Performance, cost and environmental assessment of gasification-based electricity in India: A preliminary analysis

Abha Rani¹*, Udayan Singh², Jayant¹, Ajay K Singh⁴, Siba Sankar Mahapatra²

¹ Department of Applied Mathematics, Indian Institute of Technology (Indian School of Mines), Dhanbad, INDIA
² Department of Mechanical Engineering, National Institute of Technology Rourkela, Rourkela, INDIA
³ Department of Chemical Engineering, Manipal Institute of Technology, Manipal, INDIA
⁴ CSIR-Central Institute of Mining and Fuel Research, Dhanbad, INDIA

* Corresponding Author. Email: ajayabha@yahoo.com

Abstract. Coal gasification processes are crucial to decarbonisation in the power sector. While underground coal gasification (UCG) and integrated gasification combined cycle (IGCC) are different in terms of the site of gasification, they have considerable similarities in terms of the types of gasifiers used. Of course, UCG offers some additional advantages such as reduction of the fugitive methane emissions accompanying the coal mining process. Nevertheless, simulation of IGCC plants involving surface coal gasification is likely to give reasonable indication of the 3E (efficiency, economics and emissions) prospects of the gasification pathway towards electricity. This paper will aim at Estimating 3E impacts (efficiency, environment, economics) of gasification processes using simulation carried out in the Integrated Environmental Control Model (IECM) software framework. Key plant level controls which will be studied in this paper will be based on Indian financial regulations and operating costs which are specific to the country. Also, impacts of CO₂ capture and storage (CCS) in these plants will be studied. The various parameters that can be studied are plant load factor, impact of coal quality and price, type of CO₂ capture process, capital costs etc. It is hoped that relevant insights into electricity generation from gasification may be obtained with this paper.

1. Introduction

Coal is the mainstay of the Indian power sector. While the net installed capacity of India’s power sector is more than 315 GW, around 60 percent is from the coal-fired power plants [1]. The dominance of coal has prevailed since independence and has strengthened over various five year plan (FYP) periods. The installed capacity within the coal sector has seen a seventy times increase between the end of the 11th FYP and the 1st FYP [2]. This surge has resulted in large-scale electrification for the cities and villages of the country. Coal production has also been enhanced and it is envisaged to increase the production by Coal India Ltd to 1 billion tonnes by 2019-20 [3]. While increases in coal production as well as power generation are planned and projected, sustainability in the power sector also needs to be targeted.

It should be noted that the power sector is the key contributor to greenhouse gas (GHG) emissions from India. India’s total CO₂ emissions (without LULUCF) in 2010 were about 1575 Tg, out of which 815 Tg were from power sector itself [4]. It has also been reported that significant SO₂, NOₓ and PM
pollution also results from power plants in India. The power sector thus has an important role to play in the reduction of gaseous and particulate local air pollutants. A number of key initiatives are being undertaken in this regard with active support of the Government of India. These include retirement of old and inefficient units, renovation and modernization (R&M), installation of supercritical units, and so on.

Globally, a key segment of clean coal initiatives is gasification of coal. Gasification leads to a reduction of emissions and the power generation is considered to be superior to that from pulverized coal power plants. In this paper, a highlight of various Indian works based on coal gasification shall be presented. A discussion on the current and future trajectory of use for coal and natural gas in India has also been undertaken.

1.1. Objectives and scope of this paper

This paper begins with a review of the prior work done on plant-level analysis for coal gasification, specifically in the Indian context. A background of the role of India’s emerging energy options vis-à-vis coal and natural gas are also covered. Subsequently, we adopt a simulation based approach to estimate the cost of electricity, atmospheric emission and net plant efficiency for plants employing coal gasification. The performance of such plants is compared to the plants employing pulverized coal-firing plants. The impact of CO₂ capture on gasification based plants has been studied in details. A parametric analysis of the various factors involved to aim at cost reduction has been performed.

It should be noted here that this is a simulation-based analysis focusing only upon the power plant, and therefore no discussion has been made regarding the mining of coal or its in-situ gasification. The paper is therefore just an indicative analysis for the feasibility of coal gasification and significant improvements may be made to the analysis. Further, the analysis has been done only for north-eastern (tertiary coal).

2. India’s coal sector: an overview

A large part of India’s primary energy consumption as well as power requirements is contributed to by the combustion of coal. Coal and lignite reserves in the country stand at a total of more than 350 billion tons. The annual production of coal in 2015-16 was about 640 million tons, but recently the Indian coal giant, Coal India Limited envisaged production of 1 billion tones by the end of the decade. Coal is responsible more meeting of more than 70 percent of primary energy demands [5].

On the supply side, coal has seen a significant increase in terms of the net installed capacity of coal-fired power plants. From an installed capacity of ~750 MW at the installed capacity at the time of independence, an increase of more than 250 times has been seen [2]. The growth has resulted in considerable success in terms of India’s developmental objectives. With the indication of the power ministry indicating that India is now a power-surplus nation, a transition towards a developed country will require affordable, adequate and sustainable electricity for all. Most modelling studies suggest that this will be accompanied by a further growth of coal-based electricity generating units (EGUs) [6, 7]. Shukla et al [8] project that in a business-as-usual (BAU) scenario; coal will remain the mainstay of India’s electricity sector upto 2100. They also project that coal will dominate the solid fuels mix, but its share may decrease over time due to climatic targets.

Multiple modelling studies have during the past decade forecasted the trend of coal production in the future. Patzek and Croft [9] have suggested that coal production is nearing its peak globally (also in India) and will reach its peak production in 2011, in terms of energy production. On the basis of multi-Hubbert cycle analysis, they have suggested that the annual peak of CO₂ emissions from coal use shall be 1.2 Gt/year. Mohr and Evans [10] have forecasted that coal production upto 2100. They project that bituminous coal production will peak in 2046 (at about 900 Mt/year). Similarly, lignite production has been projected to peak in the year 2010 at about 40 Mt/year. An interesting point to note here is that while the bituminous peak coal production has been predicted to be less than 900 Mt annually, CIL already intends to produce more than a billion tons of coal by 2020. Thus, the
projections for coal production are highly dynamic and largely dependent upon energy demands in the country.

![World coal production in standard outlook](image1)

**Figure 1.** Standard case outlook for future global coal production. 
Source: Ref. [11]

![World coal production in high case outlook](image2)

**Figure 2.** Even if the world’s coal reserves are twice as large as reported this does not postpone the peak in production more than two decades. Source: Ref. [11]

In another similar work, Höök et al [11] have projected that the current leading producers of coal shall retain the driving seat in the future as well. Figures 1 and 2 show global coal production in the upcoming years in the standard and high-production outlooks. The projection suggests that while Chinese coal production will drastically reduce near 2050-2060, Indian and Australian coal production will remain more or less steady at least up to 2070. Thus, it can be seen that different researchers have given widely varying estimates of coal production and peaking for India. A key facet of how long coal can be continued to be used is very much dependent upon the degree of sustainability built-in with the technology of coal usage. The unconventional gas based industry (mostly, coalbed methane (CBM) and underground coal gasification (UCG)) will play a key role in the decarbonization of coal industry, which will permit long-term use of coal even in midst of stringent climatic targets.

Similarly, the implementation of CO₂ capture and storage (CCS) technologies will play a key role in ensuring coal-based energy security for India in the long term [6]. Researchers have given their estimates on the role CCS may play in the decarbonization of the Indian power sector. Shukla et al [12] suggest that there may be two possible means towards reduction of overall power sector carbon intensity. One may be through an increased carbon tax (conventional pathway) having significant reliance upon CO₂ sequestration, while the other (sustainable pathway) will focus mostly on the increased deployment of renewable power. Singh et al [13] attempted to quantify the monetary
benefits associated with CCS in a high carbon price scenario. They projected in an CCS-intensive scenario with high carbon tax, the monetary benefits of CCS would be of the order of US$ 1.2-1.5 trillion to avoid 11,000 Mt-CO₂ over the years 2030-2050. Nevertheless, significant challenges remain for installation of CO₂ capture units in India. Singh and Rao [14] have estimated a cost of avoidance of US$ 60-85/t-CO₂ if the technology is to be utilized. Also, as Singh et al [15] have pointed out, some societal perspectives see CCS as a technology which does more harm than good. Therefore, a dedicated effort needs to be put in to reduce energy penalty and costs with the technology before it reaches anywhere close to commercialization. One possible way can be with gasification of tertiary northeastern coals, and also of lignite in Rajasthan and Gujarat. This route will be studied in this paper.

3. Coal gasification: previous studies

Initial efforts towards coal gasification started in the erstwhile Central Fuel Research Institute [16]. Krishnudu et al [17, 18] performed studies on a moving bed gasifier for Indian coals. They delineated three zones (fast devolatilization, slow devolatilization with gasification and gasification) in the gasifier for studies based on low-rank coal. They also concluded that one-third of the bed height was utilized for gasification and the rest for devolatilization. Similarly, in a parametric study to determine the effect of pressure variation on three south Indian coals. They estimated the gas yield of the order of 1.4-1.7 m₃/kg-coal. Iyengar and Haque [19] demonstrated the loss of efficiency with increase in ash content. Chatterjee et al [20] also carried out simulation and experimental work on laboratory scale and showed a significant degree of correlation between the same.

With developed numerical investigation techniques, many researchers have tried to simulate coal gasification processes. Ajilkumar et al [21] modelled entrained lab-scale gasifier using Fluent software. They predicted carbon conversion, gas heating value and cold gas efficiency with reasonable accuracy. Ajilkumar et al [22] also simulated tubular gasifier and observed strong decrease in performance with rise in ash content. Singh et al [23] tried to understand the effect of coal properties on gasification. They found that high carbon content and low ash content were instrumental for good performance of gasifier. Singh et al [24] carried out further analysis for optimum performance of the gasifier. They suggested that steam-to-coal ratio of 0.4 and 1.5 for optimal for air-based and oxygen-based systems.

Datta et al [25] attempted to study the agglomeration behaviour of Indian coals. They found that agglomeration was found at temperature close to 950°C and ash fusion temperature was above 1200°C. They concluded that compositional variations and Fe²⁺ presence led to the agglomeration. Chavan et al [26] developed multivariate variations and Fe²⁺ presence led to the agglomeration. Chavan et al [26] developed multivariate regression (MVR) and artificial neural network (ANN) models to predict outputs from fluidized bed gasifiers under steady state condition. Patil-Shinde used ANN along with genetic programming to predict the amount and quality of syngas produced [27].

Some studies have also been carried out for underground coal gasification in India. Laboratory studies on cavity growth were performed by Daggupati et al [28]. They also attempted to study product gas composition in Indian context [29]. Mandapati et al [30] further approached the problem with kinetic modelling techniques and developed a one-dimensional reaction diffusion model. Bhaskaran et al [31] further compared gasification characteristics of lignite and hard coal and found that the former was ten times more reactive and also yielded syngas with ~2.5 times more calorific value than the latter. Sanga et al [32] developed a model using COMSOL Multiphysics for chemical reactions, through characterization of coal from Kapurdi mine in Rajasthan.

3.1. Gasification with CCS

CO₂ capture using pre-combustion techniques can be performed in gasification based plants. Such plants can lead to affordable electricity at about € 77/MWh, even when operated with CO₂ capture [33]. This cost effectiveness of gasification plants (both UCG-CCS and IGCC-CCS) can be of use to the Indian energy sector. Several studies have been performed for these technologies to assess them techno-economically [33-38]. Table 1 shows some of these studies.
Table 1. A review of some gasification studies (both surface and underground coal gasification) performed globally – with inclusion of CO$_2$ capture and storage

| Reference                      | Inputs / Assumptions/ Methodology                                                                 | Results/ Conclusions                                                                 |
|--------------------------------|-----------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| Olateju and Kumar [34]         | • Plant model developed<br>• Entrained flow gasifier with pressure = 120 bar<br>• Injection temperature = 1227 deg. C<br>• Total capital cost = CAD$ 1569 million<br>• CO$_2$ flow rate = ~11000 t/day<br>• Hydrogen capacity = 660,00 kg/day<br>• Load factor = 85% | • Natural gas price is key determinant for competition between SMR and UCG for Hydrogen production<br>• UCG shows specific cost advantage when CCS is implemented<br>• Internal rate of return for success of UCG is less than 4.6-5.4<br>• H$_2$ production cost $ 1.78$/kg-H$_2$ without CCS and $ 2.1-2.7$/kg-H$_2$ with CCS<br>• UCG is most cost-effective at gas prices more than $ ~5.3$/GJ<br>• Risk of investment lower for UCG due to minimal fuel cost |
| Eftekhari et al [35]           | • A chemical equilibrium model developed<br>• The system is considered to be at a constant (user defined) pressure.<br>• Initial temperature= 35deg. C<br>• Adiabatic conditions are assumed<br>• CaO (particle size= 50µm) injected into the UCG cavity to favour H$_2$ production<br>• Effect of oxygen/water on product composition is investigated<br>• Wollastonite is reacted with CO$_2$ at 80 bar and 500K to produce H$_2$ and CO | • Conventional UCG with oxygen gives a higher recovery factor than air gasification.<br>• Zero emission recovery factors of deep UCG are negative<br>• Use of CaO in UCG to reduce CO$_2$ emission is not feasible.<br>• Calcium silicates showed better recovery than CaO<br>• Optimum practical recovery factor of 67% is achieved with CO$_2$ emission of 0.174kg/MJ<br>• Whereas, a minimum CO$_2$ emission value of 0.022Kg/MJ can achieved by keeping recovery factor at 47%<br>• The safety distance of at least 150m is proposed between the gasification channels and geologic faults<br>• UCG-CCS operations were shown to have a little effect on the ground water quality.<br>• UCG injections wells instead of production wells to be used for CO$_2$ injection to prevent corrosion of the production well<br>• UCG-CCS concluded to be economic |
| Sheng et al [33]               | • UCG feasibility study conducted on deep coal seams<br>• Coal seams selected for study were 1000-1500m deep that contained 75MT of UGC compliant coal in them<br>• Finite element software package ABAQUS was to model the thermo-geomechanical behaviour<br>• The elastic modulus of the coal is gradually decreased with temperature to simulate the mechanical failure of coal after gasification<br>• 3D thermo-mechanical model incorporating real lithological structures and other properties was |  |
| Reference          | Inputs / Assumptions/ Methodology                                                                                                                                                                                                 | Results/ Conclusions                                                                                                                                                                                                                   |
|-------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Cormos [36]       | - The model was further used to study the faults, the stresses and the permeability around the UCG cavity.                                                                                                                      | - Introduction of CCS costed 7-9% energy penalty                                                                                                                      |
| IGCC power generation with CCS | - A hydrogeological model was also prepared, for the 344 wells where examined for spreading data and hydrogeological parameters.                                                                                                 | - Shell type gasifier shows better overall net electrical efficiency                                                                                                 |
|                   | - Two entrained flow gasifiers (Shell and Siemens) were studied with and without CCS                                                                                                                                                | - Siemens type gasifier showed better hydrogen efficiency                                                                                                          |
|                   | - M701G2 gas turbine used to produce 400-500 MW                                                                                                                                                                                   | - Though the siemens type gasifier shows greater net efficiency                                                                                                     |
|                   | - CCS case studies are designed to capture more than 90% of the carbon                                                                                                                                                    | - Shell type gasifier required lesser overall capital and operation and maintenance cost.                                                                       |
|                   | - Modelling and Simulation are done using ChemCAD and Thermoflex software packages.                                                                                                                                               |                                                                                                                                                                         |
|                   | - Developed model was validated against industrial data                                                                                                                                                                             |                                                                                                                                                                         |
| Siefert and Litster [37] | - HSC Chemistry 6.0 software package was used to model GE entrained gasifier.                                                                                                                                                   | - System efficiency of 43 % for IGCC-CCS-EOR is reported                                                                                                            |
| Analysis of IGCC power plant | - Slurry of crushed coal and water is prepared and pressurised to 4.2 MPa.                                                                                                                                                      | - IRR= 8 ± 4%/yr (at 50/MWh)                                                                                                                                     |
|                   | - Gasifier exit temperature is 1200 deg. C                                                                                                                                                                                       | - NGCC is reported to yield the maximum rate of return i.e. 22%/yr                                                                                            |
|                   | - Water to carbon and oxygen to carbon ratio are kept at 0.46:1                                                                                                                                                    | - Study finds it possible for advanced coal based power plants to achieve IRR= 8%/yr at load electricity price of $50/MWh |
|                   | - 0.5% H₂S (molar basis) is assumed in the economic model                                                                                                                                                                          |                                                                                                                                                                         |
|                   | - Syngas undergoes WGS reaction at 250 deg. C and 4.5 MPa                                                                                                                                                                    |                                                                                                                                                                         |
| Kunze and Spliethoff [38] | - Aspen Plus and Ebsilon Professional software packages were used for modelling purposes                                                                                                                   | - Syngas yield of 2200 and 1644 (STP)/Kg coal as obtained                                                                                                           |
| IGCC plant model for 2020 | - Coal and biomass are characterised in a yield rector                                                                                                                                                                             | - 0.273kWh/kg O₂ of power consumption was seen for a pressure of 6 bar in high pressure column and 1.5 bar in low pressure column                                     |
|                   | - Redlich-Kwong-Soave method is selected as selected as global method in Aspen Plus                                                                                                                                           | - A net plant efficiency of 38.5% for hard coal and 41.9% for lignite is seen.                                                                                     |
|                   | - Gibbs reactor model is used for the model of reactive section                                                                                                                                                                   |                                                                                                                                                                         |
|                   | - Radfrac columns are used to model vap-liq operation                                                                                                                                                                              |                                                                                                                                                                         |
4. Comparison between combustion and gasification plants

In this paper, the Integrated Environmental Control Model (IECM) is used as a software tool to simulate the power plants. Since, we intend to understand only the gasification process; the underground coal gasification is treated akin to surface coal gasification. Thus, a comparative assessment is made for pulverized coal (PC) plants and integrated gasification combined cycle plants (IGCC) using some assumptions that describe coal costs and other assumptions fit to the Indian conditions. It should be noted that plant component costs are assumed as default IECM costs. However, replacements are made to other assumptions. For detailed methodology, the reader may refer to Berkenpas et al [39] or other works pertaining to the use of IECM in Indian conditions [40-42].

In this study, we wish to simulate a plant operating with northeastern coal. Chaulya et al [43] have performed detailed coal characterization for number of tertiary coal samples. Further, as Table 2 shows, these samples have considerable similarity to some American coals. Thus, we assume the characteristics of Appalachian coal basin since it eases syngas prediction within the model’s framework. The coal price is accordingly adjusted as per the norms and notification of the Coal India Limited.

Table 2. Similarity between Tertiary coals and American Coals (Appalachian and Illinois#6). Source: IECM Model and Chaulya et al [43]

| Coal samples     | Proximate analysis(% wt.) | Ultimate analysis(% wt.) | C.V.(Kcal/kg) |
|------------------|---------------------------|--------------------------|--------------|
|                  | M            | Ash      | C       | H       | N       |            |
| Ledo             | 2.8-3        | 5.1-18.2 | 54.8-70.2 | 2.1-6.6 | 1-1.2   | 6500-7075 |
| Baragolai        | 2.1-3.5      | 6.3-14.4 | 66.3-69.8 | 4.7-5.1 | 1.2-1.4 | 6685-7025 |
| Tirap            | 2.3-2.2      | 3.9-11.1 | 67.4-69.9 | 4.8-4.9 | 1.2-1.3 | 6900-7640 |
| Tikak            | 2.3-2.8      | 3.4-13.1 | 64.3-75.2 | 4.6-5.4 | 1.1-1.3 | 6400-7600 |
| Tipong           | 2.3-2.9      | 4.3-9.2  | 60.9-74.5 | 5.5-4.1 | 1-1.2   | 6935-7630 |
| Dilli-Jeypore    | 4.4-7.5      | 1.4-9.0  | 75.5-79.4 | 5.3-6.7 | 1-1.3   | 6335-7395 |
| Appalachian      | 5.05         | 7.24     | 73.81    | 4.88    | 1.42    | 7370       |
| Illinois#6       | 11.12        | 9.70     | 63.75    | 4.50    | 1.25    | 6486       |

The price of raw materials is taken from Singh and Rao [40] and is shown in Table 3, alongwith some other important assumptions.

Table 3. Some important assumptions for simulation of IGCC plant

| Parameter               | Value         |
|-------------------------|---------------|
| Load Factor             | 90            |
| Gasifier Make           | GE 7EA        |
| Debt:Equity Ratio       | 70:30         |
| Cooling system          | Wet Cooling Tower |
|                         | (in view of new regulations) |
| Slag management         | Landfill      |
| H₂S control             | Selexol       |
| Raw material prices     |               |
| Activated Carbon ($/t)  | 1215          |
| Ammonia ($/t)           | 376.7         |
| Caustic ($/t)           | 424.6         |
| Urea ($/t)              | 455.7         |

From Singh and Rao [40]

For the PC plant, the plant based assumptions are taken from Singh and Rao [40] with the same coal characteristics and costs as in the above case.
Without CCS, pulverized coal and gasification plants perform similar in terms of efficiency, while cost is slightly higher for IGCC. Gaseous emissions are lower by an order of magnitude for IGCC, thereby showing greater importance for air pollution. Makeup water is also significantly lower for gasification-based plants. With CCS, however, IGCC shows distinct advantage with tertiary coal in terms of cost and energy penalty. Water use increase in minor in IGCC plant, as compared to PC. In a low-carbon world, gasification will show distinct advantages. It may also be noted that Sulfinol serves dual purposes (for CCS and H₂S removal). The detailed results are shown in Tables 4 and 5.

**Table 4. Results without CO₂ capture and storage**

| Unit             | PC      | IGCC    |
|------------------|---------|---------|
| Efficiency       | %net    | 37.27   | 36.20   |
| COE              | $/MWh   | 71.92   | 83.17   |
| CO₂ Emissions    | kg/kWh  | 0.8541  | 0.8342  |
| SO₂ Emissions    | kg/kWh  | 2.473e-3| 2.889e-4|
| NO Emissions     | kg/kWh  | 3.860e-4| 4.899e-5|
| NO₂ Emissions    | kg/kWh  | 3.115e-5| 3.953e-6|
| Make up Water    | kg/kWh  | 2.499   | 1.554   |

**Table 5. Results with CO₂ capture and storage**

| Unit             | PC*     | IGCC#   |
|------------------|---------|---------|
| Efficiency       | %net    | 26.45   | 30.56   |
| COE              | $/MWh   | 122.9   | 118.0   |
| CO₂ Emissions    | kg/kWh  | 0.1206  | 9.398e-2|
| SO₂ Emissions    | kg/kWh  | Very Low (Due to Assumptions) | 3.875e-5 |
| NO Emissions     | kg/kWh  | Assumptions) | 5.606e-5 |
| NO₂ Emissions    | kg/kWh  | 5.606e-5 |
| Make up Water    | kg/kWh  | 4.377   | 1.729   |

* Amine-based capture  
# Sour-shift + Selexol

Further, it is seen that air Separation Unit and CO₂ capture unit Contributes to 21% cost each. While the gasifier contributes to 54% of the costs (see Figure 3). Thus, process improvements should target gasifiers and indigenous development of gasifiers is a must.

![Figure 3. Capital cost distribution for gasification plant](image-url)
The effect of increase in number of gas turbines also affects cost reduction, but is largely dependent on power output needed. Three turbines result in net 800 MW. An increase of gasification temperature by 56 deg. C (from 1343 to 1399), reduces COE by US$ 2/MWh. Joint Incentives in terms of carbon tax (w/CCS) or sulfur tax (w.o. CCS) can lead to higher inclination towards gasification technology. Gasification of tertiary coals can offer cheaper, cleaner means of electricity. If CCS is to be implemented, gasification of such coals can result in more feasibility (even at lower Carbon Price due to low CO$_2$ Emission Factor). Process development in gasification is the key to reducing costs and energy penalty for CCS.

Figure 4 shows the effect of increase in number of gas turbines. Increase in number of gas turbines leads to significant reduction in the cost of electricity. But it is also dependent upon the required output as three turbines result in net output of 800 MW. An increase of gasification temperature by 56 deg. C (from 1343 to 1399), reduces COE by US$ 2/MWh.

**Figure 4.** Relation of cost of electricity to number of gas turbines

5. Conclusion
Gasification of tertiary coals can offer cheaper, cleaner means of electricity. These coals have low-ash and high gross calorific value. If CCS is to be implemented, gasification of such coals can result in more feasibility (even at lower carbon price due to lower CO$_2$ emission factor). Further, significant environmental benefits in terms of air pollutants and water consumption can be seen in gasification based plants. It may be noted that process development in gasification is key to reducing costs and energy penalty for CCS. A potential question also arises – “Can avenues for gasification of lignites be opened up?” The work ahead should focus upon modelling of integrated UCG-CCS processes. Work on chemical looping based capture may also be taken up since it may offer large reduction in energy penalty.

References
[1] CEA 2017 *All India Installed Capacity – April 2017* available at <http://wwwcea.nic.in/reports/monthly/installedcapacity/2017/installed_capacity-04.pdf>
[2] CEA 2015 *Growth of Electricity Sector in India From 1947-2015* available at <http://wwwcea.nic.in/reports/others/planning/pdm/growth_2015.pdf>
[3] PIB 2015 *CIL Gearing Up For 1 Billion Tonne Coal Production Mark* available at <http://pib.nic.in/newsite/PrintRelease.aspx?relid=115635>
[4] MoEFCC 2016 *India – First Biennial Update Report to UNFCCC* (New Delhi: Ministry of
Environment, Forests and Climate Change, Government of India)

[5] CSO 2017 *India Energy Statistics* (New Delhi: Ministry of Statistics and Power Implementation)

[6] Garg A and Shukla P R 2009 *Energy* 34 1032-1041

[7] Chikkatur A P, Sagar A D and Sankar T L 2009 *Energy* 34 942-953

[8] Shukla P R, Dhar S, Pathak M, Mahadevia D and Garg A 2015 *Pathways to deep decarbonization in India* (SDSN-IDDRI)

[9] Patzek T W and Croft G D 2010 *Energy* 35 3109-3122

[10] Mohr S H, and Evans G M 2009 *Fuel* 88 2059-2067

[11] Höök M, Zittel W, Schindler J and Aleklett K 2010 *Fuel* 89 3546-3558

[12] Shukla P R and Dhar S 2016 *Enabling Asia to Stabilise the Climate* (Springer Singapore) p 41-54

[13] Singh U, Rao A B and Chandel M K 2017 *Energy Procedia* DOI: 10.1016/j.egypro.2017.03.1896

[14] Singh U and Rao A B 2016 *Energy Procedia* 90 326-335

[15] Singh U, Sharma N, Mahapatra S S 2016 *International Journal of Coal Science and Technology* 3 215-225

[16] Abrol D 2011 *Science and Modern India: An Institutional History, c.1784-1947: Project of History of Science, Philosophy and Culture in Indian Civilization* Vol 15, Part 4, ed U Dasgupta (Pearson) p 185-231

[17] Krishnudu T, Madhusudhan B, Narayan Reddy S, Sastry V S R, Seshagiri Rao K and Vaidyeswaran R 1989 *Industrial and Engineering Chemistry Research* 28 438-444

[18] Krishnudu T, Madhusudhan B, Narayan Reddy S, Seshagiri Rao K and Vaidyeswaran R 1989 *Fuel Processing Technology* 23 233-256

[19] Iyengar R K, Haque R 1991 *Fuel Processing Technology* 27 247-262

[20] Chatterjee P K, Datta A B and Kundu K M 1995 *The Canadian Journal of Chemical Engineering* 73 204-210

[21] Ajilkumar A, Sundararajan T and Shet U S P 2009 *International Journal of Thermal Sciences* 48 308-321

[22] Ajilkumar A, Sundararajan T and Shet U S P 2007 *ASME/JSME 2007 Thermal Engineering Heat Transfer Summer Conference collocated with the ASME 2007 InterPACK Conference* (Vancouver) p 297-305

[23] Singh N, Raghavan V and Sundararajan T 2013 *9th Asia-Pacific Conference on Combustion* (Gyeongju)

[24] Singh N, Raghavan V and Sundararajan T 2013 *International Journal of Energy Research* 38 737-754

[25] Datta S, Sarkar P, Chavan P D, Saha S, Sahu G, Sinha A K and Saxena V K 2015 *Applied Thermal Engineering* 86 222-228

[26] Chavan P D, Sharma T, Mall B K, Rajurkar B D, Tambe S S, Sharma B K and Kulkarni B D 2012 *Fuel* 93 44-51

[27] Patil-Shinde V, Kulkarni T, Kulkarni R, Chavan P D, Sharma T, Sharma B K, Tambe S S, and Kulkarni B D 2014 *Industrial & Engineering Chemistry Research* 53 18678-89

[28] Daggupati S, Mandapati R N, Mahajani S M, Ganesh A, Mathur D K, Sharma R K and Aghalayam P 2010 *Energy* 35 2374-2386

[29] Daggupati S, Mandapati R N, Mahajani S M, Ganesh A, Sapru R K, Sharma R K and Aghalayam P 2011 *Energy* 36 1776-1784

[30] Mandapati RN, Daggupati S, Mahajani S M, Aghalayam P, Sapru R K, Sharma R K and Ganesh A 2012 *Industrial & Engineering Chemistry Research* 51 15041-15052

[31] Bhaskaran S, Ganesh A, Mahajani S, Aghalayam P, Sapru R K and Mathur D K 2013 *Fuel* 113 837-843

[32] Sanga B, Mohanty D, Singh A K and Singh R K 2017 *Nexgen Technologies for Mining and
Sheng Y, Benderev A, Bukolska D, Eshiet K I, Gama C D, Gorka T, Green M, Hristov N, Katsimpardi I, Kempka T and Kortenski J 2016 *Mitigation and Adaptation Strategies for Global Change* **21** 595-627

[34] Olateju B and Kumar A 2013 *Applied Energy* **111** 428-440

[35] Eftekhari A A, Van Der Kooi H and Bruining H 2012 *Energy* **45** 729-745

[36] Cormos C 2012 *Energy* **42** 434-445

[37] Siefert N S and Litster S 2013 *Applied Energy* **107** 315-328

[38] Kunze C and Sliethoff H 2010 *Fuel Processing Technology* **91** 934-941

[39] Berkenpas M B, Frey H C, Fry J J, Kalagnanam J and Rubin E S 1999 *Integrated environmental control model technical documentation* (Pittsburgh: Center for Energy and Environmental Studies, Carnegie Mellon University)

[40] Singh U and Rao A B 2015 *Decision* **42** 191-209

[41] Singh U and Rao A B 2014 *International Conference on Advances in Energy Research* (IEEE) p 226–232

[42] Rao A B and Kumar P 2014 *Energy Procedia* **54** 431–438

[43] Chaulya S K et al 2016 *Development of Feasibility Assessment Model for Adaptation of Underground Coal Gasification Technology in North East Region of India* (submitted to Department of Electronics & Information Technology (Deity), Ministry of Communication and Information Technology, Government of India, New Delhi)

**Acknowledgement**

AR and AKS are grateful to the CSIR Network Project *CoalGasUrja* (Development of Underground Coal Gasification Technology in India, ESC-0302) for financial support. Authors also thank Dr. Pradeep K Singh, Director, CSIR-CIMFR and Prof. D C Panigrahi, Director, IIT (ISM), Dhanbad for their skilful guidance and support. We thank the IECM team for making the software freely available. Further, thanks are due to Prof. Anand B Rao, IIT Bombay for his continued support in use of IECM software.