2675	2008
Flue Gas flow in CC plant (tonne/hr)	2801	2547	2272	3585	2471
ESP Elec. Consumption in ref. plant (MW)	1.60	1.65	1.49	1.16	1.08
FGD Elec. Consumption in ref. plant (MW)	10.63	10.28	8.19	11.71	8.83
SCR Elec. Consumption in ref. plant (MW)	3.33	2.88	2.55	3.60	2.72
Total Auxiliary Consumption ref. plant (MW)	54.9	50.8	41.4	44.2	36.9
ESP Elec. Consumption in CC plant (MW)	1.39	1.44	1.29	1.03	0.97
FGD Elec. Consumption in CC plant (MW)	12.94	12.78	10	15.63	10.85
SCR Elec. Consumption in CC plant (MW)	4.05	3.55	3.11	4.79	3.33
CC system elec. consumption (MW)	51.38	51.90	46.74	72.05	49.13
Total auxiliary consumption CC plant (MW)	123.5	119.2	102.3	132.8	99.3
Net plant efficiency of ref. plant (%)	33.67	36.15	37.68	36.06	37.50
Net plant efficiency of CC plant (%)	23.15	24.59	26.71	21.67	26.36
Coal flow rate ref. plant (kg/s)	128.97	105.97	74.38	70.58	53.66
Coal flow rate CC plant (kg/s)	158.66	132	91	94.61	66.05
Conc. Of CO_2 in flue gas (% vol)	12.19	14.25	14.48	14.18	13.86
CO_2 emission rate of ref. plant (kg/MWh net)	960	971.72	870.69	1231.68	898.07
CO_2 emission rate of CC plant (kg/MWh net)	139.60	149.97	122.85	204.85	127.70
Annual CO_2 removed (million tonnes/yr)	3.11	3.2	2.89	4.45	3.02
LCOE of ref. plant ($/MWh)	61	58.02	47.74	46.34	60.34

(continued)

Table 58.3 (continued)

Parameters	Rajmahal	Bilaspur	Talcher	Raniganj	Indonesian
LCOE with CC plant($/MWh)	113.6	109.2	88.77	111.2	108.1
Cost of CO_2 avoided excl. T&S ($/tonne)	64.11	62.28	54.86	63.16	62

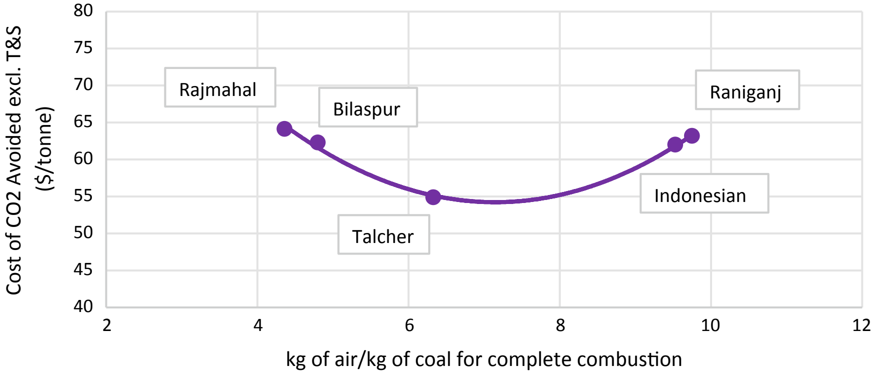

Fig. 58.1 Cost of CO_2 avoided excl. T&S ($/tonne) versus input air for complete combustion per kg of coal

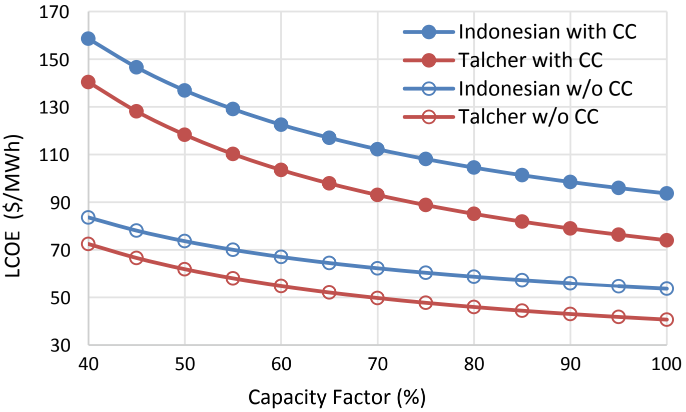

Fig. 58.2 Variation in LCOE with and without CC ($/MWh) to variation in capacity factor (%)

country was assessed in terms of net capacity, flue gas volume, boiler efficiency, net plant efficiency, CO_2 emission rate, LCOE, and cost of CO_2 avoided. It can be seen that increase in flue gas volume results in a significant increase in energy penalty on the plant. Thus, it would be more economical to install post-combustion capture

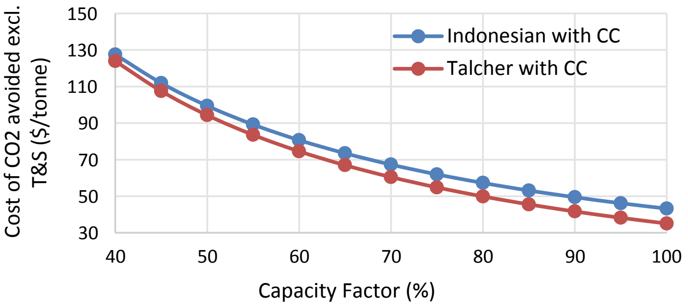

Fig. 58.3 Cost of CO_2 avoided excl. T&S ($/tonne) vs. capacity factor (%)

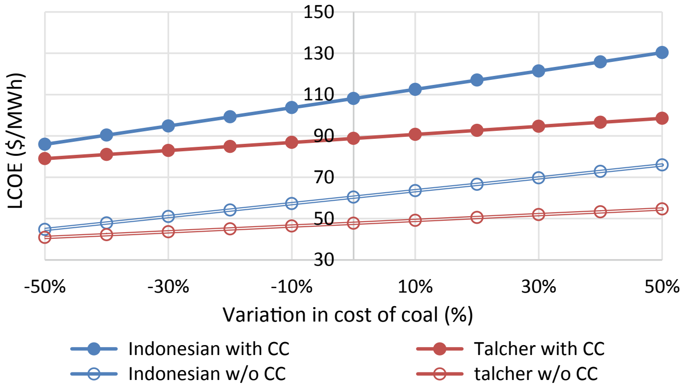

Fig. 58.4 Variation in LCOE with and w/o CC ($/MWh) due to variation in delivered cost of coal

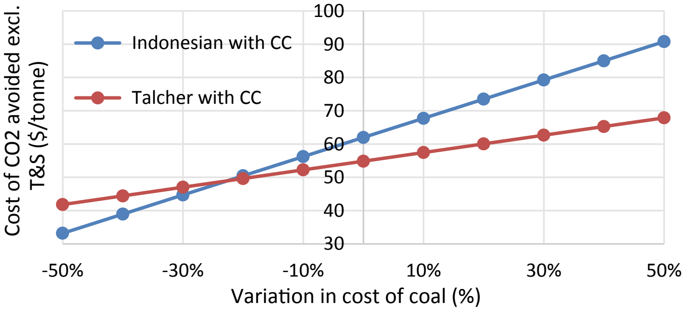

Fig. 58.5 Cost of CO_2 avoided excl. T&S($/tonne) versus variation in delivered cost of coal

technology in plants which have higher CO_2 concentration in flue gas and lower flue gas volume.

Coal with high C/O ratio and with low ash and moisture content found in West Bengal and Jharkhand generates higher flue gas volume, due to higher percentage of oxygen required for complete combustion, and thereby more CO_2 emissions; however, installing capture system in plants using these coals will further drastically reduce their net generation and efficiency. Implementing carbon capture in plants using coal with moderate C/O ratio, ash and moisture content like Talcher seems most cost-effective but these plants are already efficient in terms of CO_2 emissions as they generate the least amount of CO_2 emissions per MWh of electricity production. Furthermore, although efficient, the implementation of carbon capture in these plants will reduce their efficiencies by about 11 percentage points and will only avoid 2.89 million tonnes of CO_2 annually which is much lower compared to other plants. Implementing CC in plants using imported coal provides the best advantage in terms of net energy generation due to their high calorific value and low ash content; however, their fluctuating prices will impact the feasibility of such projects. Plants using low calorific value, high ash coal like Rajmahal and Bilaspur have higher energy consumption by emission control devices and lower boiler efficiencies which affect their overall efficiency. Thus, before the implementation of carbon capture, quality of coal along with plant characteristics should be carefully analyzed.

Carbon capture system has a co-benefit of reducing particulate emissions which is evident from lower efficiencies of ESP for similar emissions by volume; however, due to increased coal consumption, it requires more efficient SCR systems to maintain similar NO_x emissions as that of reference plants. It needs to be studied how beneficiation of high ash coal will have an impact on CCS plants. Also, more such studies using different varieties of coal are required to establish much clear trends.

The cost of coal, which is determined based on the coal quality, plays a significant role in the implementation of CCS. India has levied cess on coal, lignite, and peat produced and imported into India. Currently, this clean energy cess stands at Rs. 400/tonne [26]. With the implementation of clean energy cess, the cost of CCS will increase substantially. Without certain policy initiatives such as exemption of clean energy cess for plants with CCS or enforcement of suitable carbon tax/penalties, the implementation of CCS in Indian power plants seems an uphill task.

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