

# PARAMETRIC STUDY ON CO-FEEDING OF MUNICIPAL SOLID WASTE AND COAL IN AN IGCC POWER PLANT WITH PRE-COMBUSTION CARBON CAPTURE

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## Abstract

Municipal solid waste (MSW) is one of the top contributors in greenhouse gas (i.e. methane) emissions - particularly from landfill disposals. However, it could be a remarkable source of renewable energy. In Bangladesh, generation of municipal solid waste is at least 2.7 million tonne per year in the major cities, implying a heavy environmental burden. On the other hand, there are several coal-based power plants are in the pipeline to meet the increasing energy demand in Bangladesh with the potential of significant CO<sub>2</sub> emission. To find a remedy to the above situation, a power plant using Integrated Gasification and Combustion Cycle (IGCC) technology with pre-combustion carbon capture is considered in this study. IGCC has the advantage of producing high quality syngas from a wide variety of feed and assists in the capture of CO<sub>2</sub> at a lower cost while providing high electric efficiency. The power plant was simulated by commercial simulation packages (Aspen PLUS<sup>TM</sup> and Aspen HYSYS<sup>TM</sup>) using MSW and bituminous coal (Indonesian) as a combined feed. With a feed rate of 1800 tonne per day, Syngas produced from an entrained flow type gasifier was then treated for CO<sub>2</sub> removal using mono-ethanol amine (MEA) solvent after necessary shift in a high temperature shift reactor. About 91% efficiency was achieved in the shift reactor while the CO<sub>2</sub> capture efficiency was varied for this study from 30% to 85%. Further parametric variation was studied by varying the moisture content of MSW and MSW to coal feed ratio. Through combustion of the H<sub>2</sub> rich syngas in a gas turbine and subsequent steam cycle with reheat resulted in 125 MW of electricity at an efficiency of 28.95% while capturing 50% of the CO<sub>2</sub> generated in the process for an MSW to Coal feed ratio of 1:1. With variation in moisture content especially during monsoon season, the plant efficiency could be affected remarkably. On the other hand, it was observed that the energy requirement varied from 6 to 8 MW for every 10% increase in CO<sub>2</sub> capture quantity. Overall, by capturing 50% of the generated CO<sub>2</sub>, it is possible to reduce the emission of a same size ultra-supercritical coal-based power plant from about 700 kg CO<sub>2</sub>/MWh to about 360 kg of net CO<sub>2</sub>/MWh incorporating co-feeding and pre-combustion capture in an IGCC power plant.

**Keywords:** MSW, Gasification, Waste to Energy, IGCC, CO<sub>2</sub> Capture, Clean Energy.

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## 1. Introduction

Climate change, energy security, environmental pollution, MSW management are distinct but intricately coupled challenges that have holistic impacts on the national economy, local and global ecology, and hence the lifestyle of human civilizations. Power generation from fossil fuels - predominantly coal, is the most significant contributor for the exacerbation regarding these issues and so a technological paradigm shift is required.

The developing countries of South East Asia are witnessing an increasing demand for electric power [1]. Coal being cheapest of all fossil fuels and having ease of transport, storage, and well-established infrastructure for thermal power generation is the first choice for meeting the transient demand of an -

emerging industrial economy. However, the thermoelectric power schemes produce significant emissions and have a large water consumption footprint which lead to environmental pollution, climate change and recurrence of natural calamities. This pertains rearrangements of logistics and resources of a nation in agriculture, healthcare and education; hindering stable economic growth. So, the use of fossil fuels for rapid development poses a paradox with the traditional technology being used [2]. As of 2017, coal alone accounts for 14,502 million tonnes CO<sub>2</sub> emission which is about 40% of the CO<sub>2</sub> emissions from fossil fuel use (IEA, 2017). Countries like India, China, Vietnam, Thailand, Bangladesh, Cambodia, Philippines, Laos, Malaysia will continue to increase their coal consumption to meet energy demands [1]. It is unlikely that this consumption will shut down within a time frame consistent with climate targets (IEA, 2016).

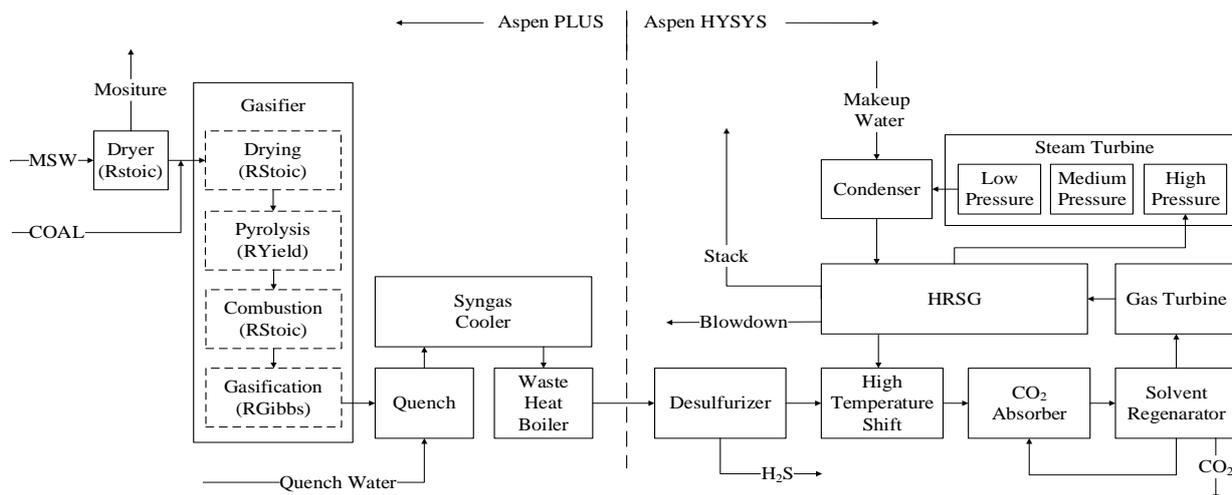


Fig 1 Block diagram of the IGCC process model

IGCC provides a solution to all these issues. Here, fuel is gasified to produce Syngas that is burned to generate electricity through a gas turbine. The remaining energy in the flue is extracted to make steam that can provide additional electricity via a steam turbine. The gasification reactions can handle a wide variety of feedstocks, lowers the production of  $\text{SO}_x$  and  $\text{NO}_x$  [3], and has a lower water footprint due to the combined cycle. Pre-combustion  $\text{CO}_2$  percentage is high in IGCC, leading to a more energy-efficient carbon capture and storage (CCS) scheme downstream. Captured  $\text{CO}_2$  can be sequestered underground in geological caverns, used in enhanced oil recovery schemes, or can be subjected to ex-situ or in-situ mineral carbonization to achieve a neutral or a negative carbon powerplant depending on feedstock composition [4, 5, 6]. For this reason, co-feeding coal with MSW or biomass is preferable [6]. MSW contains food wastes, organic debris like papers, plastics, rubbers, lignocellulosic materials and typically has an LHV of 7 MJ/kg [7]. With increasing urbanization, the amount of MSW generated is becoming more significant. In the US, 238.5 million tonnes of MSW were produced, of which 52.5% were landfilled, and 12.5% were incinerated with only 12.8% energy recovered [8, 7]. Japan leads the world in energy extraction from MSW by having 78% WTE conversion [7]. Southeast Asian countries have minimal WTE facilities [8, 9]. So, there are scope in the development of WTE facilities, mainly by IGCC.

Pilot-scale IGCC includes ELCOGAS IGCC with pre-combustion CCS with a 335 MW capacity, the EAGLE project, the Osaki CoolGen Project with a 166 MW capacity [5]. Major existing and planned IGCC commercial plants include Kemper County, Buggenum, Wabash River, Tampa, Pernis, Priolo Gargallo, Puertollano, Sarlux, Nehishi, Versova, Knox Country, Nakoso with capacities varying from 115-618 MW and CCS technology in some [10]. The LHV efficiency of commercial IGCC plants ranges

between 36%-42.2% depending on the feedstock, type of CCS technology used (if any), and extent of process integration [10]. The major developments of new IGCC projects include Don Valley Plant, Tenaska plant, Dongguan Taiyangzhou plant, Jiangsu plant with capacities ranging from 300-1200 MW with low-lost fuel co-firing, and CCS. [10]

While several pilot-scale plants are in operation or being planned to be set up, it is becoming essential to realize the true potential of the large-scale IGCC plants handling mixed feedstock with CCS. In this work, we carried out a parametric study on a full-scale IGCC plant using MSW and coal as feedstock to understand the operational flexibility and synergy among the different processes (Gasification, Water-Gas Shifting,  $\text{CO}_2$  Absorption, Combined Cycle). We further evaluated how the processes behave holistically given changes in boundary conditions like feedstock compositions, feedstock pre-processing, thermodynamics of WGS reaction and  $\text{CO}_2$  absorption percentage.

## 2. Model Description

A steady-state model of the IGCC process was developed in two parts with the help of Aspen Suite of process simulators. The solid handling and Gasification process simulation were performed in Aspen PLUS™ and the Syngas cleaning, Shift conversion, Carbon Capture, and power generation in Aspen HYSYS™. Stream data was transferred from Aspen PLUS™ to Aspen HYSYS™ by exporting stream data. The model takes in MSW and Coal data as input and analyzes the effect of the different chosen parameters on the process. The following assumptions were made while developing the model.

- The process is steady-state, isothermal, and all the unit processes and operations are uniform in pressure.

- Gasification occurs in four primary steps – Drying, Pyrolysis, Combustion, and Gasification.
- All gasification products except CO, CO<sub>2</sub>, H<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>S, and H<sub>2</sub>O are ignored.
- N<sub>2</sub> is considered to be inert throughout the process.
- The MSW considered in the process is assumed to be comprised of only biogenic waste.
- Coal and MSW are assumed to be made up of only Carbon, Hydrogen, Oxygen, Nitrogen, Sulphur, and Ash.
- Heat loss from the gasifier is considered 2% of the total heat recovered from gasifier. Other mechanical losses are ignored.
- No entrained particle remains after direct quenching of Syngas.

The simulation process is represented in a block diagram in Fig. 1. MSW is first dried and then mixed with coal to enter the gasifier. The extent of drying is controlled by Stoichiometric reactor coupled with Fortran subroutines inside Aspen PLUS™.

The proximate and the ultimate analysis of the two fuels are given in Table 1. Typically, MSW in megacities like Dhaka, Bangladesh, contains an average 12% of plastics [11], which contribute to the non-renewable carbon content of the MSW fuel, while coal contributes to the remaining 88%.

Table 1

Characteristics of two feedstock – Coal (Indonesia) and MSW on dry basis [12, 13]

Proximate Analysis <sup>a</sup>	Coal (%w/w)	MSW (%w/w)
Ash	6.4	12.47
Volatile Carbon	48.46	75.83
Fixed Carbon	45.14	11.69
Ultimate Analysis <sup>b</sup>	Coal (%w/w)	MSW (%w/w)
C	74.61	47.61
H	5.13	6.07
O	10.69	43.85
N	8.72	2.19
S	0.85	0.28
Heating Values	Coal	MSW
HHV (kJ/kg)	25500	17886
LHV (kJ/kg)	24858	16827

<sup>a</sup> dry basis, <sup>b</sup> dry ashless basis

### 2.1. Drying

Before mixing with coal, the MSW goes through an initial drying process in a steam kiln, simulated with an RStoic reactor block in aspen plus. Then, as the combined feedstock enters the gasifier, the excess

moisture is driven off first, simulated by an Aspen PLUS™ stoichiometric reactor, RStoic. FORTRAN subroutines inside the reactor control the extent of drying. It is assumed that the feedstock dries completely before the pyrolysis stage of gasification.

### 2.2. Pyrolysis

This stage was simulated by an Aspen PLUS™ RYield reactor. In this step, the feedstock devolatilizes into Carbon, Hydrogen, Nitrogen, Oxygen, and Sulfur, and Ash. The yield distribution is specified by FORTRAN subroutines according to the combined feedstock's ultimate analysis which was calculated by the software. The stream containing these components is then fed to the combustion step.

### 2.3. Combustion

An Aspen PLUS™ Rstoic reactor was used to simulate this step. The rate of conversion of total carbon was assumed to be 80% in the reactor. The selectivity of CO and CO<sub>2</sub> formation was given by the ratio between their heats of reaction. Pure O<sub>2</sub> gas below the stoichiometric ratio and pressurized CO<sub>2</sub> were introduced into the process. The unreacted carbon and the produced gases, and the other component are then fed to the gasification step. It is the combustion step that acts as the primary source of heat for the whole gasification process.

### 2.4. Gasification

This step was simulated in an Aspen PLUS™ RGibbs reactor, governed by the Gibbs free energy-based model to determine the final composition of the gasification product gases. The temperature was maintained at 1400 °C by producing Medium pressure steam from the process. The produced Syngas moves on to the Quench system leaving the ash behind as molten slag.

### 2.5. Quench and Heat recovery

The hot gases from the gasification process were quenched with water to reduce the temperature and increased the moisture content which later assisted in the shift reaction system. The Syngas then passed through the syngas cooler and waste heat boiler, simulated by a pair of heat exchangers – producing high and medium pressure steams, respectively. The heat recovered from here contributed to the Heat Recovery Steam Generator.

### 2.6. Syngas Cleaning

The cooled syngas was passed through the desulphurizer, where H<sub>2</sub>S gas was removed from the syngas. Complete removal of H<sub>2</sub>S in a ZnO-based catalytic reactor was considered here.

### 2.7. High Temperature Shift Reactor

In High Temperature Shift Reactor, the CO present in clean Syngas was converted to CO<sub>2</sub> with the help of steam, and more H<sub>2</sub> was produced in the process. This process was simulated by an Aspen HYSYS™ Equilibrium Reactor, which calculates the final composition of the shifted syngas in the specified temperature. Parameters like the CO: Steam ratio, and the temperature were modified to observe their impact. The CO<sub>2</sub>-rich syngas then sent to the CO<sub>2</sub> absorber section.

### 2.8. CO<sub>2</sub> Absorber and Stripper

30% MEA solution was used as the lean solvent for absorption. The rich MEA stream exited the absorber at the bottom of the column and enters the stripper, where the reaction is reversed. The liberated CO<sub>2</sub> left the stripper column, and the remaining MEA was recycled back to the absorber. A solution of MEA was introduced as a makeup for the purge stream. The process was simulated by an Absorber Column operating at system pressure and a Distillation column operating at lower pressure, respectively, in Aspen HYSYS™. Parameters like Mass to CO<sub>2</sub> were controlled to see its effect on the capture performance of the system. The H<sub>2</sub> rich syngas was then fed to the gas turbine.

### 2.9. Power Generation

An Equilibrium reaction model was used to simulate the combustion chamber with compressed air and an Expander to simulate the turbines. The exhausted hot stack gases pass through a network of heat exchangers simulating the Heat Recovery Steam Generator, which generates the steam required for the steam cycle and unit processes. The steam turbine uses steam at three different pressures, simulated by three expanders.

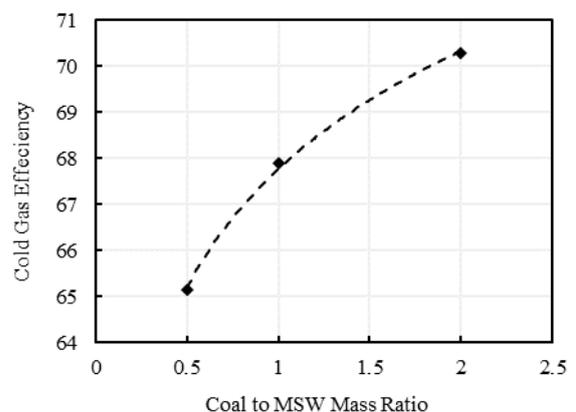
## 3. Experimental Methodology

The developed model for the process is used to analyze the effect of the chosen parameters. Gasifier inlet moisture and the co-feeding ratio were varied to see its effect on Cold Gas Efficiency. In the High temperature shift reactor, the Steam: CO ratio was varied to see the effect on the extent of conversion, CO, and CO<sub>2</sub> content in the dry syngas. The MEA: CO<sub>2</sub> mass ratio was varied to observe its effect on the percentage of CO<sub>2</sub> in the absorber inlet captured and the regenerator reboiler duty.

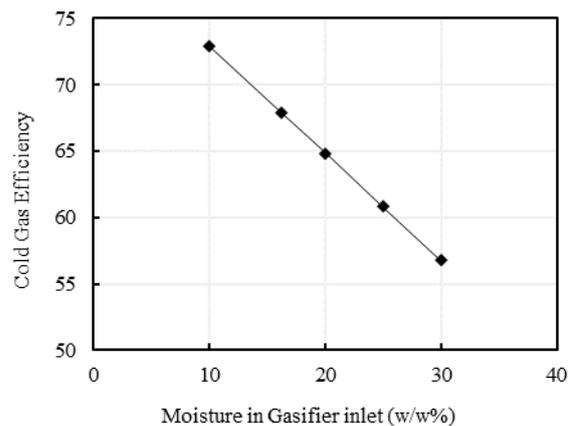
## 4. Results and Discussion

### 4.1. Cold Gas Efficiency

Cold Gas efficiency is the ratio of the lower heating value of the resulting Syngas from a gasification process to the lower heating value of the gasified fuel. In this model, the formed syngas' primary gasification products are H<sub>2</sub> and CO. The amount of these two species thus controls the Lower heating value of the syngas. Figure 2a shows that the CGE went up as more coal was used in the feed. This is primarily due to the availability of more carbon in the feed due to more coal. On the other hand, if more MSW is used, the overall moisture content in the gasifier inlet increases, impacting the cold gas efficiency of the gasifier as the water content in the



(a)



(b)

Fig 2 Effect on Cold Gas Efficiency for (a) different Coal to MSW Ratios, (b) Different Gasifier feed moistures

resulting syngas rises. The moisture content of the combined feed of the gasifier containing dried MSW and coal was varied from 10% to 30% to study the change in CGE, and the effect can be seen in fig 2b.

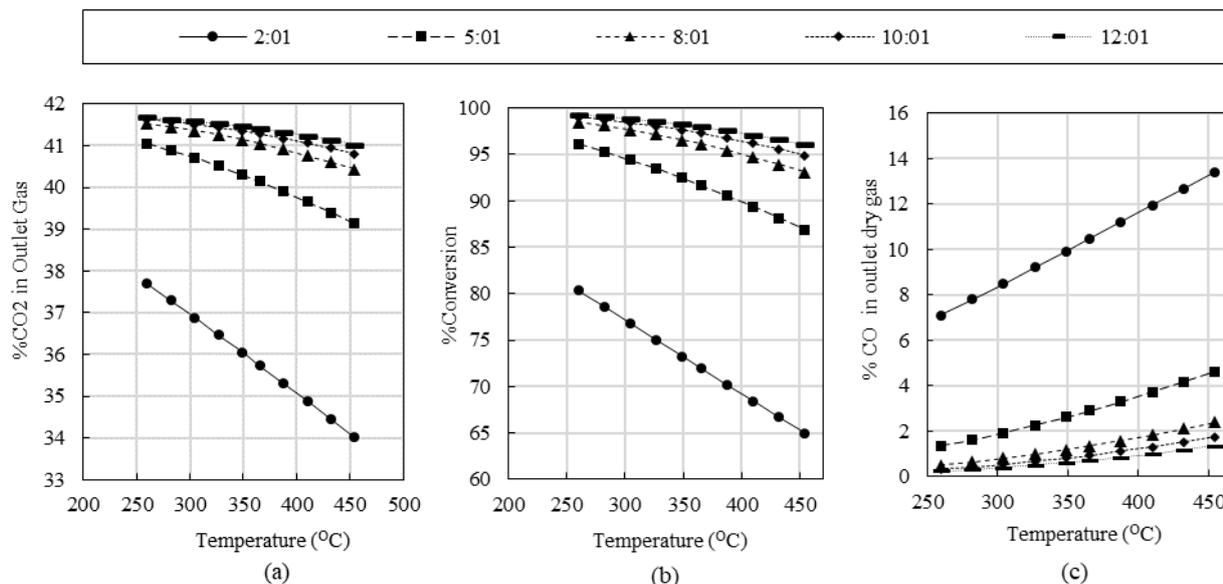


Fig 3 Effect of various Steam: CO ratio on (a) %CO<sub>2</sub> in outlet dry gas at various temperature, (b) %Conversion in shift reactor at various temperature, (c) %CO in outlet dry gas at various temperature

Higher CGE suggests higher quality Syngas and generally better power generation. The results showed that a higher Coal: MSW ratio led to higher CGE, but a higher Coal: MSW ratio would also mean that the nature of the particles in gasifier feed had changed and was abundant in coal particles which needed more time to convert. Thus, a higher residence time would be required in the gasifier resulting in a larger gasifier. We also see the tendency of the CGE to level off at higher Coal: MSW ratios, so an optimum value is required to be selected to obtain optimum efficiency.

Higher moisture in the feed also reduces CGE, so moisture should be kept as low as possible in the gasifier inlet. The primary source of moisture in the process is the MSW, so it needs to be dried by a considerable extent before gasification.

#### 4.2. Steam:CO Ratio

The ratio of added steam in HTS to the amount of CO present in the Syngas was modified. Five sets of ratios were tested to see the effects on the CO<sub>2</sub> content in the resultant syngas, the extent of conversion of CO and CO content in Syngas, presented in Fig 3a, b, c, respectively.

The extent of conversion increase as the Steam to CO ratio is increased, and thus the amount of CO<sub>2</sub> increases and is evident from Fig 3a and 3b. A similar effect could be observed in Fig 3c as the amount of CO went down with increased steam: CO ratio. In all five cases of the steam: CO ratio, we can see that the desired effect was promoted at lower temperatures and continued to drop off as the temperature rises. A drastic increase in conversion

was observed as the steam:CO ratio was changed from 2:1 to 5:1, but a similar increase in conversion was not apparent for the subsequent increments in the steam:CO ratio.

The results indicate that higher steam:CO ratio and lower temperature are favorable. However, the incremental improvement in the effect quickly slows down after exceeding the steam to CO ratio over 5:1. Higher steam:CO ratio might penalize the overall process by reducing available steam for power generation or other heating purposes. So, an optimum of 5:1 steam:CO ratio can be adequate to get a satisfactory conversion. Similarly, a lower optimum of 315-350 °C could be chosen as the operating temperature without compromising the yield.

#### 4.3. MEA Solvent to CO<sub>2</sub> Mass Ratio

The Mass ratio of MEA solvent to CO<sub>2</sub> at the inlet of the absorber was varied between 3.5 to 22. For each ratio, the amount of CO<sub>2</sub> captured had been observed, along with the reboiler duty for the regeneration column. The amount of CO<sub>2</sub> being absorbed was between 30% to 85% for low to high ratios. The result is visualized in Fig 4a and b. With increasing MEA solution, absorption of CO<sub>2</sub> increases but results in a higher flow rate and reboiler duty in the regeneration column causing a significant energy penalty.

From the observed trend of Reboiler duty and MEA solution to CO<sub>2</sub> ratio with the percentage of capture, it is apparent that higher CO<sub>2</sub> capture will require more energy and solvent. From the graph, up to 70% capture, reboiler duty increased at a comparatively lower rate. However, above this point,

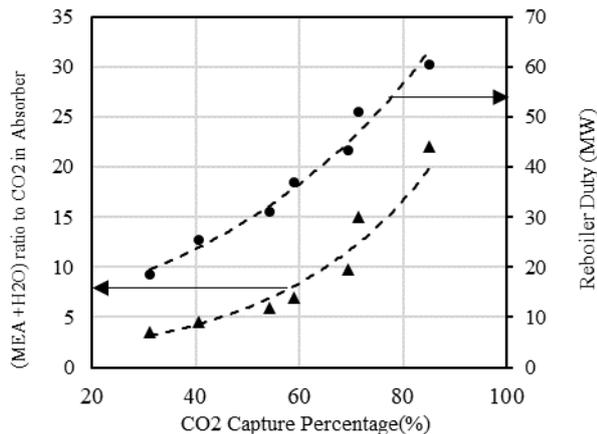


Fig 4 Effect of desired carbon capture percentage on MEA solution: CO<sub>2</sub> mass ratio and Reboiler Duty of regeneration column

for a small percentage increment in the capture, reboiler duty increased markedly. Thus, to avoid the energy penalty, 70% capture can be selected as an optimum value to achieve satisfactory results.

## 5. Conclusion

A parametric study was performed to observe the effects on output variables by changing different input parameters. The CGE of the gasifier changed non-linearly from 65% to 70% when the Coal: MSW ratio was varied from 0.5 to 2, concluding that it is sufficient to operate at a 1:1 ratio. In contrast, CGE varied from 72% to 56% for an inlet moisture content of 10% to 30%. Variation of Steam: CO ratio showed that higher Steam: CO ratio has increased conversion. It was found that the Steam: CO ratio can be chosen at around 5:1 to have the maximum impact. Although low temperature favors conversion, it decreases the reaction rate. At around 300°C, the conversion of CO is ~95% which is satisfactory. A remarkable feature of the modeled process is the reduction of CO<sub>2</sub> emission besides producing power. Percentage of CO<sub>2</sub> capture should not be chosen beyond 70%, as it requires a high ratio of MEA solution: CO<sub>2</sub> and higher reboiler duty which causes energy penalty. Overall, the net emission from CO<sub>2</sub> from fossil sources was 360 kg/MWh. Though these kinds of processes' energy efficiencies are at around 30%, it could be an effective solution for municipal waste and reduce CO<sub>2</sub> emission as a low carbon technology.

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