# $CO_2$ Capture and Storage in Coal Gasification Projects

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**Abstract**. In response to the global climate change problem, the world community today is in search for an effective means of carbon mitigation. India is a major developing economy and the economic growth is driven by ever-increasing consumption of energy. Coal is the only fossil fuel that is available in abundance in India and contributes to the major share of the total primary energy supply (TPES) in the country. Owing to the large unmet demand for affordable energy, primarily driven by the need for infrastructure development and increasing incomes and aspirations of people, as well as the energy security concerns, India is expected to have continued dependence on coal. Coal is not only the backbone of the electric power generation, but many major industries like cement, iron and steel, bricks, fertilizers also consume large quantities of coal. India has very low carbon emissions (~ 1.5 $tCO_2$ per capita) as compared to the world average (4.7 $tCO_2$ per capita) and the developed world (11.2 $tCO_2$ per capita). Although the aggregate emissions of the country are increasing with the rising population and fossil energy use, India has a very little contribution to the historical GHG accumulation in the atmosphere linked to the climate change problem. However, a large fraction of the Indian society is vulnerable to the impacts of climate change – due to its geographical location, large dependence on monsoon-based agriculture and limited technical, financial and institutional capacity. Today, India holds a large potential to offer cost-effective carbon mitigation to tackle the climate change problem. Carbon Capture and Storage (CCS) is the process of extraction of Carbon Dioxide ($CO_2$) from industrial and energy related sources, transport to storage locations and long-term isolation from the atmosphere. It is a technology that has been developed in recent times and is considered as a bridging technology as we move towards carbon-neutral energy sources in response to the growing concerns about climate change problem. Carbon Capture and Storage (CCS) is being considered as a promising carbon mitigation technology, especially for large point sources such as coal power plants. Gasification of coal helps in better utilization of this resource offering multiple advantages such as pollution prevention, product flexibility (syngas and hydrogen) and higher efficiency (combined cycle). It also enables the capture of $CO_2$ prior to the combustion, from the fuel gas mixture, at relatively lesser cost as compared to the post-combustion $CO_2$ capture. CCS in gasification projects is considered as a promising technology for cost-effective carbon mitigation. Although many projects (power and non-power) have been announced internationally, very few large-scale projects have actually

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come up. This paper looks at the various aspects of CCS applications in gasification projects, including the technical feasibility and economic viability and discusses an Indian perspective. Impacts of including CCS in gasification projects (e.g. IGCC plants) have been assessed using a simulation tool. Integrated Environmental Control Model (IECM) – a modelling framework to simulate power plants - has been used to estimate the implications of adding CCS units in IGCC plants, on their performance and costs.

## 1. Introduction

Close to one third of the population in India has no access to reliable electricity. The per capita annual energy consumption in India is ~ 1075 kWh [1] whereas the global average is ~ 3200 kWh [2]. The required electricity is presently being supplied by coal, natural gas, hydro, nuclear power, and renewable energy, with coal contributing to about 60% [1]. Table 1 provides a snapshot about current installed capacity in the country as of 31st Dec 2016.

**Table 1.** Total installed capacity in India as of 31st Dec 2016 [1]

| Energy Source | Installed Capacity (MW) | % of Total |
|---|---|---|
| Coal | 188,968 | 60.0% |
| Gas | 25,282 | 8.2% |
| Oil | 919 | 0.3% |
| Hydro | 43,139 | 13.9% |
| Nuclear | 5,780 | 1.9% |
| Renewable Energy Sources* | 45,917 | 14.8% |
| **Total** | **310,005** | **100%** |

*Renewable Energy Sources include small hydro project, biomass, waste to electricity, wind energy, solar (PV + thermal)

As per the NITI Ayog report [3], coal is expected to continue to be a major energy source in India for the next few decades due to the large demand of energy requirement of the economy, and adequate availability of coal. India has substantial reserves of low sulfur, low grade (high ash) coal, which provides a reliable, cheap baseload power. But the coal-based thermal power industry is responsible for significant share of emissions of the industrial sector in India. Main emissions from coal fired thermal power plants are $CO_2$, $NO_x$, $SO_2$, and fly ash [4]. Between 2001-02 to 2009-10, emissions from coal power plants have increased by 4.9% for $CO_2$, 4.7% for $SO_2$ and 4.9% for $NO_x$ measured in CAGR (compounded annual growth rate) [4]. Recognizing these worrying trends, several countries have imposed emission control norms for coal power plants. In India, the Ministry of Environment, Forest & Climate Change (MoEF&CC), in December 2015, announced more stringent emission control standards for coal-based thermal power plants in order to drastically reduce emissions of particulate matter (PM), sulfur dioxide ($SO_2$), oxides of nitrogen ($NO_x$). However, $CO_2$ emissions from coal power plants in India are currently unregulated. Coal power plants have the highest density of $CO_2$ emissions when normalized per unit area and unit time [5]. Recognizing that $CO_2$, a major greenhouse gas responsible for climate change, countries like Canada, US, UK have already imposed $CO_2$ emission standards for coal power plants [6]. Thus, for climate change mitigation while continuing the use of fossil fuels, a special attention needs to be given to the reduction of $CO_2$ emissions by capture and storage (CCS) techniques applied to power generation and other energy intensive industrial sectors (cement, metallurgy, oil refinery etc.) [7].

Carbon capture and storage or carbon capture and sequestration (CCS) involves capture and separation of $CO_2$ as a concentrated stream for subsequent transport and storage. Thus, the concept of carbon capture and sequestration (CCS) can be divided into three major steps namely: $CO_2$ capture, transport and storage. The separation stage (i.e. $CO_2$ capture) is the most energy intensive and largely determines the cost of the CCS as a whole. It represents ~ 75–80% of the total cost of CCS [8]. The three potential technology options which have a potential to handle $CO_2$ emissions from large-scale

point sources, such as the fossil fuel based power plants are: a) Post-combustion capture of $CO_2$ from the flue gas, b) Pre-combustion capture of $CO_2$ from the fuel gas, and c) Oxyfuel combustion for $CO_2$ capture [9]. Subsequently, the captured $CO_2$ is then transported using pipelines, ships, trucks and trains to suitable storage sites. There are broadly three ways of sequestering $CO_2$: geological storage, ocean and mineral fixation.

Most available CCS technologies capture about 85–95% of the $CO_2$ processed in a capture plant. A power plant equipped with a CCS system (with access to storage) would need roughly 10–40% more energy than a plant of equivalent output without CCS, of which most is for capture and compression. With secure storage, the net result is that a power plant with CCS could reduce $CO_2$ emissions from power plant to the atmosphere by approximately 80–90% compared to a plant without CCS [8]. Thus, CCS can be a key tool in tackling climate change and would become an unavoidable option if we are to ensure that we can meet the increasing electricity demand with an acceptable carbon footprint.

Post-combustion capture of $CO_2$ from the flue gas is employed in case of conventional power plants. However, before implementation of CCS, these power plants also require other emission control technologies for stringent $SO_2$ and $NO_x$ control. This further adds to the cost of electricity.

An alternative technology to generate power from coal is through the gasification process. Here, the coal is converted into a gaseous mixture (syngas) in a gasifier, which is then subjected to a gas turbine to generate electricity. Additional power is generated from a steam turbine using steam generated from the het recovered from the flue gases of the gas turbine. It is possible to undertake pre-combustion capture of $CO_2$ from this "Integrated Gasification Combined Cycle (IGCC) plant" where $CO_2$ can be separated from syngas at a much lower energy penalty, also resulting in much lower emissions of conventional pollutants as compared to the conventional power plants. In this paper, we focus on this advanced coal technology and the feasibility of pre-combustion capture of $CO_2$ in terms of performance, emissions, capital cost and levilised cost of electricity (LCOE).

## 2. CCS in Coal Gasification Projects

Integrated Gasification Combined Cycle (IGCC) is emerging as a promising technology to utilize low quality or contaminated energy resources such as coal. It is a technology that uses a high-pressure gasifier to turn coal and other carbon based fuels into pressurized gas—synthesis gas (syngas) and can then remove impurities from the syngas prior to the power generation cycle. This results in lower emissions of $SO_2$, particulates, mercury, and even $CO_2$. Thus, by integrating CCS with IGCC plants, drastic $CO_2$ emission reductions (81-91%) can be achieved [8]. The schematic of a typical IGCC plant with CCS has been shown in Figure 1.

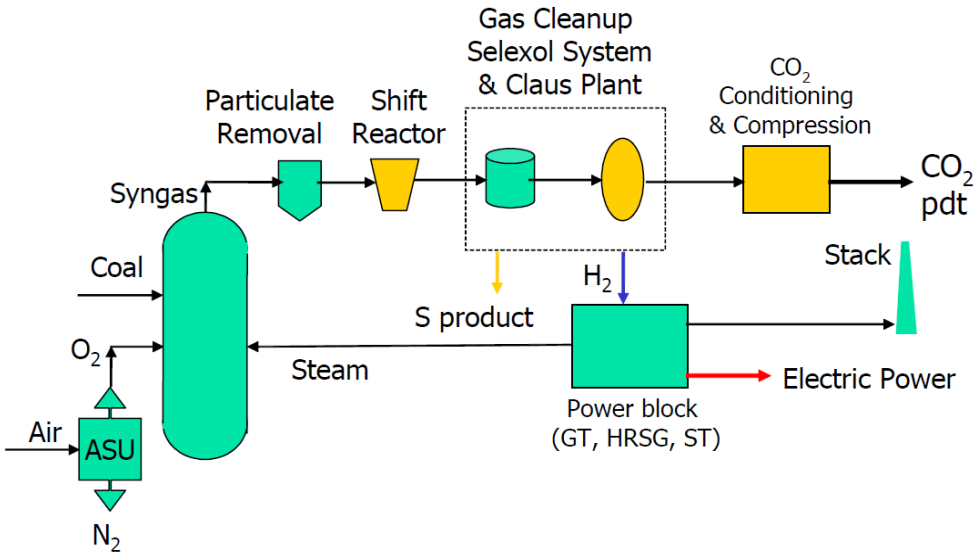



**Figure 1.** Schematic of IGCC Plant with CCS [9]

Initially, coal is fed into a high-pressure vessel called gasifier with controlled quantity of oxygen (or air) and steam (or water) to produce hot syngas. This hot syngas is then cooled and filtered to remove particulate matter. The heat extracted is used to generate high-pressure steam. The sour water gas shift (WGS) reaction is a key conversion step in the IGCC-CCS process in which carbon monoxide (CO) produced by the gasification of the fuel is reacted with steam to produce additional hydrogen and $CO_2$ in the presence of $H_2S$ [9, 10]. The resulting acid gas stream consisting of $H_2S$, $CO_2$ and $H_2O$ is sent to the Selexol$^{TM}$ system and Claus unit where $H_2S$ is recovered as elemental sulfur, which is a valuable byproduct. Most of the $CO_2$ in the flue gas stream is then recovered, compressed, transported and sequestered.

*2.1 Advantages of IGCC with CCS*

1. Less pollution: Significant reduction in emission of criteria air pollutants ($SO_2$ and $NO_x$) compared to Pulverized Coal (PC) boilers.
2. Lower energy penalty: Typically, the syngas is obtained at high pressure with substantial $CO_2$ content and hence, less energy required for the separation and capture of $CO_2$ from the syngas.
3. Multi-product flexibility: Hydrogen ($H_2$) can be consumed in the gas turbine to generate power, or as a valuable chemical agent with a great variety of industrial applications.
4. Valuable byproducts: Sulfur (almost all the sulfur in the coal can be recovered), Nitrogen (from the air separation unit) and $CO_2$ (from the $CO_2$ capture unit) are also obtained as byproducts [9].

*2.2 Disadvantages of IGCC with CCS:*

1. Gasification is a complicated chemical process and not many IGCC plants exist around the globe. For a given coal, the resulting product (syngas) depends on fine-tuning of a variety of control parameters including the gasifier design, the gasifier temperature and pressure, and the amount of steam and air/ oxygen input.
2. Uncertainty about the capture ready status of IGCC plants with CCS for Indian scenarios. Pilot projects in Indian context required. Also, compared to post-combustion capture, it is not easy to retrofit an existing IGCC plant to accommodate $CO_2$ capture unit, since it will affect the power generation from the turbines.
3. Uncertainty about use of low quality coals for IGCC plants with CCS.
4. Need for a large-scale demonstration project to establish the commercial viability of the technology
5. Higher capital cost of IGCC plants compared to PC plants, lack of experience of CCS, lack of accurate estimation of storage potential and the perceived financial risk [9].

## 3. Current Global Status of Gasification based $CO_2$ Capture

Table 2 lists some of the gasification projects that are operational/under construction/under evaluation globally which employ pre-combustion (gasification) $CO_2$ capture & storage.

**Table 2.** Some of the gasification projects that are operational/under construction/under evaluation globally which employ Pre-combustion (gasification) $CO_2$ capture & storage [11]

| Project name | Location | Purpose | $CO_2$ Capture Start | Capture capacity (Mtpa) | Transport type | Primary storage type |
|---|---|---|---|---|---|---|
| Great Plains Synfuel Plant and Weyburn-Midale Project | Canada | Production of natural gas and other by-products | 2000 | 3.0 | Pipeline | Enhanced oil recovery |

| | | | | | | |
|---|---|---|---|---|---|---|
| Kemper County Energy Facility | Mississippi, United States | Power Generation | 2017 | 3.0 | Pipeline | Enhanced oil recovery |
| Yanchang Integrated Carbon Capture and Storage Demonstration Project | China | Chemical Production | 2018 | 0.4 | Pipeline | Enhanced oil recovery |
| Texas Clean Energy Project | Texas, United States | Power Generation | 2021 (estimate) | 2.4 | Pipeline | Enhanced oil recovery |
| Huaneng GreenGen IGCC Project (Phase 3) | China | Power Generation | 2020's (planned) | 2.0 | Pipeline | Enhanced oil recovery |
| Caledonia Clean Energy Project | United Kingdom | Power Generation | 2022 (planned) | 3.8 | Pipeline | Dedicated Geological Storage |
| Coffeyville Gasification Plant | Kansas, United States | Fertiliser production | 2013 | 1 | Pipeline | Enhanced oil recovery |

Out of these projects, Kemper county energy facility is the only large scale IGCC+CCS project for electric power generation, which is expected to start $CO_2$ capture soon. A 582 MW plant using TRIG™ Integrated Gasification Combined Cycle is set to capture at least 65% of $CO_2$ emissions and use it for enhanced oil recovery by sequestering it in Mississippi oil fields, Mississippi. The total cost of the project, designed to generate electricity from burning 4.5 million tonnes of Mississippi lignite coal per year, is around $7.1 billion [11, 12].

## 4. Plant Simulations

The impact of integrating CCS in an IGCC plant has been demonstrated here through a case study simulation. Using Integrated Environmental Control Model (IECM) – a modelling framework to simulate power plants [13], we simulated an IGCC plant with and without CCS. Plants are simulated using both bituminous and sub-bituminous coal, whose composition is provided in Table 3.

**Table 3.** Characteristics of Coals considered for the Case Study

| **Bituminous Coal** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Moisture | | Ash | | C | H | N | S | O | HHV (MJ/kg) |
| 11.12 | | 9.70 | | 63.75 | 4.50 | 1.25 | 2.51 | 6.88 | 27.14 |
| **Ash Analysis (wt. %)** | | | | | | | | | |
| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | $P_2O_5$ | $TiO_2$ | CaO | $K_2O$ | $Na_2O$ | MgO | $SO_3$ |
| 46.80 | 18.00 | 20.00 | 0.20 | 1.00 | 7.00 | 1.90 | 0.60 | 1.00 | 3.50 |
| **Sub-Bituminous Coal** | | | | | | | | | |
| Moisture | | Ash | | C | H | N | S | O | HHV (MJ/kg) |
| 30.24 | | 5.32 | | 48.18 | 3.31 | 0.70 | 0.37 | 11.87 | 19.40 |
| **Ash Analysis (wt. %)** | | | | | | | | | |
| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | $P_2O_5$ | $TiO_2$ | CaO | $K_2O$ | $Na_2O$ | MgO | $SO_3$ |
| 63.19 | 30.00 | 2.90 | 0.08 | 0.09 | 0.91 | 1.49 | 0.38 | 0.76 | 0.20 |

The details about the plant configurations and some key input parameters used in IECM simulations are listed in Table 4.

**Table 4.** Configuration of IGCC plant with and without CCS

| **Parameters** | **IGCC** | **IGCC + CCS** | **IGCC** | **IGCC + CCS** |
|---|---|---|---|---|
| Gross Capacity (MW) | 724.3 | 690.3 | 748.5 | 691.4 |
| Coal | Bituminous | | Sub-Bituminous | |
| Capacity Factor (%) | 75 | | | |
| Gasifier Temperature (°C) | 1343 | | | |
| Gasifier Pressure (Mpa) | 4.24 | | | |
| Turbine Inlet Temperature (°C) | 1371 | | | |
| Cost of Fuel ($/tonne) | 42.09 | | 9.64 | |
| Annual operating hours (hours) | 6575 | | | |
| $H_2S$ Control | Selexol™ | | | |
| $H_2S$ Removal Efficiency (%) | 98 | | | |
| Plant Life (years) | 30 | | | |
| $CO_2$ Capture | - | Sour Shift + Selexol™ | - | Sour Shift + Selexol™ |

The composition of the syngas obtained from the gasifier after the gasification of coal and the performance and cost results have been provided in Table 5 and Table 6, respectively.

**Table 5.** Syngas composition obtained from gasifier

| **Syngas composition obtained using bituminous coal** | | | | | | | |
|---|---|---|---|---|---|---|---|
| CO | $H_2$ | $CH_4$ | $H_2S$ | $CO_2$ | $H_2O$ | $N_2$ | Ar |
| 30.64 | 32.92 | 0.26 | 0.97 | 18.52 | 14.86 | 0.86 | 0.87 |
| **Syngas composition obtained using sub-bituminous coal** | | | | | | | |
| CO | $H_2$ | $CH_4$ | $H_2S$ | $CO_2$ | $H_2O$ | $N_2$ | Ar |
| 22.66 | 31.06 | 0.10 | 0.12 | 22.01 | 22.53 | 0.69 | 0.79 |

**Table 6.** Simulation Results for IGCC plant with and without CCS

| **Parameters** | **IGCC** | **IGCC + CCS** | **IGCC** | **IGCC + CCS** |
|---|---|---|---|---|
| Net Capacity (MW) | 609.0 | 529.7 | 620.0 | 513.3 |
| Gross Capacity (MW) | 724.3 | 690.3 | 748.5 | 691.4 |
| Coal Type | Bituminous | | Sub-Bituminous | |
| Cost of Fuel ($/tonne) | 42.09 | | 9.64 | |
| Cost of Fuel ($/MJ) | 1551 | | 497.20 | |
| Gross Plant Heat Rate, (kJ/kWh) | 9247 | 10130 | 9448 | 10370 |
| Net Plant Heat Rate, (kJ/kWh) | 10990 | 13200 | 11410 | 13970 |
| Net Plant efficiency (%) | 32.73 | 27.27 | 31.56 | 25.78 |
| Coal Flow Rate (kg/s) | 68.55 | 71.58 | 101.27 | 102.66 |
| Total Makeup Water Requirement ($m^3$/MWh) | 1.55 | 1.76 | 1.55 | 1.81 |
| **Emissions** | | | | |
| $CO_2$ emission (kg/$MWh_{net}$) | 918.39 | 93.10 | 1006.93 | 94.07 |
| $SO_2$ emission (kg/$MWh_{net}$) | 0.57 | 0.07 | 0.09 | 0.01 |
| $NO_x$ emission (kg/$MWh_{net}$) | 0.05 | 0.06 | 0.05 | 0.06 |
| Particulate emission (kg/$MWh_{net}$) | 0.004 | 0.005 | 0.004 | 0.006 |
| **Cost (in 2014 USD)** | | | | |
| Total Capital Cost (M$) | 1643 | 2177 | 1709 | 2259 |
| Fixed O&M M$/year | 52.90 | 73.08 | 55.26 | 76.83 |
| Variable O&M M$/year | 74.91 | 94.09 | 32.21 | 49.50 |
| LCOE ($/MWh) | 78.21 | 118.5 | 68.75 | 112.9 |
| $CO_2$ Avoidance Cost ($/tonne) | - | 49.30 | - | 48.73 |

It can be seen that it is difficult to keep the same power output of the IGCC plant, if CCS is incorporated. Using CCS, the $CO_2$ emissions from the IGCC plants can be reduced by about 90% as compared to that of the IGCC plant without CCS. However, the levelised cost of electricity (LCOE) increases by about 51% for the bituminous coal case and to about 64% for the sub-bituminous coal case. Thus, CCS can substantially reduce the $CO_2$ emissions though it is significantly expensive at present.

## 5. Barriers and Issues Related to CCS

CCS is still in developmental stages globally and following are some of the main barriers in adoption of this technology [14]:

1. Technical Issues: Worldwide still there aren't many large scale successful CCS projects and thus on-field experience is still lacking with this technology. There is a lack of accurate geological storage site data and depending upon the location and plant size, feasibility studies are required. Also, there is no clarity about the feasibility of CCS retrofits for the existing plants, especially in case of IGCC plants.
2. Economic Issues: CCS technology drastically increases the levelised cost of electricity and also decreases the net plant output. Enhanced Oil Recovery (EOR) is currently the only attractive option for $CO_2$ storage, since the cost of storing the $CO_2$ is (partly) offset by the revenues accrued by oil recovered from the depleted/depleting oil fields. Access to funding from financing agencies and incentives are required.
3. Social Issues: Public acceptability of CCS is not yet understood.
4. Monitoring Issues: There is a risk of slow/accidental leakages of $CO_2$ to atmosphere. This poses a further environmental, health and safety risk. Rigorous monitoring is needed over long period of time.
5. Legal Issues: Issues related to land acquisition, ground water contamination, $CO_2$ leakages and long term liabilities need to be resolved.
6. Regulatory and Strategic Issues: Specific clearances would be required in addition to existing clearances and a smooth regulatory framework would be required.

## 6. Conclusion

CCS is a potential mitigation option to tackle global climate change problem, but it needs to overcome several barriers/challenges. The key challenges are technical feasibility, assessment of storage potential, scale up of technology, economic viability, public acceptance and monitoring issues. Pilot plants as well as demonstration projects are now under development across many countries. IGCC plant with CCS 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 combustion plants. However, the technology is yet to be demonstrated at the full scale. Gasification using the high ash containing coals in India is a challenge [15]. The issue of CCS drastically increasing the cost of electricity while reducing net power output poses the biggest barrier to acceptability of CCS in India [13]. Our priorities as a developing country - towards improving efficiency, reducing costs and increasing electricity accessibility - are in odds with that of the expected impacts of CCS implementation. However, R&D in CCS need to continue in search for more acceptable solution so as prepare ourselves for the future.

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**Acknowledgements**
The authors are grateful to the GTWG-ACT project of the Department of Science and Technology (DST), Government of India, for financial support. Authors also thank the IECM team at the Carnegie Mellon University, USA, for making the tool freely available.