Environmental Impact Assessment of Coal Gasification in Hydrogen Production

Sandeep Kumar Rajput¹, Shalini Verma¹, Abhishek Gupta¹, Akshoy Ranjan Paul¹, Anuj Jain¹ and Nawshad Haque²

¹Department of Applied Mechanics, Motilal Nehru National Institute of Technology Allahabad, Prayagraj, India
²Commonwealth Scientific and Industrial Research Organization (CSIRO), Clayton, VIC, Australia
Email: sandeepkumarknj95@gmail.com, arpaul@mnnit.ac.in

Abstract. Increasing industrialization and population demands for higher energy use as electricity. Coal has a broader share in electricity generation but there is problem of GHG emission due to direct coal combustion. Coal gasification is adopted as a cleaner technology in place of traditional method of generating electricity and hydrogen production. This study develops an assessment method to evaluate the pollutant emissions generated from coal gasification process. Life cycle assessment (LCA) is a method used for evaluation of greenhouse gas emission quantity and fossil energy consumption. A system boundary of cradle to production stage is chosen for the study. The result shows that during coal mining and cleaning process CO₂ emission has higher contribution compared to CH₄ and N₂O. In this stage, total CO₂ emission is 19,976 kg in which diesel alone emits 72.46 % of CO₂. During transportation of coal, train transport medium has lower CO₂ emission as 5,413 kg while road transportation emits 8,144 kgCO₂. Production phase suggests that carbon capture and storage condition is suitable for environmental protection as it reduces CO₂, CH₄ and N₂O emission.

Keywords. Fossil fuel consumption; Hydrogen Production; Greenhouse gas (GHG); Life cycle assessment (LCA).

1. Introduction
Coal is most abundant and cheapest source of energy in the world. It is a primary energy source to produce thermal energy and other forms of energy. Before the industrial revolution, the use of coal was limited, but coal consumption is continually on increase after the steam engine was invented. Coal reserve in India is approximately 10% of world's total coal reserve and India holds the fifth place in the world in terms of coal production. Currently, coal production in India is 729 million tonnes and coal consumption are 425 million tonnes. Coal is mostly used for production of electricity. Combustion of coal emits gases like NOₓ, SOₓ and CO₂ that affect the climate change, potentially causing global warming. These environmental pollutants have serious consequences on the human life [1]. So, there is requirement of new technology with high efficiency and low carbon for electricity production from coal. Coal gasification technology is a better option because of low cost for removal of carbon-di-oxide compared to traditional energy system rooted on direct coal combustion [2]. Coal gasification technology is an integrated way which produces electricity, chemical products and fertilizer etc. This technology includes hydrogen, methanol and liquid fuel such as diesel etc. [3]. The progress of interest on coal gasification is published in the report of the US department of energy and the national energy technology laboratory [4]. It is the most important technology for production of
hydrogen economy as Coal gasification is a dominant way to produce the hydrogen gas [5]. International energy agency (IEA) proposed that world’s energy demand will be approximately 60% in next 30 year mainly in developing countries like INDIA. In 1970-80, 3-unit coal gasification project was set up by the Fertilizer Corporation of India (FCIL) at Ramagundam, Sindri and Talcher but this project was failed because Indian coal has high ash content. Initiative of installing new projects have prevented due to scarcity of positive policy and unsuccessful project in the past. However, circumstances maybe changed through changing few ‘coals for chemical’ projects starting to be evolved by private companies like JSPL. However, India has large potential but it is not realized fully yet [6]. Now Jindal Power & Steel Limited and joint venture of CIL, GAIL, RCFL, FCIL are trying to establish a new coal gasification plant to produce ammonia, urea at Talcher facility specially to produce neem (Azadirachta indica) coated prilledurea. Coal gasification has a scope and demand in India. However, at different stages of coal gasification, there are emissions of harmful gases which affect the environment. Thus, it is important to assess the environmental impact of these gases. Life cycle analysis (LCA) is a method used for evaluation of impact on environment [7]. It is a process to quantify the greenhouse gas emission and fossil energy consumption systematically [8,9].

The present study aims to explore about the methodology and environmental impact assessment of coal gasification which eventually targets hydrogen production. To quantify the fossil energy consumption, quantity of fuel used, energy consumption and transportation mode of coal. Further study estimates the quantity of pollutant emissions (CO₂, CH₄ and N₂O) at coal extraction process, transportation process and in production phase considering both the cases of carbon captured and storage (CCS) and without CCS.

2. Methodology
In this paper, Indian coal (Bituminous coal grade D) has been used and first step is mining and cleaning by various equipment [10] after that coal is transported to unit and distance by rail and road is 500 km. Further the coal is sent to gasification unit (fluidized bed technology) [11] and air separation unit [12] to separate air and carries oxygen and steam in a controlled pressure to gasification unit. Coal combustion and reaction produces raw syngas and ash. The syngas is sent in the cyclone separator to remove the impurities like dust and another heavy particle. It is a cyclic process with three cyclone separators for cleaning the syngas and again is sent to scrubber for further cleaning. This syngas is a raw syngas because it is a mixture of various components like (CO, H₂, CO₂, CH₄ etc.) which is burnable gas but CO produces higher CO₂. Thus it is sent to water gas shift unit and gas reacts with steam over a catalyst converter (Co-Mo type) to convert CO into CO₂ and produces more hydrogen. This is an exothermic reversible reaction. This reaction is important for balancing the H₂/CO ratio. After this syngas is sent to low temperature reactor (LTR) for reducing the temperature of syngas and separate steam and mixture of hydrogen and carbon die oxide. Further syngas, steam and nitrogen is sent to rectisol [13,14] unit for further acid gas removal by organic solvent methanol and CO₂, H₂ and H₂S is separate in pure form. H₂ is sent in pressure swing adsorption unit [15] and CO₂ is sent to compressor. H₂S is sent to clause. Hydrogen in pressure swing adsorption unit (PSAU) removes some impurities in the form of tail gas and pure hydrogen is produced. The PSAU operates on an isothermal process. CO₂ is sent to compressor to collect the compressed CO₂. In clause unit H₂S reacts with oxygen to produce Sulphur and tail gas is reject into the atmosphere. Tail gas from PSA, Air and nitrogen from external source are sent to the combustor then gas turbine and steam turbine are operated to produce 1.5 MW electricity.

3. Life cycle analysis (LCA) methodology
Life cycle analysis methodology used for evaluation of environmental impact; resources used. This methodology is implemented for evaluation of life cycle greenhouse gas emission in production path way. According to ISO 14040 and 14044, LCA define four steps as Goal definition and scope, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation.
3.1 Goal and Scope
The goal of the present study is to assess the environmental impact in different stages of hydrogen production. Here I have defined system boundary and functional unit. For further analysis, the data is collected regarding fossil energy consumption, GHG emission and calculate consumption and emission at every stage of hydrogen production.

3.1.1. Functional unit. In the current study, 20 tonne coal is used to produce 2000 kg of hydrogen in every hour and functional unit is considered as 1 tonne.

3.1.2. Boundary system. In this paper, the system boundary is cradle to production as shown in figure 1. Four stages are involved to complete the production of hydrogen.

- First is coal mining and cleaning - energy consumption in kWh and energy use from diesel, coal, electricity, residual oil and natural gas to complete this stage and greenhouse gas emission in form of CO₂, CH₄ and N₂O etc.
- Second is coal transportation though railway and road transport - energy is required and emits greenhouse gases.
- Third is Gasification unit - coal is supplied by help of oxygen and reacts with steam to produce syngas and emit ash and further reaction in this unit separates hydrogen and GHG emission.
- Forth is hydrogen production.

![Diagram](image)

**Figure 1.** System boundary from cradle to production stage.

3.2. Life cycle inventory analysis
For 1kWh of energy, the inventory data is collected from research paper [16]. Fossil energy consumption for hydrogen production is shown in table 1 for different energy resources.

| Process Energy | Coal (kWh/kWh) | NG (kWh/kWh) | Oil (kWh/kWh) |
|----------------|----------------|--------------|---------------|
| Coal           | 0.30           | 0            | 0.0305        |
| Diesel         | 0.050          | 0.0085       | 0.312         |
| Gasoline       | 0.050          | 0.008        | 0.312         |
| Residual oil   | 0.040          | 0.008        | 0.295         |
| NG             | 0.030          | 0.30         | 0.014         |
| Electricity    | 0.795          | 0.008        | 0.103         |
3.2.1. Emission factor for GHG Emission.
In this paper, greenhouse gas emissions CO₂, CH₄, and N₂O are evaluated and calculated by emission factor [17]. Emission factor for the greenhouse gases can be seen in table 2. These emission factors are used to calculate the global warming potential (GWP) and GWP is calculated by eq.1 (for 100 year) [18].

\[
\text{GWP} = \text{CO}_2 + 25\text{CH}_4 + 298\text{N}_2\text{O}
\]

(1)

| Process Energy | \(\text{CO}_2\) (g/kWh) | \(\text{CH}_4\) (g/kWh) | \(\text{N}_2\text{O}\) (mg/kWh) |
|----------------|--------------------------|-------------------------|------------------------|
| Coal           | 22.67                    | 0.00027                 | 0.00027                |
| Diesel         | 20.16                    | 0.0011                  | 0.0011                 |
| NG             | 15.44                    | 0.00027                 | 0.00027                |
| Gasoline       | 18.86                    | 0.022                   | 0.00055                |
| Residual oil   | 21.06                    | 0.00055                 | 0 |

3.2.2. Coal mining and cleaning.
For hydrogen production, coal is used and its properties are presented in table 3. The coal is mined and cleaned for use. In mining and cleaning the coal, energy is required by fuel used and can be seen in table 4. In this study, 20 tonnes of coal are mined and cleaned and for this amount, the energy consumption is shown in table 5.

| Properties of Coal | Wt. % |
|--------------------|-------|
| Fixed carbon       | 75    |
| Ash                | 12    |
| Volatile matter    | 6.67  |
| Moisture           | 6.34  |
| Carbon             | 74.84 |
| Hydrogen           | 2.43  |
| Nitrogen           | 1.13  |
| Sulphur            | 0.47  |
| Oxygen             | 5.07  |
| Calorific Value    | 5 kWh/hr |

| Name            | Quantity of Energy | unit   |
|-----------------|--------------------|--------|
| Diesel          | 9.05               | kWh/kg |
| NG              | 13.47              | kWh/kg |
| Gasoline        | 12.5               | kWh/kg |
| Electricity     | 2.68               | kWh/kg coal |
| Residual oil    | 0.011              | kWh/kg |

| Name            | Required Quantity (kWh) | Total Quantity (kg) |
|-----------------|-------------------------|---------------------|
| Diesel          | 6,498.8                 | 718                 |
| NG              | 766.6                   | 56.9                |
| Gasoline        | 1,172                   | 93.76               |
| Electricity     | 20                      | 7.46                |
3.2.3. Transport of coal.
Different sources of transportation are used to transport the coal. The transported data is collected from research paper.
- In India av. Supply of coal by train is 500 km.
- Energy required per km is 0.064 kWh/tonnes km.
- By road, coal transportation is also considered for 500 km.
- Energy required per km is 0.3656 kWh/tonne km diesel
- So total energy consumes by train 640 kWh and by road is 3656 kWh.

3.2.4. Hydrogen production stage.
Different stages in hydrogen production is shown in figure 2. First step is air separation to supply oxygen into the gasification unit and also supply nitrogen to maintain calorific value. Coal and steam are supplied into the gasification unit and coal reacts with oxygen and steam to produce raw syngas and ash is rejected outside.

![Figure 2. Process chart of coal to hydrogen production and other components.](image)

Impurities in the syngas is removed by cyclone separator and then it reacts with gas shift reaction to separate hydrogen and carbon die oxide and further supplied to rectisol process (it is an acid gas removal process) that use methanol as a solvent to separate rich hydrogen gas, acid gas carbon die oxide, hydrogen sulphide (H2S). The rich hydrogen gas is supplied to PSA for pure hydrogen (99.99%) production and hydrogen sulphide (H2S) is supplied to clause process and react with oxygen to produce sulphur. Electricity is produced by help of gas turbine and steam turbine using the wastage. This electricity is used to run compressor.

3.2.5. Input and Output components in hydrogen production.
The input components in hydrogen production are coal, O2, steam. The quantity of these input components is summarized in table 6. From these inputs, we get the output components which are hydrogen, CO2 and electricity. The quantity of these outputs is summarized in table 7.

### Table 6. Primary input required

| Input  | Quantity | Unit |
|--------|----------|------|
| Coal   | 20,000   | kg/h |
Oxygen 11,833 kg/h
Steam 24,583 kg/h
Carbon conversion 90 %
Oxygen/Coal 0.56
Steam/Coal 1.229

Table 7. Quantity of hydrogen product

| Output          | Quantity | Unit  |
|-----------------|----------|-------|
| Hydrogen production | 2,000    | kg/h  |
| CO2             | 26,874   | kg/h  |
| Electricity     | 1.50     | MW    |

4. Results

4.1 Life Cycle Impact Assessment

At each step of hydrogen production, there are emissions of greenhouse gases. During Coal extraction & process step, CO2, CH4 and N2O emissions are calculated in kg for different energy process can be seen in table 8. Energy use in coal mining and cleaning is 1003.6 kg of fossil energy consume in the form of Diesel, Residual oil, Electricity, Gasoline, Natural gas and total GHG emission relies like carbon die oxide (CO2) is 19.976 kg, CH4 is 0.00734 kg, N2O is 0.00085 kg. in both the scenario (with carbon capture and without carbon capture).

Table 8. Emission in coal extraction and processing stage.

|                  | CO2 (kg) | CH4 (kg) | N2O (kg) |
|------------------|----------|----------|----------|
| Diesel           | 14.47    | 0.00079  | 0.00079  |
| Natural gas      | 0.87     | 0.000015 | 0.000015 |
| Gasoline         | 1.76     | 0.00206  | 0.0000515|
| Electricity      | 0.16     | 0.00447  | 0        |
| Residual oil     | 2.68     | 0        | 0        |

During transportation through train and road, the transportation medium emits greenhouse gases which are calculated in kg and can be seen in table 9. The coal transport to use fossil energy (By train energy intensity is 0.064 kWh/tonnes km) 238 kg of coal for generation of electricity to operate train and produce GHG emission CO2 5.413 kg, CH4 0.00006 kg, N2O 0.00006 kg. By road, 403.977 kg diesel is required and produces GHG emission as CO2:8.144 kg, CH4 0.4443 kg, N2O 0.4443 kg. Here, two modes of transport are compared with equal supply distance. There is more GHG emission (CO2) found in the road transport as compared to rail transportation. So, train transport is preferable for environmental as well as for economical viewpoints.

Table 9. Emission in transportation stage

| Transportation Mode | CO2 (kg) | CH4 (kg) | N2O (kg) |
|---------------------|----------|----------|----------|
| Train               | 5.413    | 0.000064 | 0.000064 |
| Road                | 8.144    | 0.4443   | 0.4443   |
In gasification stage, during the production phase, the emissions for 1 tonne hydrogen are shown in Table 10. Here, with carbon captured and storage (CCS) facility, carbon dioxide is relying 1675 kg/tonne from stack and without any CCS facility carbon dioxide is 24988 kg/tonne.

**Table 10. Emission in production stage**

| Emissions | Without CCS (kg/tonne) | With CCS (kg/tonne) |
|-----------|------------------------|---------------------|
| CO\(_2\)   | 24,988                 | 1,675               |
| CH\(_4\)   | 1,259                  | 791                 |
| N\(_2\)O   | 680                    | 521                 |
| Total CO\(_2\)-e unit | 2,59,103               | 1,76,708            |

CH\(_4\) without carbon capture and storage is relies 1,259 kg/tonnes and with carbon capture and storage is 791 kg/tonne. Besides, N\(_2\)O relies without carbon capture and storage is 680 kg/tonnes and with carbon capture and storage, it relies 521 kg/tonne approximately.

### 4.2 Life Cycle Interpretation

From the life cycle analysis, it is interpreted that diesel has higher contribution of CO2 and N2O emission while electricity has higher contribution of CH4 emissions in coal mining and cleaning as can be seen from figure 3 (a) and (b). It can be clearly seen that diesel has a higher contribution (72%) in CO2 emission compared to other fossil fuels. For coal transportation, two modes of transport are used which is train and road. Both the train and road transportation are used for equal supply distance (i.e. 500 km). Interpretation of the results show that train mode has lower CO2 emission (5.413 kg) CH\(_4\) and N\(_2\)O emission as compared to that generated during the road transportation. The road transport recorded more emission as shown in Figure 3, whereas, the train transport has less GHG emission. Contribution of emissions for both the road and train modes are presented in figure 4.

![Emission](image_url)

**Figure 3.** Quantity of emissions in coal mining and cleaning stage for (a) 1 tonne coal (b) 20 tonne coal.
Emission quantity in production stage is shown in figure 5 for two cases of without CCS and with CCS. With CCS, carbon die oxide relies 93.3% less compared to without CCS. CH$_4$ with CCS relies 37.17% less compared to without CCS and N$_2$O relies 23.38% less. So, without carbon capture and storage are very harmful for human life because this GHG emission are directly relies into the environment. So here carbon capture and storage case are good for environment.

**Figure 4. Quantity of emissions in coal transportation**

**Figure 5. Emission quantity in production stage**

**5. Conclusions**

Coal is generally used for electricity generation but direct combustion of coal emits greenhouse gases that causes global warming and thus affects climate. A relatively efficient and cleaner technology is coal gasification for hydrogen production (with carbon capture) and electricity production compared with conventional use of coal. Fossil fuel and greenhouse gas emission of a fluidized bed gasifier-based for hydrogen production system with carbon capture and sequestration (CCS) and without CCS are quantified using life cycle assessment methodology. In mining and cleaning of 20 tonnes coal, 1,004 kg of fossil energy is used from diesel and GHG emits 19.98 kg CO$_2$, 0.00734 kg CH$_4$ (0.61656 kg equivalent CO$_2$) and 0.00085 kg N$_2$O (0.2533 kg equivalent of CO$_2$). Thus, in mining and cleaning process, total CO$_2$ e-emission is 20.849 kg. The coal is then transported and during transportation of coal, road and train modes are used. In this process of transportation of coal, train transportation can
be preferred due to 33.52% lower emission of CO₂ as compared to road transport mode. In production phase, CO₂, CH₄, N₂O can be reduced by adopting the CCS facility. The total CO₂-e emission is calculated to be 1,76,708 kg in CCS and 2,59,103 kg in without CCS per tonnes of hydrogen production from this process. Thus, 31.8 % of CO₂-e can be reduced for CCS case compared to without CCS.

References
[1] Guo L, Jin H 2013 Boiling coal water: hydrogen production and power generation system with zero net CO₂ emission based on coal and supercritical water gasification. *Int. J. Hydrogen Energy* 38 12953-12967
[2] Ge Z, Guo S, Guo L, Cao C, Su X and Jin H 2013 Hydrogen production by noncatalytic partial oxidation of coal supercritical water: explore the way to complete gasification of lignite and bituminous coal. *Int. J. Hydrogen Energy* 38(29) 12786-12794
[3] CollotAG2004Clean Fuels from Coal IEA Clean Coal Centre, London, UK.
[4] World Gasification Database2010 Current Industry Status. Department of Energy USA, National Energy Technology Laboratory
[5] StiegelGJ, RamezanM2006 Hydrogen from coal gasification: an economical pathway to a sustainable energy future. *Int. J. Coal Geol.* 65 173-190
[6] Minchener A 2013 Challenges and opportunities for coal gasification in developing countries. IEA Clean Coal Center. CCC/225
[7] Al-Shayiji K, Aleisa E 2018 Characterizing the fossil fuel impacts in water desalination plants in Kuwait: a Life Cycle Assessment approach *Energy*158681-92
[8] Moreno J, Dufour J 2013 Life cycle assessment of hydrogen production from biomass gasification. Evaluation of different Spanish feedstocks *Int J Hydrogen Energy*38(18)7616-22
[9] Muresan M, Cormos CC, Agachi PS 2014 Comparative life cycle analysis for gasification-based hydrogen production systems *J Renew Sustain Energy*6(1) 013131-14
[10] Coal Directory of India 2011-12 Coal Statistics Government of India.
[11] Yang S, Qian Y, Liu YJ, Wang YF, Yang SY 2017Modeling, simulation, and techno-economic analysis of Lurgi gasification and BGL gasification for coal-to-SNG *Chem Eng Res Des*117355-68
[12] Ozbayoglua A M, Kasnakoglub C, Gungorc A, Bıyık oglud A, Uysal B Z 2010 An Analysis of Water Gas-Shift Reactor Battery System for Synthesis Gas Refinement *In 11th International Combustion Symposium* 1-6
[13] Bell D A, Towler B F, Fan M 2011 Sulfur Recovery *Coal Gasification and Its Applications* 113–136
[14] GattiM, MartelliE, MaréchalFand ConsonniS2014 Multi-objective optimization of a Rectisol® process. *In Computer Aided Chemical Engineering.* 331249-1254
[15] Sircar S, Golden TC2000 Purification of Hydrogen by Pressure Swing Adsorption *Separation Science and Technology*35(5) 667–687
[16] Ou X, Xiaoyu Y, Zhang X 2011 Life-cycle energy consumption and greenhouse gas emissions for electricity generation and supply in China *Applied Energy* 88(1) 289-297
[17] Ou X, Zhang X, Chang S, Guo Q 2009 Energy consumption and GHG emissions of six biofuel pathways by LCA in (the) People’s Republic of China *Applied energy* 86 S197-S208
[18] Li X, Ou X, Zhang X, Zhan Q, Zhang X 2013 Life-cycle fossil energy consumption and greenhouse gas emission intensity of dominant secondary energy pathways of China in 2010 *Energy* 50 15-23
[19] Coal india coal mining process.
[20] Xiang D, Yang SY, Li XX, Qian Y 2015 Life cycle assessment of energy consumption and GHG emissions of olefins production from alternative resources in China *Energy Convers Manag*9012-20