Hybrid Processing of Biomass and Coal with CO_2 Capture for Low Carbon Power Generation

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BY

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*Dedicated to My Beloved Parents
and Daughter*

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I ***Ashim Kumar Khan***, registered on ***26.08.2015*** do hereby declare that this thesis entitled "***Hybrid Processing of Biomass and Coal with CO_2 Capture for Low Carbon Power Generation***" contains literature survey and original research work done by the undersigned candidate as part of Doctoral studies.

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*This is to certify that the thesis entitled "**Hybrid Processing of Biomass and Coal with CO_2 Capture for Low Carbon Power Generation**" submitted by Sri. **Ashim Kumar Khan**, who got his name registered on **26.08.2015** for the award of Ph. D. (Engg.) degree of Jadavpur University is absolutely based upon his own work under the supervision of **Prof. Ranjana Chowdhury** and that neither his thesis nor any part of the thesis has been submitted for any degree or any other academic award anywhere before.*

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CHAPTER 1

INTRODUCTION

Abstract

To address twin problems of fossil fuel depletion and environmental degradation due to CO_2 emissions, there is a necessity of energy transition from high carbon conventional resources to renewable low carbon fuels. Biomass is a promising eco-friendly alternative source of renewable energy in the context of current energy scenarios. To explore the possibility of the usage of agricultural and MSW derived lignocellulosic biomass with coal in the Indian power sector, in detail, the present research focused in the following directions: (I) an evaluation of the prospect of a IGCC power plant based on mixture of coal and Agri-MSW-based biomass; (II) assessment of the effect of integration of the mixed-fuel IGCC plant with different types of post-combustion CO_2 capture, namely, solvent-based, algal routes and their combination, (III) evaluation of the effect of integration of biodiesel unit with a mixed-fuel IGCC plant with post-combustion CO_2 capture through algal route. Energy and environmental analyses of all the options (I, II &III) have been performed. The parametric sensitivities of avoidance in CO_2 emissions (ACE) and the energy return on energy investment (EROEI) were analyzed against important system parameters. All the analyses are based on ASPEN Plus® simulation data. At first, a systematic process model using ASPEN Plus® has been developed for a 30 TPD IGCC power plant co-fired by Indian coal and Agri-MSW-biomass mixture. The parametric sensitivity of EROEI and ACE were analyzed with respect to the input variables, Agri-MSW -biomass to coal ratio, gasifier temperature and the ratio of supplied air to that required for complete combustion. Optimization of EROEI and ACE of the Co-fired IGCC power plant was performed using Design Expert software. A systematic process model using ASPEN Plus® was then developed for the optimally operated 30 TPD IGCC power plant co-fired by Indian coal and Agri-MSW-biomass mixture, integrated with monoethanolamine (MEA) -based post-combustion CO_2 capture with and without regeneration of solvent. Next, the ASPEN Plus® model was developed for the same IGCC plant integrated with algal CO_2 capture separately using Chlorella *Vulgaris*, *Nannochloropsi*s *spp* and *Scenedesmus spp*. Energy return on energy investment (*EROEI)* was also calculated for the IGCC plant integrated with solvent-based and algal CO_2 capture considering the use of a) in-house power and b) grid power. *EROEI* was calculated for the 30 TPD co-fired IGCC plant integrated with a hybrid system of solvent based CO_2 capture and algal CO_2 capture and utilization considering the use of a) in-house power and b) grid power. Among all CO_2 capture options, EROI of the IGCC plant integrated with hybrid system of CO_2 capture achieves the highest value. Finally, EROEI for an integrated IGCC-algal CO_2 capture unit, coupled with biodiesel production, was also determined considering the use of a) in-house power and b) grid power. For In-house power consumption option, there is a marked increase in the EROEI values with the integration of biodiesel unit. This is due to the consideration of substitution of a part of energy from product biodiesel. The outcome of this research is expected to be useful in taking strategic decisions on running IGCC power plants using a combination of coal and Agri-MSW based biomass as feed. It is

expected that the assessment of performance of energy return and CO_2 avoidance of different CO_2 capture and utilization units will further facilitate the implementation of the plan of Government of India to use biomass along with coal in the power generation sector.

Preamble

Current global energy supply is to a large extent based on fossil fuels (oil, natural gas, coal), of which the reserves are finite. Given the growing world population, the increasing energy consumption per capita, and the evidence of global warming, the necessity for long-term alternative energy sources is obvious. For these twin crises of fossil fuel depletion and environmental degradation, energy planning and technology improvement have become the important public agenda of most developed and developing countries. Biomass is a promising eco-friendly alternative source of renewable energy in the context of current energy scenarios.

The IPCC (Inter-governmental Panel on Climate Change) has identified six anthropogenic gases with climate change potential. These are CO_2, CH_4, N_2O, SF6, (chlorofluorocarbons), and HFC'S (hydro-fluorocarbons) [1]. Although CO_2 has the lowest global warming potential among the green house gases, it has the largest global climate change impact because its total emissions are much greater than the others. Thus, more research efforts preempting climate change should focus on strategies for reduction of CO_2 emissions.

Fuel switching from high carbon to low carbon ones is an important strategy for CO_2 emissions mitigation. Biomass, an abundant agricultural and municipal waste of India, also represents the class of hydrocarbon with a much lower carbon intensity than coal. If coal is replaced by biomass, the actual fuel combustion will be carbon neutral. All associated carbon emissions will be caused by ancillary collection, processing, transportation etc. To mitigate the issue of pollution created by stubble burning, Government of India has already ordered every state to plan for co-firing of agro residues in existing power plants [2]. Municipal solid wastes (MSW) can also serve as a source of biomass. Instead of following conventional power generation using solid fuel mixtures, Integrated Gasification Combined Cycle (IGCC) power plants based on syngas generated from the mixture of solid fuel (coal+biomass) are more reliable, energy efficient and less polluting with respective to their conventional counterparts [3].

The capturing of CO_2, being released into the atmosphere during power generation, is another strategy for the reduction of CO_2 emissions. The capture may be performed either pre-combustion or post-combustion and there are a number of potential storage destinations: aquifers, depleted oil and gas reservoirs, coal seams, deep ocean floor. Among different post-capture processes, absorption using chemicals, e.g., amines; bio-capturing of CO_2 through algal cultivation and hybridization of absorptive and algal processes are promising options. The production of biodiesel from algal lipids can further increase the merit of bio-capture of CO_2. IGCC power plants using the mixture of coal and biomass along with the integration of post-combustion CO_2 capture systems can mitigate the problem of CO_2 emissions from this sector. It is obvious that power plants always operate at large scale and the extensive real time data using the mixture of biomass and Indian coal are absolutely unavailable. For the development of a guideline to take the strategic decision on the setting up of mixed fuel power plants in near future, process modeling and simulation can serve as an important tool to save the expenditure of real time large scale experiments and to get the immediate understanding of the effects of different variables on this non-conventional power generation systems.

To explore the possibility of the usage of agricultural and MSW derived lignocellulosic biomass with coal in the Indian power sector, in detail, the present research studies will be focused in the following directions: (I) an evaluation of the prospect of a IGCC power plant based on mixture of coal and Agri-MSW-based biomass; (II) assessment of the effect of integration of the mixed-fuel IGCC plant with different types of post-combustion CO_2 capture and (III) evaluation of the effect of hybridization of biodiesel unit with a mixed-fuel IGCC plant, already integrated with algal CO_2 capture. Energy and environmental analyses of different alternatives will be used as the basis of the comparison of the performance of different options.

1.1 Indian Agricultural wastes

In Table 1.1, the availability, higher heating value and the energy potential of major Indian Agricultural wastes have been provided [4-8].

Table 1.1 Availability, Higher heating value and Energy Potential of Indian Agricultural wastes

Indian crops and corresponding wastes		Annual availability (Kt/Year)	MJ/kg	PJ/Year	Ref
Rice waste: 161893.00 kT/Year	Rice Straw Rice husk	141120.00 20773.00	15.76 14.48	2224.05 300.79	[4]
Wheat (straw)		122991.00	13.77	1693.58	[4]
Sugarcane wastes: 114761.00kT/Year	Sugarcane bagasse Sugarcane tops &leaves	73775.00 40986.00	17.20 13.52	1268.93 554.13	[4]
Banana waste: 67776.00kT/Year	Banana fruit peels Banana pseudo-stem	393.00 67383.00	8.38 14.77	3.29 995.25	[4]
Millets (stalks, cobs, husk) Jowar+Bajra+Ragi		42669.8	15.27	651.56	[7]
Cotton waste: 38281.00kT/Year	Cotton stalks Cotton hull	35397.00 2884.00	14.39 21.94	509.36 63.27	[4]
Maize waste: 33720.00 kT/Year	Maize straw Maize cobs	28396.00 5324.00	16.72 13.39	474.78 71.29	[4]
Mustard waste: 16877.00kT/Year	Mustard press cake Mustard seedpod Mustard stalks	2681.00 1355.00 12841.00	13.97 19.88 15.40	37.45 1.37 197.75	[4]
Pulses* (stalks, husk)		13462.90	14.32	192.788	[4, 8]
Coconut waste: 9060.00 kT/Year	Coconut fronds Coconut shell Coconut coir pith	7769.00 726.00 565.00	17.06 20.05 17.20	132.54 14.55 9.72	[4]
Groundnut (shells)		1385.00	18.55	25.69	[4, 5]
Sesame (stalks)		1207.70	19.95	24.09	
Areca nut (fronds, husk)		1000.80	19.06	19.076	[4, 6]
Soybean husk		671.00	15.76	10.57	[4]

It is evident from the literature that the annual energy input potential (9475.874PJ or 300477MW) of Indian agro-wastes is equivalent to 300477MW of input power. Even at 50% energy efficiency of power generation, the output bio-power is comparable to the coal-based thermal power generation of 194553MW in India [4, 8].

1.2 MSW of India

Due to rapid urbanization, the volume of MSW in India is increasing at a very high rate. A detailed understanding of the mass and composition of Indian MSW is necessary for its proper utilization as an auxiliary feedstock for power plants along with coal.

1.2.1 Generation of MSW in Indian Metros

The amounts of MSW generated in Indian metro cities in 2020 are shown in Table 1.2 [4].

Table 1.2 MSW generation rates in different metro cities in India as per Annual Report on Solid Waste Management (2020-21), CPCB, Delhi [9]

City	MSW generated (TPD)
Mumbai	11000
Delhi	8700
Kolkata	4000
Chennai	5000

1.2.2 Compositions and sources of MSW of Kolkata

Overall characterization of MSW of Kolkata shows that a major portion of around 61.2% of it is constituted of lignocellulosic fraction namely paper waste, garden waste, textile waste, cardboard, wood (wooden packing) etc.[10]. The distribution of MSW according to their sources is shown in Figure 1.1 [11]. A representative composition of overall MSW, excluding metal, has been represented in and in Figure 1.2 [11]. Figure 1.1 shows that the largest contribution of MSW is from commercial and market areas (≈36.37%), followed by households (≈34.20%) and street sweeping (≈22.80%). Educational institutions contribute the minimum MSW(≈ 6.32%).

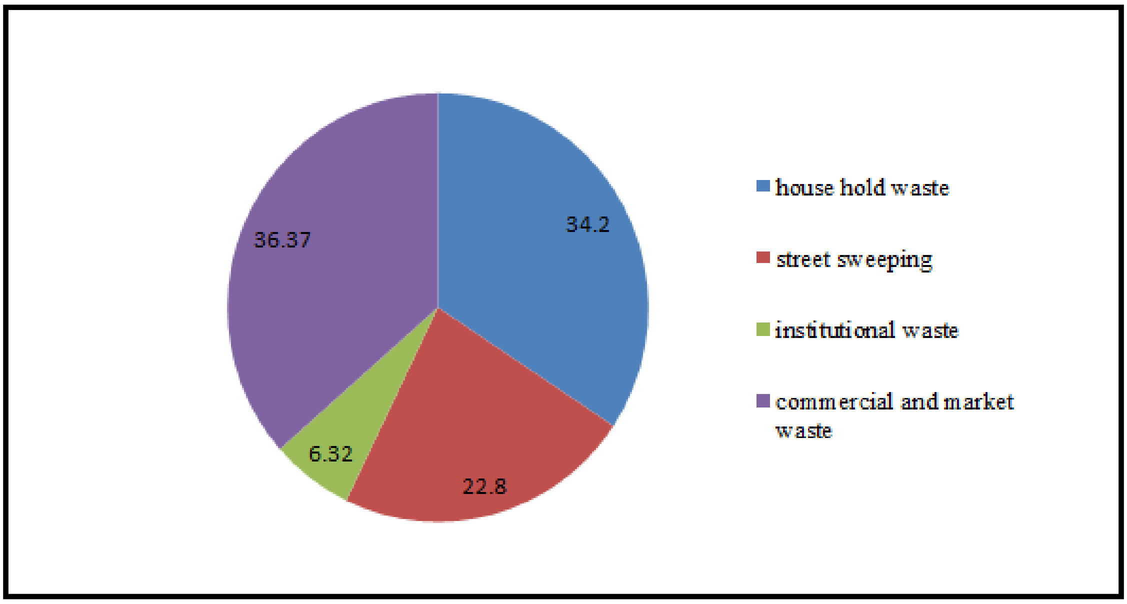


Figure 1.1 Distribution of MSW generated from several sources of KMC [11]

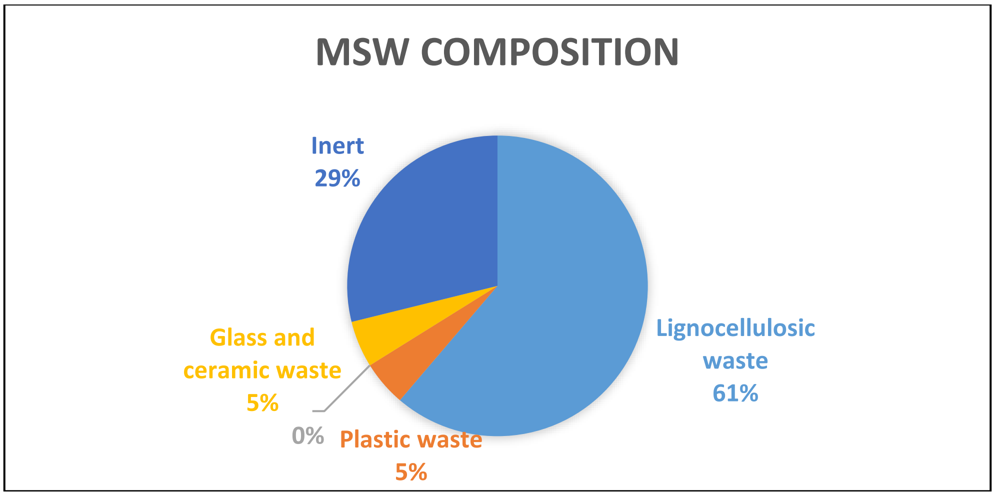


Figure 1.2 MSW compositions generated in Kolkata [10]

From the overall composition of MSW, represented in Figure 1.2, it appears that about 61% is constituted of lignocellulosic waste. The distribution of lignocellulosic waste (paper ≈80.2%,garden waste≈11.6%, and textile waste ≈8.2%) is shown in Figure 1.3.

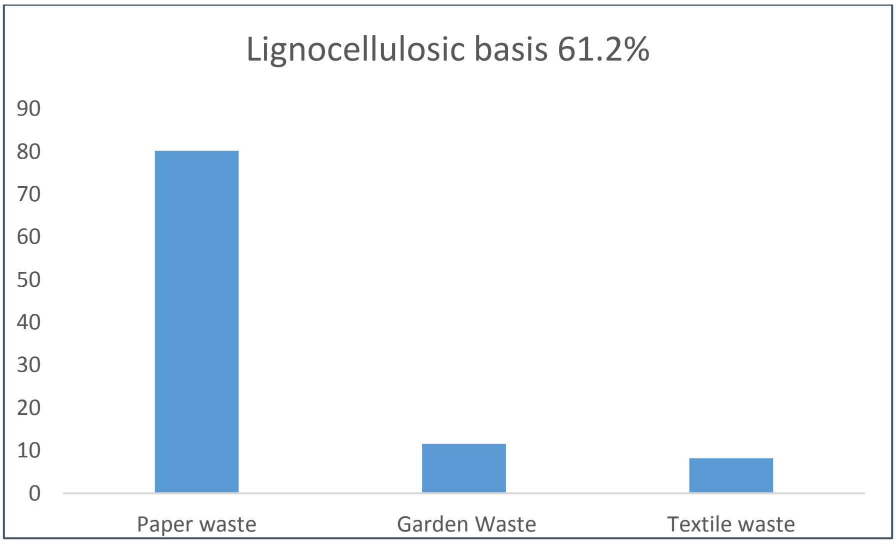


Figure 1.3 The compositions of lignocellulosic part of MSW

The percentage of some of the constituents, being recycled is shown in Table 1.3.

Table 1.3 Availability of recyclables items at the 'SWM' site of KMC [12]

Component	(%) recycled (w/w)
Coconut shell	1.1
Paper	0.9
Cardboard	0.3
Textile wastes	0.2
Wood	0.2

Major part of non-recycled lignocellulosic wastes is dumped on open landfilling sites, and a small portion, 8.5% of wastes is processed through aerobic composting [13–19]. This part can be used as an auxiliary fuel, co-fed with coal in power plants. IGCC plant is a promising option for low carbon power generation using the mixture of lignocellulosic part of MSW and coal.

1.3 IGCC Power generation

IGCC is one of the promising clean coal technologies (CCT) which ensures cleaner utilization of coal for power generation by reducing the CO_2 emissions load to the atmosphere [20, 21,23]. IGCC power plants are based on the combination of gas and steam turbines. The gas turbine is run on synthesis gas ($CO+H_2$) produced through the gasification of any carbonaceous feedstock, namely, coal biomass etc.. The steam turbine is operated using steam generated through the waste heat recovery of the exhaust gas exited from the gas turbine. The IGCC plants are energy efficient and have low CO_2 emissions potential and high flexibility towards feed-stocks compared to conventional coal-fired power plants based on steam turbines. In Figure 1.4, the flowsheet of an IGCC plant is represented.

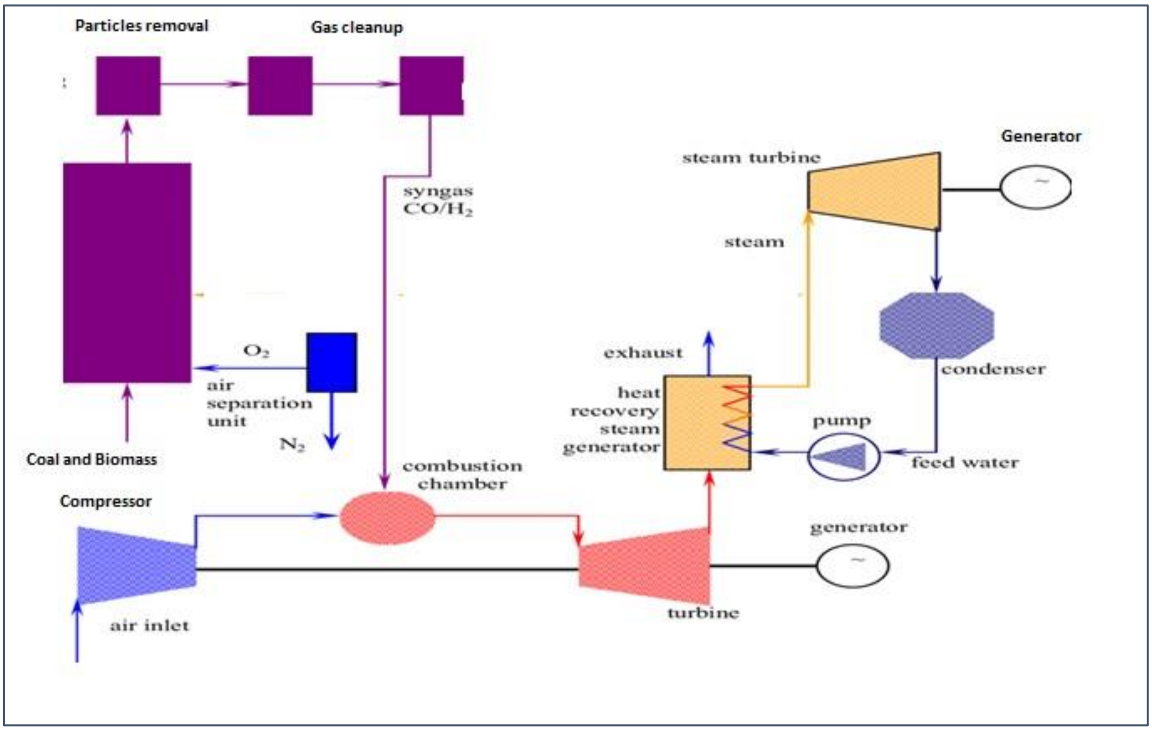


Figure1.4: Representative flowsheet of a IGCC power plant

The main thermochemical conversion process involved in the IGCC system is gasification. Through gasification, the carbon-based feedstocks are converted to syngas [24,27]. This gas can be utilized directly as a fuel for power generation in gas turbines, steam turbines etc. An integrated gasification combined cycle plant encompasses three steps: (1) Gasification; (4)-Gas cycle, and (5) Steam cycle.

1.3.1 Gasification

Mainly four stages, namely, drying, pyrolysis, combustion, reduction, and gasification are involved in the process.

1.3.2 FeedStock Drying

Drying of feedstock occurs at <150°C and causes removal of moisture [21]

1.3.3 Pyrolysis

During pyrolysis (150-700°C) thermal degradation of feedstock leads to the formation of char and volatiles. While the non-condensable volatile product, i.e., the gaseous part is constituted of H_2, CO, CO_2, CH_4, and some other light hydrocarbon gases. The condensable non-aqueous volatile part is mainly high molecular weight hydrocarbons, namely tar [22]. The pyrolysis process is represented in Figure 1.5.

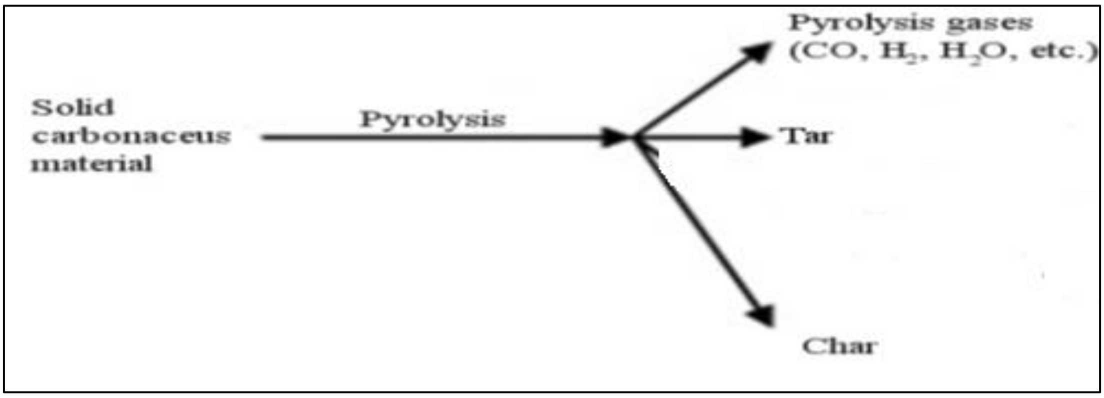


Figure 1.5. Pyrolysis pathways

1.3.4 Combustion, Reduction and Gasification

In the combustion zone (700-1500°C), some of the solid feedstock is combusted to form CO_2 and H_2O . During reduction (800-1100°C), CO_2 reacts with char to form CO (Boudouard reaction). Besides, a further reaction between H_2O with CO (Water-shift reaction), CH_4 (methane reforming), and methanation (reaction of char with hydrogen) can also occur [23]. While the combustion reaction is exothermic in nature, reduction and gasification reactions are endothermic. Some tar cracking reactions and formation of ammonia and H_2S can also occur during gasification. The heat required for endothermic reactions is supplied by exothermic combustion reactions and hence the process can be run in a self-sustained way. Different reactions which may occur during gasification are provided in Table 1.4.

Table 1.4: Array of reactions in gasifiers

Reaction	**Reaction Name**	**Heat of reaction (ΔH) (kJ/mol)**	**Reaction Number**	**Ref.**
Drying				
$Biomass_{wet} \rightarrow Biomass_{dry} + H_2O_{(g)}$	-	-	(R1)	[21]
Pyrolysis			(R2)	[22]
$Biomass_{dry} \rightarrow Gas + Tar + Char$	-	-		
Heterogeneous reaction				
$C + O_2 \rightarrow CO_2$	Complete combustion	-394	(R3)	[30,31]
$C + 0.5\, O_2 \rightarrow CO$	Char partial combustion	-111	(R4)	[30,31]
$C + CO_2 \leftrightarrow 2CO$	Boudouard reaction	+172	(R5)	[30,31]
$C + H_2O \leftrightarrow CO + H_2$	Water-gas	+131	(R6)	[28-30]
$C + 2H_2 \rightarrow CH_4$	Methane formation	-74.8	(R7)	[30,31]
Homogeneous reactions				
$CO + 0.5O_2 \rightarrow CO_2$	CO partial combustion	-284	(R8)	[28-32]
$H_2 + 0.5\, O_2 \rightarrow H_2O$	Hydrogen combustion	-242	(R9)	[28-32]
$CO + H_2O \leftrightarrow CO_2 + H_2$	Water-gas shift (WGS)	-41.2	(R10)	[28-32]
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	Methane reforming	+206	(R11)	[28-32]
$CH_4 + 1.5\, O_2 \rightarrow CO + 2H_2O$	Methane partial combustion	-520	(R12)	[30,31]
H_2S and NH_3 formation reactions				
$H_2 + S \rightarrow H_2S$	H_2S formation	-	(R13)	[30,31]
$3H_2 + N_2 \rightarrow 2NH_3$	NH_3 formation	-	(R14)	[30,31]
Tar decomposition				
$pC_nH_x \rightarrow qC_mH_y + rH_2$	Tar cracking	-	(R15)	[28-32]
$C_nH_x + nH_2O \rightarrow \left(n + \frac{x}{2}\right) H_2 + nCO$	Steam reforming of tar	-	(R16)	[28-32]
$C_nH_x + nCO_2 \rightarrow \left(\frac{x}{2}\right) H_2 + 2nCO$	Dry reforming of tar	-	(R17)	[28-32]
$C_nH_x \rightarrow nC + \left(\frac{x}{2}\right) H_2$	Carbon formation	-	(R18)	[28-32]

The quality and quantity of the syngas are extremely dependent on various operating parameters like the mass flow rate of feedstock, type of gasifying agents, gasification temperature, pressure inside gasifier, equivalence ratio for instance, the thermo-chemical property and elemental composition of the feedstock also affect the production of syngas up to certain extent [25,27]. Therefore, it is economically infeasible as well as sufficiently time consuming to experimentally determine the optimum conditions of the gasification process for any particular feedstock. It is worth mentioning that operating parameter variation leaves a combined effect on the gasification system. Process modeling of syngas reactors is necessary for a-priori prediction of performance with the variation of input parameters like feedstock properties, temperature, solid to gasifying agent ratio etc. and optimization of reactor performance with respect to the energy and environmental analysis.

The syn-gas leaving the gasifier must be cleaned of gaseous compounds and particulates before it is fed to the gas turbine.

1.3.5 Gas Turbine

Gas turbine cycles (GTC) can be classified as constant pressure combustion GTC (CPC-GTC) and constant volume combustion GTC (CVC-GTC). Constant pressure combustion GTC is mostly used and follows Brayton cycle. The Brayton cycle for Gas Turbines is represented in Figure 1.6.

In this cycle the working fluid, usually air, is pressurized isentropically and is led to the combustion chamber where the fuel is burned under isobaric conditions. The high-pressure-high temperature combustion product, flue gas, expands in the gas turbine to generate mechanical work.

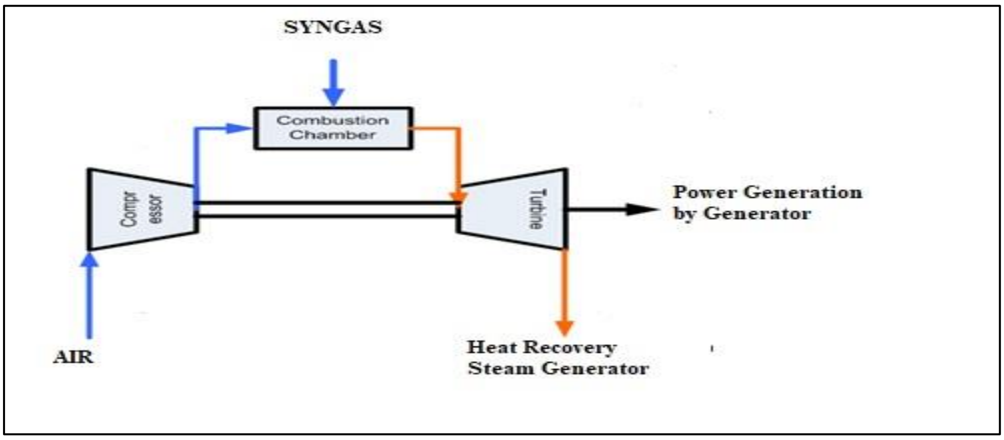


Figure 1.6. Brayton cycle for Gas Turbine

The exhaust combustion gas from the gas turbine enters the waste heat boiler of the steam turbine.

1.3.6 Steam Turbine

In the steam turbine Rankine cycle is used. The water is fed to a waste heat boiler where steam is generated by the recovery of waste heat from the flue gas exhaust of the gas turbine. The steam is compressed to a high pressure and is fed to a turbine to generate mechanical work. The low pressure steam exiting from the turbine is condensed and recycled to the waste heat boiler. The Rankine cycle for Gas Turbines is represented in Figure 1.7.

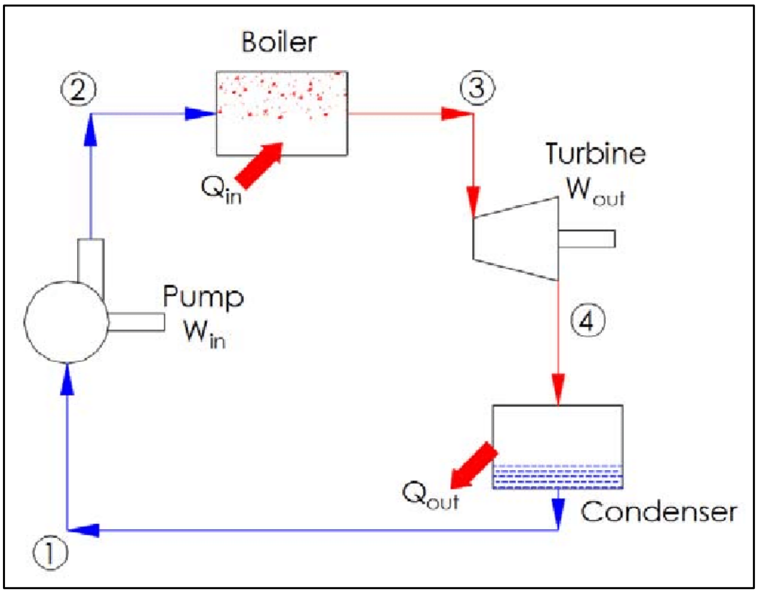


Figure 1.7. Rankine cycle for Steam Turbine

The mechanical work from the gas and steam turbines is converted into electrical energy in the generator.

1.4 Post combustion CO_2 capture

Among post-combustion capture strategies carbon capture and utilization is one of the promising ones. Carbon capture (CC) is the first step towards CCU. The captured CO_2 can either be I) utilized after desorption in a different process, or II) utilized simultaneously with the capture. CO_2 capture through the absorption by solvent is used as the first step in the CCU-type-I. The algal photosynthesis is an example of CCU-type-II.

1.5 CC by standalone solvent absorption process

Chemical absorption systems at present are the preferred option for post-combustion capture of CO_2 [33-36]. CO_2 is separated from the flue gas by passing the flue gas through a continuous scrubbing system. The system consists of an absorber and a desorber. Absorption processes utilize the reversible chemical reaction of CO_2 with an aqueous alkaline solvent, usually an amine. In the desorbed, the absorbed CO_2 is stripped from the solution and a pure stream of CO_2 is sent for compression while the regenerated solvent is sent back to the absorber. Heat is required in the reboiler to heat up the solvent to the required temperature; to provide the heat for desorption and to produce steam in order to establish the required driving force for CO_2 stripping from the solvent.

1.6 CCU using Algal route

Algal CCU is a completely eco-friendly green route for carbon capture and utilization [32-35]. Algal CO_2 capture involves a photosynthesis process which involves two stages. 1) light dependent and light-independent ones. In the light dependent stage, light energy is captured by Chlorophyl [28]. At the expense of light energy, ADP and NADP+ are converted to ATP and NADPH simultaneously with the production of oxygen. CO_2 is utilized in the light independent stage via the Calvin-Benson cycle and ultimately algal biomass is formed. The algal biomass is Calvin-Benson cycle in many biomolecules, namely carotenoids etc. Some algal species are rich in oil which can be further processed to generate biodiesel. Since it holds the prospect of production of low-emission renewable biofuels from the algal biomass, the overall process can become CO_2 neutral/negative.

1.7 Absorption-microalgae hybrid CCU

The absorption-algae hybrid the CCU comes under CCU-type-II category. In this system, an absorption-based CC is run using solvents. In the next step, the CO_2-rich solvent is introduced into an algal CCU where algal biomass is formed by the utilization of CO_2 transferred from the solvent to the aqueous culture medium.

1.8 Biodiesel from algal oil

Microalgae to biodiesel production mainly follows three sequential stages : (1) lipid extraction from dewatered algal biomass; (2) transesterification, and (3) recovery of biodiesel from reaction mixture. The algal lipid is converted to biodiesel through a transesterification reaction as follows:

$$Lipid + 3\ methyl/EthylAlcohol\ \rightarrow 3Fattyacid\ Methyl/Ethyl\ Ester\ +\ Glycerol$$

The fatty acid methyl or ethyl ester is biodiesel and can be used as a substitute for conventional diesel.

1.9 Process modeling

With the advent of information technology, process simulation has become an important tool for chemical industries. Process simulation can aid the chemical and petrochemical industries by providing inputs for the design, development, analysis and optimization of processes involved in them. The simulation tools can also be utilized by power plants and process industries. The standard Process simulators, namely, ASPEN Plus® etc., can forecast the real scenario well. Therefore, their performances are appreciated by the industries because of drastic reduction in cost and time in comparison to real time experiments. Process simulation can actually be placed at the core of an industry aiding Research and development, design and operation, as represented in the Figure 1.8 [41].

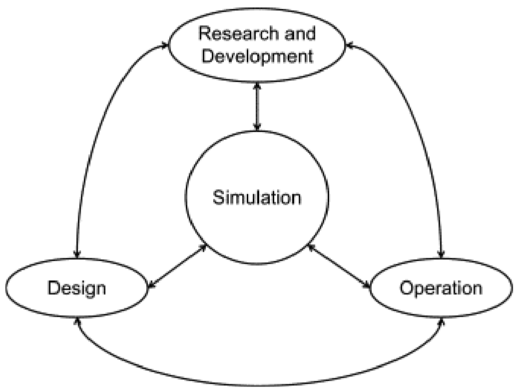


Figure 1.8. Networking of Process Simulation with R&D, Design and Operation

It is claimed that Process Simulation software are particularly useful for (1) the assessment of innovative sustainable technology and (2) improving, revamping and debottlenecking of existing industries. As claimed by ASPEN Plus® , Process simulation can act as a bridge between the initial planning to actual implementation of a technology [42].

1.10 References

[1] https://www.ipcc.ch- IPCC — Intergovernmental Panel on Climate Change, The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change.

[2] https://economictimes.indiatimes.com/industry/energy/power/power-ministry-asks-states-to-formulate-plans-for-biomass-co-firing-in-power-plants/articleshow/93085802.cms

[3] https://netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/igcc#:~:text=IGCC%20plants%20benefit%20from%20the,to%20other%20power%20generation%20technologies.

[4] Chowdhury, R., Ghosh, S., Debnath, B., & Manna, D. 2018. Indian Agro-wastes for 2G Biorefineries: Strategic Decision on Conversion Processes. In Sustainable Energy Technology and Policies (pp. 353-373). Springer, Singapore

[5] Perea-Moreno, M. A., Manzano-Agugliaro, F., Hernandez-Escobedo, Q., & Perea-Moreno, A. J. 2018. Peanut shell for energy: properties and its potential to respect the environment. Sustainability, 10(9), 3254.

[6] Ramesh, S., Sundararaju, P., Banu, K. S. P., Karthikeyan, S., Doraiswamy, U., & Soundarapandian, K. 2019. Hydrothermal carbonization of arecanut husk biomass: fuel properties and sorption of metals. Environmental Science and Pollution Research, 26(4), 3751-3761.

[7] Kuhe, A., Terhemba, A. V., & Iortyer, H. 2021. Biomass valorization for energy applications: A preliminary study on millet husk. Heliyon, 7(8), e07802.

[8] Subramanian, P., Nithiya, K., Chandrakumar, K., & Vikraman, V. K. 2022. Assessing the pyrolysis potential of redgram stalk: Thermo-kinetic study, empirical modeling and product characterization. Results in Engineering, 14, 100426.

[9] Annual Report on Solid Waste Management (2020-21), CPCB, Delhi

[10] Central Public Health and Environmental Engineering Organisation (CPHEEO), 2005. Manual on MSW management.

[11] Swapan Das, Bidyut Kr. Bhattacharyya. 2013. Municipal Solid Waste Characteristics and Management in Kolkata, India, International Journal of Emerging Technology and Advanced Engineering, 3(2).

[12] Kolkata Environmental Improvement Investment Programme, 2007.

[13] Gupta, P.K., Jha, A.K., Koul, S., Sharma, P., Pradhan, V., Gupta, V., Sharma, C., Singh, N., 2007. Methane and Nitrous Oxide Emission from Bovine Manure Management Practices in India. Journal of Environmental Pollution 146 (1), pp. 219–224.

[14] Malviya, R., Chaudhary, R., Buddhi, D., 2002. Study on solid waste assessment and management – Indore city. Indian Journal of Environmental Protection 22 (8), pp. 841–846.

[15] Kansal, A., 2002. Solid waste management strategies for India. Indian Journal of Environmental Protection 22 (4), pp. 444–448.

[16] Dayal, G., 1994. Solid wastes: sources, implications and management. Indian Journal of Environmental Protection 14 (9), pp. 669–677.

[17] Sharholy, M., Ahmad, K., Mahmood, G., Trivedi, R.C., 2006. Development of prediction models for municipal solid waste generation for Delhi city. In: Proceedings of National Conference of Advanced in Mechanical Engineering (AIME-2006), Jamia Millia Islamia, New Delhi, India, pp. 1176–1186.

[18] CPCB, 2000. Status of Municipal Solid waste Generation, Collection,Treatment and Disposal in Class I Cities, Series: ADSORBS/31/1999–2000.

[19] Reddy, S., Galab, S., 1998. An Integrated Economic and Environmental Assessment of Solid Waste Management in India – the Case of Hyderabad, India.

[20] Changyou Xi, Bin Ye, Jingjing Jiang, YutongShu· 2020. Prospect of near-zero-emission IGCC power plants to decarbonize coal-fired power generation in China: Implications from the GreenGen project, Journal of Cleaner Production, 271, 122615

[21] Zhou Xing, Zhou Ping, Zhao Xiqiang, Song Zhanlong. 2021. Applicability of municipal solid waste incineration (MSWI) system integrated with pre-drying or torrefaction for flue gas waste heat recovery, Energy, 224, 1 120157

[22] Shisong Ren Xueyan Liu Peng Lin Sandra Erkens 2022. Influence of swelling-degradation degree on rheological properties, thermal pyrolysis kinetics, and emission components of waste crumb rubber modified bitumen, Construction and Building Materials, 337(27), 127555

[23] Jin Hui Zhao Xiao Guo Liejin Zhu Chao Cao Changqing Wu Zhenqun. 2017. Experimental investigation on methanation reaction based on coal gasification in supercritical water International Journal of Hydrogen Energy, 42(7) 16, pp 4636-4641

[24] Davison, J., Bressan, L. and Domenichini, R. 2004. CO2 capture in coal-based IGCC power plants. in Seventh International Conference on Greenhouse Gas Control Technologies. Vancouver, Canada.

[25] Pruschek, R., G. Oeljeklaus, V. Brand, G. Haupt, G. Zimmermann, and J.S. Ribberink. 1995. Combined-Cycle Power-Plant with Integrated Coal-Gasification, CO Shift and CO2 Washing. Energy Conversion and Management, **36**(6-9): p. 797-800.

[26] Ordorica-Garcia, G., P. Douglas, E. Croiset, and L.G. Zheng. 2006. Technoeconomic evaluation of IGCC power plants for CO2 avoidance. Energy Conversion and Management, **47**(15-16): p. 2250-2259.

[27] Maurstad, O.,2005. *An overview of coal based Integrated Gasification Combined Cycle (IGCC) technology*. MIT LFEEE: Cambridgre, MA. p. 43. 18.

[28] S. Tata, C.P. Manosh, K. Nader. 2019. Investigation of coal particle gasification processes with application leading to underground coal gasification, Fuel, 237, pp. 1186-1202

[29] J. Wang, K. Sakanishi, I. Saito. 2005. High-yield hydrogen production by steam gasification of hypercoal(ash-free coal extract) with potassium carbonate: comparison with raw coal, Energy Fuels, 19, pp. 2114-2120.

[30] J. Wang, M.Q. Jiang, Y.H. Yao. 2009. Steam gasification of coal char catalyzed by K2CO3 for enhanced production of hydrogen without formation of methane, Fuel, 88, pp.1572-1579

[31] Ganesh Samdani, Anuradda Ganesh, Preeti Aghalayam R.K. Sapru, B.L.Lohar SanjayMahajani. 2017. Kinetics of heterogeneous reactions with coal in context of underground coal gasification, Fuel,199, pp.102-114

[32] Umesh Kumar Manosh C. Paul. 2020. Sensitivity analysis of homogeneous reactions for thermochemical conversion of biomass in a downdraft gasifier, Renewable Energy, 151, pp. 332-341

[33] Mofarahi M, Khojasteh Y, Khaledi H, Farahnak A. 2008. Design of CO2 absorption plant for recovery of CO2 from flue gases of gas turbine. Energy, 33, pp.1311–1319.

[34] Pennline HW, Luebke DR, Jones KL, Myers CR, Morsi BI, Heintz YJ. 2008. Progress in carbon dioxide capture and separation research for gasification-based power generation point sources. Fuel Process Technol,89, pp. 897–907.

[35] Romeo LM, Lara Y, Lisbona P, Martínez A. 2009. Economical assessment of competitive enhanced limestones for CO2 capture cycles in power plants. Fuel Process Technol, 90, pp. 803–811.

[36] Singh D, Croiset E, Douglas PL, Douglas MA. 2003. Techno-economic study of CO2 capture from an existing coal-fired power plant: MEA scrubbing vs. O2/CO2 recycle combustion. Energy Convers Manage, 44, pp. 3073–3091.

[37] Cuellar-Bermudez SP, Garcia-Perez JS, Rittmann BE, Parra-Saldivar R. 2014. Photosynthetic bioenergy utilizing CO2: an approach on flue gases utilization for third generation biofuels. J Cleaner Prod, 1(13).

[38] Lam MK, Lee KT, Mohamed AR. 2012. Current status and challenges on microalgae based carbon capture. Int J Greenhouse Gas Control, 10, pp. 456–469.

[39] Pires JCM, Alvim-Ferraz MCM, Martins FG, Simões M. 2012. Carbon dioxide capture from flue gases using microalgae: engineering aspects and biorefinery concept. Renew Sustain Energy Rev,16, pp. 3043–3053.

[40] Van Den Hende S, Vervaeren H, Boon N. 2012. Flue gas compounds and microalgae: (bio-) chemical interactions leading to biotechnological opportunities. Biotechnol Adv, 30, pp. 1405–1424.

[41] Integrated Design and Simulation of Chemical Processes, By Alexandre C. Dimian, Costin Sorin Bildea, Anton A. Kiss 2014 Elsevier

[42] https://www.aspentech.com/en/apm-resources/process-simulator-software

CHAPTER 2

LITERATURE REVIEW

An intense literature survey over last ten years have been performed on IGCC plants fed on mixture of coal and biomass. IGCC with Solvent-based CO_2 capture, Algae-based CCU integrated with co-fired power plants. Algae-based CCU for co-fired power plants with biodiesel generation and Hybrid CCU using solvent-based CC and algal CCU for co-fired power plants. The topic-wise, research status and gaps have also been identified.

2.1 IGCC power plant

Year of publication	Parameters	Observation	Reference
2021	• Feed-stock: **MSW** • Capacity of power plant: **1500 TPD** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not:**Yes**	• An assessment on the conversion of MSW to energy using three models, namely a) MSW to thermal energy and b) MSW to electricity on 1500 MSW ton/day and c) 750 MSW ton/day scales was reported. • On the basis of the assessment, electricity generation from MSW on both the scales was recommended showing the potential of energy generation and reduction of CO_2 emissions	[1]
2021	• Feed-stock: **biomass with coal** • Capacity of power plant: **650 MW** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Compared the CO_2 emissions of BIGCC plant with coal based plant. • They reported that negative CO_2 emissions from the plant can be achieved by BIGCC plant with CCS while near zero emissions can be achieved by coal-based plant with CCS plant. • They also compared the efficiency of IGCC with coal based plant and increased the efficiency by 3%	[2]

Year of publication	Parameters	Observation	Reference
2021	• Feed-stock: **biomass with coal** • Capacity of power plant: **Not addressed** • Real time experiment/process modeling: **laboratory experiment** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Their result shows that process performance and CO_2 emissions can be reduced by co-firing of biomass and coal. • Increasing the replacing of coal to 30% by biomass as a result CO_2 emissions decreased which reduce the overall efficiency of the gasification due to lower heating value of biomass.	[3]
2021	• Feed-stock: **MSW** • Capacity of power plant: 13**0 MW** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not:**Yes**	• Studied three configurations - I. MSW based IGCC power system, II. MSW-based IGCC polygene ration system, III. CaO-based IGCC polygene ration system • Result shows that CO_2 concentration in flue gas is higher for design 3 compared to design 1, design 2 • Pointed out that overall exergy efficiency of design 3 is lower than other design 1 and design 2.	[4]
2020	• Feed-stock: **MSW and petroleum sludge** • Capacity of power plant: **1350 TPD** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emission analysis is performed or not:**Yes**	• Both IPGCC (Integrated-Plasma gasification combustion cycle) and IGCC (Integrated-gasification combustion cycle) were established to be viable for the conversion of mixture of petroleum coke and MSW to electricity	[5]
2020	• Feed-stock: **MSW** • Capacity of power plant: **1200 TPD** • Real time experiment/process modeling:	• A life cycle analysis of MSW to energy through conventional gasification	[6]

Year of publication	Parameters	Observation	Reference
	process modeling • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not:**Yes**	processes showed attractive findings with respect to environmental impacts, namely, eutrophication, acidification, marine aquatic ecotoxicity and human toxicity potentials. • Plasma gasification turned out to be more advantageous with respect to all environmental impacts. • Based on the LCA analysis, MSW was projected to be a sustainable energy feedstock globally	
2020	• Feed-stock: **coal and biomass** • Capacity of power plant: 270 **MW** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not:**Yes**	• Studied a novel biomass fueled integrated gasification combined cycle. • To improve the efficiency of the proposed plant, they adopting the cascade CO_2 combined cycle and chemical looping air separation unit. • Result shows that higher plant efficiency of the proposed model compared to other conventional plant.	[7]
2019	• Feed-stock: **coal and biomass sludge** • Capacity of power plant: **10 MW** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **No** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Studied on efficiency improved for gasification unit utilizing liquid CO_2 slurries for enhanced biomass conversion using ASPEN Plus® simulation. • Used of CO_2 as a co-reactant, there result shows that the slurry	[8]

Year of publication	Parameters	Observation	Reference
		medium to be energy efficient while having a lower overall GHG footprint.	
2019	• Feed-stock: **coal** • Capacity of power plant: **150 MW** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Conducted techno-economic assessment IGCC plants. • Compared of three types of oxy-fuel IGCC power plants with different air separation configurations. • Also calculated the IRR for above three power plants.	[9]
2017	• Feed-stock: **70% wood pellets and 30% coal** • Capacity of power plant: **40 MW** • Real time experiment/process modeling: **studied with existing plant** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Conducted study on existing integrated gasification combined cycle power plant. • Developed the CO_2 negative IGCC power plant utilizing 70% biomass in the fuel feed. • Result on exergy analysis indicated that exergy destruction due to GT combustion.	[10]
2017	• Feed-stock: **coal, wheat straw and wood chips** • Capacity of power plant: 5**00 MW** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Conducted process modeling of IGCC Cofiring on coal and biomass. • CO_2 emissions estimated and compared with respect to coal replacement by using biomass. • Optimized the plant efficiency , minimize the CO_2 emissions.	[11]
2017	• Feed-stock: **coal and MSW** • Capacity of power plant: **Not specified** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **No**	• Article reported an Aspen Plus® model of co-gasification of MSW and coal, developed for the evaluation of potential for hydrogen	[12]

Year of publication	Parameters	Observation	Reference
	• Whether CO_2 emissions analysis is performed or not:**Yes**	production • Conversion of a biogenic fraction of MSW to energy has been reported to solve waste management issue as well as the crisis of energy demand	
2017	• Feed-stock: **coal and MSW** • Capacity of power plant: **4800 TPD** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not:**Yes**	• The co-combustion of MSW with additional fuel in a rotary kiln of cement plant was used efficiently for cement production and electricity generation	[13]
2016	• Feed-stock: **coal and biomass** • Capacity of power plant: **600 MW** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not:**Yes**	• Conducted process modeling of IGCC on existing coal based power plant. • CO_2 emissions estimated and compared among high performance plant, medium performance and low performance plant. • Also reported that atmospheric load of CO_2 can be reduced by Co-firing with biomass IGCC plant.	[14]
2014	• Feed-stock: **Forest biomass residue with coal** • Capacity of power plant: **100 MW** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **No** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Studied the Cofiring forest biomass with coal up to 20% substitution o by heat value. • They pointed out that the emissions can be decreased by 15% for CO_2, 95% for CH_4, 18% for NO_X, 82% for PM_{10}, and 27% for SO_X. PM_{10} and CH_4 emissions due to Cofiring with displacement of 20%.	[15]

Year of publication	Parameters	Observation	Reference
2014	• Feed-stock: **two different grade coal** • Capacity of power plant: **300 MW** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **No**	• Conducted IGCC plant using two different type of coal #1 and coal #2 having different heating value. • Evaluated and compared the efficiency with respect to two type of coal.	[16]
2014	• Feed-stock: **coal, olive husk, grape seed meal** • Capacity of power plant: 335 **MW** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Studied IGCC plant Cofiring with 2 wt%, 4 wt% biomass. • Developed the process model and validated with industrial data. • Result indicated that IGCC plant Cofiring with 60 wt% biomass, 54% CO_2 emissions decreased and 20% loss of efficiency.	[17]
2014	• Feed-stock: **MSW** • Capacity of incineration plant: **1000 TPD** • Real time experiment/process modeling: **real time experiment** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• The strategy of using MSW as a feedstock for co-fired power plant, can open up a new direction to solve the challenges faced in handling mixed solid waste in urban and rural areas. • This can also provide a way to eliminate emissionss of methane and scarcity of space caused by presently practiced MSW management technology, namely, landfilling • Electricity generation and district heating were possible using municipal solid waste incineration plant.	[18]

Year of publication	Parameters	Observation	Reference
2011	• Feed-stock: **coal and wheat straw, Brassica carinata** • Capacity of power plant: **300 MW** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not:**Yes**	• Conducted IGCC using two sets of feed stock. • Compared the GHG emissions of biomass fired with cofired plant. Result shows that GHG emissions of biomass fired plant is higher compare to Cofiring plant. • From this study it is reported that Cofiring plant is more beneficial with biomass fired plant with respect to efficiency as well as GHG	[19]

2.1.2 Research status and gaps on on IGCC power Plant

:From the literature review, it is clear that the research on the utilization of mixture of biomass and coal in IGCC power plants is gaining interest over the years. Although MSW has also been used as a partial substitute for coal, in some studies, mixture of biomass derived from both agricultural and MSW sources has not been used. There is a scarcity of data in the field of IGCC power generation using Indian coal and biomass. Although in some research studies, energy efficiency and reduction of CO_2 emissions have been studied, no systematic studies on effects of different process parameters on the most important response parameters, namely, Energy return on Energy investment (EROEI) and avoidance of CO_2 emissions (ACE) in IGCC plants based on Indian coal and biomass has not been reported. Although the optimization of operating conditions for the maximization of EROEI and ACE is an important criterion, no such research results are available.

2.2 IGCC Plant with Solvent-based CO_2 capture

Year of publication	Parameters	Observation	Reference
2021	• Feed-stock: **Biomass and coal** • Capacity of power plant:**600 MW** • Solvent: **MEA** • Real time experiment/process modeling: **Process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Studied the large-scale operations of BECCS plants. • Established an incentives scheme with cost advantgaes for emission reduction and energy conservation in the power sector. • Aslo reported that decarbonization actions can mitigate the gas emissions from other energy	[20]
2021	• Feed-stock: **coal** • Capacity of power plant:**400 MW** • Solvent: **MEA** • Real time experiment/process modeling: **Process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Adopting the chemical absorption system for CO_2 capture of flue gas. Also modified and studied the energy-efficient process flow-sheet. • The efficiency of Heat Recovery Steam Generator (HRSG) unit increases by CO_2 capture from flue gas using Flue-Gas Injection (FGI) into the Heller tower of the powerplant	[21]
2019	• Feed-stock: **coal** • Capacity of power plant:**500 MW** • Solvent: **MEA** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emission analysis is performed or not: **Yes**	• This study carried out the assessment on carbon reduction and analysis the performance of an integrated syngas purification process for power generation • They recommended the CO_2 capture efficiency of 90% and they also reported that	[22]

Year of publication	Parameters	Observation	Reference
		this is an economical carbon capture efficiency.	
2019	• Feed-stock: **coal** • Capacity of power plant:**500 MW** • Solvent: **MEA** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Evaluated and compared the performance and economic measure of coal based IGCC power plants with other six different modelled. • Pointed out that a coal-based IGCC power plant might be economically feasible if a satisfactory decarbonization scenario plant is integrated with the IGCC plant, depending on a trade-off between the CO_2-specific emissions and the percentage of carbon capture.	[23]
2018	• Feed-stock: **Biomass** • Capacity of power plant:**25 MW** • Solvent: **MEA** • Real time experiment/process modeling: **Process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Studied the techno-economic comparative analysis of eight BIGCC system with CO_2 capture. • Reported that Selexol CO_2 removal technology is more economical than MEA CO_2 capture process.	[24]
2017	• Feed-stock: **three different Indian coal (Coal –A, Coal-B, and Coal-C)** • Capacity of power plant:**322 MW** • Solvent: **dimethyl ether of polyethylene glycol and DEPG** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or	• Studied the performance of IGCC plant with CCS using three different grade Indian coal • Evaluated the specific emissions and overall efficiency of IGCC plant with CO_2 captue.	[25]

Year of publication	Parameters	Observation	Reference
	not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Results show that the quality of the produced syngas from gasifier significantly depends on coal types. • Result also show that the IGCC plant with CO_2 capture using Coal B is the lowest one overall efficiency. And Coal C has the highest overall efficiency .	
2017	• Feed-stock: **coal** • Capacity of power plant:**500 MW** • Solvent: **MEA** • Real time experiment/process modeling: **Real time experiment** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Studied of installation of CCS on a 500MW unit together with integration of solar concentrator for steam generation for reducing energy penalty in regeneration • Developed a pilot plant for capture of CO_2 and converting the same into usefule fuel like hudrogen for fuel cell application. • Further developed a solar plant for steam generation for solvent regeneration to increase the plant efficiency	[26]
2016	• Feed-stock: **coal** • Capacity of power plant:**500 MW** • Solvent: **Chilled Ammonia** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Studied the IGCC plant with CO_2 capture by chilled ammonia. • Studied the specific energy consumption of CO_2 capture on three levels. • Result shows that specific energy consumption deceases when switching from chilled to cooled mode	[27]

Year of publication	Parameters	Observation	Reference
		of ammonia used for CO_2 capture.	
2015	• Feed-stock: **coal and water recycly fines** • Capacity of power plant:**560 MW** • Solvent: **blended solution of ammonia and AMP** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Modeled and simulated three configurations: IGCC with post-combustion capture, IGCC with pre-combustion capture, and IGCC without CO_2 capture.. • Results show that more power used for pre-combustion capture rather than post-combustion capture. • IGCC with post combustion CO_2 capture is more efficient than precombustion CO_2 capture.	[28]
2015	• Feed-stock: **coal** • Capacity of power plant:**500 MW** • Solvent: **MEA** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Studied IGCC power plant with a complete CLC-based considering the integration of the gasification stage with power production by a CLC combined cycle and CO_2 sequestration and storage. • Evaluated the energetic efficiency of power plant integrated with chemical-looping-combustion. • Reported that the significant energy saved in carbon capture and inducing an improvement of the overall power plant thermal efficiency of the plant.	[29]

Year of publication	Parameters	Observation	Reference
2014	• Feed-stock: **coal and water slurry** • Capacity of power plant:**500 MW** • Solvent: **MEA** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Studied the comparative performance assessment of USC steam plant and IGCC plant. • Evaluated the CO_2 removal efficiency of the USC and IGCC plant using ASPEN Plus®. • Results show that USC plant provides better performance than IGCC plant. • Also reported that IGCC plant is characterized by lower eenrgy penalties compared to USC if integrated with 70% CO_2 removal.	[30]
2014	• Feed-stock: **coal** • Capacity of power plant:**300 MW** • Solvent: **MEA** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Evaluated the thermodynamic performance of various IGCC plant. • Reported that NGCC plant is most efficient while SCPC is least efficient. • Determined the energy penalty of original IGCC plant with considering of different CO_2 capture efficiency. • Comparative study also conducted and comparied the COE and cost of CO_2 avoided.	[31]
2013	• Feed-stock: **coal** • Capacity of power plant:**250 MW** • Solvent: **MEA** • Real time experiment/process	• Studied the IGCC plant with respect to two cases. I. cold gas cleanup, II. Hot gas	[32]

Year of publication	Parameters	Observation	Reference
	modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	cleanup. • Result indicate that effiicncy is higher when CO_2 capture is applied to IGCC systems with hot gas clean-up.	
2012	• Feed-stock: **coal** • Capacity of power plant:**250 MW** • Solvent: **MEA** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• Article reported a rate-based Aspen Plus® simulation for flow-sheet modifications including vapor recompression processes and split-stream. • The effects of absorber pressure and packing height on the re-boiler duty have also been reported in a research article.	[33]
2011	• Feed-stock: **coal** • Capacity of power plant:**350 MW** • Solvent: **MEA** • Real time experiment/process modeling: **process modeling** • Whether Energy analysis is done or not: **Yes** • Whether CO_2 emissions analysis is performed or not: **Yes**	• The effect of modification has been assessed through the comparison of the performance of the modified version with that of the standard processes. • The energy requirement for regeneration of solvent for CO_2 desorption has also been examined by varying different process parameters. • It has been observed by a research group that regeneration energy is sensitive with respect to those process parameters	[34]

2.2.2 Research status and gaps on IGCC Plant with Solvent-based CO_2 capture

From the literature review, it is clear that some research studies have been reported on coal-based IGCC power plants integrated with solvent-based CO_2 capture units. One such study is based on Indian coal -based plants. Only a few reports are available on the biomass-based IGCC plants integrated with solvent-based CC. Very recently, a study has been published on an IGCC plant based on coal-biomass and integrated with solvent-based CC. More data should be generated on the Indian coal-biomass-based IGCC plants integrated with solvent based CC units. The energy penalty during the regeneration of solvent has been focused in one of the studies. However, more data is required on the coal-biomass-based IGCC power plants integrated with solvent based CO_2 capture and solvent regeneration. Research gap also lies from the perspective of optimization of process parameters for the maximization of energy return and the reduction in CO_2 emissions. It is known that the energy required for the CC unit can be derived either from the in-house power generated by the IGCC plant or from the grid, and the energy return and reduction of overall CO_2 emissions are expected to be different in these two cases. Any such study from these perspectives has not yet been reported.

2.3 Algae based CCU for IGCC Power Plants and others

2.3.1 Literature Data on Algae based CCU for IGCC Power Plants and others

Year of publication	Parameters	Observation	Reference
2016	Whether integrated with IGCC power plant: Yes Feed-stock:C**oal** Capacity of power plant:**500 MW** Capacity of open raceway pond: **Not specified** Name of algae: ***Nannochloropsis*** Real time experiment/process modeling: **Process modeling** Whether Energy analysis of integrated system is done or not: **No**	• Studied the bio-fixation of CO_2 emissions from ASCPF, IGCC, NGCC power plants through microalgae cultivation. • Result shows that efficiency for ASCPF is lowest compared to IGCC & NGCC. • Compared the specific investment cost and reported that lowest	[35]

Year of publication	Parameters	Observation	Reference
	Whether CO_2 emissions analysis of integrated system is performed or not: **No**	specific investment and BESP is associated with NGCC followed by ASCPF and IGCC.	
2015	Whether integrated with IGCC power plant: No, with conventional power plant Feed-stock:C**oal** Capacity of power plant: **1260 MW** Capacity of open raceway pond: **867 m3 of photo bioreactor** Name of algae: ***Scenedesmus obliquus*** Real time experiment/process modeling: **process modeling** Whether Energy analysis of integrated system is done or not: **No** Whether CO_2 emissions analysis of integrated system is performed or not:**No**	• Represented a systematic procedure of coupling a micro algal cultivation plant with a thermal power plant which lead to biodiesel production by reducing the CO_2 emissions from thermal plant. • Developed a Cofiring power plant using product algal biomass from cultivation unit.	[36]
2014	Whether integrated with IGCC power plant: No, with conventional power plant Feed-stock:C**oal** Capacity of power plant:40**0 MW** Capacity of open raceway pond: **300**	• Studied algal CO_2 capture including biodiesel production of steam power plant. • The system achived the significant environmental	[37]

Year of publication	Parameters	Observation	Reference
	m3 Name of algae: ***Scenedesmus obliquus*** Real time experiment/process modeling: **real time experiment** Whether Energy analysis of integrated system is done or not: **No** Whether CO_2 emissions analysis of integrated system is performed or not:**No**	improvements by reductions of CO_2 emissions. • Reported that product biodiesel can be substitute of fossil fuels as renewable fuels.	
2014	Whether integrated with IGCC power plant: Not integrated with any power plant Capacity of open raceway pond: **not defined** Name of algae: , ***Chlorella spp*** Real time experiment/process modeling: **review of process** Whether Energy analysis of integrated system is done or not: **No** Whether CO_2 emissions analysis of integrated system is performed or not:**No**	• Reviewed on the process effect, especially on the effects of microalgal species, photobiochemical process, hydrodynamic process, and physicochemical process on the performance of microalgal-CO_2 fixation and biomass production.	[38]
2014	Whether integrated with IGCC power plant: Not integrated with any power plant	• Reviewed on the process effect, especially on the	[39]

Year of publication	Parameters	Observation	Reference
	Capacity of open raceway pond: **not defined** Name of algae: , ***Chlorella sp. and Pseudochlorococcum sp*** Real time experiment/process modeling: **process studied** Whether Energy analysis of integrated system is done or not: **No** Whether CO_2 emissions analysis of integrated system is performed or not:**No**	effects of physicochemical process, microalgal species, photobiochemical process, and hydrodynamic process on the performance of biomass production and microalgal-CO_2 fixation.	
2012	Whether integrated with IGCC power plant: Not integrated with any power plant Capacity of open raceway pond: **not defined** Capacity of open raceway pond: **not defined** Name of algae: , ***Scenedesmus sp and Chlorella spp*** Real time experiment/process modeling: **process studied** Whether Energy analysis of integrated system is done or not: **No**	• Reviewed the strategies of CO_2 emissions mitigation by microalgal culture, photobioreactor systems used to cultivate the microalgae for CO_2 fixation, concentrating the microalgae by harvesting and dewatering methods, and product algae biomass used as applications of valuable by-products like biodiesel.	[40]

Year of publication	Parameters	Observation	Reference
	Whether CO_2 emissions analysis of integrated system is performed or not:**No**	• Reported that ***Chlorella spp*** have a low operation cost, high growth rate, high CO_2 fixation ability, low contamination risk.	

2.3.2 Research status and gaps on Algae based CCU for IGCC Power Plants and others

From the literature review, it is clearly evident that Nannochloropsis Scenedesmus sp and Chlorella spp are the microalgal species which have been studied for the CO_2 capture from IGCC plants. Although a few reports are available on the coal-based IGCC plants integrated with algal CCU, more data should be generated for the implementation of these biochemical CO_2 capture units, integrated with Indian coal-biomass based IGCC power plant. Although the algal CCU units also require energy for their operation, no reports are available on the overall energy return of IGCC power plants integrated with algal CCU.

2.4 Hybrid CCU using solvent based CC and algal CCU

2.4.1 Literature Data on Hybrid CCU using solvent based CC and algal CCU

Year of publication	Parameters	Observation	Reference
2018	Name of solvent :**sodium bi carbonate** Capacity of open raceway pond: **used photo bioreactor** Name of algae: ***Chlorella sp*** Real time experiment/process modeling: Review of process Whether integrated with power plant:No Whether Energy analysis of integrated system is done or not:No	• Reported that Chlorella sp. LPF is a saline-alkaline tolerant strain that can be sustained with higher pH values and a higher growth rate of algal biomass production. • Pointed out that Chlorella sp used bicarbonate as carbon source to promote the	[41]

Year of publication	Parameters	Observation	Reference
	Whether CO_2 emissions analysis of integrated system is performed or not:No	growth and lipid production and it also tolerated high concentrations of sodium bicarbonate.	
2018	Name of solvent : **diethanolamine (DEA) and potassium carbonate (K_2CO_3)** Capacity of power plant: Capacity of open raceway pond: **used photo bioreactor** Name of algae: ***Spirulina*** Real time experiment/process modeling: Reviewing of process Whether integrated with power plant:No Whether Energy analysis of integrated system is done or not: **No** Whether CO_2 emissions analysis of integrated system is performed or not:**No**	• Reported that chemical absorbent addition in *Spirulina* sp. LEB 18 cultivation can increase CO_2 biofixation, increase the biomass production, and molecules such as phycocyanin or carbohydrates. • Result shows that the mixture of K_2CO_3 and DEA added in the *Spirulina* sp. LEB 18 cultivation had significant effects on its growth.	[42]
2015	Name of solvent :**MEA** Capacity of power plant: Capacity of open raceway pond: Name of algae: ***Spirulina sp.*** Real time experiment/process modeling: Experimental study Whether integrated with power plant:No	• Studied the biofixation of CO_2 using amine solvent followed by algal cultivation. • Reported that in the cultivation with MEA, were obtained higher results of specific growth rate, CO_2 biofixation, biomass productivity,	[43]

Year of publication	Parameters	Observation	Reference
	Whether Energy analysis of integrated system is done or not: **No** Whether CO_2 emissions analysis of integrated system is performed or not:**No**	CO_2 use efficiency, and lower generation time. • Pointed out also that require higher concentrations of carbohydrates, such as in bioethanol production.	
2013	Name of solvent :**MEA, DEA, triiethanolamine (TEA)** Capacity of power plant: Capacity of open raceway pond: **used photo bioreactor** Name of algae: ***Scenedesmus sp*** Real time experiment/process modeling: Experimental study Whether integrated with power plant:No Whether Energy analysis of integrated system is done or not: **No** Whether CO_2 emissions analysis of integrated system is performed or not:**No**	• Studied the biofixation of CO_2 using different amine solvent followed by algal cultivation. • Reported that TEA exhibited a best enhancement in CO_2 fixation performance compared to other absorbents.	[44]
2013	Name of solvent :**sodium bio carbonate** Capacity of power plant: Capacity of open raceway pond: **used photo bioreactor** Name of algae: ***haloalkaliphilic cyanobacterium strain*** Real time experiment/process modeling: Experimental study	• Studied the biofixation using Bicarbonate-based Integrated Carbon Capture and Algae Production System (BICCAPS). • Recommended that a high biomass production rate can be achieved in a	[45]

Year of publication	Parameters	Observation	Reference
	Whether integrated with power plant:No Whether Energy analysis of integrated system is done or not:No Whether CO_2 emissions analysis of integrated system is performed or not:No	BICCAPS.	
2012	Name of solvent :**MEA** Capacity of power plant: Capacity of open raceway pond: **used photo bioreactor** Name of algae: ***Scenedesmus sp*** Real time experiment/process modeling: Experimental study Whether integrated with power plant:No Whether Energy analysis of integrated system is done or not:No Whether CO_2 emissions analysis of integrated system is performed or not:No	• Invesstigated on the influence of monoethanolamine (MEA) as a CO_2 absorbent on photoautotrophic culture of CO_2-fixing using *Scenedesmus sp* microalgae. • Result shows that CO_2-fixation rate increased with increase of MEA concentration	[46]

2.4.2 Research status and gaps on Hybrid CCU using solvent based CC and algal culture

From the literature review, it is evident that the hybrid CO_2 reduction systems utilizing the capture of CO_2 by solvent, followed by algal capture and utilization of CO_2 is advantageous over the stand alone solvent based CC and algal CCU. In this case, solvent regeneration occurs without any additional energy penalty. On the other hand, the yield of algae is higher when amine solvents are used instead of biocarbonate solutions. However, only lab-scale experiments have been reported. Till date, no data are available for integrated system of IGCC power plant and hybrid CO_2 capture. In-depth energy and environmental analysis should be conducted before the implementation of hybrid CO_2 capture units for power plants, particularly coal-biomass IGCC power plants.

2.5 Biodiesel from algal oil integrated with power plant

2.5.1 Literature Data on Biodiesel from algal oil integrated with power plant

Year of publication	Parameters	Observation	Reference
2017	Specification of power plant: Not provided Capacity of open raceway pond: **not defined** Name of algae: ***Chrysophyta and Chlorella sp*** Name of alcohol used in transesterification: **methanol** Real time experiment/process modeling: **process studied** Whether Energy analysis of integrated system is done or not: **No** Whether CO_2 emissions analysis of integrated system is performed or not: **No**	• Conducted a study on continuous biodiesel production for two kinds of microalgae *Chlorella sp.* and *Chrysophyta*. • Results showed that the temperature, pressure, particle size of microalgae, molar ration of methanol to oil, flow of CO_2 and n-hexane all have effects on the yield of biodiesel production.	[47]
2014	Specification of power plant: Not provided Capacity of open raceway pond: **not defined** Name of algae: ***chlorella sp. and Pseudochlorococcum sp*** Name of alcohol used in transesterification: **not defined** Real time experiment/process modeling: **process studied**	• Results show that the highest CO_2 biofixation rate has been observed using *Chlorella sp*. • Lipids extracted from Nannochlorpsis sp., harvested marine strain, and enzymatically transesterified to produce biodiesel in supercritical	[48]

Year of publication	Parameters	Observation	Reference
	Whether Energy analysis of integrated system is done or not: **No** Whether CO_2 emissions analysis of integrated system is performed or not: **No**	CO_2 (SCeCO2) medium. • Reported that the conversion of biodiesel produced from microalgae lipids was higher.	
2014	Specification of power plant: 400MW coal-based steam power plant Capacity of open raceway pond: **not defined** Name of algae: ***Spirulina, Chlorella*** Name of alcohol used in transesterification: **methanol** Real time experiment/process modeling: **process studied** Whether Energy analysis of integrated system is done or not: **No** Whether CO_2 emissions analysis of integrated system is performed or not: **No**	• Studied the feasibility of biodiesel production from microalgae as third generation biodiesel feedstock . • Reported that maximum biodiesel yield obtained using simultaneous extraction and transesterification using hexane as a solvent. • Established the potential of microalgae for biodiesel production.	[49]

2.5.2 Research status and gaps on Biodiesel from algal oil froduced from algal CCU integrated with power plant

Research status and gaps:From the literature review it appears that *Pseudo chlorococcum sp, Spirulina, Chrysophyta, Chlorella sp Pseudochlorococcum sp* are the microalgae which are rich in oil and have been utilized for the production of biodiesel. Only one report is available where a biodiesel plant is integrated with a conventional coal-fired power plant, not an IGCC plant. As the biodiesel unit also requires energy, in-depth studies should be oriented towards the generation of data for IGCC plants, integrated with biodiesel production units. Thorough energy and environmental analyses for the integrated systems are very much required**.**

CHAPTER 3

AIMS AND OBJECTIVES

Based on the literature review and the research gaps identified in Chapter 2 in the field of energy and environmental analyses of IGC power plant co-fed on coal and biomass and integrated systems of such plants with various types of CO_2 capture and utilization units, the research studies are conducted with the following aims and objectives with the relevant work plans:

<table>
<tr><td colspan="3">Aim 1: Selection of biomass and thermochemical characterization
The main objectives and work plan for Aim1 are as follows:</td></tr>
<tr><td>Objectives</td><td></td><td>Work Plan</td></tr>
<tr><td>▪ Selection of biomass</td><td>⟶</td><td>• Agri-MSW-based biomass constituted of abundant Indian agricultural waste and MSW biomass, mainly garden waste appearing in the municipal solid waste (MSW) of Kolkata was selected.</td></tr>
<tr><td>▪ Determination of thermochemical characteristics of the selected biomass</td><td>⟶</td><td>• The thermochemical characteristics of the selected Agri-MSW-based biomass were determined through proximate and ultimate analysis.
• Pyrolysis data of the selected Agri-MSW-based biomass were generated at 500°C by conducting experiments under nitrogen atmosphere.</td></tr>
<tr><td colspan="3">Aim 2: Comparison of energy and environmental performances of integrated gasification combined cycles (IGCC)- based power plants using coal and coal- Agri-MSW-based biomass mixtures
The main objectives and work plan for Aim 2 are as follows:</td></tr>
<tr><td>Objectives</td><td></td><td>Work Plan</td></tr>
<tr><td>▪ Generation of energy and material flow data for an IGCC power plant run on only coal and mixtures of coal and Agri-MSW-based biomass</td><td>⟶</td><td>• Using process simulation software, the data on energy output and the CO_2 emissions of a 30TPD power plant were determined using the ratio of coal to biomass; gasification temperature and the supply of air as parameters.
• Optimization of pairs of parameters, namely,</td></tr>
</table>

		(a) ratio of coal-to- Agri-MSW-based biomass and gasification temperature; (b) ratio of coal-to- Agri-MSW-based biomass and % of air required for complete combustion to maximize energy return and CO_2 avoidance.
Aim 3: Energy performances of the 30 TPD IGCC power plant with CO_2 capture using solvent-based absorption The main objectives and work plan for Aim 3 are as follows:		
Objectives		**Work Plan**
▪ Generation of data on the energy return and CO_2 emissions avoidance for an IGCC power plant with CO_2 capture using solvent	→	• Optimization of MEA absorption using response surface methodology based on ASPEN generated data. • Using process simulation software, the energy return and the CO_2 avoidance were calculated for the IGCC plant integrated with a CO_2 capture system based on absorption using monoethanolamine (MEA) with solvent recovery considering the use of in-house power and grid power. • Using process simulation software, the energy return and the CO_2 avoidance were calculated for the IGCC plant integrated with a CO_2 capture system based on absorption using monoethanolamine (MEA) without solvent recovery considering the use of in-house power and grid power. • Comparison of energy return for the IGCC plant integrated with a CO_2 capture system based of absorption using MEA with and without solvent recovery considering use of in-house power. • Comparison of energy return for the IGCC plant integrated with a CO_2 capture system

		based of absorption using MEA with and without solvent recovery considering use of grid power. • Comparison of CO_2 avoidance for the IGCC plant integrated with a CO_2 capture system based of absorption using MEA with solvent recovery considering use of in-house power and grid power. • Comparison of CO_2 avoidance for the IGCC plant integrated with a CO_2 capture system based of absorption using MEA without solvent recovery considering use of in-house power and grid power. • Comparison of the energy return and the CO_2 avoidance data of the IGCC plant with and without CO_2 capture (using MEA) using in-house power and grid power.
Aim 4: Energy performances of the 30 TPD IGCC power plant with CO_2 capture using three different types of micro algal cultivation and Algae to biodiesel production The main objectives and work plan for Aim 4 are as follows:		
Objectives		**Work Plan**
▪ Generation of data on the energy return and CO_2 emissions avoidance for an IGCC power plant with CO_2 capture using algal cultivation	⟶	• Using process simulation software, the energy return, and the CO_2 avoidance were calculated for the IGCC plant integrated with a CO_2 capture system using three different micro algal cultivation considering the use of in-house power. • Using process simulation software, the energy return and the CO_2 avoidance were calculated for the IGCC plant integrated with a CO_2 capture system using three different micro algal cultivation considering the use of grid power.

		• Comparison of the energy return calculated for the IGCC plant integrated with a CO_2 capture system using algal cultivation considering the use of in-house power and grid power. • Comparison of CO_2 avoidance were calculated for the IGCC plant integrated with a CO_2 capture system using algal cultivation considering the use of in-house power and grid power. • Comparison of the energy return and the CO_2 avoidance data of the IGCC plant with and without CO_2 capture using algal cultivation.
▪ Generation of data on the energy return and CO_2 emissions avoidance for an IGCC power plant with algal CO_2 capture and biodiesel production	⟶	• Using process simulation software, the energy return and the CO_2 avoidance were calculated for the IGCC plant integrated with a CO_2 capture system using algal cultivation followed by algae to biodiesel production considering the use of in-house power. • Using process simulation software, the energy return and the CO_2 avoidance were calculated for the IGCC plant integrated with a CO_2 capture system using algal cultivation followed by algae to biodiesel production considering the use of grid power. • Comparison of energy return were calculated for the IGCC plant integrated with a CO_2 capture system using algal cultivation followed by algae to biodiesel production considering use of in-house power and grid power. • Comparison of CO_2 avoidance were calculated for the IGCC plant integrated with

		a CO_2 capture system using algal cultivation followed by algae to biodiesel production considering use of in-house power and grid power. • Comparison of the energy return and the CO_2 avoidance data of the IGCC plant with and without CO_2 capture (using algal cultivation and followed by biodiesel production) .
Aim 5: Comparison of energy performance of the IGCC power plants integrated with CO_2 capture using standalone solvent absorption using MEA and Absorption-microalgae hybrid CO_2 capture The main objectives and work plan for Aim 5 are as follows:		
▪ Comparison of energy performance of the IGCC power plants integrated with CO_2 capture by standalone solvent absorption using MEA and Absorption-microalgae hybrid CO_2 capture system	→	• Based on the data generated using the process simulation software, the energy return of the IGCC plant integrated with a CO_2 capture system based solvent absorption route and absorption-microalgae hybrid CO_2 capture system were compared.

CHAPTER 4

MATERIALS
AND
EXPERIMENTALMETHODS

4.1 Feedstocks

Agri-MSW-based biomass

Sugar cane bagasse is one of the most abundant Indian agricultural waste biomass. Similarly, garden waste is the MSW based dry biomass which is lignocellulosic in nature. Hence in the present research, a 1:1 mixture of sugar cane bagasse and garden waste of Kolkata municipal corporation has been characterized and considered as the Agri-MSW-based biomass to be co-fed with coal.

Bituminous coal

Bituminous coal was used for this study as Cofiring of IGCC power plant and Coal Analysis data were supplied by Mahanadi Coal Ltd., Orissa.

4.2 Process Simulation

For process simulation, ASPEN Plus® was used. ASPEN Plus® is a simulation tool used for the prediction of the performance of large scale chemical processes through simulation, modeling and optimization using existing database in the built-in library of ASPEN Plus® and the information supplied by the user based on laboratory-scale experiments. The sensitivity analysis of plant and large scale plants and their economic evaluation is possible through the use of ASPEN Plus® with properly described material and energy schemes and the reaction involved in the process. Therefore, the ASPEN Plus® can be efficiently used for making strategic decisions to be made on the implementation of a new technology on industrial scale. In the present study, process simulation modeling using ASPEN Plus® has been used for the integrated system of the IGCC power plant, run on Indian coal and MSW, CO_2 capturing unit through absorption with solvent recovery and a micro algal CO_2 capturing unit.

4.3 Response surface methodology

Design Expert software is used for statistical modeling and design of experiments. A statistical model is developed under the situation where deterministic modeling is out of question due to lack of information on the physical and thermodynamic laws correlating the response variable with the input variables of a complex system. The statistical model connects any response variable, Y with the input variables, X_1, X_2, ...X_k by a function

$Y = \phi(X_1, X_2......X_k)$. Response surface methodology is particularly useful when the response variable is influenced by several variables and the ultimate objective is to optimize the response. The independent variables are called factors. The space with the coordinates X1, X2, ...Xk is called the factorial space. The geometric portrait of the response function in the factorial space is called the response surface, which may be depicted by contour diagrams.

4.4 Experimental methods

4.4.1 Proximate analysis

ASTM D 3175 – 85, ASTM D 3173 – 87, and ASTM D 3174 – 89 methods were used for the determination of volatile matter, moisture, and ashes respectively. The volatile matter and ash content of all feed stocks were determined using a muffle furnace. The moisture content of all feed stocks were determined using an Air oven.

4.4.2 Determination of higher heating value

The higher heating values of feedstock samples were determined by using bomb calorimeters (ASTM D 2015 – 85).

4.4.3 Ultimate analysis

Ultimate analyses of all feed stocks have been done using CHNSO analyzer at IACS, Kolkata to determine the elemental composition with respect to contents of carbon, hydrogen, nitrogen, sulfur and oxygen. The elemental compositions of char and pyro-oil obtained at 500 ^{o}C pyrolysis temperature.

4.4.4 Gas chromatograph (GC)

The analyses of gaseous product obtained from pyrolysis of Lignocellulosic feedstock have been done using Gas chromatograph (GC). The model number is Thermo Scientific 11065807.

4.5 Experimental set-up

Experimental set-up of pyrolysis of lignocellulosic based feedstock

Figure 4.1 shows the experimental set-up of pyrolysis of lignocellulosic feed material. A 640 mm long and 50 mm diameter cylindrical stainless steel fixed-bed reactor was placed horizontally in a tubular furnace. A stainless steel chain was used for hanging the pyrolysis reactor. This chain is attached to a weighing machine for continuous observing of the residual mass of solids for all feedstocks in the reactor. The furnace temperature was set at 773K for all feedstocks. The rate of heating was maintained at 10^{o}C/min. The pyrolyser was inserted into the furnace when the furnace temperature attained a pre-set value. Throughout the entire period of pyrolysis, the isothermal condition was maintained. Pyrolysis was carried out for one hour for all feedstocks at 773K. To maintain the inert atmosphere in the reactor and to sweep the volatiles produced during pyrolysis, throughout the experiment, nitrogen was supplied to the pyrolyzer at a rate of 0.833 L/min. The outlet stream of the pyrolyzer was mixed with nitrogen and the volatile product was directed to a water-cooled condenser, followed by a series of vessels placed in one ice bath. Finally, the pyro-gas was collected in a gas sampling bottle after passing through a silica gel bed. The organic part of tar i.e. pyro - oil was collected by extraction in a rotary evaporator using benzene and the quantity of pyro-oil was determined.

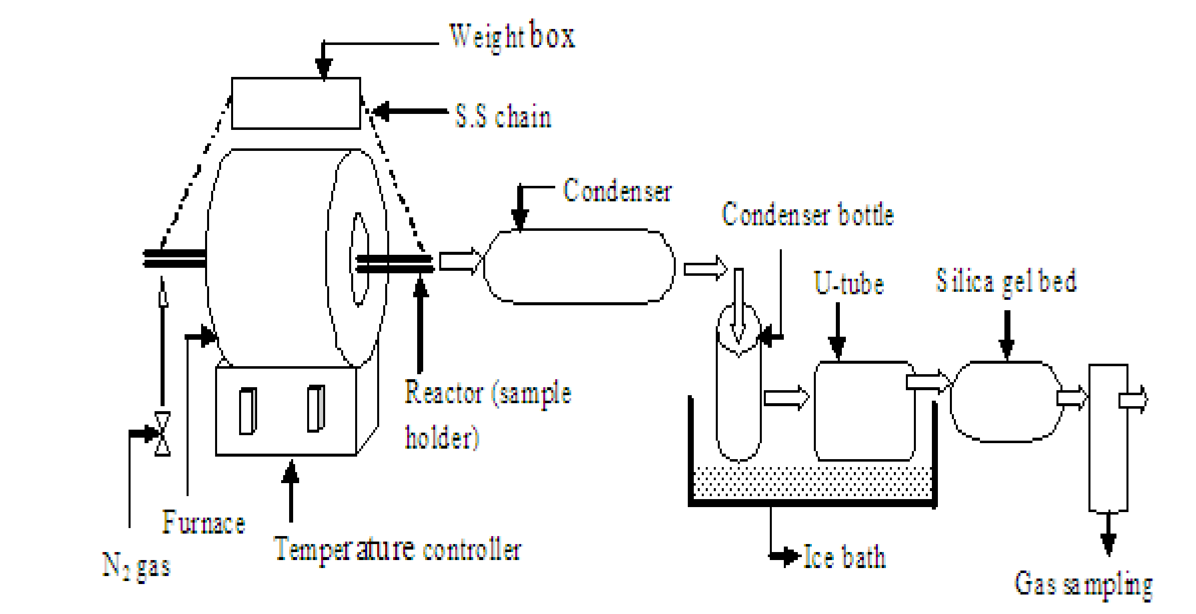


Figure 4.1 The schematic of experimental set-up of horizontal semi-batch reactor

4.6 Specification of analytical instruments used

4.6.1 Muffle furnace: A muffle furnace (Figure 4.2) was manufactured by the S.C.Dey Company, Kolkata, India.

Figure 4.2 Photograph of muffle furnace

4.6.2 Bomb Calorimeter: Bomb calorimeter (Figures 4.3) was manufactured by S.C.Dey Company, Kolkata, India.

Figure 4.3 Photograph of Bomb Calorimeter

4.6.3 Air Oven : Air Oven (Figure 4.4) was manufactured by G.B.Enterprise , Kolkata, India

Figure 4.4 Photograph of Air Oven

CHAPTER 5

THERMOCHEMICAL CHARACTERIZATION

5.1 Characterization of feedstock for IGCC plant

5.1.1 Results of Proximate and ultimate analyses

The higher heating values and the results of proximate and ultimate analyses of Agri-MSW-based biomass and coal, considered under this study, have been provided in Table 5.1

Table 5.1 Proximate and ultimate analyses and higher heating values of all feed stock

Method	Propoerties	Agri-MSW based Biomass	Coal
Proximate analysis	Volatile matter (wt%)	76.00	28.70
	Fixed carbon (wt%)	11.10	29.10
	Ash (wt%)	4.50	33.20
	Moisture (wt%)	8.40	9.00
Ultimate Analysis	Ash (wt%)	4.50	33.20
	Moisture (wt%)	8.40	9.00
	C% (w/w)	42.90	46.86
	H% (w/w)	6.30	2.94
	O% (w/w)	35.50	6.31
	N% (w/w)	1.84	1.22
	S% (w/w)	0.46	0.47
	Higher heating value (MJ/kg)	17.6	18.84

5.2 Yield of Pyro-products of Agri-MSW based Biomass and Indian coal

Figure 5.1 and 5.2 show the profiles of yields of pyro-solid, pyro liquid and pyro-gas, as obtained from the pyrolysis of Agri-MSW based Biomass and coal at 500^oC using the experimental procedure, described in Chapter 4. The results have also been provided in Table 5.2.

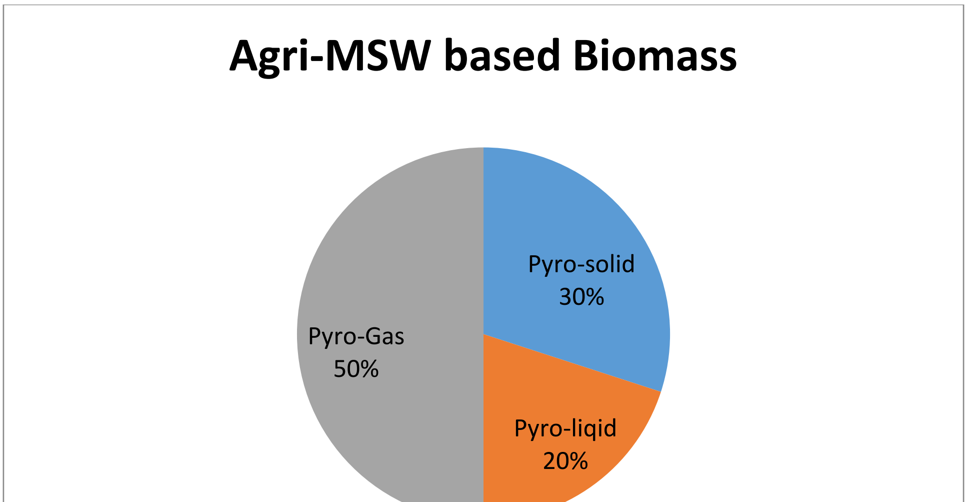


Fig 5.1a

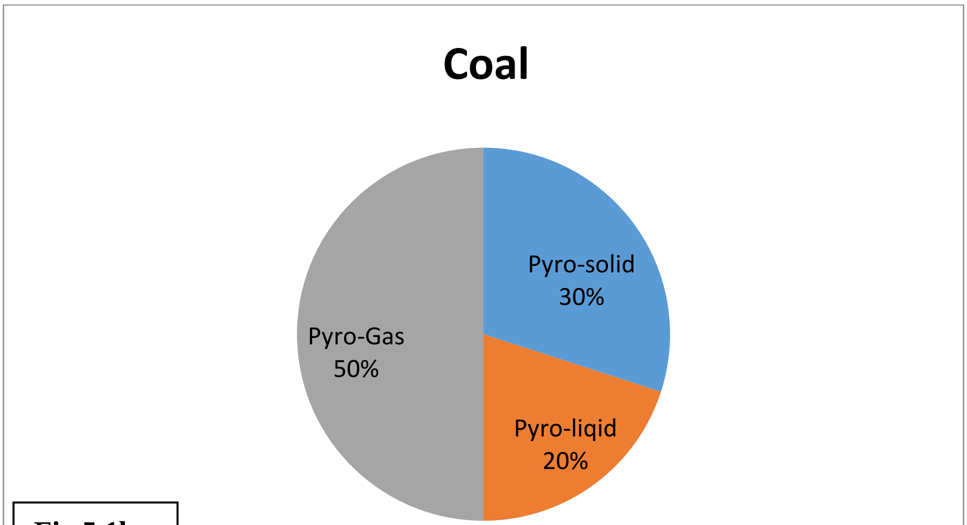


Fig 5.1b

Figure 5.1a and 5.1b Yield of Pyro-products of Agri-MSW based Biomass and coal

Table 5.2 Yield of Pyro-products of Agri-MSW based Biomass and coal

Pyro-product	**Agri-MSW based Biomass % (w/w)**	**Coal % (w/w)**
Pyro-solid	22	30
Pyro-liqid	20	20
Pyro-Gas	58	50

In case of Agri-MSW based Biomass, out of 22% Pyro-solid, ash and recalcitrant solid account for 7% and 15% respectively. Similarly, in case of coal, out of 30% pyro-solid, ash and recalcitrant solid account for 20% and 10% respectively.

5.3 Composition of Pyro-Gas from Agri-MSW based Biomass and Indian coal

The composition of dry pyro-gas has been analyzed for hydrogen, CO, CO_2, CH_4, and C_2H_4 using the gas-chromatograph, as described in Chapter 4. Considering NH_3 and H_2S as the gas constituents containing N and S, the concentration of NH_3 and H_2S has been determined by mass balance.

The composition of pyro- gas has been provided in Table 5.3.

Table 5.3 composition of pyro- gas from Agri-MSW based Biomass and Indian coal

Constituent	**Agri-MSW based Biomass %(w/w)***	**Coal %(w/w)***
CO	32.7	22.73
CO_2	4.03	3.25
CH_4	2.9	2.53
NH_3	2.2	1.095
H_2O	9.7	6.71
H_2S	0.48	0.627
C_2H_4	5.8	12.89
H_2	0.19	0.168

*__Basis: Weight of biomass/coal pyrolysed__

CHAPTER 6

IGCC POWER PLANT WITHOUT CO_2 CAPTURE

6.1 Introduction

The substitution of coal with carbon neutral waste biomass for power generation is one of the routes for mitigation of CO_2 emissions [1-3]. Biomass co-firing also provides other benefits. It requires a smaller initial investment with minor modifications compared with other lower emission technologies [4, 5]. This is because of the fact that the most common technology used in this integration is basically gasification followed by combustion and can be incorporated in any existing coal-fired power plant.

Although agricultural residues are the major source of biomass, Indian municipal solid wastes are also rich in biomass. The quantity of MSW is increasing at an alarming rate in India due to rapid urbanization and high population growth [5]. The strategy of using MSW as a feedstock for co-fired power plants, can open up a new direction to solve the challenges faced in handling mixed solid waste in urban and rural areas. This can also provide a way to eliminate emissions of methane and scarcity of space caused by presently practiced MSW management technology, namely, landfilling [6, 7]. Different reports are available on biomass integrated power plants [8-11]. From the literature review, it is clear that for the purpose of efficient waste management and environmental protection, the conversion of municipal solid wastes to energy, either alone or with coal is being researched by several groups [12-29]**.** Electricity generation and district heating were possible using municipal solid waste incineration plants [30]. Some studies have been reported on the generation of electric, thermal or mechanical energy as an alternative energy source in urban areas through the production of biogas from MSW by anaerobic digestion process [31, 34]. Biological treatment of leachate of landfill MSW, meant for establishment of sustainable system of solid waste management, was also reported by a research group [32]. Another article reported an Aspen Plus model of co-gasification of MSW and coal, developed for the evaluation of potential for hydrogen production [33]. The co-combustion of MSW with additional fuel in a rotary kiln of cement plant was used efficiently for cement production and electricity generation [35]. Conversion of a biogenic fraction of MSW to energy has been reported to solve waste management issues as well as the crisis of energy demand [36]. In a recent publication, an assessment on the conversion of MSW to energy using three models, namely a) MSW to thermal energy and b) MSW to electricity on 1500 MSW ton/day and c) 750 MSW ton/day scales was reported. On the basis of the assessment, electricity generation from MSW on both the scales was recommended showing the potential of energy generation and reduction of CO_2 emissions [37]. A life cycle analysis of MSW to energy through conventional gasification processes showed attractive findings with respect to environmental impacts, namely, eutrophication, acidification, marine aquatic ecotoxicity and human toxicity potentials. Plasma gasification turned out to be more advantageous with respect to all environmental impacts. Based on the LCA analysis, MSW was projected to be a sustainable energy feedstock globally [38]. According to a reported study, both IPGCC (Integrated-Plasma gasification combustion cycle) and IGCC (Integrated- gasification combustion cycle) were established to be viable for the conversion of mixture of petroleum coke and MSW to electricity [41]. In another report, IGCC using co-gasification of refused derived fuel (RDF) and lignite on different scales has been assessed and setting up of such projects has been advocated for environmental protection [44]. Considering the research gap in the area of IGCC plant operated using mixture of Indian coal and Agri-MSW -based lignocellulosic biomass, the main focus of this Chapter is to develop a process model of IGCC plant using a mixture of Indian Agri-MSW and coal using Aspen Plus® engineering tool. A statistical modeling using Response surface methodology has also been used to analyze the parametric sensitivity on energy return and avoidance of CO_2 emissions. In order to investigate the parametric sensitivity of the plant, Agri-MSW -coal ratio, gasifier temperature and the ratio of supplied air to that required for complete combustion have been used as input variables.

6.2 Materials and Methods

6.2.1 Design of Experiments and Optimization

As discussed in Chapter 4, one of the most important aspects of statistical modeling is the design of experiments, which is the strategy to obtain an adequate model with a minimum number of experiments. In this work, three-factor Box-Behnken design (BBD) has been used to examine the interaction effect of factors, namely, gasifier temperature (X_1), Agri-MSW -coal ratio (X_2) and the ratio of supplied air to that required for complete combustion (X_3) on response variables, namely, total CO_2 emissions avoidance (Y_1) and the energy return on energy investment (Y_2). When experiments are planned to correlate a dependent variable with multiple independent factors, Box-Behnken design (BBD) under RSM, based on an evenly spaced three level fractionate factorial principle, can be followed [45, 46]. A quadratic model is estimated by creating experimental planning according to BBD. This design is highly rotatable and generates strong coefficients at the center of the cube. BBD does not involve corner points on the hypercube and hence the experiments at the extreme conditions can be avoided without missing any adequacy of the model. As experimental runs signifies investment, the BBD is more cost effective than the plan of experiments following central composite design (CCD) [46, 47, 48, 49]. Under the present study, the combination of independent variables has been chosen following BBD. However, the accuracy of the model is also compared with that obtained using CCD.

The values of response variables have been generated using ASPEN Plus® model at the conditions pre-set by Box-Behnken design (BBD) of experiments. A second-degree polynomial Eq. (1) has been attempted.

$$Y = A_0 + A_1X_1 + A_2X_2 + A_3X_3 + A_{12}X_1X_2 + A_{13}X_1X_3 + A_{23}X_2X_3 + A_{11}{X_1}^2 + A_{11}{X_1}^2 + A_{22}{X_2}^2 + A_{33}{X_3}^2 \quad (1)$$

The values of *Y* at different combinations of X_1, X_2 and X_3, pre-set by Box-Behnken method of design of experiments, have been generated using ASPEN Plus® software. The Design Expert (Version 8.0.6, Stat-Ease Inc., Minneapolis, USA) software package has been used for experimental design, regression and response surface analysis.

6.2.2 Simulation Model Development using ASPEN Plus®

The block diagram of IGCC is shown in Figure 6.1. Process simulation model of IGCC using mixture of Agri-MSW -based lignocellulosic biomass and coal as feed-stocks has been developed by use of ASPEN Plus® and simulation flow sheet for IGCC is shown in Figure 6.3.

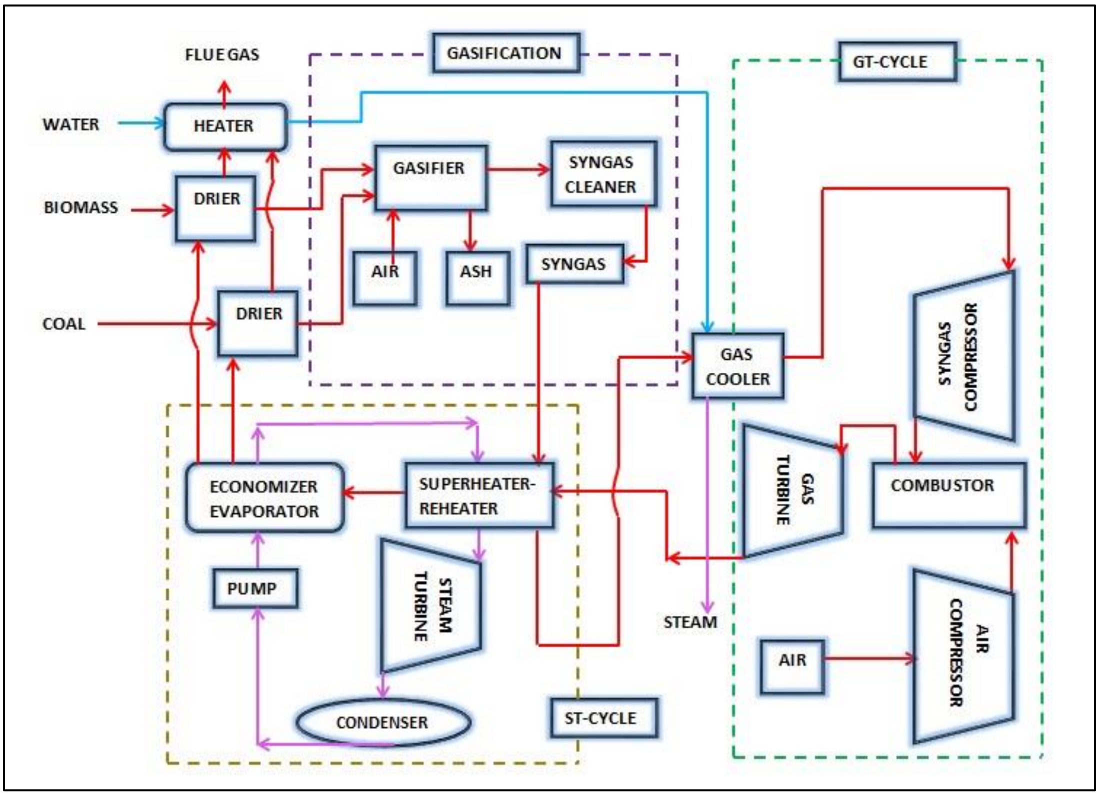


Figure 6.1. Block Diagram of IGCC

Since the thermodynamic data for biomass are not available in ASPEN Plus®, it is considered no-conventional. The steps followed for the modeling of gasification of coal and Agri-MSW -biomass mixture in ASPEN Plus® are represented in Figure 6.2.

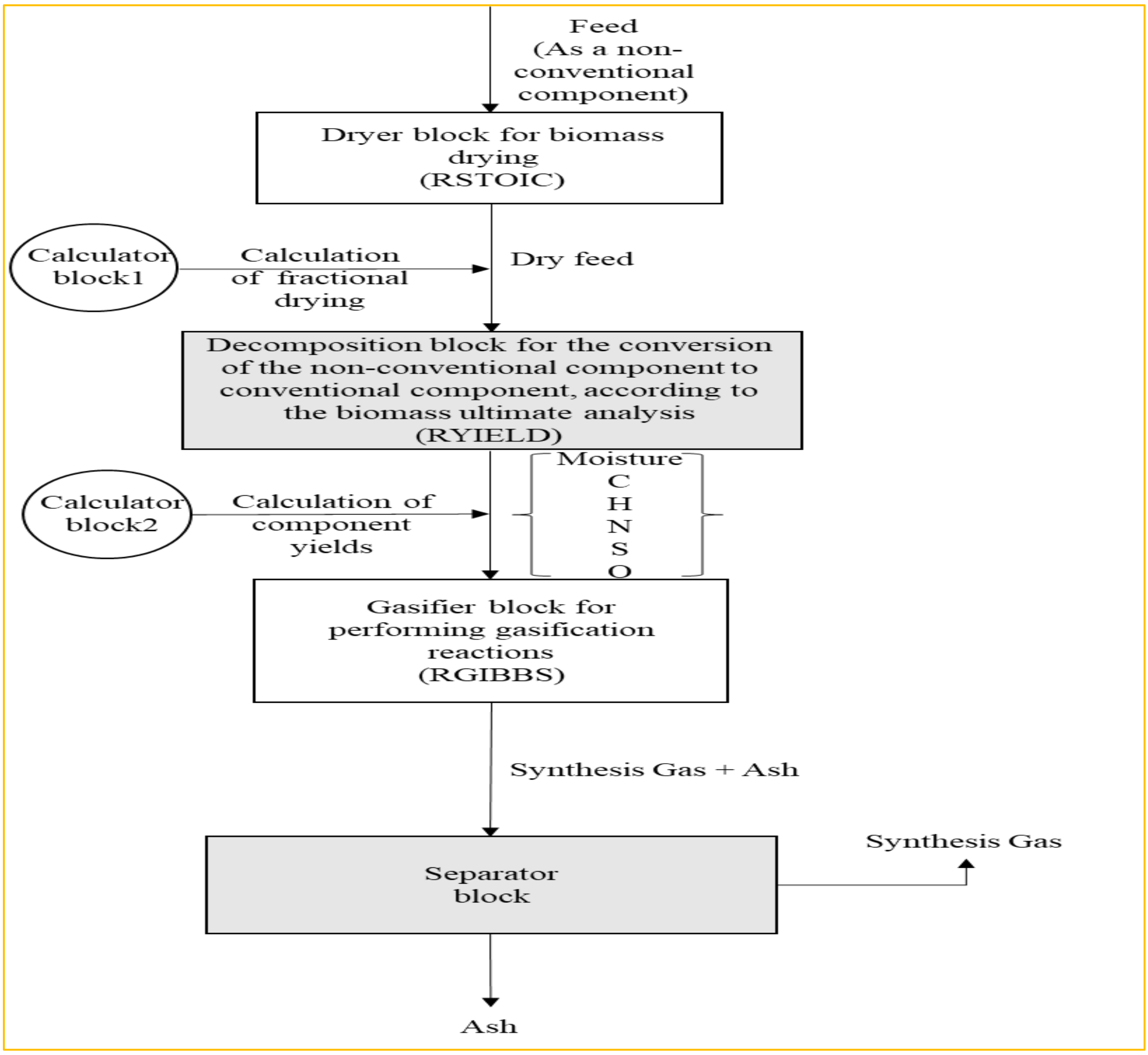


Figure 6.2 Steps to be followed for Gasification Model in ASPEN Plus®

Process simulation model of IGCC using mixture of Agri-MSW -based lignocelluloses biomass and coal as feed-stocks has been developed by use of ASPEN Plus® and simulation flow sheet for IGCC is shown in Figure 6.3.

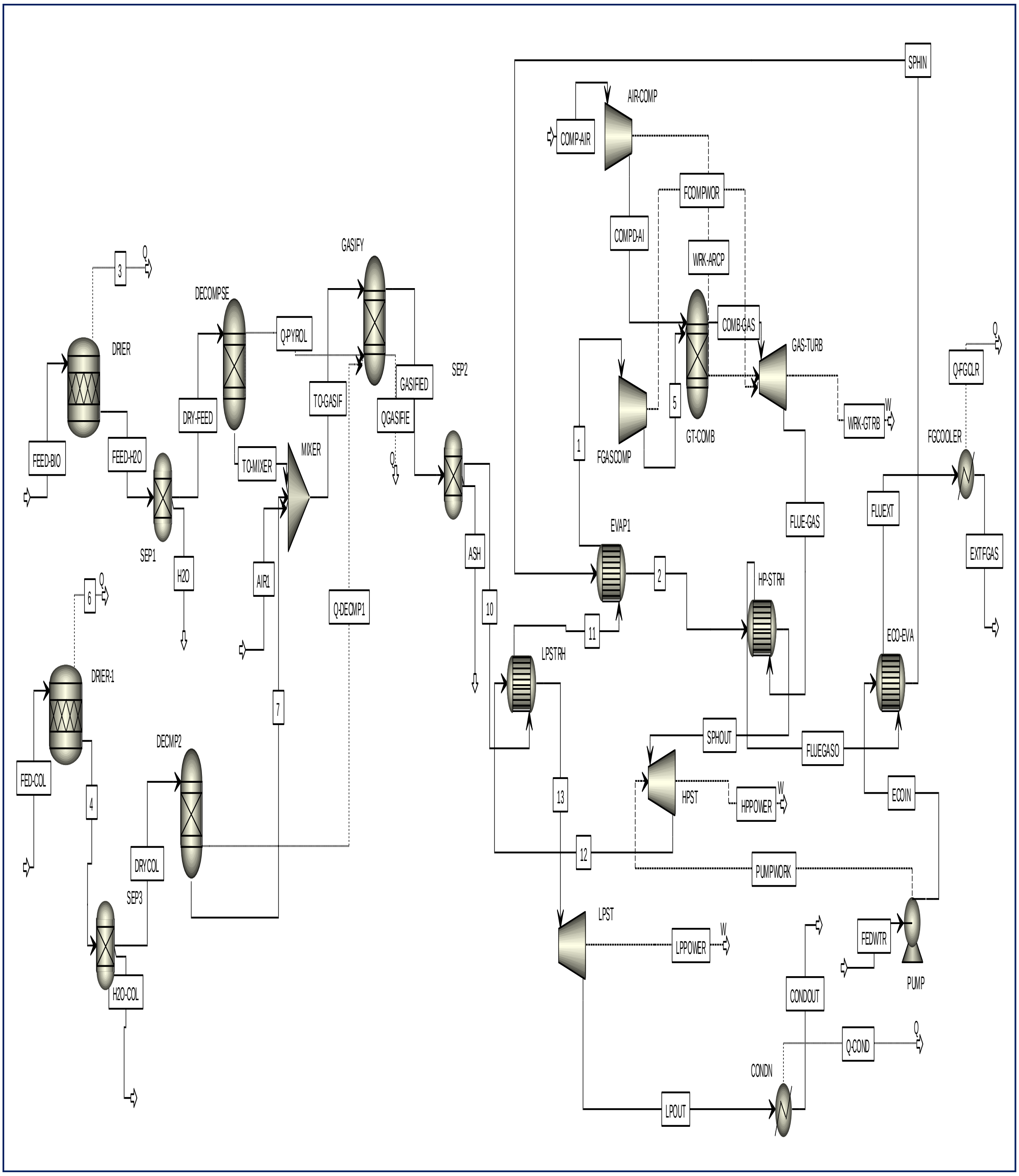


Figure 6.3. ASPEN Plus® simulation flow sheet for IGCC

All the blocks and components, used in the ASPEN Plus**®** flow sheet (Figure 6.3), is briefly described in Tables 6.1 and Table 6.2

Table 6.1 Description of the blocks used in the ASPEN Plus® modeling

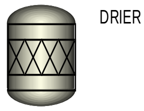
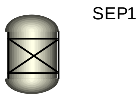
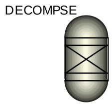
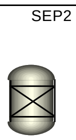
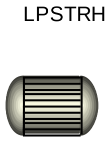
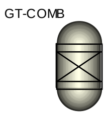
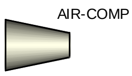
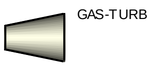
Block ID	Module selected	Schee	Description
DRIER	RSTOIC		DRIER 1 is used to dry the wet Agri-MSW biomass and DRIER 2 is used to dry the wet coal.
SEPARATOR	SEP2		SEP 2 is used to separate the water from dried Agri-MSW biomass and SEP3 is used to separate the water from coal
DECOMPOSE	RYield		DECOMPSE 1 is used to pyrolysis the dry Agri-MSW biomass and DECOMPSE 2 is used to pyrolysis the dry coal.
GASIFY	RGibbs		Gasifier unit is used to gasification of Cofiring mixture of Agri-MSW biomass and coal
SEPARATOR	SEP2		SEP 2 is used to separate the ash from syngas i.e. mixture of char, tar and gaseous product from Gasifier unit
REHEATERR	HeatX		LPSTRH is used to reheat the syngas. EVP1 is used to reheat the water for production of steam from Heat Recovery Steam Generator (HRST). HP-STRH is used to utilize the heat from exit flue gas from Gas Turbine unit to produce the steam for Steam Turbine. ECO-EVA is used to utilize the low heat recovery of the exit flue gas from HRST.
GT COMBUSTION	RGibbs		GT Combustion is used for combustion of compressed syngas to generate the power from Gas Turbine.
AIRCOMP	Compressor		AIRCOMP is used to supply the compressed air to GT Combustion unit
GAS TURBINE	Compressor		GAS-TURBINE is used to generate the power using combusted syngas
STEAMTURBINE	Compressor		HPST is used to generate power using high pressure steam. LPST is used generate the power using low pressure steam

Table 6.2: Detailed data of the components modeled in the simulation.

Component ID	Type	Component name	Formula
H_2O	Conventional	WATER	H_2O
CO	Conventional	CARBON-MONOXIDE	CO
CO_2	Conventional	CARBON-DIOXIDE	CO_2
CH_4	Conventional	METHANE	CH_4
QUINONE	Conventional	QUINONE	$C_6H_4O_2$
H_2	Conventional	HYDROGEN	H_2
N_2	Conventional	NITROGEN	N_2
O_2	Conventional	OXYGEN	O_2
BIOMASS	Nonconventional		
ASH	Nonconventional		
C_2H_6	Conventional	ETHANE	C_2H_6
C_3H_8	Conventional	PROPANE	C_3H_8
H_3N	Conventional	AMMONIA	H_3N
N-PRO-01	Conventional	N-PROPYL-BENZOATE	$C_{10}H_{12}O_2$
PHENO-01	Conventional	PHENOL	C_6H_6O
TOLUE-01	Conventional	TOLUENE	C_7H_8
BENZE-01	Conventional	BENZENE	C_6H_6
COAL	Nonconventional		
C_2H_4	Conventional	ETHYLENE	C_2H_4

The overall IGCC based co-generative power plant consists of four main islands- drying, gasification by stoichiometric air, power generation by gas turbine and power generation by steam turbine using steam generated through waste heat recovery. Sulfur-free data, based on ultimate analysis, reported in Table 5.1, are used in the ASPEN model. The thermo-chemical properties of Indian Agri-MSW based Biomass and coal, used in the model, are provided in Table 6.3.

Table 6.3 Thermo-chemical properties of Indian Agri-MSW based Biomass and coal, used in the ASPEN model

Method	**Propoerties**	**Agri-MSW based Biomass**	**Coal**
Proximate analysis	Volatile matter (wt%)	76.00	28.70
	Fixed carbon (wt%)	11.10	29.10
	Ash (wt%)	4.50	33.20
	Moisture (wt%)	8.40	9.00
Ultimate Analysis	Ash (wt%)	4.50	33.20
	Moisture (wt%)	8.40	9.00

Method	Propoerties	Agri-MSW based Biomass	Coal
	C% (w/w)	42.97	47.08
	H% (w/w)	6.71	2.95
	O% (w/w)	35.58	6.54
	N% (w/w)	1.84	1.23
	Higher heating value (MJ/kg)	17	18.84

6.2.3 Unit Operations and Processes

6.2.3.1 Drying

Moisture content of the Agri-MSW based Biomass and coal has been primarily reduced by drying process using RStoic reactors of ASPEN Plus® block. The separated water vapor is drained out of the process and the solid stream consists of dry Agri-MSW based Biomass and coal goes on to the next unit for the decomposition of dried feed.

6.2.3.2 Gasification

The gasification process is modeled with two reactors. The first reactor is decomposer reactor (RYield), which converts the non-conventional Agri-MSW based Biomass and coal into conventional components including Hydrogen (H_2), Oxygen (O_2), Carbon (C), N_2 and ash by specifying the yield distribution according to the feedstock's proximate and ultimate analysis.

The outlet stream from the decomposer reactor is fed to the second reactor (RGibbs). Gasification is modeled for Agri-MSW based Biomass and coal with stoichiometric air in gasifier according to following reactions.

$C + O_2$	$\leftrightarrow$	CO_2	Partial combustion of char	(2)
$C + H_2O$	$\leftrightarrow$	H_2+CO	Water gas reaction	(3)
$C + 2H_2$	$\leftrightarrow$	CH_4	Methanation reaction	(4)
$2H_2 + O_2$	$\leftrightarrow$	$2H_2O$	Hydrogen combustion	(5)
$CO_2+ C$	$\leftrightarrow$	$2CO$	Boundouard reaction	(6)
$CO+ H_2O$	$\leftrightarrow$	$CO_2 + H_2$	CO shift conversion	(7)
$CH_4 + H_2O$	$\leftrightarrow$	$CO + 3H_2$	Steam reforming of methane	(8)

The outlet stream from gasification unit is sent to cleaning unit for removal of dust particles and ash. The clean syngas is sent to a superheater-reheater to reheat the steam in the power cycle as well as removal of NH_3 from syngas by using a syngas cooler for improvement of the efficiency of the gas turbine of the combined cycle.

6.2.3.3 Power Generation using Gas Turbine and Steam Turbine

The clean syngas has then been utilized for power generation in a combined cycle which consists of a syngas compressor, air compressor and gas turbine. The clean syngas is fed to a combustion chamber via a syngas compressor with compressed air. In a combustion chamber, unreacted char and CO in syngas are oxidized to flue gas by compressed air. The highly pressurized flue gas is then expanded in a gas turbine for generation of power. Steam is generated in a heat recovery steam generator (HRSG), by the recovery of waste heat in the flue gas of the gas turbine.

6.2.4 Simulation by using ASPEN Plus®

6.2.4.1 Physical Property Method

In ASPEN Plus® model, the stream class has been set as MIXCINC which represents all the streams such as MIXED, CONVENTIONAL and NON-CONVENTIONAL. To estimate all physical properties of the conventional components for the IGCC based co-generative power plant, Redlich-Kwong-Soave cubic equation of state with Boston-Mathias alpha function (RKS-BM) has been used. Initial conditions of feedstocks and primary parameters in the model are summarized in Table 6.4

Table 6.4. Input parameters and operating conditions for IGCC [50]

Configurations	Parameters	Value
Inlet feed stream (mixture of Agri-MSW based Biomass and Coal)	Mass flow rate	1250 kg/hr
	Agri-MSW based Biomass - Coal Ratio (by mass)	20% - 80%
	Temperature	25^0C
	Pressure	1 atm
Gasifier	Temperature	600^0C - 900^0C
	Ratio of supplied air to that required for complete combustion	20% - 60%
	Pressure	1 atm
Syngas compression and Air compression for combustion	Isentropic efficiency	0.85
	Pressure ratio	14

Configurations	Parameters	Value
	Air mass flow rate	20% excess of complete combustion
Gas turbine	Isentropic efficiency	0.9
	Pressure ratio	14
HP steam turbine	Isentropic efficiency	0.9
	Discharge Pressure	30 bar
	HP steam temperature	570^{0}C
	HP steam pressure	70 bar
LP steam turbine	Isentropic efficiency	0.9
	Discharge Pressure	1.2 bar
	LP steam temperature	553^{0}C
	LP steam pressure	bar

6.2.5 Energy and environmental analysis

The energy and CO_2 emissions components used for the Energy Return on Energy Investment (*EROEI*) and Avoidance in CO_2 Emission (*ACE*) are schematically explained in the Figure 6.4 schematic diagram:

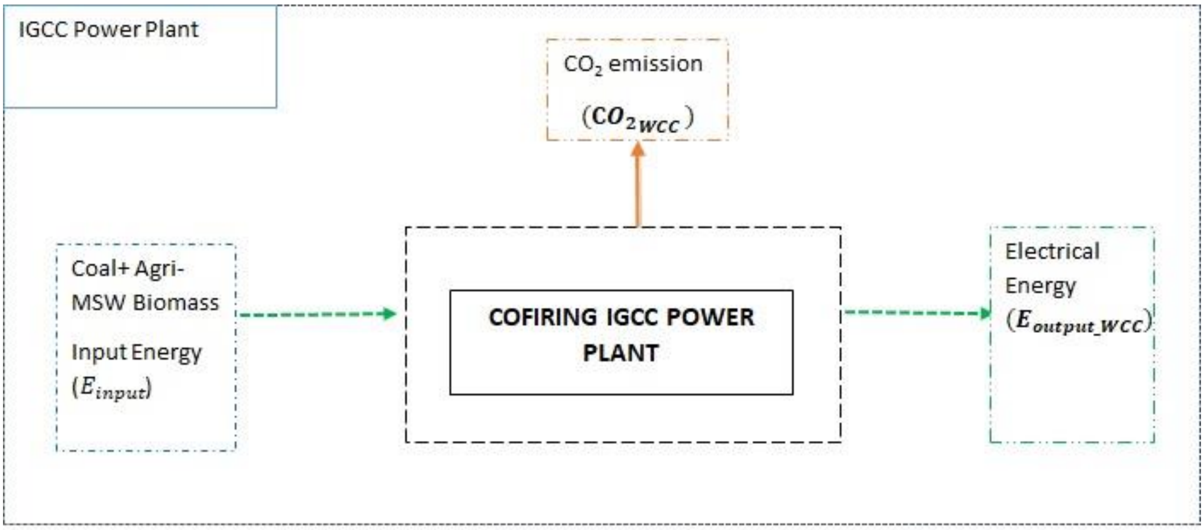


Figure 6.4 Schematic diagram of the energy and CO_2 emissions for Cofiring IGCC Power Plant

6.2.5.1 Energy Return on Energy Investment (*EROEI*)

Based on the simulation results using the ASPEN Plus®**,** the energy return on energy investment (*EROEI*) for the IGCC plant without CO_2 capture has been calculated.

EROEI without CO_2 capture ($EROEI_{WCC}$) has been calculated as follows:

$$EROEI_{WCC} = \frac{\text{Energy return from cofired IGCC plant } (ER_{wcc})}{\text{Energy Input of Cofired IGCC plant } (EI_{IGCC})} * 100 \quad (1)$$

6.2.5.2 Avoidance in CO_2 Emission (*ACE*)

Avoidance in CO_2 emissions (*ACE*) has been calculated with reference to the CO_2 emissions of a coal fired power plant of same capacity (30TPD) .For the calculation of *ACE* for the IGCC power plant without CO_2 capture (ACE_{WCC}), the consumption of CO_2 during the production of Agri-MSW based Biomass through photosynthetic route ($CO_{2_{MSWBPH}}$) has been taken into account. Therefore,

$$ACE_{WCC} = \frac{\text{Total } CO_2 \text{ emission avoidance for the IGCC power cofired power plant without } CO_2 \text{ capture}}{CO_2 \text{ emission from coal plant}(CO_{2_{COAL}})} * 100$$

(2)

For the IGCC power plant without CO_2 capture, total CO_2 emissions avoidance has been calculated as follows:

$$\text{Total } CO_2 \text{ emission avoidance for the IGCC power cofired power plant without } CO_2 \text{ capture} = \text{Plant emission avoided due to switching over from coal fired to Cofired IGCC mode}\left(\text{ACE}_{COAL\ to\ Cofiring}\right) + CO_2 \text{ consumed during the production of Agri\_MSW based Biomass } (\text{ACE}_{MSWBPH}) \quad (3)$$

$CO_{2_{MSWBPH}}$ has been calculated from the weight fraction of carbon in the Agri-MSW based Biomass (w_{cMSWB}) and the mass of Agri-MSW based Biomass fed M_{MSWB} to the power plant. As all the carbon in the biomass is derived from atmospheric CO_2, therefore, the CO_2 consumed for photosynthesis (ACE_{MSWBPH}) has been calculated as follows:

$$\text{ACE}_{MSWBPH} = \frac{M_{MSWB} * w_{cMSWB} * MW_{CO_2}}{MW_C} \quad (4)$$

Where, $MW_{CO_2} = molecular\ weight\ of\ CO_2 = 44\,\frac{kg}{kmol}\ and$

$$MW_C = molecular\ atomic\ weight\ of\ C = 12\,\frac{\text{kg}}{\text{kmol}}. \quad (5)$$

6.3.1 Result and discussions

The results obtained by process simulation using ASPEN Plus® software as per Box-Behnken DOE are presented in Table 6.5. The results are given as input to the Design Expert

Software for further analysis. On examining the fit summary, it is understood that the quadratic model is statistically significant for both the responses, i.e. CO_2 emissions avoidance (Y_1) and energy return on energy investment (Y_2). The corresponding data table generated by ASPEN Plus® has been provided in the Appendix of this chapter.

Table 6.5. Box-Behnken Design Matrix

Run	***X_1*** **(degree C)**	***X_2*** **(%)**	***X_3*** **(%)**	***Y_1*** **(%)**	***Y_2*** **(%)**
1	750.00	20.00	60.00	19.7	17.4
2	750.00	50.00	40.00	49.3	31.2
3	900.00	50.00	20.00	49.4	50.25
4	900.00	20.00	40.00	19.7	36.8
5	600.00	80.00	40.00	79.8	31.2
6	750.00	80.00	60.00	78.9	12.7
7	750.00	50.00	40.00	49.3	31.2
8	900.00	80.00	40.00	78.9	37.5
9	600.00	20.00	40.00	19.7	30.8
10	600.00	50.00	20.00	49.3	42.6
11	750.00	50.00	40.00	49.3	31.2
12	600.00	50.00	60.00	49.3	13.4
13	750.00	50.00	40.00	49.3	31.2
14	750.00	50.00	40.00	49.3	31.2
15	750.00	80.00	20.00	78.9	41.2
16	900.00	50.00	60.00	49.3	20.1
17	750.00	20.00	20.00	19.8	46.1

6.3.2 ANOVA for response on CO_2 emissions avoidance

Analysis of Variance (ANOVA) is a proficient statistical decision making tool that is used to test the satisfactoriness of a model for the responses in data obtained from ASPEN Plus®. Table 6.6 summarizes the ANOVA for response surface quadratic model for CO_2 emissions avoidance of IGCC process. It is noted that variables X_1 (gasifier temperature) and X_2 (Agri-MSW based Biomass -coal ratio) and X_3 having P-value <0.05 are statistically significant in the regression model with 95% confidence level. Hence, it can be inferred that X_1 and X_2 are major contributing factors in CO_2 emissions avoidance in comparison to X_3 (the ratio of supplied air to that required for complete combustion).

Table 6.6 ANOVA analysis (Partial sum of squares) for CO_2 emissions avoidance

Source	Sum of Squares	DOF	Mean Square	F- Value	p-value	Comment
Model	7057.15	9	784.13	21955.57	< 0.0001	significant
X_1	0.080	1	0.080	2.24	0.1781	
X_2	7056.72	1	7056.72	1.976E+005	< 0.0001	
X_3	5.000E-003	1	5.000E-003	0.14	0.7194	
$X_1 X_2$	0.20	1	0.20	5.67	0.0488	
$X_1 X_3$	2.500E-003	1	2.500E-003	0.070	0.7990	
$X_2 X_3$	2.500E-003	1	2.500E-003	0.070	0.7990	
X_1^2	0.053	1	0.053	1.49	0.2614	
X_2^2	0.053	1	0.053	1.49	0.2614	
X_3^2	0.032	1	0.032	0.90	0.3737	
Residual	0.25	7	0.036	-	-	
Lack of Fit	0.25	3	0.083	-	-	
Pure Error	0.000	4	0.000	-	-	
Cor Total	7057.40	16	-	-	-	

The model F-value of 21955.57 implies that the model is significant. In the model, X_2, X_1X_2 are significant model terms. Figure 6.5 shows the three-dimensional response surface which has been constructed to show the interaction effect of X_1 and X_2 on CO_2 emission avoidance.

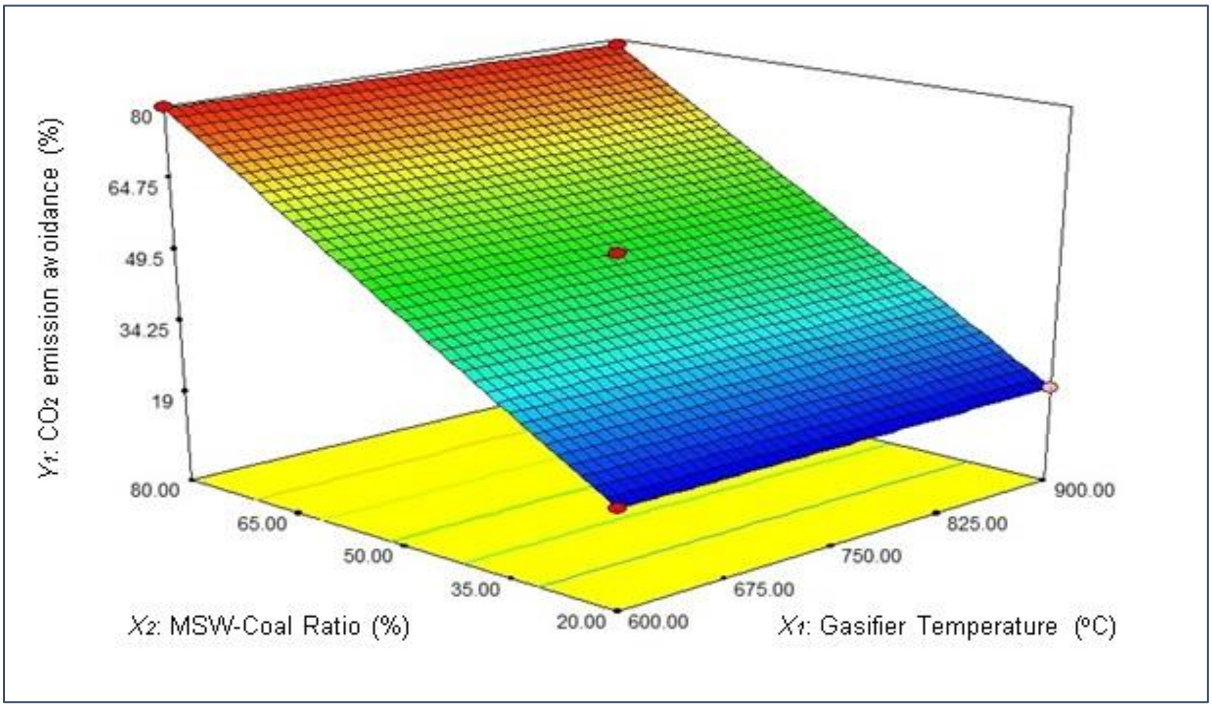


Figure 6.5. Three-dimensional response surface plot of CO_2 emissions avoidance (effect of gasifier temperature and the Agri-MSW based Biomass -Coal ratio) of IGCC

A second order polynomial model equation has been obtained to represent the functional relationship between the process parameters and response, i.e., CO_2 emissions avoidance. The predicted influence on CO_2 emissions avoidance (Y_1) obtained in terms of coded factors excluding terms containing X_3 is as follows:

$$Y_1 = 49.03 - 0.1X_1 + 29.7X_2 - 0.23X_1X_2 \quad + 0.11{X_1}^2 + 0.11{X_2}^2 \qquad (6)$$

The value of R^2 of unity indicates good agreement between the data as obtained from ASPEN Plus® and values of the response predicted by RSM model. The obtained ratio of 413.784 can be noted as an adequate signal, which is greater than 4 as shown in Table 6.7.

Table 6.7. Different statistical values from ANOVA analysis for CO_2 emissions avoidance using BBD

R-Squared	Adj R-Squared	Pred R-Squared	Adeq Precision	Mean	C.V. %
1.000	0.9999	0.9994	413.784	49.36	0.3828

In addition, Figure 6.6 shows the predicted values versus actual values as obtained from ASPEN Plus® for CO_2 emissions avoidance.

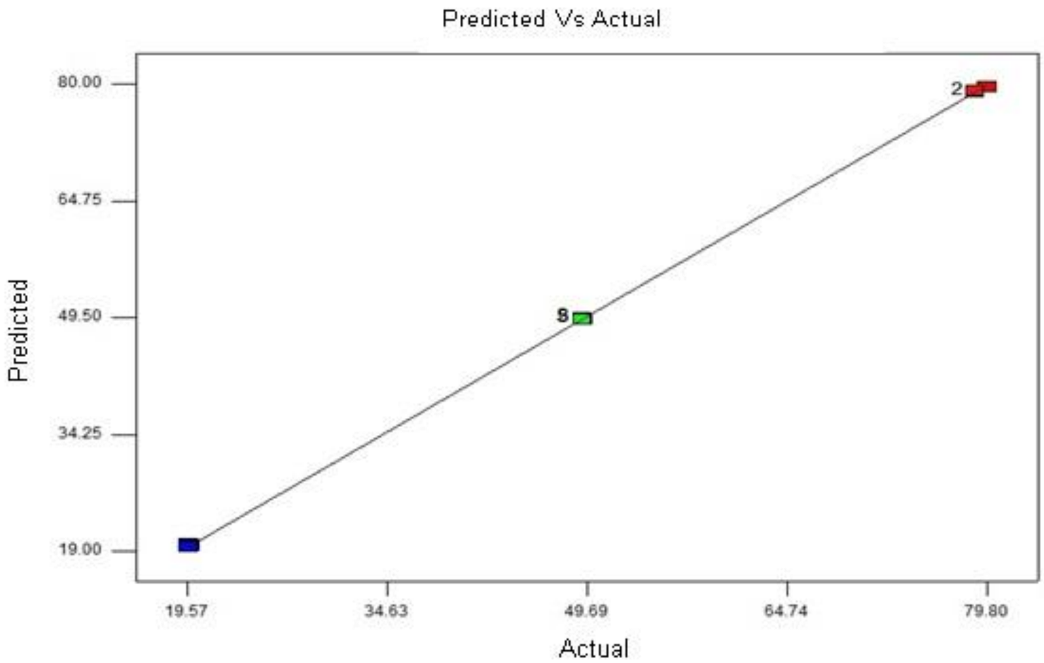


Figure 6.6. Predicted versus simulated data of ASPEN Plus® for CO_2 emissions avoidance

6.3.3 ANOVA on Energy returns on energy investment (EROEI)

From the ANOVA for three-factor interaction model for EROEI as shown in Table 6.8, indicate F-value of 92.92 and P-value < 0.05 implying the significance of the model. In this case, X_1, X_3, X_1^2 and X_3^2 factors are significant model terms.

Table 6.8. ANOVA analysis (Partial sum of squares) for EROEI

Source	Sum of Squares	DOF	Mean Square	F Value	p-value (Prob> F)	
Model	1841.53	9	204.61	92.92	< 0.0001	significant
X_1	88.78	1	88.78	40.32	0.0004	
X_2	9.03	1	9.03	4.10	0.0825	
X_3	1697.99	1	1697.99	771.09	< 0.0001	
$X_1 X_2$	0.023	1	0.023	0.010	0.9223	
$X_1 X_3$	0.23	1	0.23	0.10	0.7582	
$X_2 X_3$	1.000E-002	1	1.000E-002	4.541E-003	0.9482	
X_1^2	27.51	1	27.51	12.49	0.0095	
X_2^2	0.43	1	0.43	0.19	0.6727	
X_3^2	19.80	1	19.80	8.99	0.0200	
Residual	15.41	7	2.20	-	-	
Lack of Fit	15.41	3	5.14	-	-	
Pure Error	0.000	4	0.000	-	-	
Cor Total	1856.94	16	-	-	-	

Figure 6.7 shows the three-dimensional response surface which has been constructed to show the interaction effect of X_1 and X_2 on EROEI.

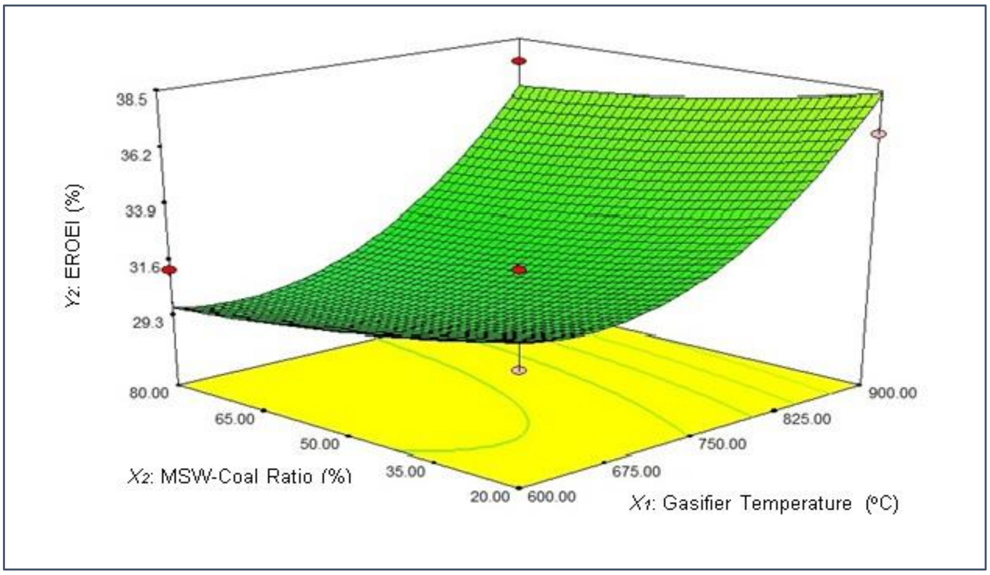


Figure 6.7. Three-dimensional response surface plot of energy return on energy investment (effect of gasifier temperature and the Agri-MSW based Biomass -coal ratio) of IGCC

A second order polynomial model equation of the following form has been obtained to represent influence on EROEI. The predicted response on EROEI (Y_2) obtained in terms of coded factor is as:

$$Y_2 = 31.2 + 3.33X_1 - 1.06X_2 - 14.57X_3 + 0.075X_1X_2 - 0.24X_1X_3 + 0.05X_2X_3 + 2.56{X_1}^2 + 0.32{X_2}^2 - 2.17{X_3}^2 \quad (7)$$

The value of R^2 (0.9917) close to 1, indicates good fitness of the data predicted by the quadratic model with those data obtained through ASPEN Plus®. The Adeq. Precision of 31.593> 4.0 again indicates the goodness of fit as shown in Table 6.9

Table 6.9. Different statistical values from ANOVA analysis for EROEI using BBD

R-Squared	Adj R-Squared	Pred R-Squared	Adeq Precision	Mean	C.V. %
0.9917	0.9810	0.8672	31.593	31.53	4.71

In addition, Figure 6.8 shows the predicted values versus actual values as obtained from ASPEN Plus® for EROEI.

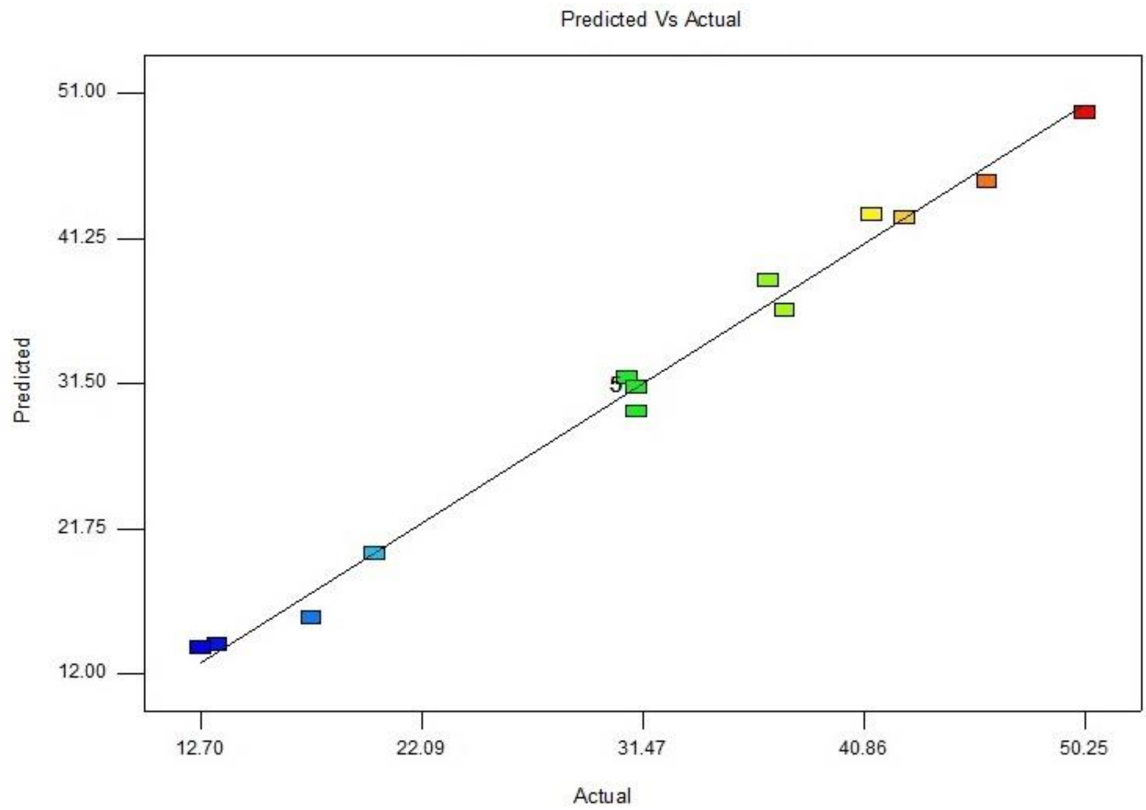


Figure 6.8. Predicted versus simulated data of ASPEN Plus® for energy return on energy investment

Table 6.10 depicts the statistical values from ANOVA analysis of CCD for the CO_2 emissions avoidance based models, Likewise Table 6.11 represents the statistical values from ANOVA analysis using CCD for the EROEI based models. While the values of the coefficient of determination (R^2) for CO_2 emissions avoidance and EROEI using BBD have been determined to be 1.000 and 0.9917 respectively, those using CCD are 0.9969 and 0.9620 respectively for CCD. Thus, the BBD based models are superior to CCD ones for the present analysis. This is also true with respect to the values of adj R^2, and pred R^2.

Table 6.10. Different statistical values from ANOVA analysis for CO_2 emissions avoidance using CCD

R-Squared	Adj R-Squared	Pred R-Squared	Adeq Precision	Mean	C.V. %
0.9969	0.9941	0.9764	55.4725	34.84	3.47

Table 6.11. Different statistical values from ANOVA analysis for EROEI using CCD

R-Squared	Adj R-Squared	Pred R-Squared	Adeq Precision	Mean	C.V. %
0.9620	0.9278	0.7107	21.7428	31.54	7.85

6.3.4 Comparison with experimental data

The performance of the proposed model is also compared with operating plant data published by Hemant Kumar 2015 [28] and experimental data published by Surroop D 2011 [29]. As evident from data provided in Table 6.12 and Table 6.13, most of the results are in good agreement.

Table 6.12. Performance of the proposed model with operating plant data

Operating parameters	*Operating plant data* Hemant Kumar 2015 [28]	Prediction of the model developed in Run 17 as per Table 6.5 of present work
Cofiring (Biomass: Coal)	Rice husk: Coal	Municipal solid waste : Coal
Fuel Feed rate (ton/hr)	11	1.25
Fuel Composition (mass basis)	30:70	20:80
Gasifier Temperature (°C)	750-800	750
Energy return on energy investment (%)	49	46.1

Table 6.13. Performance of the proposed model with published experimental data

Operating parameters	experimental data published by Surroop D 2011 [29]	Prediction of the model developed in Run 3 as per Table 6.5 of present work
Cofiring (Biomass: Coal)	Municipal solid waste : Coal	Municipal solid waste : Coal
Fuel Feed rate (ton/hr)	58.29	1.25
Fuel Composition (mass basis)	80:20	80:20
Gasifier Temperature (^oC)	900	900
Energy return on energy investment (%)	55.92	50.25
CO2 emissions avoidance (%)	45.5	49.4

It depicts that EROEI and CO_2 emissions avoidance of Run 3 are 90.0% and 91.5 % accurate respectively with experimental data published by Surroop D 2011 [29]. From the optimum values of EROEI and CO_2 emissions avoidance it appears that IGCC of mixture of Indian Agri-MSW based Biomass and coal can serve as a potential process for efficient waste management and alternative energy. However, different challenges were identified by several investigators and some recommendations were made. According to a scientific group, for the economic feasibility of the MSW-to-electricity (WTE) plants, introduction and implementation of some government policies are required [37, 40, 43]. These are policies ensuring government's responsibility of collection of MSW and transportation to WTE plants; purchasing of the generated electricity at the same price as that of the existing supplies and tax exemption on the income of the owners of WTE plants for ten years [14]. In a recent article, it has been reported that although distributed electrical power generation through gasification of MSW is a potential option for renewable energy, there are some challenges like increase of efficiency of gasification, reduction in the contaminant level of syngas and increase in the efficiency of conversion of electrical power from syngas [17]. Different MSW management models encompassing efficient collection, transportation, material recovery, and the generation of energy have been recommended by another investigation [20].These challenges should be addressed and the recommendations should be considered before taking any strategic decision regarding utilization of Agri-MSW based Biomass in India.

Symbols used

X_1	[°C]	gasifier temperature
X_2	[%]	ratio of municipal solid waste to coal
X_3	[%]	ratio of supplied air to that required for complete combustion
Y_1	[%]	CO_2 emissions avoidance
Y_2	[%]	ratio of energy return on energy investment

Abbreviations

ANOVA	analysis of variance
ASPEN	Plus® advanced system for process engineering
ACE	avoidance in CO_2 emissions
BBD	box-behnken design
DOE	design of expert
EROEI	energy return on energy investment
GHG	greenhouse gas
HRSG	heat recovery steam generator
HFC	hydro fluorocarbons
IPCC	intergovernmental panel on climate change
IGCC	integrated gasification combined cycle
MSW	municipal solid waste
RSM	response surface methodology
SR	stoichiometric ratio
WGS	water gas-shift

6.4 References

[1] M.K. Mann and P. L.Spath, *Clean Technologies and Environmental Policy*. **2001**, 3(2), 81-91. DOI: 10.1007/s100980100109

[2] Rathnam, K. R., Kärki, J., Nieminen, M., Leinonen, A., Jain, P., & Raju, T. N, *Energetica India*. **2013**, (8), 68-73. DOI: www.energetica-india.net/download.php

[3] Dan Loeffler, Nathaniel Anderson, *Applied Energy*. **2014**, 113, 67-77. DOI: 10.1016/j.apenergy.2013.07.011

[4] Prabir Basu, James Butler, Mathias A. Leon, *Renewable Energy*. **2011**, 36(1), 282-288. DOI: 10.1016/j.renene.2010.06.039

[4] Hrvoje Mikulčić, Damijan Cerinski, Jakov Baleta, Xuebin Wang, *Chemical Engineering & Technology*. **2019**, 42 (12), 2539-2545. DOI:10.1002/ceat.201900086

[5] Alec Liu, Fei Ren, Wenlin Yvonne Lin, Jing-Yuan Wang, I*nternational Journal of Sustainable Built Environment*. **2015**, 4, 165-188. DOI: 10.1016/j.ijsbe.2015.11.002

[6] Sieting Tana, Haslenda Hashima, Chewtin Leea, Mohd Rozainee Taiba, Jinyue Yanb, *Energy Procedia*. **2014**, 704-708. DOI: 10.1016/j.egypro.2014.11.947

[7] Scarlat, N., Fahl, F. & Dallemand, J., *Waste Biomass Valorization.* **2019**, 10, 2425–2444. DOI: 10.1007/s12649-018-0297-7

[8] Seth Addai-Asante, Tang Hao, *The International Journal of Engineering and Science*. **2017**, 6(3), 21-31. DOI: 10.9790/1813-0603022131

[9] www.coalcontroller.gov.in (2016-17)

[10] Geoffrey Guest, Ryan M. Bright, Francesco Cherubini, Ottar Michelsen, and Anders Hammer Strømman, *Journal of Industrial Ecology*. **2011**, 15 (6), 908-921. DOI: 10.1111/j.1530-9290.2011.00375.x

[11] K V Narayanan, E. Natarajan, *Renewable Energy*. **2007**, 32 (15), 2548-2558. DOI: 10.1016/j.renene.2006.12.018

[12] Usama Mohamed, Ying-jie Zhao , Qun Yi, Li-juan Shi ,Guo-qing Wei ,William Nimmo. 2021. Evaluation of life cycle energy, economy and CO2 emissions for biomass chemical looping gasification to power generation, Renewable Energy, 176, pp.366-387

[13] Nicolas Spiegl , Xiangyi Long , Cesar Berrueco , Nigel Paterson , Marcos Millan. 2021. Oxy-fuel co-gasification of coal and biomass for negative CO2 emissions, Fuel, 306, 121671

[14] Wei Wu , Lei Zheng, Bin Shi, Po-Chih Kuo. 2021. Energy and exergy analysis of MSW-based IGCC power/ polygeneration systems, Energy Conversion and Management 238, 114119

[15] Luca Mazzoni, Isam Janajreh, Sherien Elagroudy, Chaouki Ghenai, *Energy*. **2020,** 196. DOI: 10.1016/j.energy.2020.117001

[16] Swanand Tupsakhare, John Dooher, Dean Modroukas, Marco Castaldi. 2019. Improved gasification efficiency in IGCC plants & viscosity reduction of liquid fuels and solid fuel dispersion using liquid and gaseous CO2, Fuel, 256, 115848

[17] Bin Shia, Wen Xu, Wei Wu, Po-Chih Kuo. 2019. Techno-economic analysis of oxy-fuel IGCC power plants using integrated intermittent chemical looping air separation, Energy Conversion and Management, 195, pp. 290–301

[18] A. Thallam Thattai, V. Oldenbroek, L. Schoenmakers, T. Woudstra, P.V. Aravind. 2017. Towards retrofitting integrated gasification combined cycle (IGCC) power plants with solid oxide fuel cells (SOFC) and CO2 capture – A thermodynamic case study, Applied Thermal Engineering, 114 ,pp. 170–185

[19] Mai Bui, Mathilde Fajardy, Niall Mac Dowell. 2017. Thermodynamic evaluation of carbon negative power generation: Bio-energy CCS (BECCS), Energy Procedia, 114, pp. 6010 – 6020

[20] Udayan Singh, Anand B. Rao. 2016. Techno-economic assessment of carbon mitigation options for existing coal-fired power plants in India, Energy Procedia, 90, pp. 326 – 335

[21] Dan Loeffler, Nathaniel Anderson. 2014. Emissions tradeoffs associated with cofiring forest biomass with coal: A case study in Colorado, USA, Applied Energy, 113, pp. 67–77

[22] Jae Chul Lee, Hyeon Hui Lee, Yong Jin Joo, Chang Ha Lee , Min Oh. 2014. Process simulation and thermodynamic analysis of an IGCC (integrated gasification combined cycle) plant with an entrained coal Gasifier, Energy, 64, pp. 58-68

[23] Daniele Sofia, Pilar Coca Llano, Aristide Giulianoa, Mariola Iborra Hernández, Francisco García Pe˜na, Diego Barletta. 2014. Co-gasification of coal–petcoke and biomass in the Puertollano IGCC power plant, chemical engineering research and design, 9 2, pp.1428–1440

[24] Muhammad Asif , Chul-u Bak , Muhammad Wajid Saleem , Woo-Seung Kim. 2015. Performance evaluation of integrated gasification combined cycle (IGCC) utilizing a blended solution of ammonia and 2-amino-2-methyl-1- propanol (AMP) for CO2 capture, Fuel, 160, pp. 513–524

[25] F. Sebastián, J. Royo, M. Gómez. 2011. Cofiring versus biomass-fired power plants: GHG (Greenhouse Gases) emissions savings comparison by means of LCA (Life Cycle Assessment) methodology, Energy, 36, pp. 2029-2037

[26] Diego Moyaa, Clay Aldás, Germánico López, Prasad Kaparaju, *Energy Procedia*. **2017**, 134, 286–295. DOI: 10.1016/j.egypro.2017.09.618

[27] Beena Patel and Bharat Gami, *Iranica Journal of Energy & Environment*. **2012**, 3(2), 123-128. DOI: 10.5829/idosi.ijee.2012.03.02.0071

[28] Hemant Kumar, S KMohapatra, Raviinder Singh, *Indian Academy of Sciences June.* **2015**, *40*, 1283–1299. DOI: www.ias.ac.in/article/fulltext/sadh/040/04/1283-1299

[29] Surroop D, Juggurnath A, *University Of Mauritius Research Journal*. **2011**, 17. DOI: 10.4314/umrj.v17i1.70732

[30] Merve Ozturk, Ibrahim Dincer, *Greenhouse Gases: Science and Technology*. **2020**, 10 (4), 855-864. DOI: 10.1002/ghg.1955

[31] Noorlisa Harun, Zuraini Hassan, Norazwina Zainol, Wan Hanisah Wan Ibrahim, Haslenda Hashim, *Chemical Engineering & Technology*. **2019**, 42 (9), 1834-1839. DOI: 10.1002/ceat.201800637

[32] Dario Bove, Sara Merello, Davide Frumento, Saleh Al Arni, Bahar Aliakbarian, Attilio Converti, *Chemical Engineering & Technology*. **2015**, 38 (12), 2115-2126. DOI: 10.1002/ceat.201500257

[33] Wei Gao, Li Yan, Mohammad Tahmoures, Amir Hossein Asgari Safdar, *Chemical Engineering & Technology*. **2017**, 41 (3), 447-453. DOI: 10.1002/ceat.201700272

[34] L. C. Martins das Neves, A. Converti, T. C. Vessoni Penna, *Chemical Engineering & Technology*. **2009**, 32 (8), 1147-1153. DOI: 10.1002/ceat.200900051

[35] W. H. Cheung, K. K. H. Choy, D. C. W. Hui, J. F. Porter, G. Mckay, *Developments in Chemical Engineering and Mineral Processing*. **2008**, 14 (1-2), 193-202. DOI: 10.1002/apj.5500140117

[36] Satish J. Dabe, Poonam J. Prasad, A. N. Vaidya, H. J. Purohit, *Environmental Progress & Sustainable Energy*. **2018**, 38 (2), 654-671. DOI: 10.1002/ep.12981

[37] Rawan A Tayeh, Mohammed F Alsayed, Yahya A Saleh, *Journal of Cleaner Production*. **2021**, 279. DOI: 10.1016/j.jclepro.2020.123753

[38] Ana Ramos, Abel Rouboa, *Environmental Impact Assessment Review.* **2020**, 85. DOI: 10.1016/j.eiar.2020.106469

[39] Caroline Smith Lewin , Ana Rosa Fonseca de Aguiar Martins , Florian Pradelle, *Energy*. **2020**, 210. DOI: 10.1016/j.energy.2020.118498

[40] Natarianto Indrawan, Ajay Kumar, Michel Moliere, Khaled A. Sallam, Raymond L. Huhnke, *Journal of the Energy Institute.* **2020**. DOI: 10.1016/j.joei.2020.07.001

[41] Luca Mazzoni, Isam Janajreh, Sherien Elagroudy, Chaouki Ghenai, *Energy*. **2020,** 196. DOI: 10.1016/j.energy.2020.117001

[42] Juntao Wei, Qinghua Guo, Lu Ding, Kunio Yoshikawa, Guangsuo Yu, *Applied Energy.* **2017,** 206, 1354-1363 . DOI: 10.1016/j.apenergy.2017.10.005

[43] Gabriela Ionescu, Elena Cristina Rada, Marco Ragazzi, Cosmin Marculescu, Adrian Badea, Tiberiu Apostol, *Energy Conversion and Management.* **2013,** 76, 1083-1092. DOI: 10.1016/j.enconman.2013.08.049

[44] N. Koukouzas, A. Katsiadakis, E. Karlopoulos, E. Kakaras, *Waste Management.* **2008,** 28, 1263-1275. DOI: 10.1016/j.wasman.2007.04.011

[45] Raymond H. Myers, Douglas C. Montgomery, Christine M. Anderson-Cook, *Response Surface Methodology,* 4th ed., Wiley Series in Probability and Statistics, John Wiley & Sons, Inc., Hoboken **2016**.

[46] Isa Martins Fukuda, Camila Francini Fidelis Pinto, Camila dos Santos Moreira, Alessandro Morais Saviano, Felipe Rebello Lourenço, *Brazilian Journal of Pharmaceutical Sciences.* **2018,** 54. DOI: 10.1590/s2175-97902018000001006

[47] Bezerra MA, Santelli RE, Oliveira EP, Villar LS, Escaleira LA, *Talanta.* **2008,** 76 (5), 965-977. DOI: 10.1016/j.talanta.2008.05.019

[48] Candioti LV, De Zan MM, Cámara MS, Goichoechea HC, *Talanta.* **2014,**124, 123-138. DOI: 0.1016/j.talanta.2014.01.034

[49] Politis SN, Colombo P, Colombo G, Rekkas DM, *Drug Develop Ind Pharm.* **2017,**43 (6), 889-901. DOI: 10.1080/03639045.2017.1291672

[50] Ashim Kumar Khan , Ranjana Chowdhury, Chem. Eng. Technol. 2021, 44, No. 2, 291–299. DOI: 10.1002/ceat.202000230

APPENDIX_CHAPTER 6

Table A.6.1 ASPEN Plus® generated data and the Calculation of ($EROEI_{WCC}$) of IGCC Co-fired power plant without CO_2 capture

Description	Unit	Value
IGCC Co-fired Power Plant Capacity	TPD	30
Cofiring ratio i.e. Agri-MSW based Biomass to coal ratio (wt/wt)	%	50
Agri-MSW based Biomass feed rate (M_{MSW})	Kg/hr (kg/s)	625 (0.1736)
LHV of Agri-MSW based Biomass (LHV_{MSW})	kJ/kg	15900
Coal Feed rate(M_{COAL})	Kg/hr (kg/s)	625 (0.1736)
LHV of coal (LHV_{COAL})	kJ/kg	17600
Rate of Energy input (E_{input}) of IGCC co-fired power plant M_{MSW}x LHV_{MSW} + M_{COAL}x LHV_{COAL}	kw	$0.1736 \times 15900 + 0.1736 \times 17600$ =5815
Energy output (E_{output}) from IGCC co-fired power plant without CO_2 capture	kw	2922
EROEI without CO_2 capture ($EROEI_{WCC}$) has been calculated as per eqn. (1) $EROEI_{WCC} = \frac{\text{Energy outpu}(E_{output})\text{ from cofired IGCC plant}}{\text{Energy Input}(E_{input})\text{ of Cofired IGCC plant}}$*100		
EROEI without CO_2 capture ($EROEI_{WCC}$)	%	$\frac{2922}{5815} \times 100$ =50.2

Table A.6.2. ASPEN Plus® generated data and the Calculation of (ACE_{WCC}) of IGCC Co-fired power plant without CO_2 capture

Description	Unit	Value
Plant Capacity	TPD	30
CO_2 emissions from coal fired power plant	Kg/hr	2120
CO_2 emissions from IGCC co-fired power plant	kg/hr	1950
Cofiring ratio i.e. Agri-MSW based Biomass to coal ratio (wt/wt)	%	50
Agri-MSW based Biomass feed rate (M_{MSW})	kg/hr	625.00
Consumption of CO_2 during the production of MSW biomass through photosynthetic route ($CO_{2\,MSWBPH}$) as per eqn. (4) $CO_{2\,MSWBPH} = \frac{M_{MSWB} * w_{cMSWB} * MW_{CO_2}}{MW_C}$		
Weight fraction of carbon in the MSW biomass (w_{cMSWB})		0.43
Molecular weight of CO2 (MW_{CO_2})	Kg/kmol	44
Molecular weight of Carbon (MW_C)	Kg/kmol	12
$CO_{2\,MSWBPH}$	Kg/hr	$\frac{625 \times 0.43 \times 44}{12}$ =985.42

Plant emissions avoidance due to switching over from coal fired to co-fired IGCC mode i.e. CO_2 emissions from coal fired power plant - CO_2 emissions from IGCC co-fired power plant	Kg/hr	2120-1950 =170
Total CO_2 emissions for IGCC co-fired plant without CO_2 capture has been calculated as per eq. no. (3)	Kg/hr	170+985.42 =1155.42

ACE for the IGCC power plant without CO_2 capture (ACE_{WCC}) as per eqn. (2)

$$ACE_{WCC} = \frac{\text{Total } CO_2 \text{ emissions avoidance for the IGCC power cofired power plant without } CO_2 \text{ capture}}{CO_2 \text{ emissions from coal plant}} * 100$$

ACE_{WCC}	%	$\frac{1155.42}{2120} \times 100$ =54.5

Table A.6.3. ASPEN Plus® generated Heat data of IGCC Co-fired power plant

Heat							
Stream Name	3	6	Q-COND	Q-DECMP1	Q-FGCLR	Q-PYROL	QGASIFIE
QCALC MMkcal/hr	0.036925411	0.127002753	2.45218036	-0.22862289	0.251408226	-0.206923416	-0.255352255
TBEGIN C	100	100	217.720984	100	100.794337	100	
TEND C	25	25	66.0834029	500	40	500	

Table A.6.4. ASPEN Plus® generated Work data of IGCC Co-fired power plant

Work						
Stream Name	FCOMPWOR	HPPOWER	LPPOWER	PUMPWORK	WRK-ARCP	WRK-GTRB
POWER kW	680.554066	-380.813207	-530.759991	10.8884184	1094.23136	-1851.78041

CHAPTER 7

IGCC POWER PLANT WITH CO_2 CAPTURE BY SOLVENT ABSORPTION

7.1 Introduction

One of the major causes of climate change is CO_2 emissions from fossil fuel (oil, natural gas, coal) based power plants [1, 2]. Thus, more research efforts preempting climate change should focus on strategies for the reduction of CO_2 emissions from these sources. To reduce CO_2 emissions, three most commonly known processes, namely, post-combustion CO_2 capture, pre-combustion CO_2 capture, and oxy-fuel combustion [3] are in practice. For the existing fossil fuel-based power plants, post-combustion CO_2 capture is one of the potential options [4]. Different reports on the post-combustion CO_2 capture are available at different technological levels of maturity [5-6]. From the literature reviews, it is clear that a large amount of energy is consumed during CO_2 capture and storage [7]. This energy penalty reduces the overall efficiency of the plants with CO_2 capture and poses a challenge to the process engineers. Integration of post-combustion CO_2 capture by MEA-based solvents to existing coal-based plants leads to minor energy penalties [8-10]. The gross output energy from the coal-based power plants as well as co-fired biomass IGCC plants has been reduced by more than 10% due to solvent regeneration of the CO_2 capture process by means of MEA-based post-combustion [11-18]. The reduction of gross output is mainly caused by the extraction of steam from the steam cycle of the power plant for the reboiler of the stripping column for solvent regeneration [19].

In recent times, several research studies are also being focused on this perspective. Some studies have been reported on the modifications of process flow-sheets for energy-efficient CO_2 capture from flue gas using chemical absorption [20, 21]. One research article reported on CO_2 capture from flue gas using increased the efficiency of Heat Recovery Steam Generator (HRSG) Flue-Gas Injection (FGI) into the Heller tower of the power plant [22]. Recently, a research article reported a rate-based Aspen Plus simulation for flow-sheet modifications including split-stream and vapor recompression processes [23 - 25]. Ultimately, the effect of modification has been assessed through the comparison of the performance of the modified version with that of the standard processes [26]. The energy requirement for regeneration of solvent for CO_2 desorption has also been examined by varying different process parameters, namely, rich solvent flow rate, MEA concentration, feed solvent temperature, rich solvent loading, reboiler temperature, and stripper operating pressure. It has been observed by a research group that regeneration energy is sensitive with respect to those process parameters [27, 28]. Recently, the effects of absorber pressure and packing height on the re-boiler duty have also been reported in a research article [29].

Literature data also reveal that CO_2-neutral power generation can be achieved by integrating biomass gasification with efficient combined cycle power plants [30,31. As the Indian energy sector is mainly based on coal-based power plants, it is understandable that immediate replacement of coal by mixed feed (coal-municipal solid waste; coal-agricultural biomass, etc) can directly mitigate CO_2 emissions [32-34]. Integration of post-combustion capturing of CO_2 with coal-solid waste-based-power plants using IGCC can obviously offer an attractive solution from the perspective of reduction of CO_2 emissions in the Indian energy sector. Before the implementation of these strategies, rigorous analysis should be performed using the process simulation tool. Thorough analyses of energy return on energy investment and CO_2 reduction potential of an IGCC-based power plant using Indian coal and MSW have been reported in chapter-6. It is revealed through the process simulation modeling that from the perspectives of both EROEI and CO_2 reduction, the mixed feed-based plant is far ahead of a coal-based conventional power plant.

No studies are, however, available on mixed feed-based IGCC power plants integrated with post-combustion CO_2 capture for Indian coal- Agri-MSW feed.

Therefore, under the present research study, energy return on energy investment (EROEI) and avoidance of CO_2 emission (ACE) of an IGCC power plant, run on Indian coal and Agri-MSW , and integrated with a post-combustion CO_2 capturing system and solvent regeneration, has been studied using a process simulation tool, namely, ASPEN Plus®. The sensitivity of energy return incorporating the additional energy investment on CO_2 regeneration will be studied with respect to several process parameters.

7.2 Methodology

ASPEN Plus® software has been used to develop a process simulation model for an MEA-based post- combustion CO_2 capture.

7.2.1 30 TPD cofired IGCC Power plant

Table 7.1 summarizes the operating parameters, output energy, and CO_2 emissions information of the 30 TPD co-fired IGCC power plant without a CO_2 capturing facility described in Chapter 6.

Table 7.1. **Technical information of 30 TPD co-fired IGCC plant without CO_2 capture**

Parameter	**Unit**	**Value**
Cofiring (biomass:coal)	:	Indian Agri-MSW : Coal
Feed composition (mass basis)	:	50:50
Gasifier Temperature	^oC	900
Indian Agri-MSW feed flow rate as per cofired mass basis	Kg/h	625
Coal feed flow rate as per cofired mass basis	Kg/h	625
Higher heating value of Indian Agri-MSW	MJ/kg	17.6
Higher heating value of Coal	MJ/kg	18.84
Energy return on Eenrgy Investment (EROEI)	%	50.25
Avoidance in CO_2 emissions (ACE)	%	49.4

7.2.2 CO_2 Capture-Solvent absorption

7.2.2.1 Baseline MEA Process

The conventional MEA-based CO_2 capture process consists of a CO_2 cooler unit and a CO_2 capture unit, as shown in Figure 7.1. The composition of flue gas emitted from the 30 TPD cofired IGCC power Plant, as reported in the previous chapter-6, is shown in Table 7.2. According to the process model of the IGCC plant, the flue gas temperature after gas cleaning is 58^{o}C. As the exit temperature of the flue gas is too high to be introduced to the CO_2 capture unit, a direct contact cooler is incorporated into the process flowsheet to decrease the flue gas temperature to 30^{o}C.

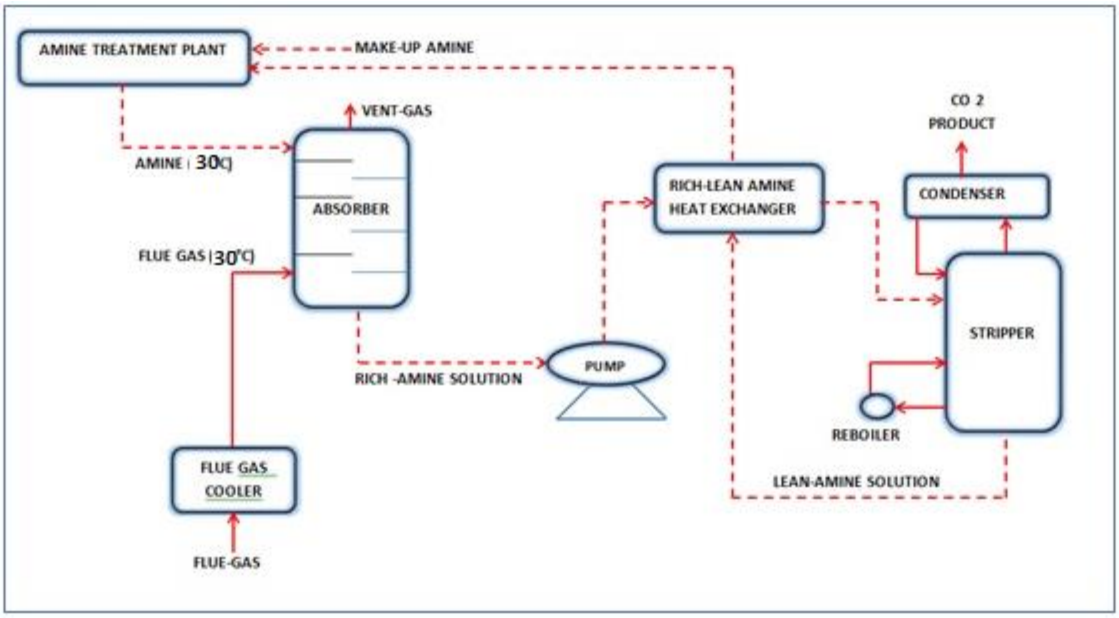


Figure 7.1. Block Diagram of post combustion CO_2 capture.

Table 7.2. Flue gas composition of 30 TPD cofired IGCC Power plant [24].

Parameter	Unit	Value
CO_2	(mol/mol)%	10.14
H_2O	(mol/mol)%	6.76
O_2	(mol/mol)%	9.02
N_2	(mol/mol)%	74.08

7.2.2.2 Simulation by using ASPEN Plus®

Physical Property Method

In the ASPEN Plus® model, the stream class has been set as MIXCINC, which represents all the streams such as MIXED, CONVENTIONAL, and NON-CONVENTIONAL.

Aqueous monoethyl amine (MEA) has been selected as a solvent for the post-combustion CO_2 capture process [9-11]. Electrolyte Non-Random Two-Liquid (ELECNRTL) property method [35] has good accuracy to estimate the thermo-physical properties of the carbon capture process. The operating parameters for the amine-based CO_2 capture system have been provided in Table 7.3.

Table 7.3. Operating parameters for simulation of CO_2 capture of 30 TPD co-fired IGCC.

Configurations	Parameters	Value
Flue Gas	Temperature	30°C
	Pressure	1.7 bar
	CO_2 concentration	10.14 % by mole
	Flowrate	450 kmol/hr
Lean amine solution	Temperature	30 °C
	Pressure	1.1 bar
	Amine concentration	30 % by mass
	Lean amine solution flowrate	1000 – 2000 kmol/hr
Lean loading	CO_2 / amine (mole basis)	23%
Absorber column	Calculation type	Equilibrium
	No. of stages	10
	Condensor pressure	0.9 – 1.2 atm
Stripper column	Calculation type	Equilibrium
	No. of stages	20
	Condensor pressure	Partial vapor
	Reflux ratio	0.3
Rich-lean heat exchanger	Hot inlet –cold outlet temperature difference	15 °C

7.2.3 Unit Operations and Processes for CO_2 capture by solvent absorption

Considering post-combustion solvent absorption is the most favored method for the separation of CO_2. This process is the most preferred capture method because this process can be easily installed to capture the CO_2 emissions of a running power plant without changing the design of the original running power plant.

The ASPEN Plus® flow diagram incorporating the amine-based post-combustion facility along with the 30 TPD co-fired IGCC power plant is represented in Fig. 7.2a and Fig. 7.2b. The solvent absorption method involves passing the flue gas through the absorption and is followed by a stripping column.

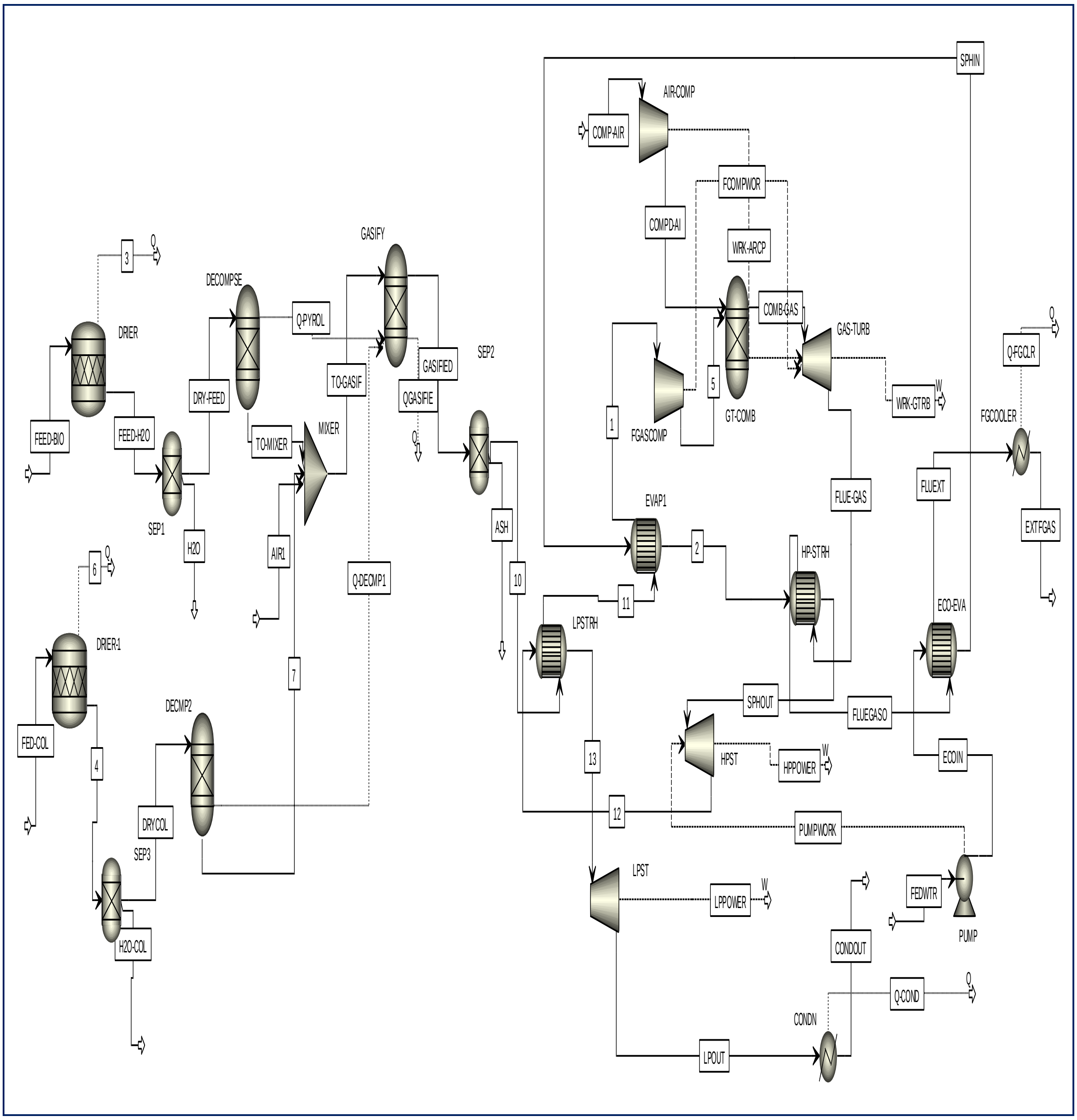


Figure 7.2a. ASPEN Plus® simulation flow sheet for IGCC Plant

Carbon dioxide in the flue gas gets scrubbed through the contact with amine during the counter flow through the absorber. CO_2 -rich amine solution exits from the bottom of the absorber while CO_2-free flue gas leaves from the top of the absorber. Ultimately, in the stripping unit, the absorbed carbon dioxide is stripped from the CO_2-rich amine solution using thermal energy. While the amine solution devoid of CO_2 exits the stripper from the bottom and is recycled to the absorber, CO_2 leaves the stripper from the top of the stripping column.

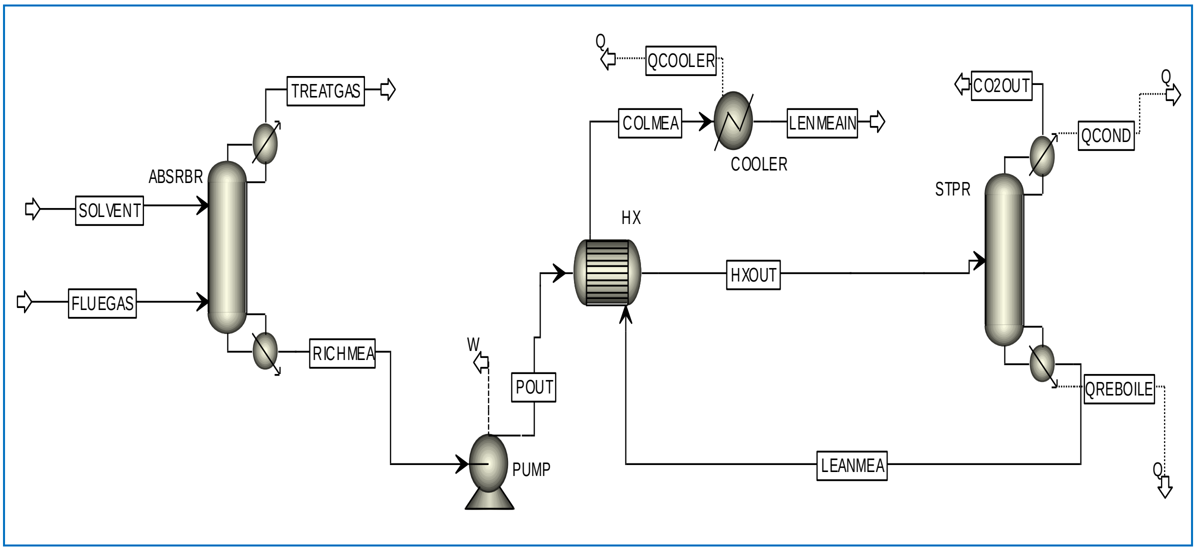
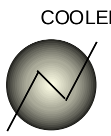
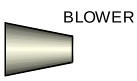
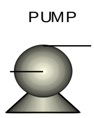
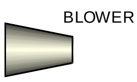
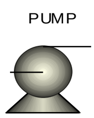


Figure 7.2b. ASPEN Plus® simulation flow sheet for post combustion CO_2 capture of IGCC plant

All the blocks and components, used in the ASPEN Plus® flow sheets (Figures 7.2a and 7.2b), are briefly described in Tables 7.4 and 7.5.

Table 7.4 Description of the blocks used in the ASPEN Plus® modeling

Block ID	**Module selected**	**Scheme**	**Description**
COOLER	HEAT EXCHANGER		In this simulation, Cooler has been used for the reduction of flue gas temperature from 95ºC to 30 degree C.
BLOWER	COMPRESSOR		Blower has been used for the supply of CO_2 to Absorber unit.
PUMP_STEAM	PUMP		Pump has been used for the supply of steam from IGCC power plant to re-boiler of stripping unit for solvent regeneration.
BLOWER	COMPRESSOR		Compressors has been used to compress the CO_2 for storage.
PUMP_STEAM	PUMP		Pump has been used for the supply of compressed CO_2 to storage

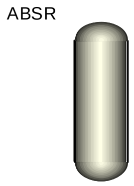
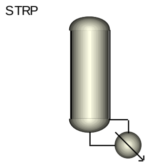
Block ID	Module selected	Scheme	Description
ABSORBER	RADFRAC		RADFRAC unit used as Absorber for absorption of CO_2 by mano ethylene amine (MEA) solvent. Absorber Pressure : 1 atm
STRIPPER	DSTWU		DSTWU block used for regeneration of solvent. Stripper Pressure : 1.7 atm

Table 7.5: Detailed data of the components modeled in the simulation.

Component ID	Type	Component name	Formula
CO_2	Conventional	CARBON-DIOXIDE	CO_2
H_2O	Conventional	WATER	H_2O
O_2	Conventional	OXYGEN	O_2
MEA	Conventional	MANOETHYLENE AMINE	C_2H_7NO

The electrolytic reactions occurring in the absorber columns and stripper columns are given in Table 7.6 along with the coefficients in the equation of temperature dependence of equilibrium rate constants,

$\ln(K_{eq}) = A + B/T + C \ln(T) + DT$, T in Kelvin, used by ASPEN Plus®.

Table 7.6. Equilibrium constant for reactions of CO_2 with aqueous MEA solution.

Reactions	A	B	C	D
$2H_2O \leftrightarrow H_3O^+ + OH^-$	132.89888	-13445.9	-22.477301	0
$CO_2 + 2H_2O \leftrightarrow H_3O^+ + HCO_3^-$	231.465439	-12092.1	-36.781601	0
$HCO_3^- + H_2O \leftrightarrow H_3O^+ + CO_3^{2-}$	216.050446	-12431.7	-35.481899	0
$MEACOO^- + H_2O \leftrightarrow MEA + HCO_3^-$	-0.52135	-2545.53	0	0
$MEAH^+ + H_2O \leftrightarrow MEA + H_3O^+$	-3.038325	-7008.3569	0	-0.003135

7.2.4 Energy and environmental analysis

The energy and CO_2 emissions components used for the Energy Return on Energy Investment (*EROEI*) and Avoidance in CO_2 Emissions (*ACE*) are schematically explained in the following Figure 7.3a, 7.3b, 7.3c, and 7.3d schematic diagram:

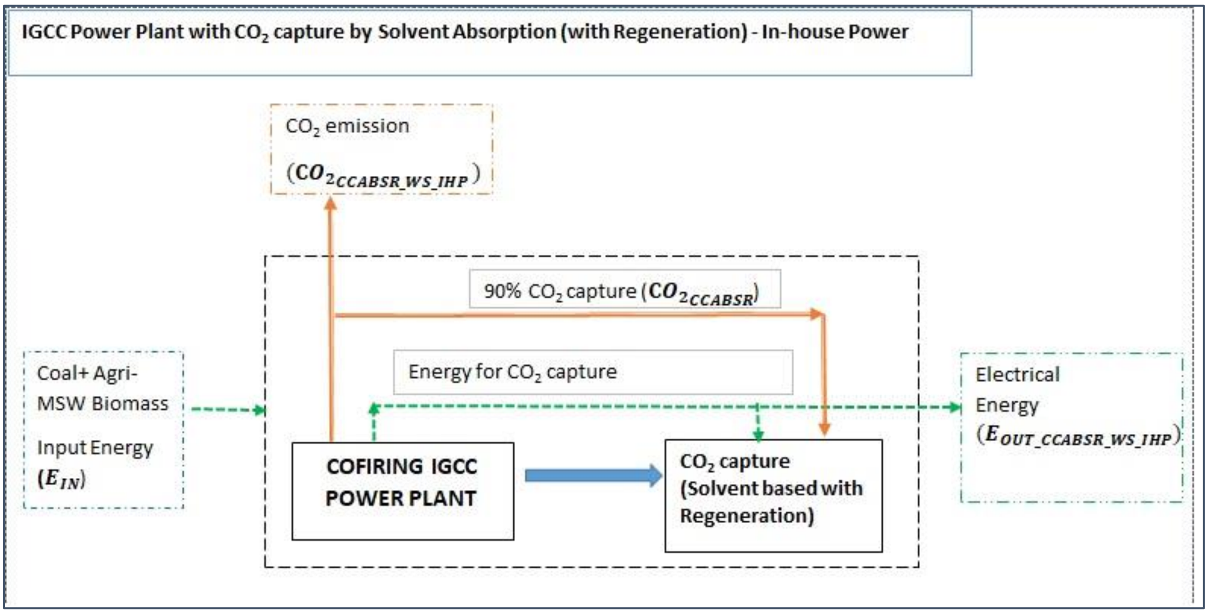


Figure 7.3a Schematic diagram of the energy and CO_2 emissions for Cofiring IGCC Power Plant and CO_2 capture by solvent absorption with solvent regeneration considering the use of in-house power

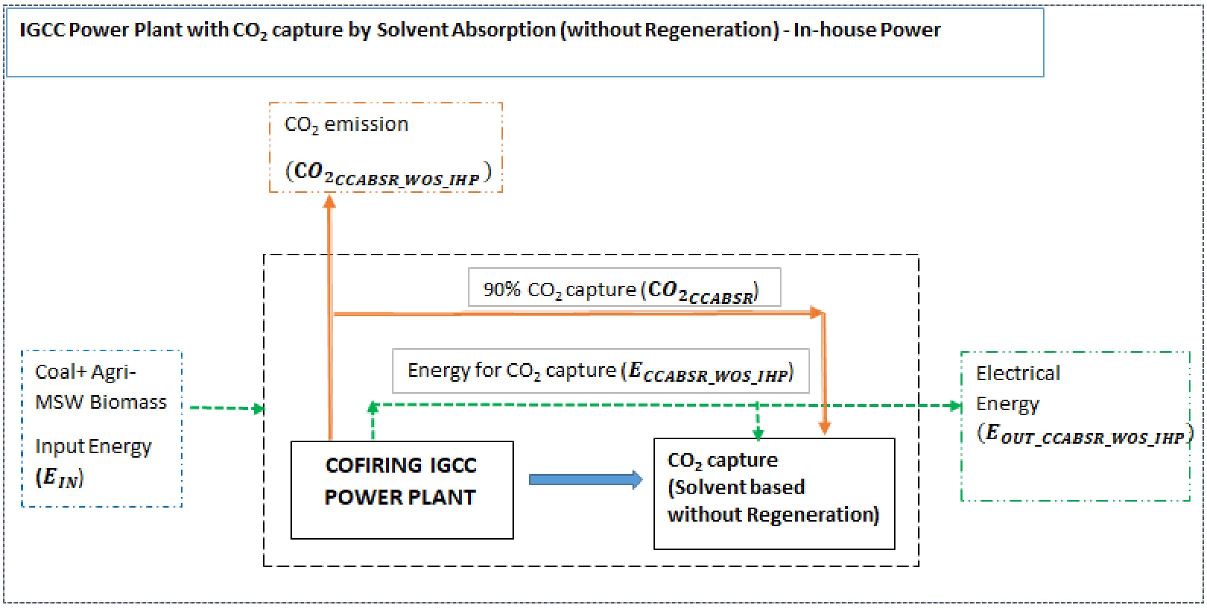


Figure 7.3b Schematic diagram of the energy and CO_2 emissions for Cofiring IGCC Power Plant and CO_2 capture by solvent absorption without solvent regeneration considering the use of in-house power

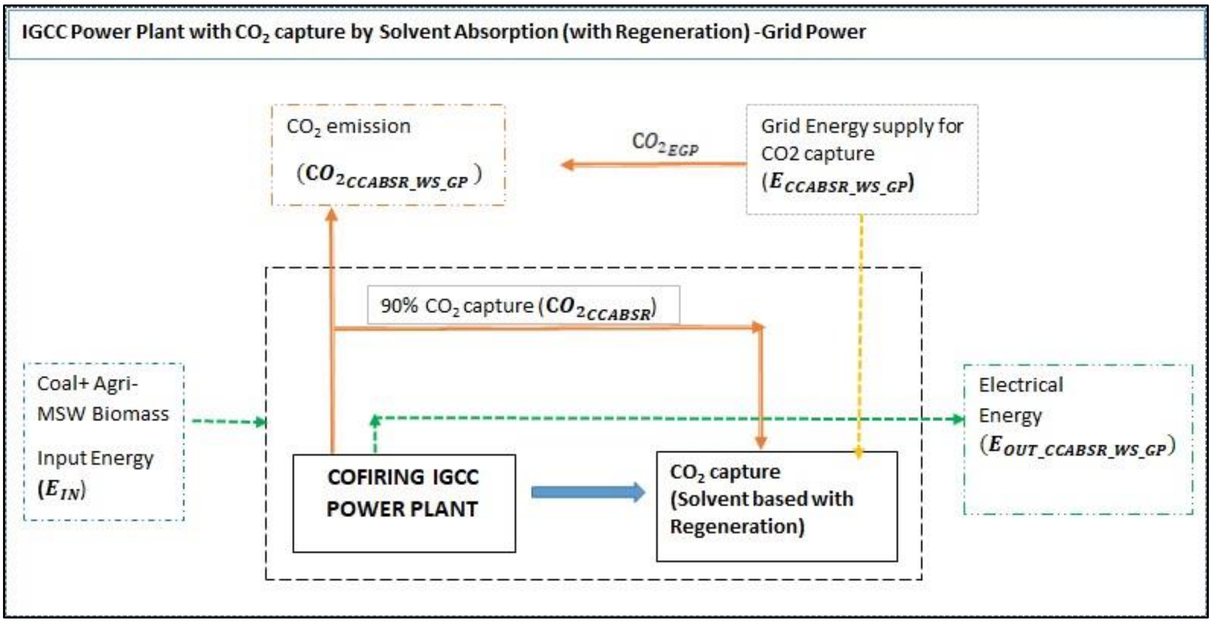


Figure 7.3c Schematic diagram of the energy and CO_2 emissions for Cofiring IGCC Power Plant and CO_2 capture by solvent absorption with solvent regeneration considering the use of grid power

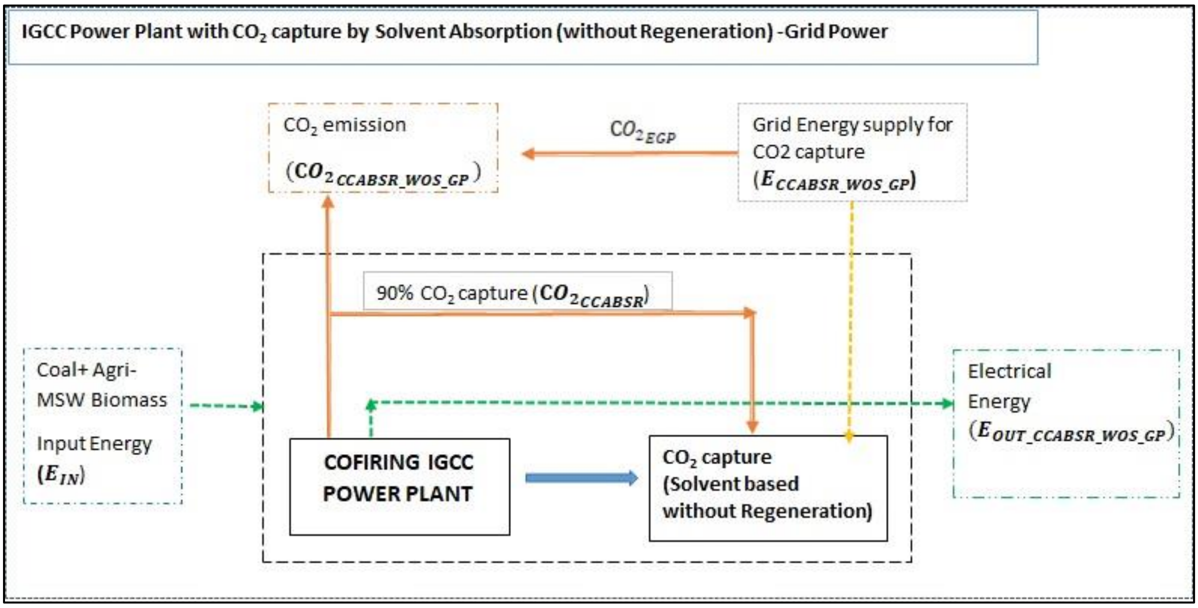


Figure 7.3d Schematic diagram of the energy and CO_2 emissions for Cofiring IGCC Power Plant and CO_2 capture by solvent absorption without solvent regeneration considering the use of grid power

7.2.4.1 Energy Return on Energy Investment (*EROEI*) for CO_2 absorption system

Based on the simulation results using the ASPEN Plus®, the energy return on energy investment (*EROEI*) for the IGCC plant with and without CO_2 capture using solvent by absorption have been calculated.

EROEI without CO_2 capture ($EROEI_{WCC}$) has been calculated as follows:

$$EROEI_{WCC} = \frac{\text{Energy return from cofired IGCC plant } (ER_{wcc})}{\text{Energy Input of Cofired IGCC plant } (EI_{IGCC})} * 100 \quad (1)$$

During the calculation of *EROEI* with CO_2 capture, $EROEI_{CCABSR}$, the total energy requirement, E_{CCABSR}, for the solvent absorption has been considered. E_{CCABSR} includes the heat energy consumption in reboiler of stripping column for the solvent regeneration, E_{HE}, pumping energy for the steam supply to reboiler, $E_{steam\ pump}$, pumping energy for the CO_2 delivery, $E_{CO2\ blower}$, and energy required for CO_2 compressing, $E_{compress}$. The values of $EROEI_{CCABSR}$ have been calculated for four possible cases, I: E_{CCABSR} is derived from the in-house energy generated by the IGCC plant with solvent regeneration; I: E_{CCABSR} is derived from the in-house energy generated by the IGCC plant without solvent regeneration III: E_{CCABSR} is derived from the grid with solvent regeneration; IV: E_{CCABSR} is derived from the grid without solvent regeneration. The *EROEI* for case-I, case-II, case-III, and case-IV are designated by $EROEI_{CCABSR\_WS\_IHP}$, $EROEI_{CCABSR\_WOS\_IHP}$, $EROEI_{CCABSR\_WS\_GP}$ and $EROEI_{CCABSR\_WOS\_GP}$. The definitions of $EROEI_{CCABSR\_WS\_IHP}$, $EROEI_{CCABSR\_WOS\_IHP}$, $EROEI_{CCABSR\_WS\_GP}$ and $EROEI_{CCABSR\_WOS\_GP}$ $are\ as\ follows$:

$$E_{CCABSR} = E_{HE} + E_{steam\ pump} + E_{CO2\ blower} + E_{compress} \quad (2)$$

Heat energy consumption for the solvent regeneration of stripping unit, E_{HE}, is supplied by steam from in-house power plant. Therefore, E_{HE} has not been considered in E_{CCABSR} for determination of $EROEI_{CCABSR}$.

Therefore,

$$E_{CCABSR} = E_{steam\ pump} + E_{CO2\ blower} + E_{compress} \quad (3)$$

EROEI with CO_2 capture using absorption method with solvent (MEA) recovery ($EROEI_{CCABSR\_WS\_IHP}$) has been calculated use of in-house power as follows

$$EROEI_{CCABSR\_WS\_IHP} = \frac{\text{Energy return from cofired IGCC plant } (ER_{wcc}) - \text{Energy requirement for } CO_2 \text{ capture through absorption with solvent recovery}}{\text{Energy Input of Cofired IGCC plant } (EI_{IGCC})} * 100 \quad (4)$$

EROEI with CO_2 capture using absorption method without solvent (MEA) recovery ($EROEI_{CCABSR\_WOS\_IHP}$) has been calculated use of in-house power as follows

$$EROEI_{CCABSR\_WOS\_IHP} = \frac{\text{Energy return from cofired IGCC plant } (ER_{wcc}) - \text{Energy requirement for } CO_2 \text{ capture through absorption without solvent recovery}}{\text{Energy Input of Cofired IGCC plant } (EI_{IGCC})} * 100 \quad (5)$$

EROEI with CO_2 capture using absorption method with solvent (MEA) recovery ($EROEI_{CCABSR\_WS\_GP}$) has been calculated use of grid power as follows

$$EROEI_{CCABSR\_WS\_GP} = \frac{\text{Energy return from cofired IGCC plant } (ER_{wcc})}{\text{Energy Input of Cofired IGCC plant } (EI_{IGCC}) + \text{Energy requirement for } CO_2 \text{ capture through absorption with solvent recovery}} * 100 \quad (6)$$

EROEI with CO_2 capture using absorption method without solvent (MEA) recovery ($EROEI_{CCABSR\_WOS\_GP}$) has been calculated use of grid power as follows

$$EROEI_{CCABSR\_WOS\_GP} = \frac{\text{Energy return from cofired IGCC plant } (ER_{wcc}) -}{\text{Energy Input of Cofired IGCC plant } (EI_{IGCC}) + \text{Energy requirement for } CO_2 \text{ capture through absorption without solvent recovery}} * 100 \quad (7)$$

7.2.4.2 Avoidance in CO_2 Emissions (*ACE*) for CO_2 absorption system

Avoidance in CO_2 emissions (*ACE*) has been calculated with reference to the CO_2 emissions of a coal fired power plant of same capacity (30tpd) .For the calculation of *ACE* for the IGCC power plant without CO_2 capture (ACE_{WCC}), the consumption of CO_2 during the production of Agri-MSW biomass through photosynthetic route (${CO_2}_{MSWBPH}$) has been taken into account. Therefore,

$$ACE_{WCC} = \frac{\text{Total } CO_2 \text{ emissions avoidance for the IGCC power cofired power plant without } CO_2 \text{ capture}}{CO_2 \text{ emissions from coal plant} ({CO_2}_{COAL})} * 100 \quad (8)$$

For the IGCC power plant without CO_2 capture, total CO_2 emissions avoidance has been calculated as follows:

$\text{Total } CO_2 \text{ emissions avoidance for the IGCC power cofired power plant without } CO_2 \text{ capture} =$

Plant emissions avoided due to switching over from coal fired to Cofired IGCC mode$\left(\mathrm{ACE}_{COAL\ to\ Cofiring}\right)$ + $\mathrm{C}O_2$ consumed during the production of Agri_MSW Biomass (ACE_{MSWBPH}) (9)

$\mathrm{C}O_{2_{MSWBPH}}$ has been calculated from the weight fraction of carbon in the Agri-MSW biomass (w_{cMSWB}) and the mass of Agri-MSW biomass fed M_{MSWB} to the power plant. As all the carbon in the biomass is derived from the atmospheric CO_2, therefore, the CO_2 consumed for photosynthesis (ACE_{MSWBPH}) has been calculated as follows:

$$\mathrm{ACE}_{MSWBPH} = \frac{M_{MSWB} * w_{cMSWB} * MW_{\mathrm{C}O_2}}{MW_{\mathrm{C}}} \quad (10)$$

Where, $MW_{\mathrm{C}O_2} = molecular\ weight\ of\ \mathrm{C}O_2 = 44\,\frac{kg}{kmol}\, and$

$$MW_{\mathrm{C}} = molecular\ atomic\ weight\ of\ \mathrm{C} = 12\,\frac{\mathrm{kg}}{\mathrm{kmol}}. \quad (11)$$

The calculation of ACE for the IGCC power plant with CO_2 capture through absorption with solvent recovery ($ACE_{CCABSR\_WS\_IHP}$) the quantum of CO_2 captured by absorption ($\mathrm{C}O_{2_{CCABSR}}$) has also been taken into account.

$$ACE_{CCABSR\_WS\_IHP} = \frac{\text{Total } \mathrm{C}O_2 \text{ emissions avoidance for the IGCC power cofired power plant with } \mathrm{C}O_2 \text{ capture with solvent use in-house power}}{\mathrm{C}O_2 \text{ emissions from coal plant}(\mathrm{C}O_{2_{COAL}})} * 100 \quad (12)$$

For the IGCC power plant with CO_2 capture through absorption with solvent recovery, total CO_2 emissions avoidance has been calculated with consideration of in-house power as follows:

Total $\mathrm{C}O_2$ emissions avoidance for the IGCC power cofired power plant with $\mathrm{C}O_2$ capture =
Plant emissions avoided due to switching over from coal fired to Cofired IGCC mode$\left(\mathrm{ACE}_{COAL\ to\ Cofiring}\right)$ +
$\mathrm{C}O_2$ consumed during the production of Agri_MSW Biomass (ACE_{MSWBPH}) +
CO2 captured by solvent absorption (ACE_{CCABSR}) (13)

The calculation of ACE for the IGCC power plant with CO_2 capture through absorption with solvent recovery ($ACE_{CCABSR\_WS\_GP}$) use of grid power.

$$ACE_{CCABSR\_WS\_GP} == \frac{\text{Total } \mathrm{C}O_2 \text{ emissions avoidance for the IGCC power cofired power plant with } \mathrm{C}O_2 \text{ capture with solvent use grid power}}{\mathrm{C}O_2 \text{ emissions from coal plant}(\mathrm{C}O_{2_{COAL}})} * 100 \quad (14)$$

For the IGCC power plant with CO_2 capture through absorption with solvent recovery, total CO_2 emissions avoidance has been calculated considering use of grid power as follows:

Total $\mathrm{C}O_2$ emissions avoidance for the IGCC power cofired power plant with $\mathrm{C}O_2$ capture =
Plant emissions avoidance due to switching over from coal fired to Cofired IGCC mode +

CO_2 consumed during the production of Agri_MSW Biomass $(\mathrm{ACE}_{MSWBPH}) +$
CO2 captured by solvent absorption $(\mathrm{ACE}_{CCABSR}) -$
CO_2emissions due to grid power requirement for CO_2 capture by absorption with solvent regeneration$(\mathrm{CO2}_{EGP})$ (15)

The calculation of ACE for the IGCC power plant with CO_2 capture through absorption without solvent recovery ($ACE_{CCABSR\_WOS\_GP}$) use of grid power.

$$ACE_{CCABSR\_WOS\_GP} = \frac{\text{Total } CO_2 \text{ emissions avoidance for the IGCC power cofired power plant with } CO_2 \text{ capture without solvent regeneration use grid power}}{CO_2 \text{ emissions from coal plant}} * 100 \quad (16)$$

For the IGCC power plant with CO_2 capture through absorption without solvent recovery, total CO_2 emissions avoidance has been calculated with consideration of grid power as follows:

Total CO_2 emissions avoidance for the IGCC power cofired power plant with CO_2 capture =
Plant emission avoidance due to switching over from coal fired to Cofired IGCC mode +
CO_2 consumed during the production of Agri_MSW Biomass $(\mathrm{ACE}_{MSWBPH}) +$
CO2 captured by absorption $(\mathrm{ACE}_{CCABSR}) -$
CO_2emissions due to grid power requirement for CO_2 capture by without solvent regeneration$(\mathrm{CO2}_{EGP})$
(17)

CO_2 emissions due to the use of grid power (${CO_2}_{EGP}$), supplied for CO_2 capture by solvent absorption with solvent, has been calculated with due consideration of distribution losses of around 5% [38]. Therefore, ${CO_2}_{EGP}$ can be defined as follows:

$${CO_2}_{EGP} = \text{Total power demand for } CO_2 \text{ capture by algae culture process} * 1.05 * CO_2 \text{ emissions factor } \left(\frac{\mathrm{kg}}{\mathrm{kWh}}\right) \quad (18)$$

Where, CO_2 emissions factor signifies the CO_2 emissions per unit energy generated by a coal-fired power plant. The value of CO_2 emissions factor is 0.95kg/kWh for conventional Indian power plant [39].

Therefore,

$${CO_2}_{EGP} = 1.05 * E_{CCAL} * 0.95 \quad (19)$$

7.2.5 Design of Experiments and Optimization

As discussed in Chapter 4, one of the most important aspects of statistical modeling is the design of experiments, which is the strategy to obtain an adequate model with a minimum number of experiments. In this work, three-factor Box-Behnken design (BBD) has been used to examine the interaction effect of factors, namely, X_1 (*Lean Loading*), X_2 (solvent concentration) and X_3 *(solvent temperature)* on response variables, namely, total CO_2 capture (Y_1) and the energy return on energy investment (Y_2). When experiments are planned to correlate a dependent variable with multiple independent factors, Box-Behnken design (BBD) under RSM, based on an evenly spaced three level fractionate factorial principle, can be followed [1,2]. A quadratic model is estimated by creating the experimental planning according to BBD. Under the present study, the combination of independent variables has been chosen following BBD.

The values of response variables have been generated using ASPEN Plus® model at the conditions pre-set by Box-Behnken design (BBD) of experiments. A second-degree polynomial Eq. (1) has been attempted.

$$Y = A_0 + A_1X_1 + A_2X_2 + A_3X_3 + A_{12}X_1X_2 + A_{13}X_1X_3 + A_{23}X_2X_3 + A_{11}{X_1}^2 + A_{11}{X_1}^2 + A_{22}{X_2}^2 + A_{33}{X_3}^2 \quad (20)$$

The values of Y_1 and Y_2 at different combinations of X_1, X_2 and X_3, pre-set by Box-Behnken method of design of experiments, have been generated using the ASPEN Plus® software.

7.3 Results and discussion

7.3.1 Effect of individual process parameters on CO_2 absorption and stripping

7.3.1.1 CO_2 loading in lean amine solution

The effect of CO_2 loading in lean amine solution on CO_2 capture is represented in Figure 7.4. The figure indicates that the values of % CO_2 capture decrease with the increase in the CO_2 loading in the lean amine solution. An increase in CO_2 loading in lean amine solutions causes a decrease in the existing active amine concentration, which consequently decreases the concentration gradient between the gas phase a (flue gas) and the solvent phase. Therefore, the mass transfer driving force from the gas phase to the liquid phase decreases when the amount of CO_2 loading in the lean amine solution is high. Thus, the pattern of dependence of CO_2 capture on the CO_2 loading in the lean amine can be explained.

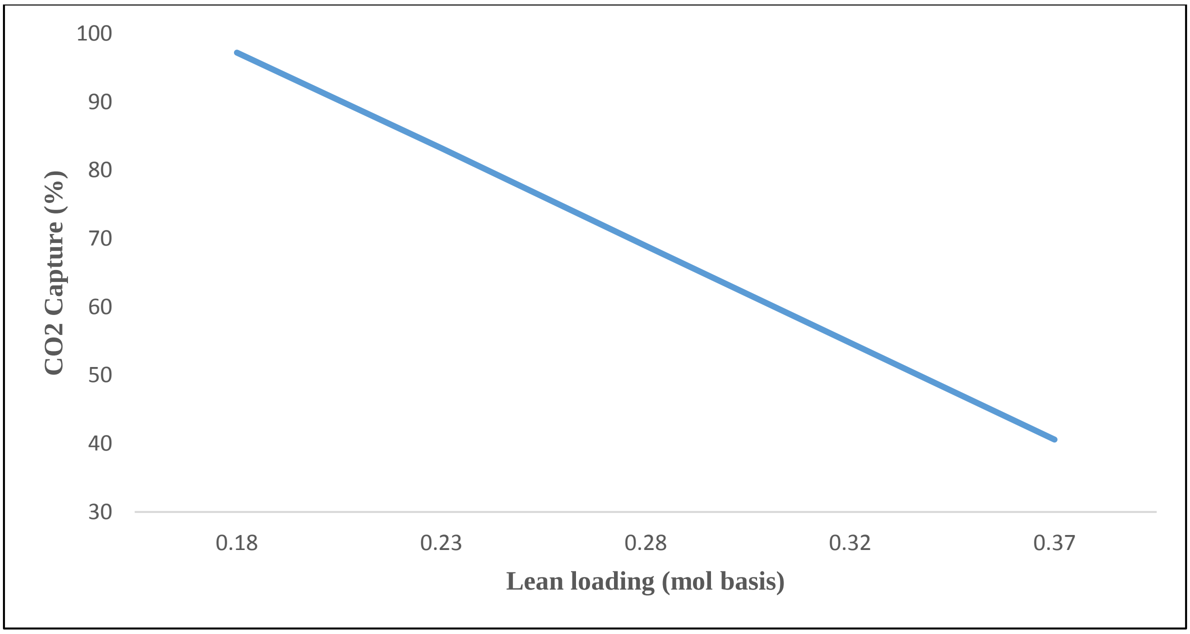


Figure 7.4. Variation of CO_2 capture with lean loading.

Because of the same fact, the pattern of dependence of CO_2 capture on the amine loading in the lean amine is just the reverse, i.e. the %capture increases with the increase in solvent loading, as shown in Figure 7.5 .

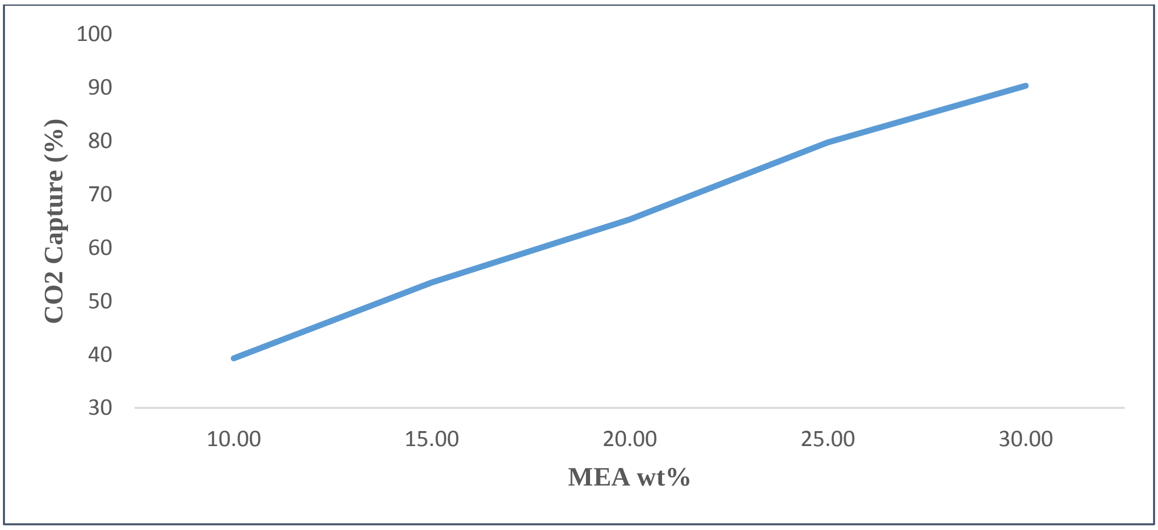


Figure 7.5. Variation of CO_2 capture with MEA Concentration.

7.3.1.2 Solvent temperature

Solvent temperature is one of the prime parameters which can also have an effect on reaction kinetics, overall mass transfer coefficient ($K_{GCO2}av$), and equilibrium solubility. Figure 7.6 shows the dependence of CO_2 capture on the temperature of the process. It is clearly observed that the percentage of CO_2 capture increases with the increase in the process temperature. Similar observations have been reported in the literature [40, 41, 42]. Simultaneous chemical reaction and mass transfer occur during the transfer of CO_2 from the flue gas to the amine. The overall rate of transfer is dependent on the value of overall mass transfer coefficient and the existing driving force, i.e., the difference between the equilibrium and the bulk concentration of CO_2 in amine. As the solubility of CO_2 decreases with the increase of temperature, the driving force decreases. However, overall mass transfer coefficient increases with temperature due to the increase in the rate of reaction between CO_2 and amine and the diffusivity, as suggested in the literature [40, 41, 42]. As reported in the literature, within an inlet temperature range of amine of 303-333K, the effect of increase in the overall mass transfer coefficient outweighs the decrease in the driving force. Therefore, similar to the literature reports, the increase of CO_2 removal efficiency with the increase in amine temperature is justified [40, 41, 42].

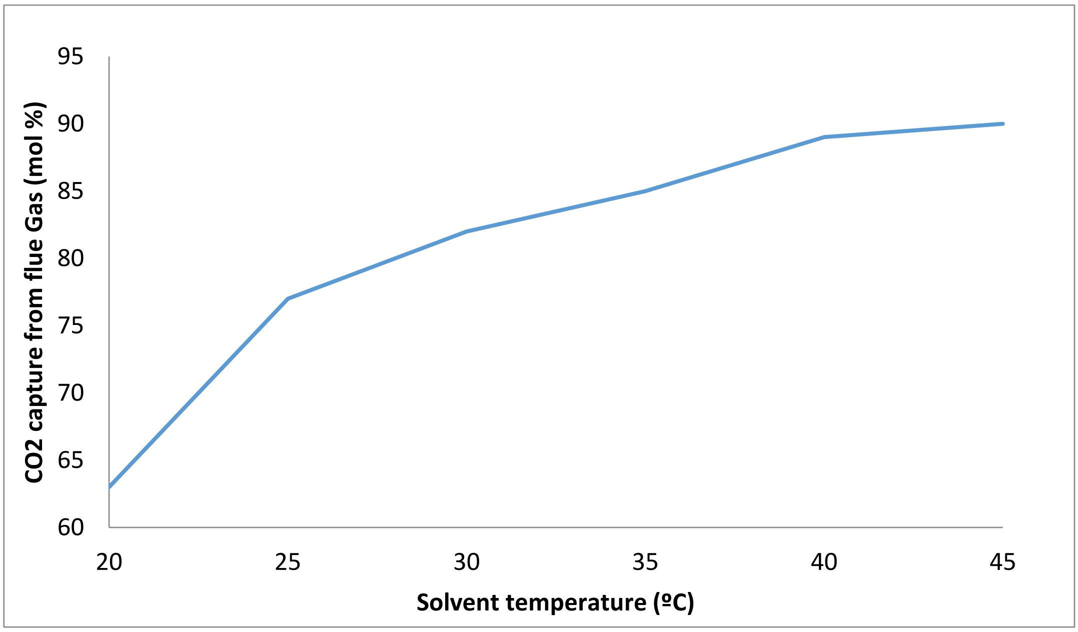


Figure 7.6. Variation of CO_2 capture with Solvent temperature.

7.3.1.3 Effect of Lean loading on reboiler heat duty

The main issue with the post-combustion capture is the high energy demand in the solvent regeneration sector, i.e. re-boiler duty in the stripping column. From Figure 7.7, it has been observed that the reboiler duty is very high at low lean loadings since, at low loadings, the liquid phase concentration of CO_2 is in equilibrium with the partial pressure of CO_2. Hence, a substantial amount of steam has to be supplied to strip the solution to the required low lean loading. However, the increase in equilibrium partial pressure of CO_2 with the increases in the lean loading and the relative amount of steam that needs to be vaporized decreases. This causes the reboiler duty to fall. The liquid flow rate required to achieve the desired capture increases beyond a certain lean loading because of the dominance of sensible heat required for solvent heating.

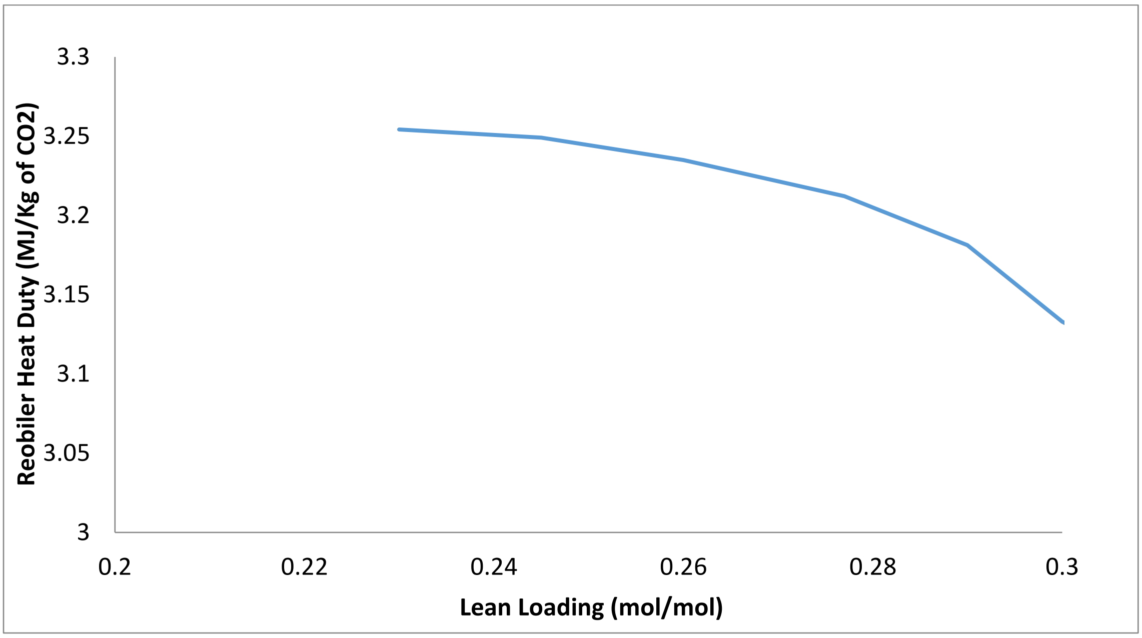


Figure 7.7. Variation of lean loading with reboiler heat duty

7.3.1.4 CO_2 removal efficiency and required Re-boiler heat duty for solvent regeneration

In Figure 9, re-boiler heat duty has been plotted against CO_2 capture. The figure reveals that reboiler heat duty increases with the increase in the CO_2 capture. This is due to the fact that a larger quantity of solvent is required to capture the increased amount of CO_2 and thus more energy is required as sensible heat in the re-boiler. Penalty in re-boiler heating and corresponding relative gain in CO_2 capture are combined in a linear equation. Heat duty (MJ/kg) = -0.3254* Capture Efficiency **(%)**+ 4.9295 (R^2=0.9953) to determine the net effect of these two counter-balancing effects as shown in Figure 7.8.

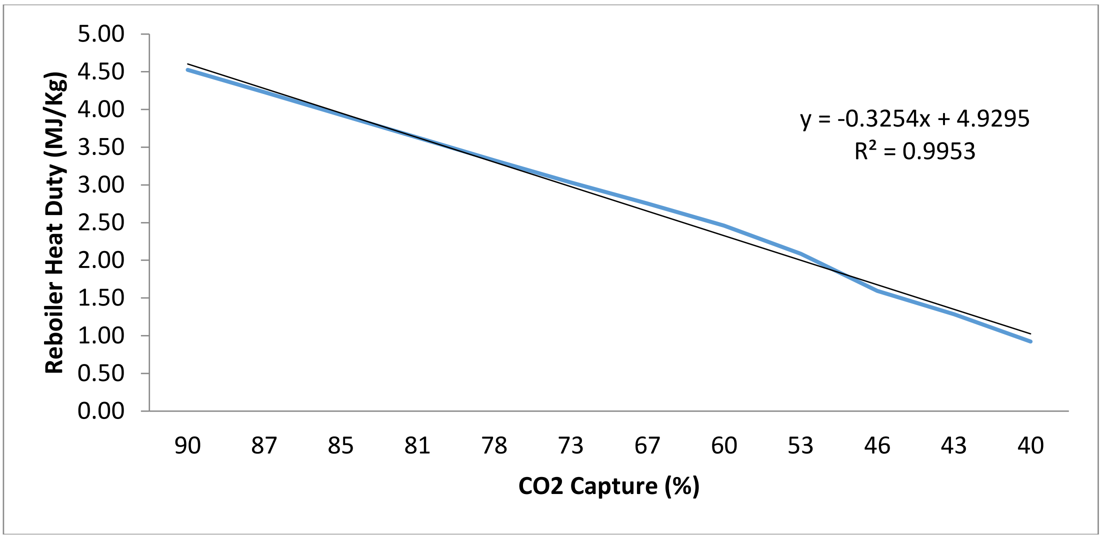


Figure 7.8. Variation of reboiler heat duty with CO_2 capture.

7.3.2 Analysis of CO_2 capture and EROEI by Response surface methodology

The results of CO_2 capture by solvent absorption obtained by process simulation using ASPEN Plus® software as per Box-Behnken DOE are presented in the Table 7.7. The results are given as input to the Design Expert Software for further analysis. On examining the fit summary, it is understood that the quadratic model is statistically significant for both the responses, i.e. CO_2 capture (Y_1) and energy return on energy investment (Y_2).

Table 7.7. Box-Behnken Design Matrix

Run	*Lean Loading (X_1)* (CO_2 / amine (mole basis)	*Solvent Concentration (X_2)* (%)	*Solvent temperature (X_3)* (degree C)	CO_2 capture (Y_1) (%)	*EROEI (Y_2)* (%)
1	0.28	20.00	20	53.80	43.08
2	0.15	20.00	30	78.91	40.45
3	0.40	30.00	20	34.64	45.09
4	0.40	20.00	10	34.64	45.09
5	0.28	10.00	10	38.05	44.73
6	0.28	20.00	20	53.80	43.08
7	0.40	20.00	30	28.68	45.71
8	0.28	20.00	20	53.80	43.08
9	0.28	30.00	30	68.57	41.53
10	0.28	20.00	20	53.80	43.08
11	0.28	20.00	20	53.80	43.08
12	0.15	10.00	20	47.48	43.74
13	0.28	10.00	30	32.96	45.26
14	0.15	20.00	10	78.91	40.45
15	0.15	30.00	20	99.90	38.24
16	0.28	30.00	10	68.57	41.53
17	0.40	10.00	20	32.96	45.26

7.3.2.1 ANOVA for response on CO_2 capture

Analysis of Variance (ANOVA) is a proficient statistical decision making tool that is used to test the satisfactoriness of a model for the responses in data obtained from ASPEN Plus®. Table 7.8 summarizes the ANOVA for response surface quadratic model for CO_2 capture of IGCC process. It is noted that variables X_1 (*Lean Loading*) and X_2 (solvent concentration) and X_3 *(solvent temperature)* having P-value <0.05 are statistically significant in the regression model with 95% confidence level. Hence, it can be inferred that X_1 and X_2 are major contributing factors in CO_2 capture in comparison to X_3 *(solvent temperature)*.

Table 7.8 ANOVA analysis (Partial sum of squares) for CO_2 capture

Sum of Source	**Squares**	**Mean df**	**F Square**	**p-value Value**	**Prob > F**	
Model	6277.41	6	1046.23	157.55	< 0.0001	significant
X_1-Lean loading	3796.43	1	3796.43	571.70	< 0.0001	
X_2-Amine Concentration	1806.73	1	1806.73	272.07	< 0.0001	
X_3-Solvent temperature	15.28	1	15.28	2.30	0.1603	
X_1 X_2	643.60	1	643.60	96.92	< 0.0001	
X_1 X_3	8.88	1	8.88	1.34	0.2744	
X_2 X_3	6.49	1	6.49	0.98	0.3463	
Residual	66.41	10	6.64			
Lack of Fit	66.41	6	11.07			
Pure Error	0.000	4	0.000			
Cor Total	6343.82	16				

The model F-value of 157.55 implies that the model is significant. In the model, X_1, X_2, X_1X_2 are significant model terms. Figure 7.9 shows the three-dimensional response surface which has been constructed to show the interaction effect of X_1 and X_2 on CO_2 capture.

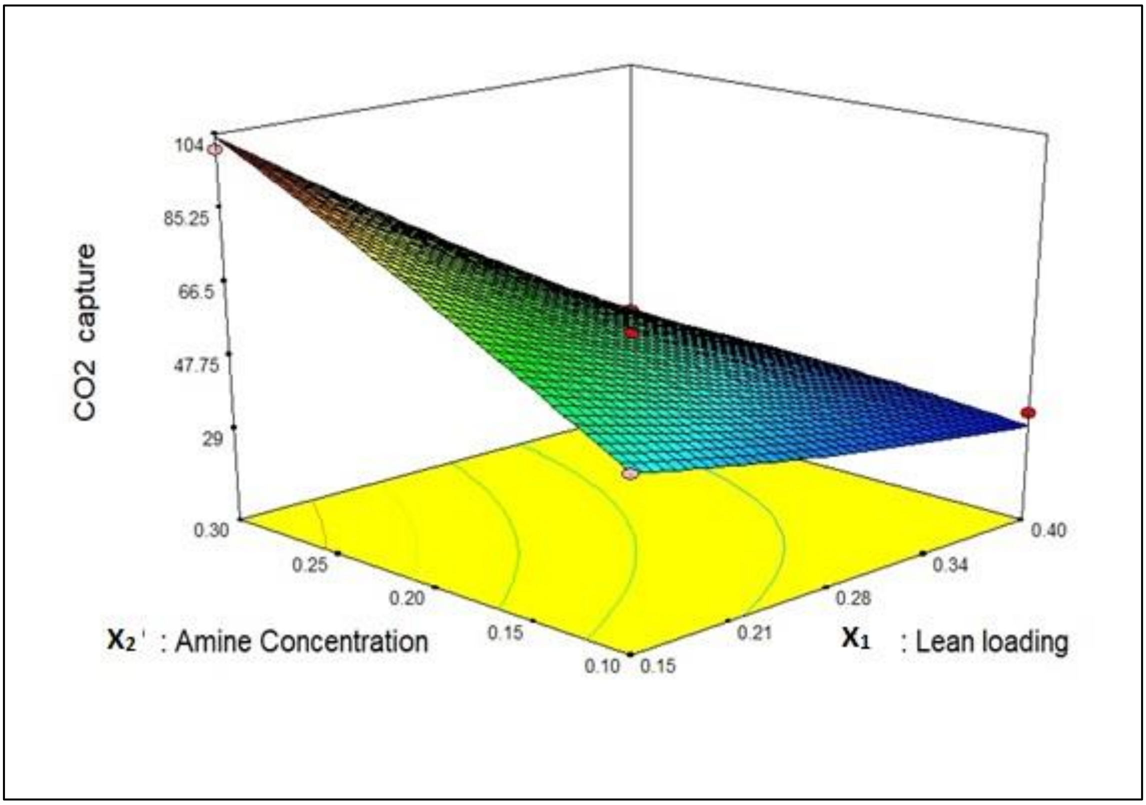


Figure 7.9. Three-dimensional response surface plot of CO_2 capture (effect of lean loading and solvent concentration temperature and the Agri-MSW-Coal ratio) of IGCC

A second order polynomial model equation has been obtained to represent the functional relationship between the process parameters and response, i.e., CO_2 capture. The predicted influence on CO_2 capture (R_1) obtained in terms of coded factors excluding terms containing X_3 is as follows:

$$Y_1 = 53.80 - 21.78 * X_1 + 15.03 * X_2 - 1.38 * X_3 - 12.68 * X_1 * X_2 - 1.49 * X_1 * X_3 + 1.27 * X_2 * X_3 + 1.60 * X_1 2 - 1.65 * X_2 2 - 0.11 * X_3 2 \qquad (21)$$

The value of R^2 (0.9927) close to 1indicates good agreement between the data as obtained from ASPEN Plus® and values of the response predicted by the RSM model. The obtained ratio of 413.784 can be noted as an adequate signal, which is greater than 4 as shown in Table 7.9.

Table 7.9. **Different statistical values from ANOVA analysis for CO_2 emissions avoidance using BBD**

R-Squared	Adj R-Squared	Pred R-Squared	Adeq Precision	Mean	C.V. %
0.9929	0.9837	0.8859	37.754	53.72	4.73

7.3.2.2 ANOVA on Energy returns on energy investment (EROEI)

From the ANOVA for three-factor interaction model for EROEI as shown in Table 7.10, indicate F-value of 92.92 and P-value < 0.05 implying the significance of the model. In this case, X_1, X_3, X_1^2 and X_3^2 factors are significant model terms.

Table 7.10. ANOVA analysis (Partial sum of squares) for EROEI

Sum of Source	Squares	Mean df	F Square	p-value Value	Prob > F	
Model	69.04	6	11.51	157.55	< 0.0001	significant
X_1-Lean loading	*41.75*	*1*	*41.75*	*571.70*	*< 0.0001*	
X_2-Amine Concentration	*19.87*	*1*	*19.87*	*272.07*	*< 0.0001*	
X_3-Solvent temperature	*0.17*	*1*	*0.17*	*2.30*	*0.1603*	
$X_1 X_2$	*7.08*	*1*	*7.08*	*96.92*	*< 0.0001*	
$X_1 X_3$	*0.098*	*1*	*0.098*	*1.34*	*0.2744*	
$X_2 X_3$	*0.071*	*1*	*0.071*	*0.98*	*0.3463*	
Residual	0.73	10	0.073			
Lack of Fit	*0.73*	*6*	*0.12*			
Pure Error	*0.000*	*4*	*0.000*			
Cor Total	69.77	16				

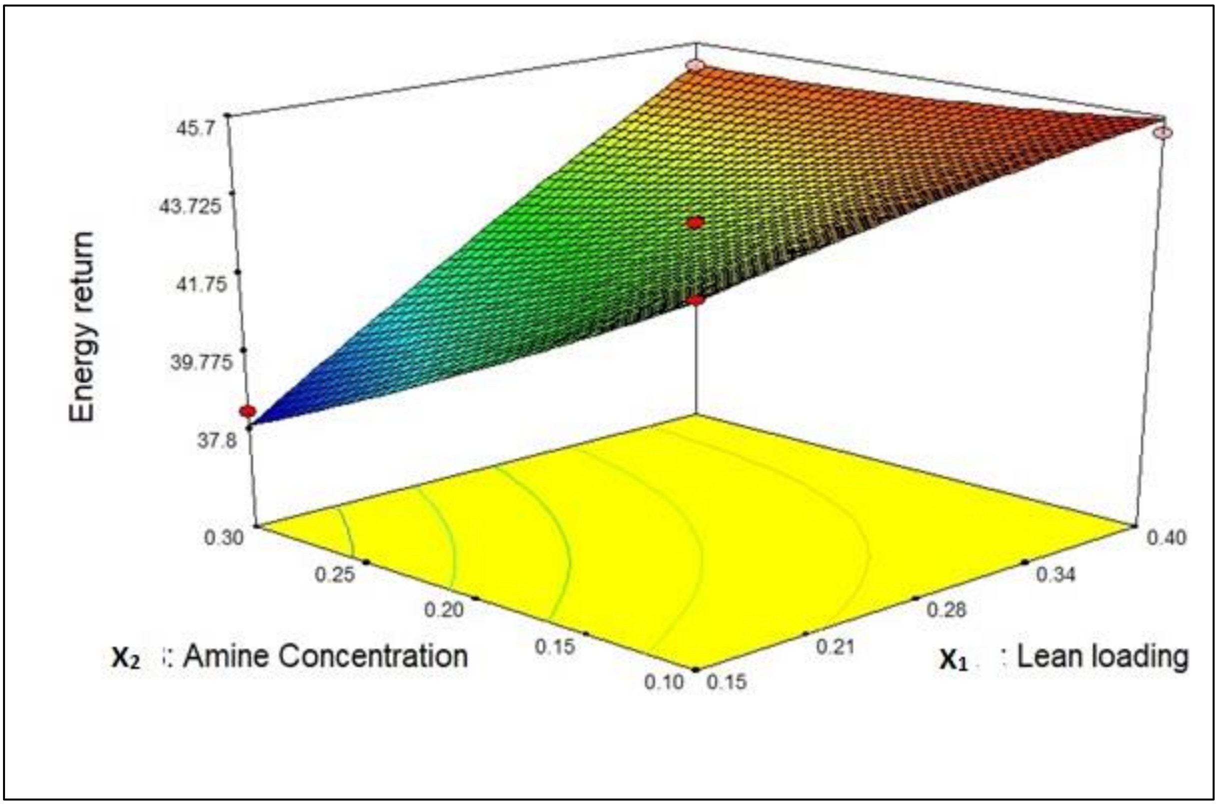


Figure 7.10 shows the three-dimensional response surface which has been constructed to show the interaction effect of X_1 and X_2 on EROEI.

A second order polynomial model equation of the following form has been obtained to represent influence on EROEI. The predicted response on EROEI (Y_2) obtained in terms of coded factor is as:

$$Y_2 = 43.08 + 2.28 * X_1 - 1.58 * X_2 + 0.14 * X_3 + 1.33 * X_1 * X_2 + 0.16 * X_1 * X_3 - 0.13 * X_2 * X_3 - 0.17 * X_1 2 + 0.17 * X_2 + 0.011 * X_3 2 \quad (22)$$

The value of R^2 (0.9917) close to 1, indicates good fitness of the data predicted by the quadratic model with those data obtained through ASPEN Plus®. The adequate (Adeq) Precision of 371.593> 4.0 again indicate the goodness of fit as shown in Table 7.11

Table 7.11. Different statistical values from ANOVA analysis for EROEI using BBD

R-Squared	Adj R-Squared	Pred R-Squared	Adeq Precision	Mean	C.V. %
0.9929	0.9837	0.8858	371.593	43.09	0.62

7.3.2.3 Optimum Conditions

These optimum values are obtained from study of design expert software by BBD model considering the set value of minimize lean loading, minimize solvent concentration and 30 ^oC of solvent temperature and maximize the CO_2 capture. The optimum design parameters of solvent temperature of 30^{o}C, solvent concentration of 22 wt% and lean loading of 0.15 are required to capture the CO_2 of 90%.

7.3.3 Distribution of Energy consumption in different processes/operations in the unit

The energy requirement for various units /processes of the CO_2 capture by solvent absorption has been calculated using ASPEN Plus® considering optimum design parameters. Table 7.12 summarizes some results with consideration of 90% CO_2 capture

Table 7.12. Results of Absorption & Solvent Regeneration process

Variable	Unit	Value	%
Rate of Heat Eenrgy consumption for solvent regeneration	kW	2200	77.6
Rate of Electricity consumption for CO_2 delivery by blower & auxiliaries for Absorption $E_{CO2\ blower}$	kW	87.2	3.1

Variable	Unit	Value	%
Rate of Electricity consumption for supply of steam in stripping unit by pump $E_{steam\ pump}$	kW	372	13.1
Rate of Electricity consumption for CO_2 compression($E_{compress}$)	kW	175	6.2
Rate of Total Energy consumption	kW	2834	

7.3.4 Comparison of EROEI with literature data

The performance of the efficiency penalty of the proposed model is also compared with literature data published by Dumitru, Loana 2017 [26], and Xiaoyan Liu 2015 [27]. As evident from the data provided in Table 7.13, most of the results are in good agreement.

Table 7.13. Performance of efficiency penalty the proposed model with published literature data.

Operating parameters	literature data published by Dumitru, Loana 2017 [36].	literature data published by X. Liu et al. / Fuel 158 (2015) [37].	This study
Cofiring (Biomass: Coal)	Hybrid poplar: Coal	Coal	Municipal solid waste : Coal
L/G mass flow rate ratio	3.87-3.92	2.75	2.9
Lean loading (mol CO_2/mol MEA)	0.25	0.23	0.23
MEA concentration (wt%)	30	30	30
Reboiler heat duty (MJ/kg CO2 captured)	3.5	4.6	4.53
Efficiency penalty (%)	10.21	9.75	10.9

Energy return on energy investment (*EROEI)* has been studied of 90 % of CO_2 capture of 30 TPD cofired IGCC plant with solvent regeneration and without solvent regeneration considering use of in-house power and grid power as shown in Figure 11. EROEI of CO_2 capture by solvent absorption with solvent regeneration has decreased from 50.2 % for original IGCC plant to 39.3 %, and 45.3% considering the use of in-house power and grid power respectively. EROEI of the IGCC plant integrated with CO_2 capture by solvent absorption without solvent regeneration, has decreased to 48.75 %, and 49.5% considering the use of in-house power and grid power, respectively, compared to 50.2 %.for the original IGCC plant.

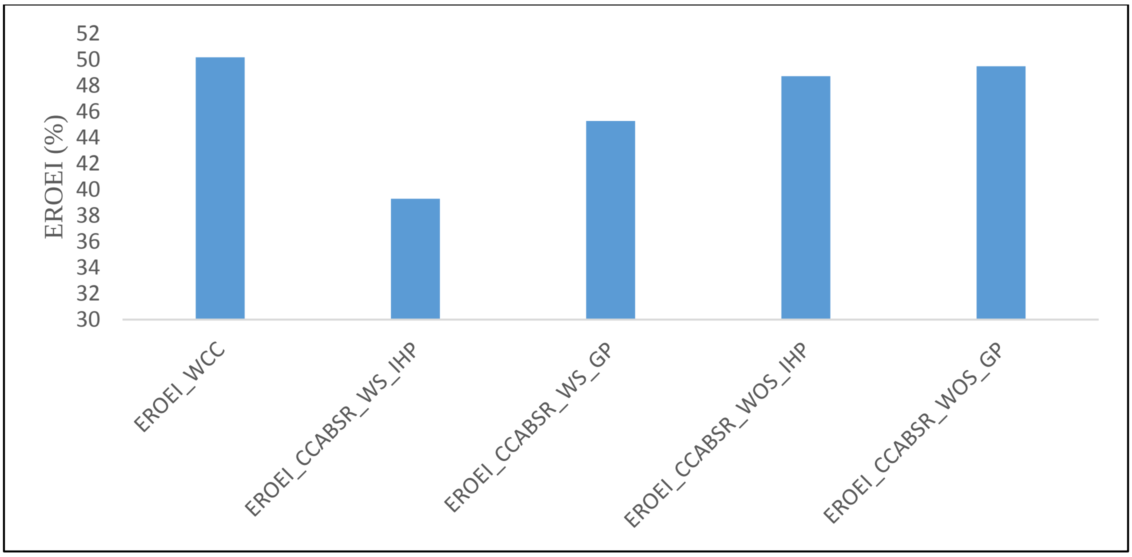


Figure 7.11. Comparison of EROEI of IGCC plant for with and without CO_2 capture considering use of in-house power and grid power and with solvent and without solvent regeneration

Energy return on energy investment($EROEI_{CCABSR}$) has been calculated using the data generated by ASPEN Plus®. The sample calculations and the ASPEN Plus® data are provided in the Appendix of this Chapter.

7.3.5 Study on ACE of post combustion CO_2 absorption

Avoidance in CO_2 emissions (ACE) has been studied for 90 % of CO_2 capture of 30 TPD co-fired IGCC plant with and without solvent regeneration, considering the use of in-house power and grid power. The trends have been depicted in Figure 7.12.

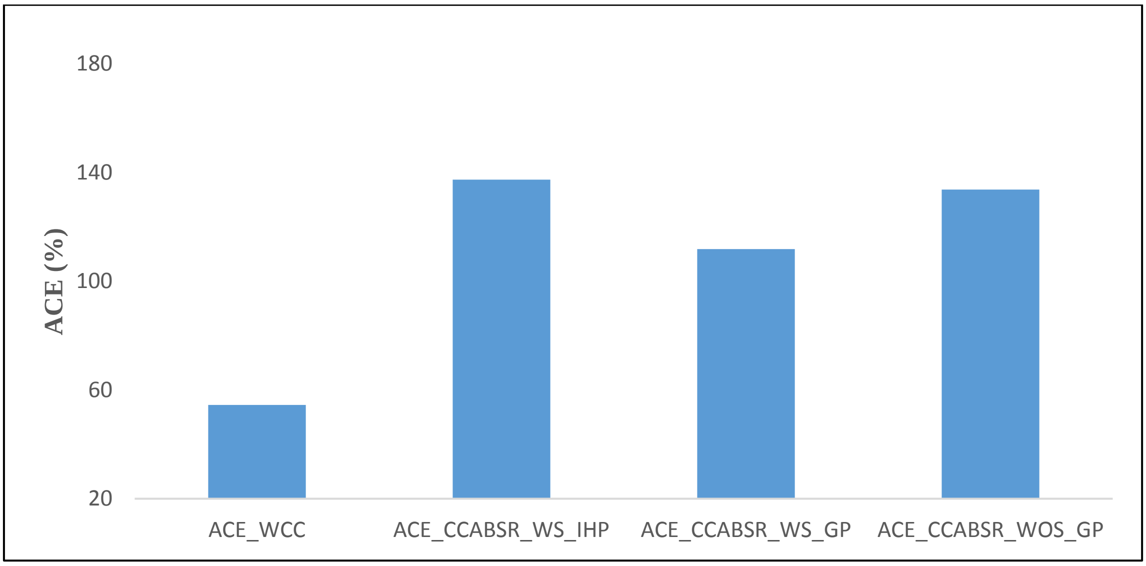


Figure 7.12. Comparison of Avoidance in CO_2 emissions (ACE) of 30 TPD cofired IGCC plant for with and without CO_2 capture considering use of in-house & grid power and with & without solvent regeneration.

Indian Agri-MSW as biomass feedstock for the cofired plant has a great capacity to capture CO_2 during photosynthetics production. Conditions should be sought to increase the ratio of Agri-MSW -coal in cofired power plants to increase the CO_2 capture for photosynthetic.

The CO_2 emissions has been avoided by 54.5% by using Indian Agri-MSW in cofired IGCC plants, as reported in the Chapter 6. Now post-combustion of 90% CO_2 capture has been implemented in 30TPD cofired IGCC plant and zero-emission of CO_2 has been achieved from that plant and avoidance in CO_2 emissions is 137% with the consideration of use of in-house power and CO_2 capture by absorption with solvent regeneration. ACE can be achieved at 111.8% considering the use of grid power to supply the power to the CO2 absorption system with solvent regeneration. This drop in ACE is due to CO_2 emissions for the use of the grid power, generated in coal-fired power plants. Further increases in the ACE can be achieved up to 133% as the grid power is required only for flue gas supply to the absorption unit and not for regeneration.

The performance of CO_2 emissions of the proposed model is also compared with literature data published by Dumitru, and Loana 2017 [36]. As evident from the data provided in Table 7.14, most of the results are in good agreement.

Table 7.14. Performance of CO_2 emissions of the proposed model with published literature data

Operating parameters	literature data published by Dumitru, Loana 2017 [36].	literature data published by X. Liu et al. / Fuel 158 (2015) [37].	This study
CO_2 capture rate (%)	90	90	90
Specific CO_2 emissions (kg/MWh)	110.6	110.55	112.17
Net CO_2 emissions (kg/MWh)	0	0	0

Avoidance in CO_2 emissions has been analyzed for the above plant using the data generated by ASPEN Plus®. The calculations and the data are provided in the Appendix of this chapter.

Symbols used

$K_G\, a_V$ [-] Gas-phase volumetric overall mass transfer coefficient

a_V [m2] effective interfacial area

Py^i_{CO2} [Pa] partial preesure of CO2 at interface

Py^*_{CO2} [Pa] CO_2 concentration in the liquid bulk

Py_{CO2}	[Pa]	CO_2 partial pressure in the gas bulk
ACE	[%]	Avoidance in CO2 emissions
EROEI	[%]	ratio of energy return on energy investment
L/G	[-]	mass flow rate ratio

Abbreviations

ASPEN	Plus® advanced system for process engineering
ACE	avoidance in CO_2 emissions
EROEI	energy return on energy investment
FGI	Flue-Gas Injection
GHG	greenhouse gas
HRSG	heat recovery steam generator
HFC	hydro fluorocarbons
IPCC	intergovernmental panel on climate change
IGCC	integrated gasification combined cycle
LHV	lower heating value
MSW	municipal solid waste
MEA	monoethyl amine
TPD	ton per day

7.4 References

[1] IPCC. Climate change 2014: mitigation of climate change: contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge (United Kingdom)/New York (NY, USA): Cambridge University Press; 2014.

[2] Colin F. Alie , *CO2 Capture with MEA: Intergrating the Absorption Process and Steam Cycle of an Existing Coal-Fired Power Plant*. Degree of Master of Applied Science , University of Waterloo, Canada; **2004.**

[3] Asli Vural, *Clean coal and carbon capture and storage technology roadmap of Turkey*. Degree of Master of Science in Petroleum and Natural Gas Engineering Middle East Technical University, Turkey; **2010**.

[4] Anusha Kothandaraman, *Carbon dioxide capture by Chemical Absorption: A Solvent Comparison Study*. PhD Thesis, Massachusetts Institute of Technology, USA; **2010**.

[5] *Rubin ES, Mantripragada H, Marks A, Versteeg P, Kitchin J, Progress in Energy and Combustion Science.* **2012,** 38(5), 630-671, DOI: 10.1016/j.pecs.2012.03.003 .

[6] *Yang H, Xu Z, Fan M, Gupta R, Slimane RB, Bland AE, Wright I. Journal of Environmental Sciences.* ***2008****, 20, 14–27, DOI:* 10.1016/S1001-0742(08)60002-9 J.

[7] *Strube R., Manfrida G., International Journal Greenhouse Gas Control.* **2011**, 5(4), 710-726. DOI: 10.1016/j.ijggc.2011.01.008

[8] Cebrucean D, Cebrucean V, Ionel I.. *Energy Procedia*. **2014**, 63, 18–26. DOI:10.1016/j.egypro.2014.11.003

[9] Bo Yang, Yi-MingWei, Lan-Cui Liue, Yun-Bing Hou , Kun Zhang, Lai Yang, Ye Feng. 2021. Life cycle cost assessment of biomass co-firing power plants with CO2 capture and storage considering multiple incentives, Energy Economics, 96, pp. 105173

[10] Woo-Sung Lee , Hyun-Taek Oh, Jae-Cheol Lee, Min Oh, Chang-Ha Lee. 2019. Performance analysis and carbon reduction assessment of an integrated syngas purification process for the co-production of hydrogen and power in an integrated gasification combined cycle plant, Energy, 171, pp. 910-927

[11] NETL. Cost and performance baseline for fossil energy plants. Volume 3b: Low rank coal to electricity: Combustion cases. DOE/NETL-2011/1463; March **2011**.

[12] NETL. Cost and performance baseline for fossil energy plants. Volume 1: Bituminous coal and natural gas to electricity. DOE/NETL-2010/1397, Revision 2a; September **2013**.

[13] CAESAR. D 4.9, *European best practice guidelines for assessment of CO2 capture technologies*. **2011**.

[14] Nasir M.A. Al Lagtah, Sagheer A. Onaizi, Ahmad B. Albadarin, Fadi A. Ghaith, Mutasim I. Nour. 2019. Techno-economic analysis of the effects of heat integration and different carbon capture technologies on the performance of coal-based IGCC power plants, Journal of Environmental Chemical Engineering, 7, pp. 103471

[15] Angel Jimenez Alvaro, Ignacio Lopez Paniagu, Celina Gonzalez Fernandez, Javier Rodriguez Martin, Rafael Nieto Carlier. 2015. Simulation of an integrated gasification combined cycle with chemical-looping combustion and carbon dioxide sequestration, Energy Conversion and Management, 104, pp. 170–179

[16] Giorgio Cau, Vittorio Tola, Paolo Deian.2014. Comparative performance assessment of USC and IGCC power plants integrated with CO2 capture systems, Fuel, 116 pp. 820–833

[17] Mohammad Mansouri Majoumerd , Mohsen Assadi. 2014. Techno-economic assessment of fossil fuel power plants with CO2 capture e Results of EU H2-IGCC project, International Journal of hydrogen energy, 39 , pp.16771 -16784

[18] Stefania Moioli , Antonio Giuffrid , Matteo C. Romano , Laura A. Pellegrini, Giovanni Lozza. 2016. Assessment of MDEA absorption process for sequential H2S removal and CO2 capture in air-blown IGCC plants, Applied Energy, 183,pp. 1452–1470

[19] Oexmann J, Kather A, Linnenberg S, Liebenthal U. *Greenhouse Gases:Science and Technology*. **2012,** 2(2), 80–98. DOI:10.1002/ghg.1273

[20] Cousins, A, Wardhaugh, LT, Feron, PHM. *International Journal of Greenhouse Gas Control*. **2011,** 5, 605-619. DOI: 10.1016/j.ijggc.2011.01.002.

[21] Le Moullec, Y, Kanniche, M. Inernational J Greenhouse Gas Control. **2011**, 5(4), 727-740. DOI: 10.1016/j.ijggc.2011.03.004.

[22] A.Sharif, A.Jahangiri, M.Ameri. *Sustainable Energy Technologies and Assessments,* **2021**, Volume 45, 101102. DOI: 10.1016/j.seta.2021.101102.

[23] Cousins, A, Wardhaugh, LT, Feron, PHM, *Chemical Engineering Research and Design.* **2011**, 89, 1237-1251. DOI: 10.1016/j.cherd.2011.02.008

[24] Fernandez, ES, Bergsma, EJ, de Miguel Mercader, F, Goether, ELV, Vlugt, TJH, *International Journal of Greenhouse Gas Control*. 2012, 11, S114-121. DOI: 10.1016/j.ijggc.2012.09.007

[25] Karimi, M, Hillestad, M, Svendsen, HF, Chemical Engineering Research and Design. **2011**, 89, 1229-1236. DOI: 10.1016/j.cherd.2011.03.005

[26] Davide Bonalumi, Alessio Ciavatta, Antonio Giuffrid. 2016. Thermodynamic Assessment of Cooled and Chilled Ammonia-Based CO2 Capture in Air-Blown IGCC Plants, Energy Procedia, 86 , pp. 272 – 281

[27] Freguia S, Rochelle GT, *AIChE Journal.* **2003**, 49, 1676–1686. DOI: 10.1002/aic.690490708

[28] Moullec YL, Kanniche M,. *International Journal of Greenhouse Gas Control*.**2011,** 5(4),727–740. DOI: 10.1016/j.ijggc.2011.03.004

[29] Oyenekan BA, Rochelle GT, *AIChE Journal*. **2007**, 53(12), 3144–3154. DOI: 10.1002/aic.11316

[30] Van Loo S, Koppejan J. *The handbook of biomass combustion and co-firing*. Earthscan, London; **2008**.

[31] Guiyan Zanga, Junxi Ji, Sharma Tejasvi, Albert Ratner, Electo Silva Lora. 2018. Techno-economic comparative analysis of Biomass Integrated Gasification Combined Cycles with and without CO2 capture, International Journal of Greenhouse Gas Control, 78, pp. 73–84

[32] NETL. Greenhouse gas reductions in the power industry using domestic coal and biomass. Volume 2: Pulverized coal plants. DOE/NETL-2012/1547; February **2012**.

[33] Mohammad Mansouri Majoumerd, Han Raasc, Kuntal Jana, Sudipta De, Mohsen Assadi. 2017. Coal quality effects on the performance of an IGCC power plant with CO2 capture in India, Energy Procedia, 114, pp. 6478 – 6489

[34] Vinod Krishna Sethia, Savita Vyasb. 2017. An Innovative Approach for Carbon Capture & Sequestration on a Thermal Power Plant through Conversion to Multi-Purpose Fuels –A Feasibility Study in Indian Context, Energy Procedia, 114, pp. 1288 – 1296

[35] Lars Erik Øia, Stian Holst Pedersen Kvama, *Energy Procedia*. **2014**, 63, 18–26. DOI:10.1016/j.egypro.2014.11.003

[36] Dumitru Cebrucean, Viorica Cebrucean , Ioana Ionel, *researchgate.net/publication/316915681*.**2017**. DOI: 10.5772/67188.

[37] Xiaoyan Liu, Jian Chen, Xiaobo Luo, Meihong Wang, Hui Meng, *Fuel*. **2015**, 158, 625–633. DOI:10.1016/j.fuel.2015.06.033.

[38] Yuzuru Ued, Kosuke Kurokaw, *Member, IEEE*, Takayuki Tanabe, Kiyoyuki Kitamur, and Hiroyuki Sugihar, 2008. Analysis Results of Output Power Loss Due to the Grid Voltage Rise in Grid-Connected Photovoltaic Power Generation systems, IEEE transactions on industrial electronics, 55 (7).

[39] Moti L. Mitta, 2015. Estimates of Emissions from Coal Fired Thermal Power Plants in India

[40] Udara Sampath P.R.Arachchige, Morten Christian Melaaen, *Energy Procedia, 2012,* 23, 391 – 399. DOI: 10.1016/j.egypro.2012.06.060

[41] Nur Farhana Ajua Mustafa, Azmi Mohd Shari, Wee Horng Tay, Hairul Nazirah Abdul Halim, and Siti Munirah Mhd Yusof, *Sustainability* 2020, 12, 3873; doi:10.3390/su12093873

[42] Roc´ıo Maceiras, Estrella A´ lvarez, M. A´ ngeles Cancela, *Chemical Engineering Journal*,2008, 138 ,295–300

APPENDIX_Chapter 7

Table A.7.1 ASPEN Plus® generated data and the Calculation of ($EROEI_{CCABSR}$) of IGCC Co-fired power plant with CO_2 capture using solvent absorption

Description	Unit	Value
IGCC Co-fired Power Plant Capacity	TPD	30
Cofiring ratio i.e. Agri-MSW to coal ratio (wt/wt)	%	50
Biomass i.e. Agri-MSW feed rate (M_{MSW})	Kg/hr (kg/s)	625 (0.1736)
HHV of Agri-MSW (HHV_{MSW})	kJ/kg	17600
Coal Feed rate(M_{COAL})	Kg/hr (kg/s)	625 (0.1736)
HHV of coal (HHV_{COAL})	kJ/kg	18840
Rate of Energy input (E_{input}) of IGCC co-fired power plant M_{MSW} x HHV_{MSW} + M_{COAL} x HHV_{COAL}	kw	$0.1736 \times 17600 + 0.1736 \times 18840$ =5815
Energy output (E_{output}) from IGCC co-fired power plant without CO_2 capture	kw	2922
EROEI without CO_2 capture ($EROEI_{WCC}$) has been calculated as per eqn. (1) $EROEI_{WCC} = \frac{\text{Energy outpu}(E_{output})\text{ from cofired IGCC plant}}{\text{Energy Input}(E_{input})\text{ of Cofired IGCC plant}}*100$		
EROEI without CO_2 capture ($EROEI_{WCC}$)	%	$\frac{2922}{5815} \times 100$ =50.2
Total energy demand for CO_2 capture through solvent absorption (E_{CCABSR}) as per eqn. (3) $(E_{CO2\ blower}) + (E_{steam\ pump}) + (E_{CO2\ compress})$	kw	87+372+175 = 634
EROEI with CO_2 capture by solvent absorption ($EROEI_{CCABSR\_WS\_IHP}$) with solvent regeneration has been calculated considering use of in-house power as per eqn. (4) $EROEI_{CCABSR\_WS\_IHP} = \frac{\text{Energy output from cofired IGCC plant} - \text{Energy demand for } CO_2 \text{ capture through solvent absorption}}{\text{Energy Input of Cofired IGCC plant}}*100$		
EROEI with CO_2 capture using solvent absorption ($EROEI_{CCABSR\_WS\_IHP}$)	%	$\frac{2922 - 634}{5815} \times 100$ =39.3
EROEI with CO_2 capture using solvent absorption ($EROEI_{CCABSR\_WS\_GP}$) with solvent regeneration has been calculated considering use of grid power as per eqn. (6) $EROEI_{CCABSR\_WS\_GP} = \frac{\text{Energy output from cofired IGCC plant}}{\text{Energy Input of Cofired IGCC plant} + \text{Energy demand for } CO_2 \text{ capture through solven}} * 100$		
EROEI with CO_2 capture using solvent absorption ($EROEI_{CCABSR\_WS\_GP}$)	%	$\frac{2922}{5815 + 634} \times 100$

Description	Unit	Value
		=45.3

EROEI with CO_2 capture by solvent absorption ($EROEI_{CCABSR\_WOS\_IHP}$) without solvent regeneration has been calculated considering use of in-house power as per eqn. (5)

$$EROEI_{CCABSR\_WOS\_IHP} = \frac{\text{Energy output from cofired IGCC plant} - \text{Energy demand for } CO_2 \text{ capture through solvent absorption}}{\text{Energy Input of Cofired IGCC plant}} * 100$$

Description	Unit	Value
EROEI with CO_2 capture using solvent absorption ($EROEI_{CCABSR\_WOS\_IHP}$)	%	$\frac{2922 - 87}{5815} \times 100$ =48.75

EROEI with CO_2 capture using solvent absorption ($EROEI_{CCABSR\_WOS\_GP}$) without solvent regeneration has been calculated considering use of grid power as per eqn. (7)

$$EROEI_{CCABSR\_WOS\_GP} = \frac{\text{Energy output from cofired IGCC plant}}{\text{Energy Input of Cofired IGCC plant} + \text{Energy demand for } CO_2 \text{ capture through solvent absorption}} * 100$$

Description	Unit	Value
EROEI with CO_2 capture using solvent absorption ($EROEI_{CCABSR\_WOS\_GP}$)	%	$\frac{2922}{5815 + 87} \times 100$ =49.5

Table A.7.2. ASPEN Plus® generated data and the Calculation of (ACE_{CCABSR}) of IGCC Co-fired power plant with CO_2 capture using solvent absorption

Description	Unit	Value
Plant Capacity	TPD	30
CO_2 emissions from coal fired power plant	Kg/hr	2120
CO_2 emissions from IGCC co-fired power plant	kg/hr	1950
Cofiring ratio i.e. Agri-MSW to coal ratio (wt/wt)	%	50
Agri-MSW biomass feed rate (M_{MSW})	kg/hr	625.00
Consumption of CO_2 during the production of Agri-MSW biomass through photosynthetic route ($CO_{2_{MSWBPH}}$) as per eqn. (10) $CO_{2_{MSWBPH}} = \frac{M_{MSWB} * w_{cMSWB} * MW_{CO_2}}{MW_C}$		
Weight fraction of carbon in the Agri-MSW biomass (w_{cMSWB})		0.43
Molecular weight of CO2 (MW_{CO_2})	Kg/kmol	44
Molecular weight of Carbon (MW_C)	Kg/kmol	12
$CO_{2_{MSWBPH}}$	Kg/hr	$\frac{625 \times 0.43 \times 44}{12}$ =985.42
Plant emissions avoidance due to switching over from coal fired to co-fired IGCC mode i.e. CO_2 emissions from coal fired power plant - CO_2 emissions from IGCC co-fired power plant	Kg/hr	2120-1950 =170
Total CO_2 emissions for IGCC co-fired plant without CO_2 capture has been calculated as per eq. no. (9)	Kg/hr	170+985.42 =1155.42
ACE for the IGCC power plant without CO_2 capture (ACE_{WCC}) as per eqn. (8) $ACE_{WCC} = \frac{\text{Total } CO_2 \text{ emissions avoidance for the IGCC power cofired power plant without } CO_2 \text{ capture}}{CO_2 \text{ emissions from coal plant}} * 100$		

Description	Unit	Value
ACE_{WCC}	%	$\frac{1155.42}{2120} \times 100$ =54.5
CO_2 capture by absorption with solvent of IGCC co-fired power plant	%	90.00
CO_2 captured by absorption with solvent ($CO_{2_{CCABSR}}$)	Kg/hr	1950×0.9 =1755
Total CO_2 emissions for IGCC co-fired plant with CO_2 capture with solvent regeneration considering use of in-house power has been calculated as per eq. no. (13)	kg/hr	170+985.42+1755 =2910.42
ACE for the IGCC power plant with solvent absorption CO_2 capture (ACE_{CCABSR_IHP})as per eqn. (12) of manuscript considering use of in-house power $ACE_{CCABSR_{IHP}} = \frac{\text{Total } CO_2 \text{ emissions avoidance for the IGCC power cofired power plant with } CO_2 \text{ capture considering use of in-house power}}{CO_2 \text{ emissions from coal plant}} * 100$		
ACE_{CCABSR_IHP}	%	$\frac{2910.42}{2120} \times 100$ =137.3
CO_2 emissions due to energy supplied from grid power as per eq. no. (18)	Kg/hr	1.05*0.95*634= 538.9
Total CO_2 emissions avoidance for IGCC co-fired plant with CO_2 capture with solvent regeneration considering use of grid power has been calculated as per eq. no.(15)	kg/hr	170+985.42+1755-538.9 =2371.52
ACE for the IGCC power plant with CO_2 capture ($ACE_{CCABSR\_WS\_GP}$) with solvent regneration as per eqn. (14) of manuscript considering use of grid power $ACE_{CCABSR_{WS_{GP}}} = \frac{\text{Total } CO_2 \text{ emissions avoidance for the IGCC plant with } CO_2 \text{ capture with solvent regen considering use of grid power}}{CO_2 \text{ emissions from coal plant}} * 100$		
$ACE_{CCABSR\_WS\_GP}$	%	$\frac{2371.52}{2120} \times 100$ =111.8
CO_2 emissions due to energy supplied from grid power as per eq. no. (18)	Kg/hr	1.05*0.95*87= 86.78
Total CO_2 emissions avoidance for IGCC co-fired plant with CO_2 capture without solvent regeneration considering use of grid power calculated as per eq. no. (17)	kg/hr	170+985.42+1755-86.78 =2823.47
ACE for the IGCC power plant with CO_2 capture ($ACE_{CCABSR\_WOS\_GP}$) without solvent regneration as per eqn. (16) of manuscript considering use of grid power $ACE_{CCABSR\_WOS\_GP} = \frac{\text{Total } CO_2 \text{ emissions avoidance for the IGCC plant with } CO_2 \text{ capture without solvent regen considering use of grid power}}{CO_2 \text{ emissions from coal plant}} * 100$		
$ACE_{CCABSR\_WOS\_GP}$	%	$\frac{2823.47}{2120} \times 100$ =133.7

CHAPTER 8

IGCC POWER PLANT WITH ALGAL CO2 CAPTURE AND BIODIESEL PRODUCTION

8.1 Introduction

The capture of CO_2 by photoautotrophic algae is an option with regard to post combustion CO_2 capture [1]. Due to the presence of simple cellular structures, the photosynthesis efficiency of algae is much higher than that of terrestrial plants [2]. According to published claims, 1 kg of algal biomass can be produced by the absorption of 1.88 kg of carbon dioxide [2, 3]. From the literature review it is clear that biofuels as well as biochemicals can be produced from the algal biomass [3-6]. There exist many oleaginous species of algae which can serve as prominent candidates for the production of biofuels, biochemicals and protein. Due to the presence simple photosynthesis structure in algae, the biomass and oil productivities are usually much higher than that obtained from the terrestrial oil crops. This ultimately reduces the requirement of land for algal cultivation in comparison to the fertile land required for the production of oil crops [7]. For the capture of CO_2 to the same extent, the overall culture period of algae is also much less than that required by their counterparts i.e. terrestrial plants [8]. The parameters to be considered during the selection of algal strains for the post-combustion CO_2 capture are very important. The withstanding capacity of high concentrations of CO_2, NOx, and SOx present in power plant flue gas is one of the important criteria for the selection of algal strains [9, 10]. The oleaginous algal strains having the capability of production of high quality oil with high growth rate of biomass are particularly suitable for the post-combustion capture of CO_2. *Chlorella* species represent one of the oleaginous algal strains which can withstand the CO_2 concentration upto 40%(v/v) with high CO_2 fixation rate between 0.73 to 2.22 g/L/day [9-11]. They are also capable of withstanding NOx, and Sox, etc. present in power plant flue gas [9-11]. It has been reported that algal strains belonging to *Chlorella* species can easily remove NO_x, SO_x etc. along with CO_2 [9-11]. They can utilize the nitrous or nitric acid generated through the dissolution of NO_x as their nitrogen substrate. Among different modes of growth of algal species, namely heterotrophic, photoautotrophic, and mixotrophic ones, the first one utilizing the inorganic carbon source, particularly CO_2, is the most efficient one [12,32, 33]. Hence, the photoautotrophic mode of growth of algae, based on the consumption of CO_2 from the waste flue gas from power plants, is gaining scientific interest [13]. In this process, the growth of algae is based on the utilization of the waste stream and it ascertains the production of biofuels and biochemicals in return. Therefore, it supports the concept of a sustainable circular economy. The integration of algal production with power plant can come up as the future biorefinery from which biofuels and biochemicals can be produced by the mitigation of CO_2 emissions [31].

There are two main types of cultivation units, namely open raceway pond (ORP) and photobioreactor (PBR) which are used for algal growth [14, 15,34]. While the ORPs usually utilize solar energy as the energy source of photons the photobioreactor utilize the artificial lighting. From the literature review it appears that several research studies have been reported on the post-combustion CO_2 capture using different algal strains [14-20]. The reported data suggest that the efficiency of CO_2 reduction lies in the range of 30% to 75 % and 40% to 80% for the open raceway pond and the photobioreactor respectively [15]. Although the efficiency of photobioreactors is much higher than open raceway ponds, the cost involved in the former is also much higher than the latter [17]. From the literature review it is evident that post-combustion algal CO_2 capture has been studied mostly with conventionally run power plants. It is under stable that IGCC based power plants driven by combining the conventional fuel with biomass is capable of mitigating CO_2 emissions to a large extent [18, 35, 36]. In a recent study, the present group has established that 55% CO_2 emissions of a 30 TPD IGCC plant, run on Indian coal, can be avoided when a 1:1 mixture of Indian coal and Agri-MSW based Biomass is used. However, there is further scope of mitigating CO_2 of an IGCC plant by incorporating any of the post-combustion CO_2 capture processes. There is a scarcity of data on an IGCC plant integrated with post-combustion CO_2 capture by algae. After identifying the research gap, the present study will focuses on: (I) the analyses of energy return on energy investment (EROEI) and CO_2 emissions avoidance

(ACE) of the same 30TPD IGCC plant, fed by 1:1 mixture of Indian coal and Agri-MSW based Biomass, integrated with a microalgal CO_2 capturing unit using process simulation tool, namely, ASPEN Plus®; (II) comparison of the energy return on energy investment (EROEI) of the IGCC plant with algal CO_2 capture and biodiesel production from the algae produced by CO_2 capture system of IGCC plant.

8.2 Materials and methods

8.2.1 30 TPD cofired IGCC Power plant

Table 8.1 summarizes the operating parameters, output energy and CO_2 emissions information of the 30 TPD co-fired IGCC power plant without CO_2 capturing facility as discussed in Chapter 6. The data were determined through process simulation modeling using ASPEN Plus® engineering tool.

Table 8.1. Technical information of 30 TPD co-fired IGCC plant without CO_2 capture

Parameter	Unit	Value
Cofiring (biomass:coal)	:	Indian Agri-MSW based Biomass : Coal
Feed composition (mass basis)	:	50:50
Gasifier Temperature	^oC	900
Indian Agri-MSW based Biomass feed flow rate as per cofired mass basis	Kg/h	625
Coal feed flow rate as per cofired mass basis	Kg/h	625
Higher heating value of Indian Agri-MSW based Biomass	MJ/kg	17.6
Higher heating value of Coal	MJ/kg	18.84
Energy return on Eenrgy Investment (EROEI)	%	50.25
Avoidance in CO_2 emissions (ACE)	%	54.5

The composition of flue gas emitted from 30 TPD co-fired IGCC power Plant, as reported in the Chapter 6, is shows in Table 8.2.

Table 8.2. Flue gas composition of 30 TPD cofired IGCC Power plant

Parameter	Unit	Value
CO_2	(mol/mol)%	10.14
H_2O	(mol/mol)%	6.76
O_2	(mol/mol)%	9.02
N_2	(mol/mol)%	74.08

8.2.2 Selection of Algal Strain

The parameters to be considered during the selection of algal strains for the post-combustion CO_2 capture are very important. The withstanding capacity of high concentrations of CO_2, NOx, and SOx present in power plant flue gas is one of the important criteria for the selection of algal strains [15, 16]. The oleaginous algal strains having the capability of production of high quality oil with high growth rate of biomass are particularly suitable for the post combustion capture of CO_2. *Chlorella* species represent one of the oleaginous algal strains which can withstand the CO_2 concentration upto 40%(v/v) with high CO_2 fixation rate between 0.73 to 2.22 g/L/day [16, 17]. They are also capable of withstanding NOx, and Sox, etc. present in power plant flue gas [16, 17]. It has been reported that algal strains belonging to *Chlorella* species can easily remove NO_x, SO_x etc. along with CO_2 [16-18]. They can utilize the nitrous or nitric acid generated through the desolution of NO_x as their nitrogen substrate [18]. Algal strains like *Chlorella Vulgaris*, *Nannochloropsis spp.*, *Scenedesmus spp.* etc. have already been used for the biocapture of CO_2 from the gas emitted from power plants [19, 20].

8.2.3 ASPEN Plus®

ASPEN Plus® is a simulation tool used for the prediction of the performance of large scale chemical processes through simulation, modeling and optimization using existing database in the built-in library of ASPEN Plus® and the information supplied by the user based on laboratory scale experiments. The sensitivity analysis of plant and large scale plant and their economic evaluation are possible by through the use of ASPEN Plus® with properly described material and energy schemes and the reaction involved in the process. Therefore, the ASPEN Plus® can be efficiently used for making a strategic decisions to be made on the implementation of a new technology in industrial scale. In the present study, process simulation modeling using ASPEN Plus® has been used for the integrated system of the IGCC power plant, run on Indian coal and Indian Agri-MSW based Biomass, a micro algal CO_2 capturing unit and algae to biodiesel production unit.

8.2.4 Case Descriptions and Model Design

Microalgal biomass production mainly comprises two major stages: (a) microalgae cultivation; (b) biomass harvesting and dewatering. The flow diagram for the integrated IGCC plant with algal CO_2 capture unit has been schematically represented in Figure 8.1**.** The IGCC network has already been described in the Chapter 6.

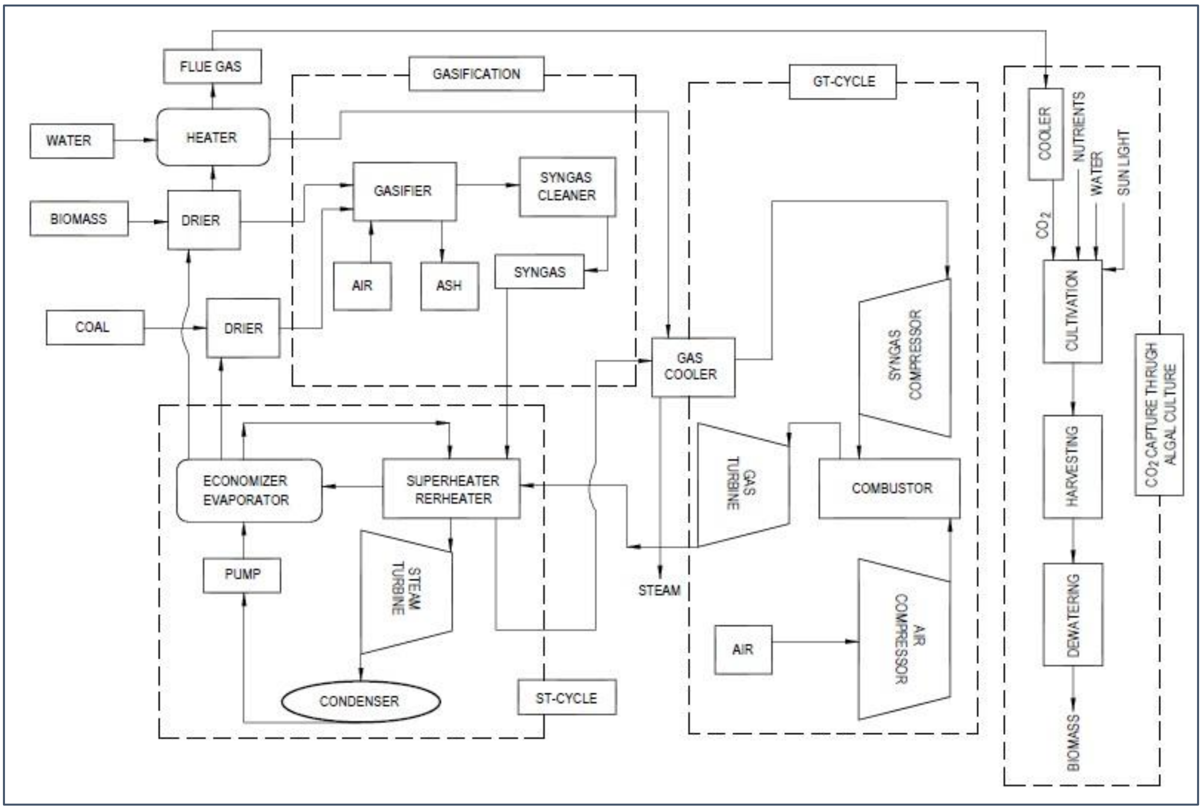


Figure 8.1. Process Flow Diagram for Integrated IGCC plant with microalgal biomass production

CO_2 capture by the algal method involves passing the flue gas through the cultivation unit followed by harvesting and dewatering units. Before entering the cultivation unit, the flue gas is cooled to the cultivation temperature. Exit biomass-water suspension stream of the cultivation unit is fed to the harvesting unit for concentration. The outlet stream of the harvesting unit is fed to remove water from the concentrated biomass suspension. The dewatered biomass has been used for the production of valuable biofuels i.e. biodiesel and biochemicals i.e. glycerol. Therefore, the downstream processing of the algal biomass is the production of biodiesel. Microalgae to bio-diesel production mainly follows three sequential stages: (1) lipid extraction from dewatered algal biomass, (2) transesterification, and (3) recovery of biodiesel from reaction mixture. The flow diagram for the production of biodiesel from algae has been schematically represented in Figure 8.2.

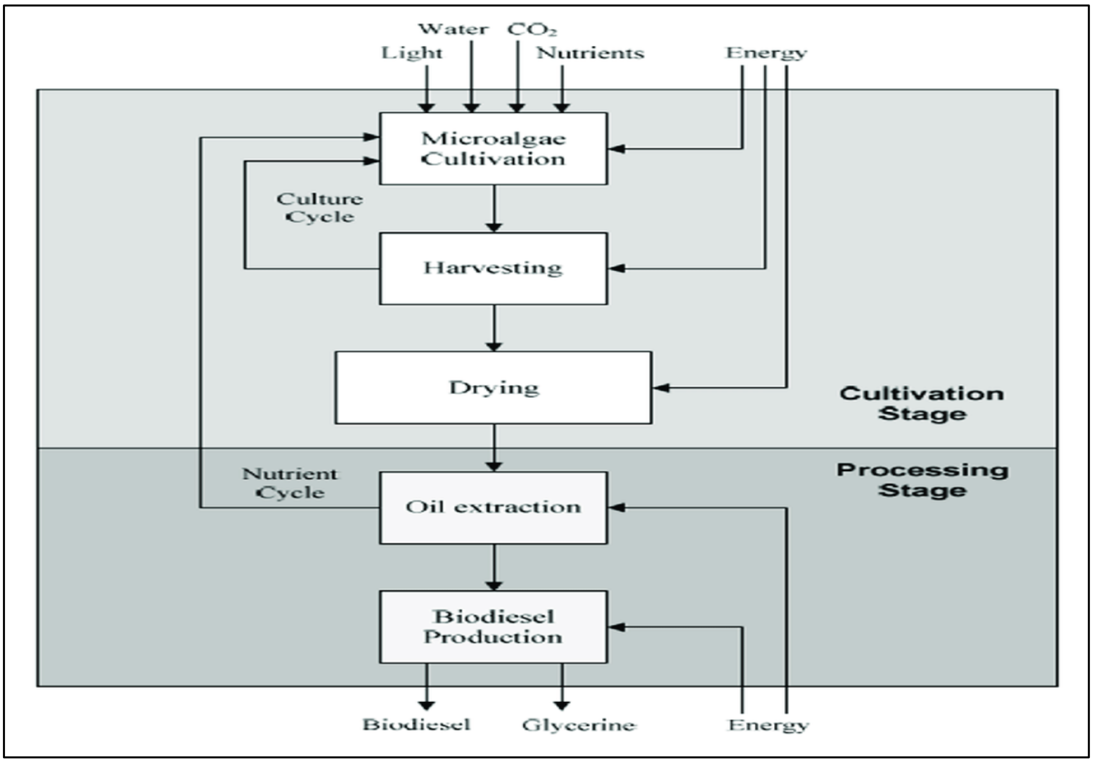


Figure 8.2. **Process flow diagram for algae to biodiesel production**

8.2.5. Production and recovery of algal biomass through the capture of CO_2

The input streams, reactions and unit operations considered in the production of algal biomass through the consumption of CO_2 in the flue gas are described below:

8.2.5.1 Cultivation of Algae

Open raceway pond (ORP) has been selected for the cultivation of *Chlorella spp., Nannochloropsis spp.* and *Scenedesmus* spp. *each* to handle the CO_2 stream emitted from 30 TPD IGCC power plant under this study. ORP type cultivation unit has been chosen because of the mutuality of technology and its economic feasibility for large scale algal cultivation [19, 20]. The cultivation has been initiated by inoculation with a stock culture having a concentration of biomass of 1.5g/L [20]. CO_2 capture by another two nos. Micro algae i.e. *Nannochloropsis, Scenedesmus* has also been considered under the study.

The molecular composition of the *Chlorella spp, Nannochloropsis spp,* and *Scenedesmus spp* and the reaction involved in the generation of algal mass from CO_2 using these three algal species are as follows:

8.2.5.1.1 Composition of three (*Chlorella spp, Nannochloropsis spp,* and *Scenedesmus spp,)* algal species

As algae are non-conventional feedstocks for ASPEN Plus® software, their physical properties are not available in the built-in database. In a technical report of NREL [21], the early, mid- and late phase composition of *Chlorella vulgaris, Nannochloropsis spp,* and *Scenedesmus spp* , with respect to carbohydrates, lipids, and proteins, have been provided. Under this study, the late phase composition of these micro algal species, as represented in Table 8.3, have been used in the ASPEN Plus® simulation. As reported by previous researchers, sucrose, triolein and L-phenylalanine have been used to represent carbohydrates, lipids and proteins, respectively [22].

Table 8.3 Composition of *Chlorella vulgaris, Nannochloropsis spp and Scenedesmus spp*

Algal Species	Carbohydrate Sucrose ($C_{12}H_{22}O_{11}$) MW*: 342		Lipids Triolein ($C_{57}H_{104}O_6$) MW*: 884		Proteins L-phenylalanine ($C_9H_{11}NO_2$) MW*: : 165	
	% (w/w) (dry basis)	% (molar)	% (w/w) (dry basis)	% (molar)	% (w/w) (dry basis)	% (molar)
Chlorella vulgaris	21	14.2	22	5.8	57	80
Nannochloropsis spp	25	22	40	14	35	64
Scenedesmus spp	35	27	25	8	40	65

Based on the composition of the algal species, the empirical formulae of *Chlorella vulgaris, Nannochloropsis spp* and *Scenedesmus spp* are assigned to be $C_{12.21}\ H_{7.778}\ O_{14.344}\ N_{0.8}$, $C_{21.48}\ H_{38.5}\ O_{8.64}\ N_{0.14}$, and $C_{23.91}\ H_{43.26}\ O_{8.93}\ N_{0.08}$respectively.

8.2.5.1.2 Biochemical Reaction for formation of *Chlorella vulgaris, Nannochloropsis spp and Scenedesmus spp*

The generalized stoichiometric equation representing the biochemical reaction for the formation of the algal biomass from CO_2 can be written as follows:

$$aCO_2 + bH_2O + c\,NH_3 \xrightarrow{Light\ energy\ (h\gamma)} C_{57}H_{104}O_6 + e\,C_9H_{11}NO_2 + f\,C_{12}H_{22}O_{11} + gO_2 \quad (1)$$

Triolein | L-phenylalanine | Sucrose

By making the atom balance for C, H, N and O, the stoichiometric coefficients, a-g have been determined for the three algal species and have been represented in Table 8.4.

Table 8.4: stoichiometric coefficients of biochemical reaction

Algal Species	stoichiometric coefficients of biochemical reaction						
	a	b	c	d	e	f	g
Chlorella vulgaris	12.21	7.778	0.8	0.058	0.8	0.142	14.344
Nannochloropsis spp	16.38	12.26	0.64	0.14	0.64	0.22	20.24
Scenedesmus spp	13.65	9.73	0.65	0.08	0.65	0.27	16.14

Therefore, the stoichiometric equations of biochemical reaction for three algal species can be written as follows:

Chlorella vulgaris

$$12.21CO_2 + 7.778H_2O + 0.8\,NH_3 \xrightarrow{Light\ energy\ (h\gamma)} 0.058\,C_{57}H_{104}O_6 + 0.8\,C_9H_{11}NO_2 + 0.142C_{12}H_{22}O_{11} + 14.344O_2 \quad (2)$$

$$\Delta H^{o}_{R(Chlorella\ vulgaris)} = 3734.4\text{kJ/mol}$$

Nannochloropsis spp

$$16.38CO_2 + 12.26H_2O + 0.64\,NH_3 \xrightarrow{Light\ energy\ (h\gamma)} 0.14\,C_{57}H_{104}O_6 + 0.64\,C_9H_{11}NO_2 + 0.22C_{12}H_{22}O_{11} + 20.24O_2 \quad (3)$$

$$\Delta H^{o}_{R(Nannochloropsis\ spp.)} = 6272.7\text{kJ/mol}$$

Scenedesmus spp

$$13.65CO_2 + 9.738H_2O + 0.65\ NH_3 \xrightarrow{Light\ energy\ (h\gamma)} 0.08\ C_{57}H_{104}O_6 + 0.65\ C_9H_{11}NO_2 + 0.27C_{12}H_{22}O_{11} + 16.14O_2 \quad (4)$$

$$\Delta H^o_{R(Scenedesmus\ spp.)} = 4382.7\text{kJ/mol}$$

8.2.5.1.3 Calculation of Area and Volume of ORPs for three algal species

The area and the volume of the raceway pond have been determined with the following assumptions:

The raceway pond operates under semi batch mode; the gas is fed and discharged continuously, and the liquid and solid phases are in batch mode.

Batch time (t_B) of six days has been assumed [22]. This signifies that the algal biomass is harvested at an interval of six days.

Percentage conversion of inlet CO_2 to algal biomass is 70%. [23].

The productivity (P_B) of algal biomass is 25 g/m^2/day or, 0.001kg/m^2/h [18, 21, 22].

The biomass concentration (Cx) at the end of six days is 0.5 g/L [18, 21, 22].

Light energy required for photosynthesis is supplied by natural sunlight.

The solar flux, of Eastern India, is in a range of 5-30Wh/m^2/d.[24]

As per literature data, the pH of 7 is maintained during algal cultivation process [8].

According to assumption no. 4, biomass productivity (PB)= 0.001kg/m2/h or, . Again P_B can be defined as follows:

$$P_B = \frac{Biomass\ production\ rate\ (\dot{m}_B)}{cultivationa\ area\ (A)} \quad (5)$$

Calculation for the cultivation of *Chlorella vulgaris*, *Nannochloropsi*s *spp* and *Scenedesmus spp*.

According to the stoichiometric equation (2) one mole of algal biomass is produced from 12.21 mol of CO_2. This signifies that 1 g of biomass of ***Chlorella vulgaris*** is produced from 2.32 g ($= \frac{12.21mol*molecular\ weight\ (44g/mol) of\ CO2}{1mol*molecular\ weight\ (234.2g/mol) of\ algae\ (C12.21\ H7.778\ O14.344\ N0.8}$) of CO_2. This is close to the reported value, i.e., 1.88g CO_2 per gram of algal biomass produced [18, 19].

Similarly, using equations (3) 1 g of biomass of ***Nannochloropsi***s *spp* is produced from 2.36 g ($= \frac{16.38\ mol*molecular\ weight\ (44g/mol) of\ CO2}{1mol*molecular\ weight\ (304.6g/mol) of\ algae\ (C21.48\ H38.5\ O8.64\ N0.14}$) of CO_2.

In case of ***Scenedesmus spp.,*** using equations (4), 1 g of biomass is produced from 2.22 g ($= \frac{13.65\ mol*molecular\ weight\ (44g/mol) of\ CO2}{1mol*molecular\ weight\ (270.3g/mol) of\ algae\ (C23.91\ H43.26\ O8.93\ N0.08}$) of CO_2.

All these values are close to the reported value, i.e., 1.88g CO_2 per gram of algal biomass produced [18, 19].

Algal biomass production rate for *Chlorella vulgaris, Nannochloropsi*s *spp.* and *Scenedesmus spp.* ($\dot{m}_{Chlorella\ vulgaris}, \dot{m}_{Nannochloropsis}\ and\ \dot{m}_{Scenedesmus}$) can be calculated as follows:

$$\dot{m}_{Chlorella\ vulgaris}(\frac{kg}{h}) = \frac{\text{input rate of CO2 } (\dot{m}_{CO2} kg/h) * \text{fractional conversion of CO2 } (X_{CO2})}{\frac{2.32 kg\ CO2}{kg\ \ algal\ biomass\ produced}} \quad (6)$$

$$\dot{m}_{Nannochloropsis}\ (\frac{kg}{h}) = \frac{\text{input rate of CO2 } (\dot{m}_{CO2} kg/h) * \text{fractional conversion of CO2 } (X_{CO2})}{\frac{2.36 kg\ CO2}{kg\ \ algal\ biomass\ produced}} \quad (7)$$

$$\dot{m}_{Scenedesmus}\ (\frac{kg}{h}) = \frac{\text{input rate of CO2 } (\dot{m}_{CO2}) * \text{fractional conversion of CO2 } (X_{CO2})}{\frac{2.22 kg\ CO2}{kg\ algal\ biomass\ produced}} \quad (8)$$

According to assumption no. 3, fractional conversion of CO_2 (X_{CO2}) is 0.7

Therefore, using equations (5), (6), (7) and (8), the area of raceway ponds ($A_{ORP\_Chlorella\ vulgaris}, A_{ORP\_Nannochloropsi}\ and\ A_{ORP\_Scenedesmus}$)) for the cultivation of algal biomass of *Chlorella vulgaris, Nannochloropsi*s *spp.* and Scenedesmus *spp.* can be determined as follows:

$$A_{ORP_{Chlorella}} vulgaris(m^2) = \frac{\dot{m}_{CO2(\frac{kg}{h})} * 0.7}{P_B(\text{kg/m2/h}) * 2.32(\frac{kg}{kg})} \quad (9)$$

$$A_{ORP\_Nannochloropsis}(m^2) = \frac{\dot{m}_{CO2(\frac{kg}{h})} * 0.7}{P_B(\text{kg/m2/h}) * 2.36(\frac{kg}{kg})} \quad (10)$$

$$A_{ORP\_Scenedesmus}(m^2) = \frac{\dot{m}_{CO2(\frac{kg}{h})} * 0.7}{P_B(\text{kg/m2/h}) * 2.22(\frac{kg}{kg})} \quad (11)$$

The volume of raceway pond ($V_{ORP\_Chlorella\ vulgaris}, V_{ORP\_Nannochloropsis}\ and\ V_{ORP\_Scenedesmus}$) for the cultivation of algal biomass of Chlorella vulgaris, Nannochloropsis spp. and Scenedesmus spp. has been calculated as follows:

Using the concentration of algal biomass after each batch time (t_B), the biomass productivity, $P_{B_{Chlorella} vulgaris}$, $P_{B\_Nannochloropsis}$ and $P_{B\_Scenedesmus}$ can be defined as,

$$P_{B_{Chlorella} vulgaris} = \frac{V_{ORP\_Chlorella\ vulgaris} * (C_{X\ t=t_B} - C_{X\ t=0})}{t_B * A_{ORP\_Chlorella\ vulgaris}} \tag{12}$$

$$P_{B\_Nannochloropsis} = \frac{V_{ORP\_Nannochloropsis}) * (C_{X\ t=t_B} - C_{X\ t=0})}{t_B * A_{ORP\_Nannochloropsis}} \tag{13}$$

$$P_{B\_Scenedesmus} = \frac{V_{ORP\_Scenedesmus}) * (C_{X\ t=t_B} - C_{X\ t=0})}{t_B * A_{ORP\_Scenedesmus}} \tag{14}$$

Where,

$C_{X\ t=t_B} = biomass\ concentration\ after\ one\ batch\ time (t_B)$

$C_{X\ t=0} = initial\ biomass\ concentration$

Therefore, using equation (12), (13) and (14)

$$V_{ORP\_Chlorella\ vulgaris} = \frac{P_{B_{Chlorella} vulgaris} * t_B * A_{ORP\_Chlorella\ vulgaris}}{(C_{X\ t=t_B} - C_{X\ t=0})} \tag{15}$$

$$V_{ORP\_Nannochloropsis} = \frac{P_{B\_Nannochloropsis} * t_B * A_{ORP\_Nannochloropsis}}{(C_{X\ t=t_B} - C_{X\ t=0})} \tag{16}$$

$$V_{ORP\_Scenedesmus} = \frac{P_{B\_Scenedesmus}\ t_B * A_{ORP\_Scenedesmus}}{(C_{X\ t=t_B} - C_{X\ t=0})} \tag{17}$$

8.2.5.1.4 Energy consumption for the cultivation of algae

There are two energy components involved in the cultivation process a) light energy consumed for photosynthesis reaction to occur and b) auxiliary energy consumed for running the paddles, for CO_2 delivery, for water pumping in cultivation unit.

Based on the stoichiometric equations, the energy (light energy) required for the biochemical reaction is computed using the ASPEN Plus® software. As per assumption 6, all light energy is supplied by natural sunlight. The required light conversion efficiency (LCE) is calculated using the literature data on solar flux, $E_{Solar\ flux}$ of Eastern India (5-30Wh/m^2/d), and required energy per unit time ($\dot{E}_R$) for the biochemical conversion, as calculated from the ASPEN Plus®. LCE for *Chlorella vulgaris*, *Nannochloropsis spp.* and Scenedesmus *spp.* can be defined as follows:

$$LCE_{Chlorella\ vulgaris}(\%) = \frac{\dot{E}_{R,Chlorella\ vulgaris} * t_b}{E_{Solar\ flux} * A_{ORP\_Chlorella\ vulgaris} * t_B} * 100 \tag{18}$$

$$LCE_{Nannochloropsis\ spp}(\%) = \frac{\dot{E}_{R,Nannochloropsis\ spp} * t_b}{E_{Solar\ flux} * A_{ORP\_Nannochloropsis} * t_B} * 100 \tag{19}$$

$$LCE_{Scenedesmus\ spp}\ (\%) = \frac{\dot{E}_{R,Scenedesmus\ spp} * t_b}{E_{Solar\ \ flux} * A_{ORP\_Scenedesmus} * t_B} * 100 \tag{20}$$

Where, $\dot{E}_{R,Chlorella\ vulgaris} = \dot{\xi}_{Chlorella\ vulgaris} * \Delta H^o_{R(Chlorella\ vulgaris)}$ (21)

$$\dot{E}_{R,Nannochloropsis\ spp} = \dot{\xi}_{Nannochloropsis\ spp} * \Delta H^o_{R(Nannochloropsis\ spp)} \tag{22}$$

$$\dot{E}_{R,Scenedesmus\ spp} = \dot{\xi}_{Scenedesmus\ spp.} * \Delta H^o_{R(Scenedesmus\ spp.)} \tag{23}$$

Where, ξ = extent of reaction

$$\dot{\xi}_{Chlorella\ vulgaris} = \frac{Consumption\ rate\ of\ CO_2}{Modulus\ of\ stoichiometric\ coefficient\ of\ CO_2\ in\ Eq.(2)} = \frac{\dot{m}_{CO2} * t_b}{\lfloor a_{Chlorella\ vulgaris} \rfloor}$$

(24)

$$\xi_{Nannochloropsis\ spp} = \frac{Consumption\ rate\ of\ CO_2}{Modulus\ of\ stoichiometric\ coefficient\ of\ CO_2\ in\ Eq.(3)} = \frac{\dot{m}_{CO2} * t_b}{\lfloor a_{Nannochloropsis\ spp} \rfloor}$$

(25)

$$\xi_{Scenedesmus\ spp.} = \frac{Consumption\ rate\ of\ CO_2}{Modulus\ of\ stoichiometric\ coefficient\ of\ CO_2\ in\ Eq.(4)} = \frac{\dot{m}_{CO2} * t_b}{\lfloor a_{Scenedesmus\ spp.} \rfloor}$$

(26)

a=stoichiometric coefficient of CO_2 in stoichiometric equations (2), (3) and (4).

For *Chlorella vulgaris, Nannochloropsis spp.* and Scenedesmus *spp. the calculation LCE is as follows:*

Chlorella vulgaris

Considering $E_{Solar\ \ flux}$ of 5 Wh/m^2/d, $LCE(\%) = \frac{3765.2*3600*1000*100}{5*3600*564827*6} = 22.7$

Considering $E_{Solar\ \ flux}$ of 30Wh/m2/d, $LCE(\%) = \frac{3765*3600*1000*100}{30*3600*564827*6} = 3.7$

Nannochloropsis spp

Considering $E_{Solar\ flux}$ of 5 Wh/m^2/d, $LCE(\%) = \frac{4714.3*3600*1000*100}{5*3600*555254*6} = 28.3$

Considering $E_{Solar\ flux}$ of $30\text{Wh/m2/d}, LCE(\%) = \frac{4109*3600*1000*100}{30*3600*555254*6} = 4.7$

Scenedesmus spp.

Considering $E_{Solar\ flux}$ of 5 Wh/m^2/d, $LCE(\%) = \frac{3952.6*3600*1000*100}{5*3600*590270*6} = 22.3$

Considering $E_{Solar\ flux}$ of $30\text{Wh/m2/d}, LCE(\%) = \frac{3952.6*3600*1000*100}{30*3600*590270*6} = 3.7$

The stirring energy is calculated using literature data, keeping the power per unit volume (P/V) constant [McCabe]. The value of P/V, as reported in the literature is 0.02kWh/m^3/d [21, 22]. The power consumption for stirring is calculated by multiplying P/V by the present reactor volume. The energy consumption for CO_2 delivery/pumping i.e. BkW of CO_2 delivery pump is calculated by ASPEN Plus®. The energy consumption for water pumping in cultivation unit i.e. BkW of water supply pump is also calculated by ASPEN Plus®.

8.2.5.2 Biomass harvesting and dewatering

Harvesting

Algal biomass is harvested after each batch of cultivation. In this stage, the biomass concentration is raised from 0.5 g/l to 50 g/l using the method of flocculation in the clarifier.

Dewatering

Through dewatering using centrifuge, the concentration of exit biomass from the harvesting unit is raised to 200 g/l.

Cooling of flue gas

The temperature of the flue gas emitted from the IGCC plant after passing through the gas cleaning unit is 95^o C. However, the optimum temperature for the growth *of Chlorella Vulgaris*, *Nannochloropsis, and Scenedesmus* ranges from 20 to 35 ^{o}C [16, 18]. Therefore, cooling arrangement has been made to lower down the flue gas temperature to 30 ^{o}C

8.2.6 Algae to biodiesel production

The three major stages of microalgal bio-diesel production are described as follows:

8.2.6.1 Lipid extraction

Hexane is used in the solvent-based lipid extraction process with a solvent /algal biomass mass ratio of 5:1 [25]. The extraction is conducted at 40^{o}C [25, 26]. The lipid stream i.e. triolein and hexane resulting from the extraction stage is subjected to a flash evaporation at 80^{o}C to remove 93.6 % of hexane within the stream and concentrate the lipid [26,35]. The lipid stream is cooled to 60^{o}C and is subsequently introduced into a reactor meant for transesterification. [25,37].

8.2.6.2 Transesterification

The stoichiometric equation representing the transesterification reaction of lipid (triolein) is as follows:

$$C_{57}H_{104}O_6 + 3CH_3OH \rightarrow 3\, C_{19}H_{36}O_2 + C_3H_8O_3 \qquad (27)$$

The lipid stream at 60^{o}C is fed to the transesterification reactor. Methanol at an alcohol/lipid molar ratio of 6:1 is also fed to the same reactor at 60^{o}C. Alkali catalyst (sodium hydroxide) is fed at 5% (w/w) of the lipid feed is added to the reactor to initiate the transesterification reaction [26].

8.2.6.3 Recovery of Biodiesel from the Reaction mixture

During the transesterification reaction, the lipid is converted to crude biodiesel and glycerol. Excess unreacted methyl alcohol is also present in the reactor. The reaction mixture containing all products and unreacted methanol are fed to a distillation tower. Methanol is recovered up to 98% from the top of the distillation unit and the mixture of biodiesel and glycerol is obtained as the bottom product.[26]. Phosphoric acid is used to remove any trace of alkali (NaOH) from the bottom product. The resulting mixture of biodiesel and glycerol is introduced into a second distillation unit. Clean biodiesel is recovered from the top and glycerol is obtained as the bottom product.

8.2.7 Simulation by using ASPEN Plus®

In ASPEN Plus® model, the stream class has been set as MIXCINC. This represents all the streams such as MIXED, CONVENTIONAL and NON-CONVENTIONAL.

8.2.7.1 Generation of algae by post combustion CO_2 capture

An ASPEN Plus® scheme for the simulation of the microalgal CO_2 capture unit for cultivation including CO_2 supply and water pumping to ORP [kim 2011] has been represented in Figure 8.3. The unit processes, i.e., cultivation, CO_2 supply system and water pumping system have been represented by REACTOR, BLOWER and PUMP blocks respectively in the ASPEN Plus® scheme.

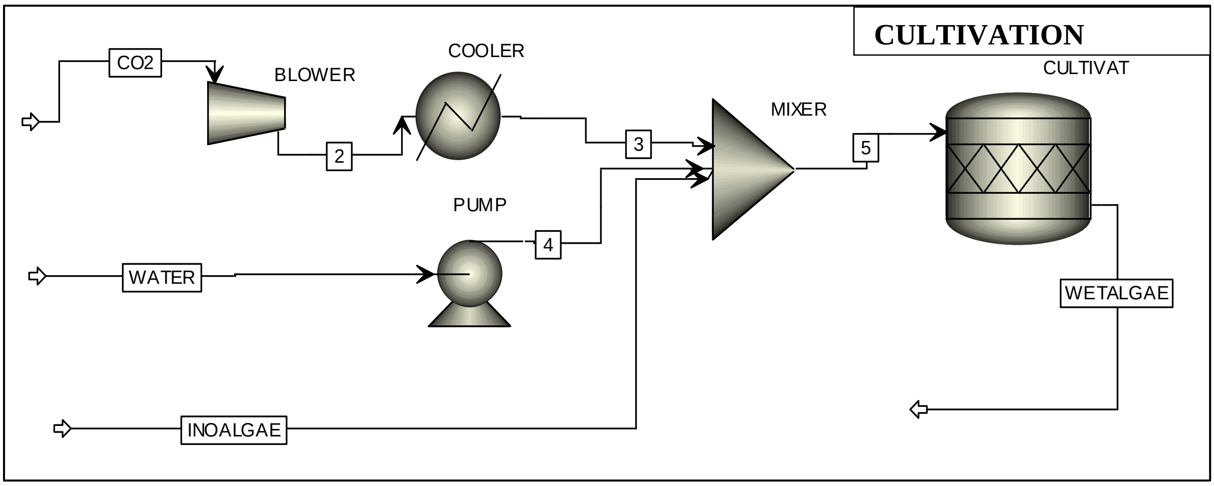


Figure 8.3. **Cultivation of Microalgal biomass process modeled in ASPEN Plus®**

After the cultivation process, the product algae is thickened by passing through the harvesting and dewatering unit. The process has been represented in Figure 8.4. The unit operations, i.e., harvesting (bio flocculation in a clarifier) and dewatering (centrifuge) have been represented by SEPARATOR and CENTIFUGE blocks respectively in the ASPEN Plus® scheme.

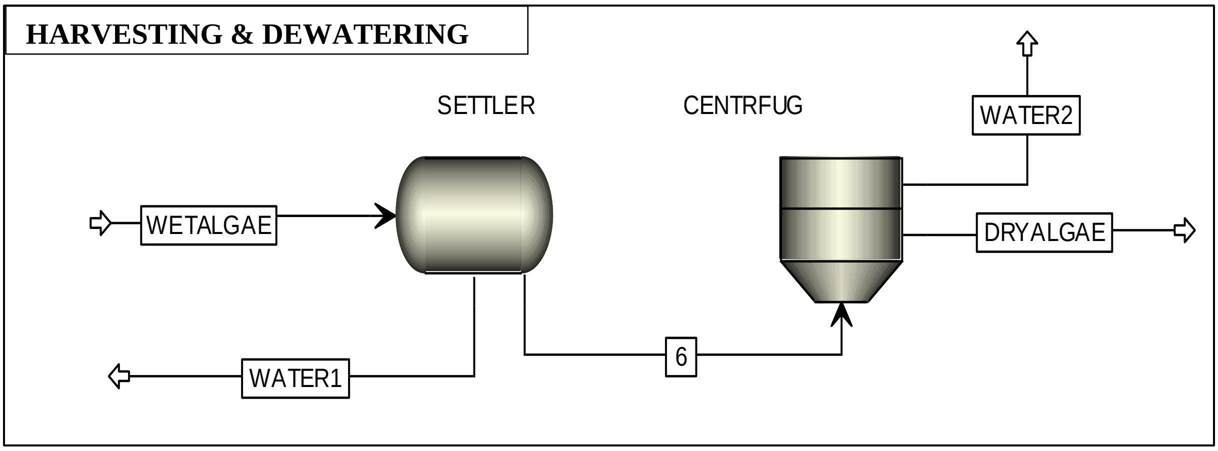


Figure 8.4. **Harvesting & Dewatering of Microalgal biomass process modeled in ASPEN Plus®**

The same scheme is used for all three algal species, namely, *Chlorella vulgaris, Nannochloropsis spp and Scenedesmus spp*.

8.2.7.2 Algae to biodiesel conversion

An ASPEN Plus® scheme for the simulation of the biodiesel production process, as described in section 8.2.5.3 is represented in Figure 8.5.

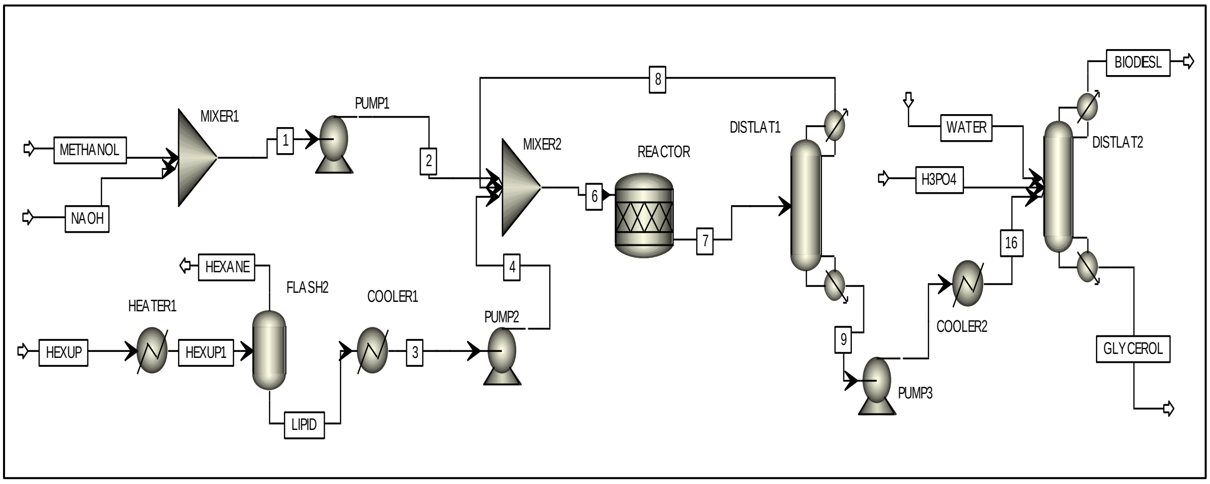
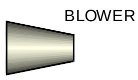
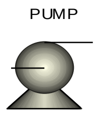
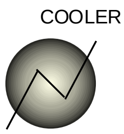
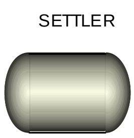


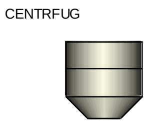
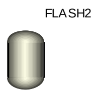
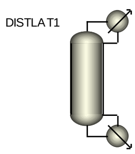
Figure 8.5. **ASPEN Plus® process flow sheet for algae to biodiesel production**

8.2.7.3 Block Specification

All the blocks used in the ASPEN Plus® flow sheets are briefly described in Table 8.5.

Table 8.5. Description of the blocks used in the ASPEN Plus® modeling

Block ID	Module selected	Scheme	Description
BLOWER	COMPRESSOR		Blower has been used for the supply of CO_2 to cultivation units.
PUMP	PUMP		Pump has been used for the supply of water to cultivation unit.
COOLER	HEAT EXCHANGER		In this simulation, Cooler has been used for the reduction of flue gas temperature from 95°C to 30 °C
CULTVAT	RSTOIC		In this simulation, cultivation unit has been used for modeling the photosynthesis reaction as per the stoichiometric equations (2), (3), and (4)
SETTLER	DECANTER		In this simulation, SETTLR stands for harvesting unit. It is used to raise the biomass concentration to 50 g/l using the method of flocculation in the clarifier. The

Block ID	Module selected	Scheme	Description
			decanter has been controlled by a design specification block. This block separates the inlet stream (i.e. outlet stream of cultivate unit) into the concentrated algal biomass and water.
CENTRFG	CENTRIFUGE		CENTRFG stands for the dewatering unit. In this unit, the biomass concentration is raised to 200 g/l. The spilt fraction has been controlled by a design specification block. This block separates the inlet stream (i.e. exit stream of harvesting unit) into the concentrated algal biomass and water.
Main blocks for biodiesel production from three algae (i.e. *Chlorella Vulgaris, Nannochloropsis, Scenedesmus)*			
SEPARATOR	Flash2		Evaporator used for recovery of hexane for Lipid extraction process
REACTOR	RSTOIC		RStoic reactor used for esterification reaction for biodiesel production following the stoichiometric equation (27)
DISTILLATION	RADFRAC		Distillation unit-1 is used to separate methanol from biodiesel-glycerol mixture and Distillation unit-2 is used to separate biodiesel from glycerol.

8.2.7.4 Components

The components involved in the overall system have been classified as per the requirements of ASPEN Plus® software. In Table 8.6, all the components have been classified.

Table 8.6 Classification of all the components

Component ID	Type	Component name	Formula
CO_2	Conventional	CARBON-DIOXIDE	CO_2
H_2O	Conventional	WATER	H_2O
O_2	Conventional	OXYGEN	O_2
NH_3	Conventional	AMMONIA	H_3N
Algae (declared as a combination of Carbohydrate, Protein and Lipid)	Conventional	LIPID	$C_{57}H_{104}O_6$
	Conventional	PROTEIN	$C_9H_{11}NO_2$
	Conventional	CARBOHYDRATE	$C_{12}H_{22}O11$
NaOH	Conventional	SODIUM HYDROXIDE	NaOH
Hexane	Conventional	HEXANE	C_6H_{14}
CH_3OH	Conventional	METHYL ALCOLHOL	CH_3OH
Lipid	Conventional	TRIOLEIN	$C_{57}H_{104}O_6$
Biodiesel	Conventional	METHYL OLEATE	$C_{19}H_{36}O_2$
Glycerol	Conventional	GLYCEROL	$C_3H_8O_3$

8.2.7.5 Stream Specification

Streams used in the process modeling have been described in Table 8.7.

Table 8.7 Streams in different flow sheets

Stream no	material
FOR CULTIVATION PROCESS	
2	Carbon di oxide
3	Carbon di oxide
4	Water
INOALGAE	Ammonia + algae
5	Carbon di oxide +Ammonia +Water +algae
WETALGAE	Wet algae biomass (concentration-0.5 g/l)
FOR HARVESTING & DEWATERING PROCESS	
6	Wet algae biomass (concentration-50 g/l)
WATER1	Water
DRYALGAE	Algae biomass

Stream no	material
	(concentration-200 g/l)
WATER2	Water
FOR ALGAE TO BIODIESEL PRODUCTION	
1	Methyl alcohol
3	Triolein
6	Triolein + Methyl alcohol (i.e. ratio of 1:5)
7	Methyl-oleate +Glycerol +unreacted Triolein +Methyl alcohol
8	Methyl alcohol
9	Methyl-oleate +Glycerol
12	Methyl-oleate (Biodiesel)
13	Glycerol

8.3.7 Energy and environmental analysis

The energy and CO_2 emissions components used for the Energy Return on Energy Investment (*EROEI*) and Avoidance in CO_2 Emissions (*ACE*) are schematically explained in the following Figure 8.6a, 8.6b, 8.6c, and 8.6d schematic diagram

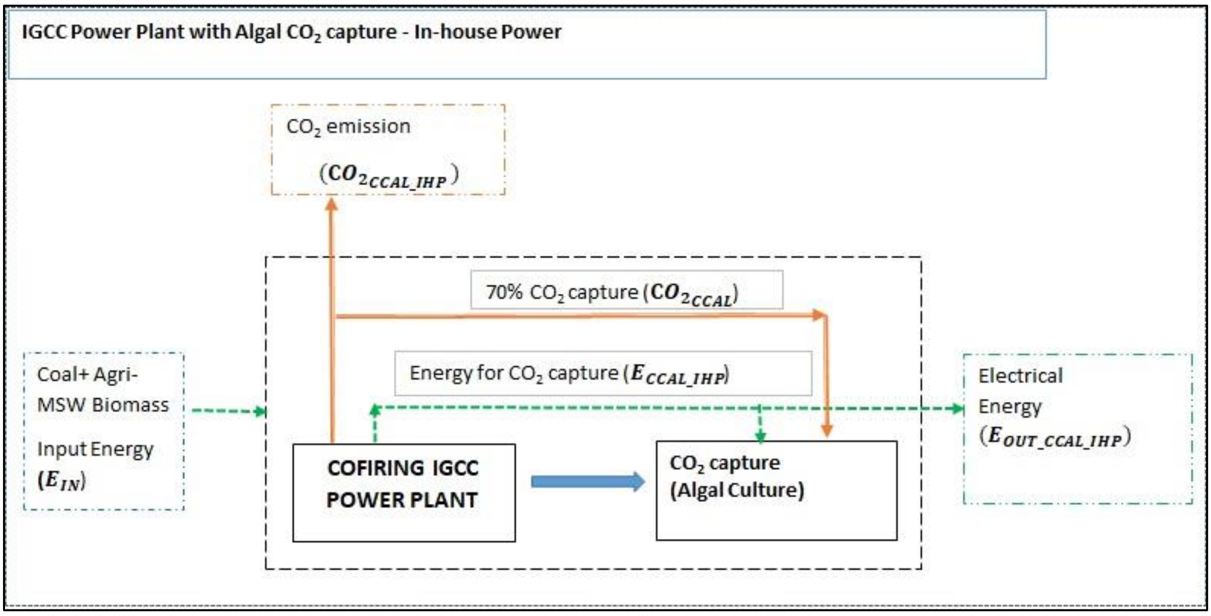


Figure 8.6a Schematic diagram of the energy and CO_2 emissions for Cofiring IGCC Power Plant and Algal CO_2 capture considering the use of in-house power

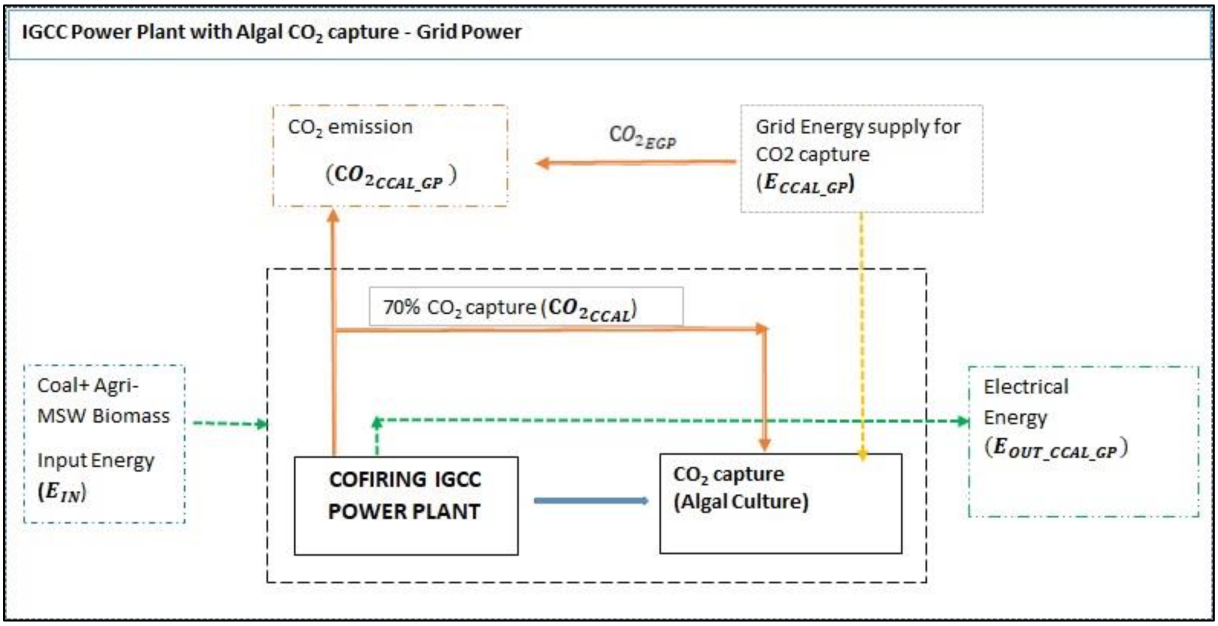


Figure 8.6b Schematic diagram of the energy and CO_2 emissions for Cofiring IGCC Power Plant and Algal CO_2 capture considering the use of grid power

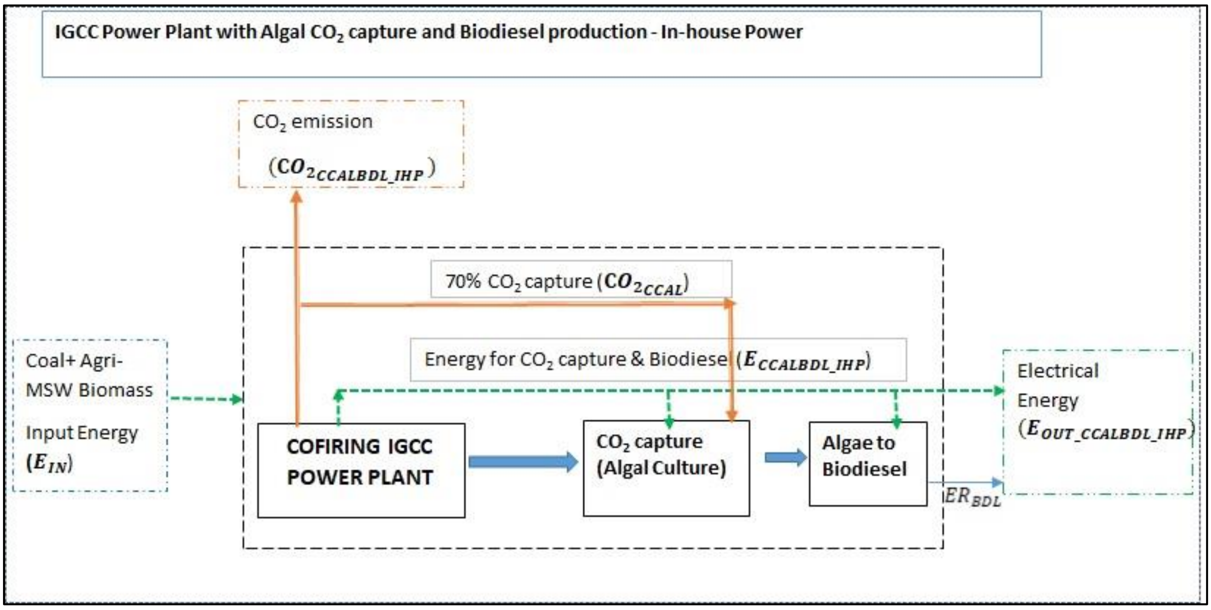


Figure 8.6c Schematic diagram of the energy and CO_2 emissions for Cofiring IGCC Power Plant and Algal CO_2 capture including biodiesel production considering the use of in-house power

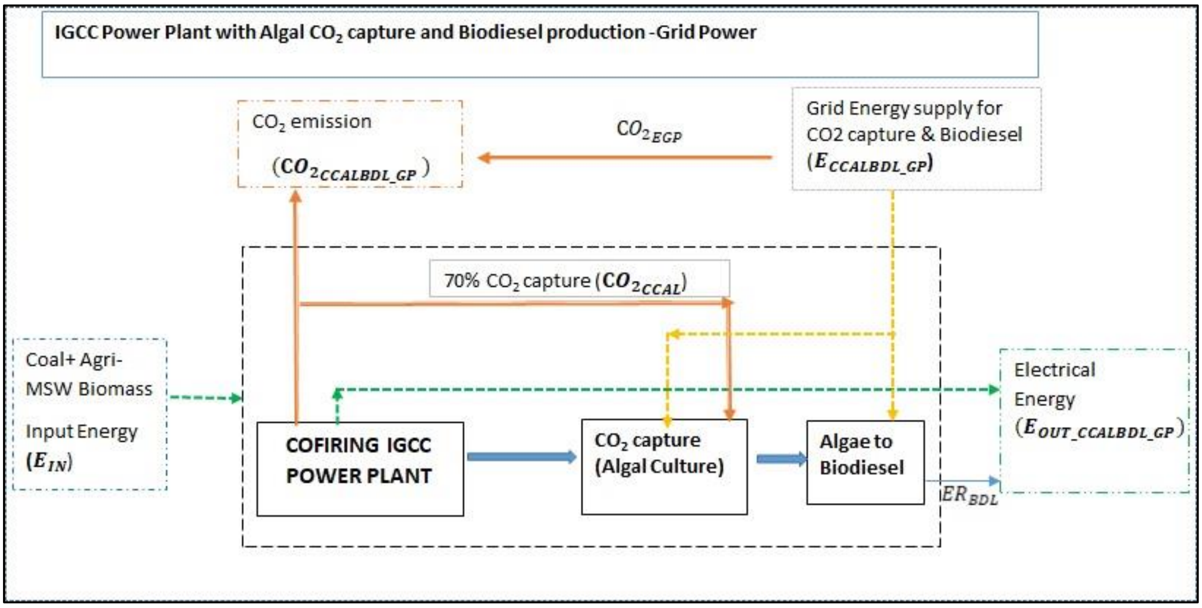


Figure 8.6d Schematic diagram of the energy and CO_2 emissions for Cofiring IGCC Power Plant and Algal CO_2 capture including biodiesel production considering the use of grid power

8.3.7.1 Energy Return on Energy Investment (*EROEI*)

Based on the simulation results using the ASPEN Plus®**,** the energy return on energy investment (*EROEI*) for the IGCC plant with and without CO_2 capture using *Chlorella vulgaris*, *Nannochloropsis spp* and *Scenedesmus spp*. have been calculated

EROEI without CO_2 capture ($EROEI_{WCC}$) has been calculated as follows:

$$EROEI_{WCC} = \frac{\text{Energy return from cofired IGCC plant } (ER_{WCC})}{\text{Energy Input of Cofired IGCC plant } (EI_{IGCC})} \quad (28)$$

During the calculation of *EROEI* with CO_2 capture, $EROEI_{CCAL}$ the total energy requirement, E_{CCAL}, for the algal culture has been considered. E_{CCL} includes the energy consumption for the generation of algae through the photosynthesis reaction, E_R, stirring energy utilized in the ORP, $E_{stirrer}$, pumping energy for the water supply, $E_{water\ pump}$, pumping energy for the CO_2 delivery, $E_{CO2\ blower}$, energy required for harvesting, $E_{harvesting}$ and energy required for dewatering by centrifuge, $E_{centrifuge}$. The values of $EROEI_{CCAL}$ have been calculated for two possible cases, I: E_{CCAL} is derived from the in-house energy generated by the IGCC plant; II: E_{CCAL} is derived from the grid. The *EROEI* for case-I and case-II are designated by $EROEI_{CCAL\_IHP}$ and $EROEI_{CCAL\_GP}$. The definitions of $EROEI_{CCAL\_IHP}$ and $EROEI_{CCAL\_GP}$ $are\ as\ follows$:

$E_{CCAL}=E_R + E_{stirrer}+ E_{water\ pump}+ E_{CO2\ blower}+E_{harvesting} + E_{centrifuge}$ (29)

Energy consumption for the generation of algae through the photosynthesis reaction, E_R, is supplied neither from in-house power nor grid power. Sunlight is providing the energy E_R. Therefore, E_R has not been considered in E_{CCAL} for determination of $EROEI_{CCAL}$.

Therefore,

$E_{CCAL}=E_{stirrer}+ E_{water\ pump}+ E_{CO2\ blower}+E_{harvesting} + E_{centrifuge}$ (30)

$$EROEI_{CCAL_{IHP}} = \frac{\text{Energy return from cofired IGCC plant } (ER_{wcc}) - \text{Energy requirement for } CO_2 \text{ capture through algal route} (E_{CCAL})}{\text{Energy Input of Cofired IGCC plant } (EI_{IGCC})} \quad (31)$$

$$EROEI_{CCAL\_GP} = \frac{\text{Energy return from cofired IGCC plant } (ER_{wcc})}{\text{Energy Input of Cofired IGCC plant } (EI_{IGCC}) + \text{Energy supplied from grid for } CO_2 \text{ capture through algal route} (E_{CCAL})} \quad (32)$$

When the biodiesel production unit is integrated with an algal culture system for CO_2 capture, in addition to the total energy consumption of the algal unit, E_{CCAL}, consumption of energy in the biodiesel production unit, E_{BDL}, is also considered. E_{BDL} includes the energy for oil extraction, $E_{\text{extraction}}$, energy consumption during esterification, $E_{\text{esterification}}$ and the energy consumption in the two distillation towers, Edist-I and Edist-II.

Therefore, $E_{BDL}= E_{extraction}+ E_{esterification}+ E_{Dist\ I}+ E_{Dist\ II}$ (33)

EROEI with CO_2 capture using algal culture, followed by biodiesel production, ($EROEI_{CCALBDL}$), has been calculated by considering both energy consumption by the integrated system, $E_{CCAL}+E_{BDL}$, and the energy return potential of biodiesel, ER_{BDL}. $EROEI_{CCALBDL}$ The values of $EROEI_{CCALBDL}$ have also been calculated for two possible cases, I: Total required energy, ($E_{CCALBDL} = E_{CCAL}+E_{BDL}$) is derived from the in-house energy generated by the IGCC plant; II: ($E_{CCALBDL}$ is derived from the grid. The *EROEI* for case-I and case-II are designated by $EROEI_{CCALBDL\_IHP}$ and $EROEI_{CCALBDL\_GP}$. The definitions of $EROEI_{CCALBDL\_IHP}$ and $EROEI_{CCALBDL\_GP}$ $are\ as\ follows$:

$$EROEI_{CCALBDL\_IHP} = \frac{\text{Energy return from cofired IGCC plant } (ER_{wcc}) - \text{Energy requirement for } CO_2 \text{ capture through algaeincluding biodiesel} (E_{CCALBDL}) + \text{Energy return by biodiesel}}{\text{Energy Input of Cofired IGCC plant } (EI_{IGCC})} \quad (34)$$

$$EROEI_{CCALBDL\_GP} = \frac{\text{Energy return from cofired IGCC plant } (ER_{wcc}) + \text{Energy return by biodiesel} (ER_{BDL})}{\text{Energy Input of Cofired IGCC plant } (EI_{IGCC}) + \text{Energy requirement for } CO_2 \text{ capture through algaeincluding biodiesel} (E_{CCALBDL})} \quad (35)$$

$Energy\ return\ by\ biodiesel = ER_{BDL} = LHV_{Biodiesel} * Biodiesel\ production\ rate$ (36)

As per literature data [27], the lower heating value of biodiesel is 42 MJ/Kg.

8.3.7.2 Avoidance in CO_2 Emissions (*ACE*)

Avoidance in CO_2 emissions (*ACE*) has been calculated with reference to the CO_2 emissions of a coal fired power plant of the same capacity (30TPD) considering use of in-house power and grid power.

For the calculation of ACE for the IGCC power plant without CO_2 capture(ACE_{WCC}), the consumption of CO_2 during the production of Indian Agri-MSW based Biomass through photosynthetic route ($CO_{2_{MSWBPH}}$) has been taken into account.

Therefore,

$$ACE_{WCC} = \frac{\text{Total } CO_2 \text{ emissions avoided for the cofired IGCC power plant without } CO_2 \text{ capture } (CO_{2_{COAL\ to\ Cofiring}})}{CO_2 \text{ emissions from coal plant} (CO_{2_{COAL}})} \quad (37)$$

For the IGCC power plant without CO_2 capture, total avoided CO_2 emissions has been calculated as follows:

$$\begin{aligned}&\text{Total } CO_2 \text{ emission avoided for the IGCC power cofired power plant without } CO_2 \text{ capture}\\ &= \text{Plant emission avoided due to switching over from coal fired to Cofired IGCC mode} \left(\text{ACE}_{COAL\ to\ Cofiring}\right)\\ &+ CO_2 \text{ consumed during the production of Agri\_MSW Biomass } (\text{ACE}_{MSWBPH})\end{aligned} \quad (38)$$

$CO_{2_{MSWBPH}}$ has been calculated from the weight fraction of carbon in the Indian Agri-MSW based Biomass (w_{cMSWB}) and the mass of Indian Agri-MSW based Biomass fed M_{MSWB} to the power plant. As all the carbon in the biomass is derived from the atmospheric CO_2, therefore, the CO_2 consumed for photosynthesis (ACE_{MSWBPH}) has been calculated as follows:

$$\text{ACE}_{MSWBPH} = \frac{M_{MSWB} * w_{cMSWB} * MW_{CO_2}}{MW_C} \quad (39)$$

Where, $MW_{CO_2} = molecular\ weight\ of\ CO_2 = 44\,\frac{kg}{kmol}\ and$

$$MW_C = molecular\ atomic\ weight\ of\ C = 12\,\frac{\text{kg}}{\text{kmol}}. \quad (40)$$

During the calculation of ACE for the IGCC power plant with algal CO_2 capture ACE_{CCAL} considering use of in-house power, the quantum of CO_2 captured by algae ($CO_{2_{CCAL}}$) has also been taken into account.

$$ACE_{CCAL} = \frac{\text{Total } CO_2 \text{ emission avoided for the cofired IGCC power plant with } CO_2 \text{ capture through algal culture use of in} - \text{house power}}{CO_2 \text{ emission from coal plant} (CO_{2_{COAL}})} \quad (41)$$

For the IGCC power plant with CO_2 capture through algal culture, total CO_2 emissions avoidance has been calculated as follows considering use of in-house power:

$$\begin{aligned} &\text{Total } CO_2 \text{ emission avoided for the IGCC power cofired power plant with } CO_2 \text{ capture} \\ &= \text{Plant emission avoided due to switching over from coal fired to Cofired IGCC mode} (\text{ACE}_{COAL\ to\ Cofiring}) \\ &+ CO_2 \text{ consumed during the production of Agri\_MSW Biomass } (\text{ACE}_{MSWBPH}) \\ &+ CO_2 \text{ captured by algae } (\text{ACE}_{CCAL}) \end{aligned} \quad (42)$$

During the calculation of ACE for the IGCC power plant with algal CO_2 capture ACE_{CCAL} considering use of grid power, the quantum of CO_2 captured by algae ($CO_{2_{CCAL}}$) has also been taken into account.

$$ACE_{CCAL} = \frac{\text{Total } CO_2 \text{ emission avoided for the cofired IGCC power plant with } CO_2 \text{ capture through algal culture using grid power}}{CO_2 \text{ emission from coal plant} (CO_{2_{COAL}})} \quad (43)$$

For the IGCC power plant with algal CO_2 capture, total CO_2 emissions avoidance has been calculated as follows considering the use of grid power:

$$\begin{aligned} &\text{Total } CO_2 \text{ emission avoided for the cofired IGCC power plant with } CO_2 \text{ capture} \\ &= \text{Plant emission avoided due to switching over from coal fired to Cofired IGCC mode} (\text{ACE}_{COAL\ to\ Cofiring}) \\ &+ CO_2 \text{ consumed during the production of Agri\_MSW Biomass } (\text{ACE}_{MSWBPH}) \\ &+ CO_2 \text{ captured by algae } (\text{ACE}_{CCAL}) \\ &- CO_2 \text{emission due to grid power requirement for } CO_2 \text{ capture by algae } (CO_{2_{EGP}}) \end{aligned} \quad (44)$$

CO_2 emissions due to the use of grid power ($CO_{2_{EGP}}$), supplied for CO2 capture by algae process, has been calculated with due consideration of distribution losses of around 5%[28]. Therefore, $CO_{2_{EGP}}$ can be defined as follows:

$$CO_{2_{EGP}} = \text{ Total power demand for } CO_2 \text{ capture by algae culture process} * 1.05 * CO_2 \text{ emissions factor } \left(\frac{\text{kg}}{\text{kWh}}\right) \quad (45)$$

Where, CO_2 emissions factor signifies the CO_2 emissions per unit energy generated by a coal-fired power plant. The value of CO_2 emissions factor is 0.95kg/kWh for conventional Indian power plant [29].

Therefore,

$$CO_{2_{EGP}} = 1.05 * E_{CCAL} * 0.95 \quad (46)$$

During the calculation of ACE for the IGCC power plant with algal CO_2 capture including algae to biodiesel production $ACE_{CCALBDL}$ considering the use of in-house power,

$$ACE_{CCALBDL\_IHP} = \frac{\text{Total } CO_2 \text{ emission avoided for the cofired IGCC plant with algal } CO_2 \text{ capture and biodiesel production using in} - \text{house power}}{CO_2 \text{ emission from coal plant}(CO_{2_{COAL}})} \quad (47)$$

Where,

Total CO_2 emissions avoidance has been calculated as follows considering the use of in-house power:

$$\text{Plant emission avoided due to switching over from coal fired to Cofired IGCC mode}\left(\text{ACE}_{COAL\ to\ Cofiring}\right) + CO_2 \text{ consumed during the production of Agri\_MSW Biomass } (\text{ACE}_{MSWBPH}) + CO_2 \text{ captured by algae } (\text{ACE}_{CCAL}) + \text{CO2 emission avoidance } (\text{ACE}_{BDL}) \text{ due to the use of biodiesel energy} \quad (48)$$

CO_2 emissions avoidance ($CO_{2_{BDL}}$) due to use of biodiesel-energy using generator to substitute a part of grid power, ER_{BDL} has been calculated as follows:

Higher heating value of algal biodiesel: 42MJ/kg (Nannochloropsis spp.) [26]

CO_2 emissions factor for algal biodiesel: 2.48ton/m^3 [26]

Again, density of algal biodiesel: 873kg/m^3[26]

Therefore, CO_2 emissions factor for algal biodiesel on mass basis: $\frac{2480kg/m^3}{873kg/m^3} = 2.84kg/kg$

Again indicated in Eq.44, for the use of 1kWh grid energy from Indian coal-based power plant, CO_2 emissions including distribution loss $1.05 * 0.95 = 0.998kg$
If $1kWh$ *of grid energy is substituted, the* CO_2 *emission would be*

$$: \frac{1*3600kJ}{\frac{42000kJ}{kgbiodiesel}} * \frac{2.84kg\text{CO2}}{\text{kg}biodiesel}\text{CO2} = 0.243\text{kg } CO_2 \quad (49)$$

Therefore, for the substitution of $1kWh\ of\ grid\ energy$, avoidance of $CO_2\ emission$

=0.998 −0.24=0.75kg

Therefore, $ACE_{BDL}(kg) = ER_{BDL}(kWh) * 0.75\text{kg/kWh}$ (50)

During the calculation of ACE for the IGCC power plant with algal CO_2 capture including algae to biodiesel production $ACE_{CCALBDL}$ considering use of grid power, the quantum of CO_2 avoidance by biodiesel ($CO_{2_{BDL}}$) has also been taken into account.

$$ACE_{CCALBDL} = \frac{\text{Total } CO_2 \text{ emission avoided for the cofired IGCC plant with algal } CO_2 \text{ capture and biodiesel production using grid power}}{CO_2 \text{ emission from coal plant}(CO_{2_{COAL}})} \quad (51)$$

Where,

Total CO_2 emission avoided for the cofired IGCC plant with algal CO_2 capture and biodiesel production using grid power =

$$\begin{aligned}&\text{Plant emission avoided due to switching over from coal fired to Cofired IGCC mode}\left(ACE_{COAL\ to\ Cofiring}\right)\\&+ CO_2 \text{ consumed during the production of Agri\_MSW Biomass } (ACE_{MSWBPH})\\&+ CO_2 \text{ captured by algae } (ACE_{CCAL})\\&- -CO_2 \text{emission due to grid power requirement for algal } CO_2 \text{ capture and biodiesel production } \left(CO_{2_{EGPBDL}}\right)\\&+ \text{ avoidance of CO2 emission due to substitution of a part, } ER_{BDL} \text{ of required grid power by biodiesel}(ACE_{BDL})\end{aligned} \quad (52)$$

8.3 Results and discussion

The values of Area, Volume and stirring power for the open raceway pond have been estimated for all three algal species shown in Table 8.8. The table reported that volume and area of ORP for *Scenedesmus Spp* is high value compared to Chlorella vulgaris and Nannochloropsis spp due to high value of algal biomass produced from *Scenedesmus Spp.*

Table 8.8: Values of different calculated parameters

Parameters	Unit	Value considered for *Chlorella vulgaris*	Value considered for *Nannochloropsis spp.*	Value considered for *Scenedesmus Spp.*	Calculation procedure
Volume of ORP	m^3	1,69,448.28	1,66,576.27	1,77,081.08	Calculated using euation (15), (16) & (17)
Area of ORP	m^2	564827.6	555254.24	590270.27	Calculated using equation (9), (10) & (11)
P	kWh/d	3,388.97	3,331.53	3,541.62	calculated
Light conversion efficiency (LCE)	% ($E_{Solar\ flux}$) 5 Wh/m^2/d 30Wh/m^2/d	22.7 3.7	28.7 4.7	22.3 3.7	Calculated using equation (18), (19) & (20)

Based on the Aspen Plus® simulation results, presented in the Appendix of this chapter, energy and environmental analyses of the IGCC power plant integrated with algal CO_2 capture unit, with and without Biodiesel production have been made.

8.3.1 Energy demand for algal CO2 capture

The process of algal CO_2 capture using three different types of microalgae, namely *Chlorella Vulgaris, Nannochloropsis spp, and Scenedesmus spp*., integrated with 30 TPD co-fired IGCC power plant, has been studied using the data generated by the ASPEN Plus® simulation tool.

Based on the simulation results using the ASPEN Plus® and the stoichiometry of biochemical reactions (Eq. 2, 3 & 4), energy consumption for the generation of algae through the photosynthesis reaction, E_R of the algal culture process for Chlorella *vulgaris*, *Nannochloropsi*s *spp* and Scenedesmus *spp* has been represented in Figure 8.7.

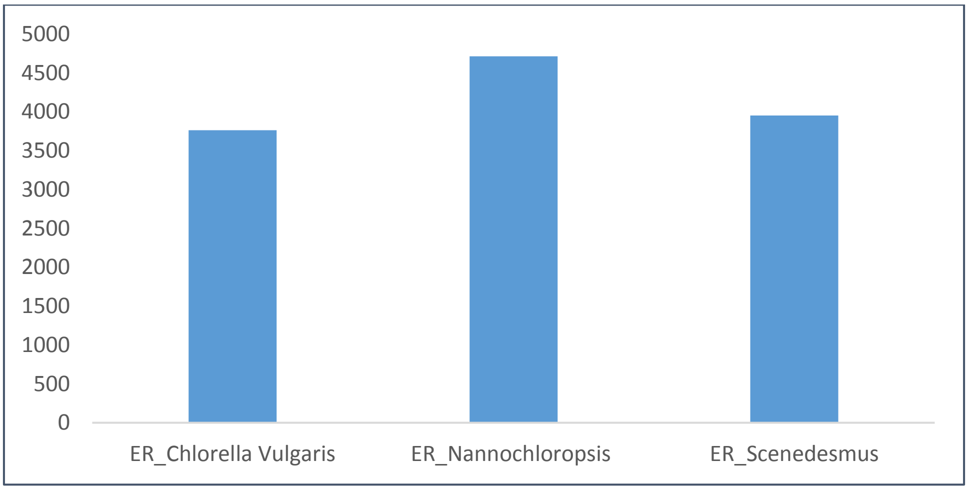
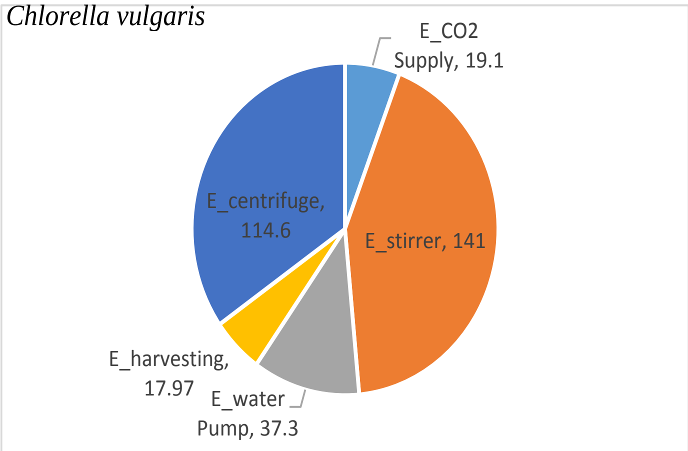
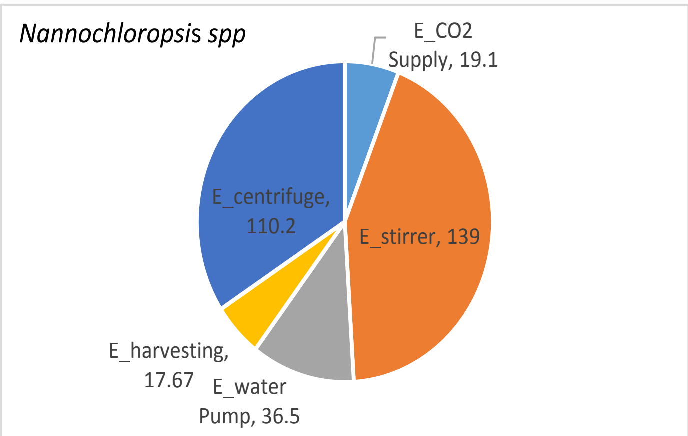


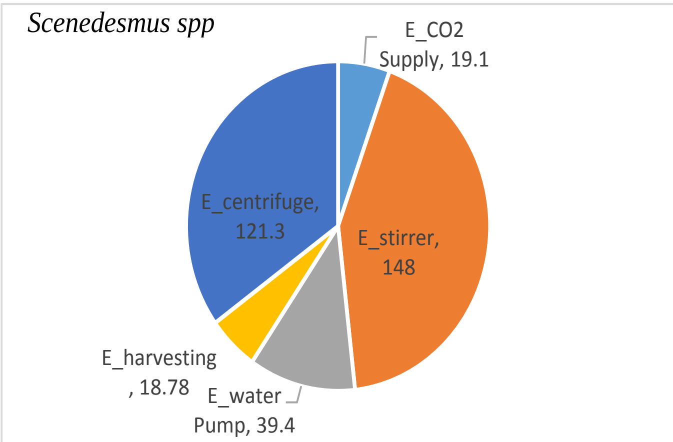
Figure 8.7: Comparison of E_R of photosynthesis reaction for three different algae

Figure 8.6 shows that the value of E_R of Nannochloropsis spp ($C_{21.48}$ $H_{38.5}$ $O_{8.64}$ $N_{0.14}$) is the highest. This is due to the high molar % carbon in the chemical formula compared to the other two microalgae i.e. Chlorella Vulgaris ($C_{12.21}$ $H_{7.778}$ $O_{14.344}$ $N_{0.8}$), and Scenedesmus spp ($C_{23.91}$ $H_{43.26}$ $O_{8.93}$ $N_{0.08}$). From the calculated values of E_R and other energy components for all three algal strains, under consideration, it is revealed that 92%, 93.6% and 92% of the total energy for the algal culture unit is consumed by the biochemical reaction in case of Chlorella Vulgaris , Nannochloropsis spp and Scenedesmus, respectively. For the optimally operated co-fired 30tpd IGCC plant using biomass to coal ratio of 50:50, temperature:900oC and air supply:20% of the stoichiometric requirement for full combustion, the energy requirement for the algal CO2 capture using ORP is equivalent to 11.3%, 11.03% and 11.8% of the original energy output for Chlorella Vulgaris, Nannochloropsis spp and Scenedesmus spp respectively. If any external light source other than solar energy were used, the demand for the capture unit could not be sustained by the power plant. Therefore, for large power plants, the use of photobioreactors for algal CO2 capture cannot be recommended.

Based on the simulation results using the ASPEN Plus® and other calculations related to the energy requirement for various units of algal culture process, except the value of E_R , the data for *Chlorella vulgaris*, *Nannochloropsis spp* and *Scenedesmus spp* have been represented in Figure 8.8.







From Figure 8.7, it can be inferred that the energy requirement for stirring of ORP for *Scenedesmus spp* is the highest among all three algal species *Scenedesmus spp*, producing the highest quantity of biomass among the three also requires the largest culture volume. The power, and tin turn the energy requirement for stirring has been calculated on the basis of constancy of P/V. Therefore, the requirement of highest stirring energy by *Scenedesmus spp* is explained. It can also be reported that the yield, $Y_{\frac{Biomass}{CO_2}}(\frac{kg}{kg})$ of algal biomass of *Scenedesmus spp* with respect to CO_2 capture is also the highest, i.e., 0.45(=1/2.22)kg/kg, in comparison to 0.42kg/kg and 0.43kg/kg for *Nannochloropsis spp* and *Chlorella Vulgaris* respectively. For the reason, the energy requirements for the harvesting and dewatering are also higher in case of *Scenedesmus spp* in comparison to *Nannochloropsis spp* and *Chlorella Vulgaris*.

Figure 8.8: Comparison of total energy, E_{CCAL} of various units of algal culture using three different algae

Table 8.9 summarizes some results of Energy consumption in different processes/operations in the CO_2 Capture by algal culture.

Table 8.9. Distribution of Energy consumption in different processes/operations in the CO_2 Capture by algal culture

Variable	Unit	*Chlorella Vulgaris*	*Nannochloropsis*	*Scenedesmus*
CO_2 capture through algal culture	Kg/h	1365	1365	1365
Algal Biomass production ($\dot{m}_B$)	Kg/h	588.3	578.3	614.8
Light (Solar) Eenrgy consumption for cultivation in raceway pond, E_R	kW	3765	4714	3952
Energy required for CO2 delivery/pumping in cultivation ($E_{CO2\ blower}$)	kW	19.1	19.1	19.1
Energy required for cultivation of by paddle wheel ($E_{stirrer}$) = P/V* volume of cultivation unit	kW	141	139	148
Energy required for water pumping in cultivation ($E_{water\ pump}$)	kW	37.3	36.5	39.4
Energy required for harvesting unit of by floculation ($E_{harvesting}$) = 0.11 GJh/ton algae* algae production rate ($m_{B)}$	kW	17.97	17.67	18.78
Energy required for dewatering (centrifuge) ($E_{centrifuge}$)	kW	114.6	110.2	121.3

8.3.2 Energy requirement for different process units of algae to biodiesel production

The process of CO_2 capture by algal culture followed by algae to biodiesel production plant using three different type microalgae namely *Chlorella vulgaris, Nannochloropsi*s *spp* and *Scenedesmus spp*. has been studied integrated with 30 TPD IGCC cofired plant by the Aspen Plus® simulation tool.

Based on the simulation results using the ASPEN Plus**®** the energy requirements for various units of algae to biodiesel production process using Chlorella *vulgaris, Nannochloropsi*s *spp* and Scenedesmus *spp* has been represented in Figure 8.9.

Figure 8.8, indicates that energy requirements for extraction unit, esterification unit, distillation unit I and distillation II are high for *Nannochloropsis spp* compared to *Chlorella Vulgaris*, and *Scenedesmus spp*. This is due to the high wt% of lipid of *Nannochloropsis spp* microalgae causing higher the biodiesel production rate of biodiesel with respect to *Chlorella Vulgaris*, and *Scenedesmus spp*.

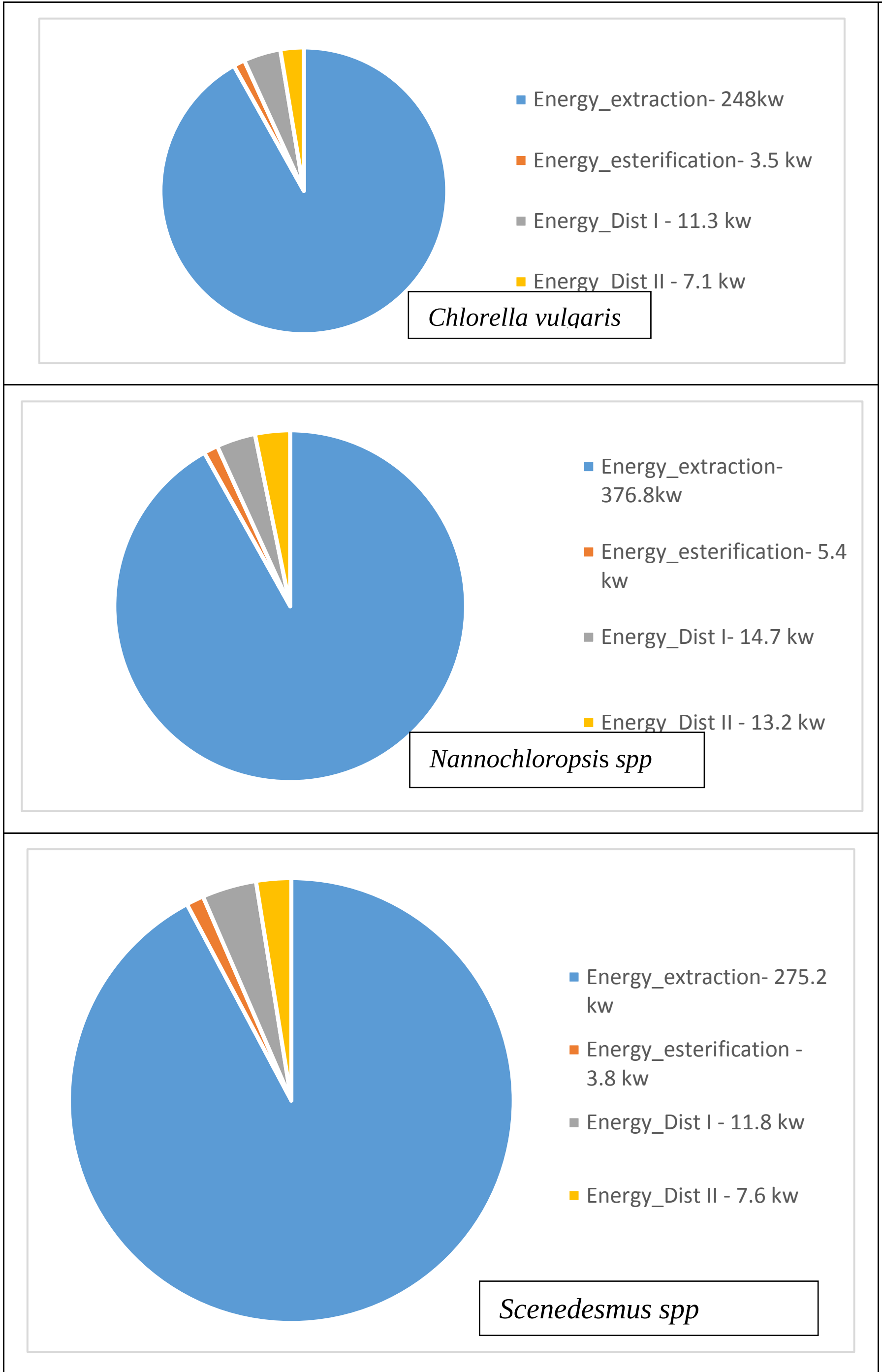


Figure 8.9: Comparison of energy demand of different processes/unit operations for biodiesel production from algal lipid of *Chlorella Vulgaris*, *Nannochloropsis spp* and *Scenedesmus*

The energy requirement for various units /processes of the biodiesel production from algae has been calculated using ASPEN Plus® and shown in Table 8.10.

Table 8.10. Distribution of Energy consumption in different processes/operations in the Biodiesel production

Variable	Unit	*Chlorella Vulgaris*	*Nannochloropsis*	*Scenedesmus*
Lipid content (L_C)in micro algae	Wt%	22	40	25
Lipid produced from algae (m_{lipid}) =($\dot{m}_B$)*L_C	Kg/h	129.5	231.3	153.7
Heat Energy required for lipid extraction($E_{extraction}$)	kW	248	376.8	275.2
Heat Energy required for esterification ($E_{esterification}$)	kW	3.5	5.4	3.8
Heat Energy required for solvent recovery of distillation unit I($E_{Dist\ I}$)		11.3	14.7	11.8
Heat Energy required for distillation unit II ($E_{Dist\ II}$)	kW	7.1	13.2	7.6

8.3.3 EROEI of IGCC power plant integrated with algal CO_2 capture($EROEI_{CCAL}$)

Considering the use of in-house power and grid power for CO_2 capture through algal culture, the Energy return on energy investment of 30 TPD IGCC plant has been compared with respect to without and with 70% of CO_2 capture using three algal species namely, *Chlorella vulgaris, Nannochloropsis spp and Scenedesmus spp* as shown in Figure 8.10. From the analysis of the figure, it is clear that there is a drop in the value of EROEI from 50.2% to 44.5%, 44.7% and 44.3% respectively for Chlorella *vulgaris, Nannochloropsi*s *spp* and Scenedesmus *spp* when the algal CO2 capture unit, run on in-house power, is integrated with the IGCC plant. When the algal capture unit is run by using grid power, the value of EROEI decreases to 47.5%, 47.6%, and 47.4% for Chlorella *vulgaris, Nannochloropsi*s *spp* and Scenedesmus *spp*, respectively. In both the cases, the observed drop in EROEI is due to the consumption of energy by the algal capture unit.

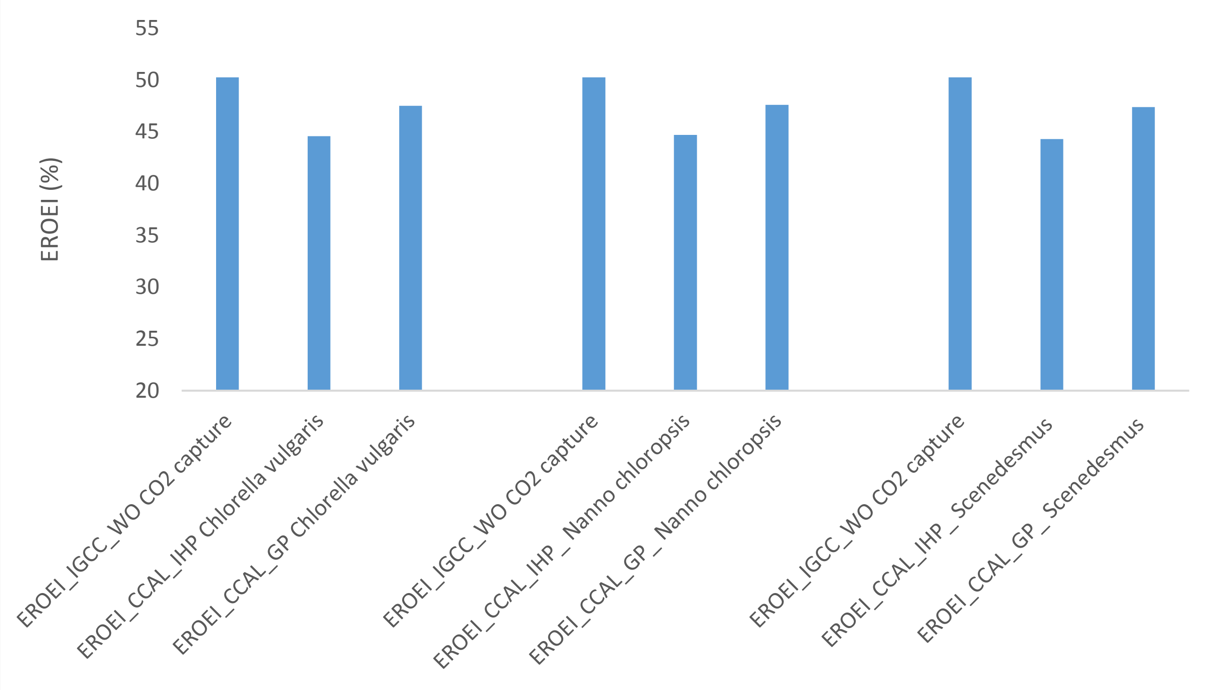


Figure 8.10. **Comparison of EROEI of 30 TPD cofired IGCC plant for with and without CO_2 capture by three algal species considering use of in-house power and grid power**

8.3.4 EROEI of IGCC Plant Integrated with algal CO_2 capture and Biodiesel Production($EROEI_{CCALBDL}$)

In Figure 8.11, the values of EROEI for IGCC plant integrated with algal CO_2 capture and biodiesel unit using in-house power, $EROEI_{CCALBDL\_IHP}$ and grid power, $EROEI_{CCALBDL_{GP}}$ have been compared with the values of EROEI for the original IGCC plant, $EROEI_{WCC}$. The comparison has been carried out for all three algal strains, *Chlorella Vulgaris*, *Nannochloropsis spp* and *Scenedesmus*. It has been observed that the values of $EROEI_{CCALBDL\_IHP}$ *using Chlorella Vulgaris, Nannochloropsis spp* and *Scenedesmus* are 64.6 %, 81.7%, 68.4 % and are much higher than $EROEI_{WCC}$ *which is* 50.2%. Similarly, the EROEI values, $EROEI_{CCALBDL_{GP}}$ for *Chlorella Vulgaris, Nannochloropsis spp* and *Scenedesmus* using grid power are 67.9%, 83.7%, and 71.6% . Also, these values clearly exceed the value of $EROEI_{WCC}$, *i.e.* 50.2% . In both the cases, the increase in EROEI is caused due to the consideration of substitution of a part of energy, required for algal CO2 capture and biodiesel production, by the energy generated from the product biodiesel. From the comparison of the $EROEI_{CCALBDL\_IHP}$ *and* $EROEI_{CCALBDL_{GP}}$ of three algal strains, it is clear that *Nannochloropsis spp* gives the highest value, followed by *Scenedesmus* and *Chlorella Vulgaris*. This is due to the maximum lipid content of

$Nannochloropsis\ spp$ leading to the highest production rate of biodiesel.

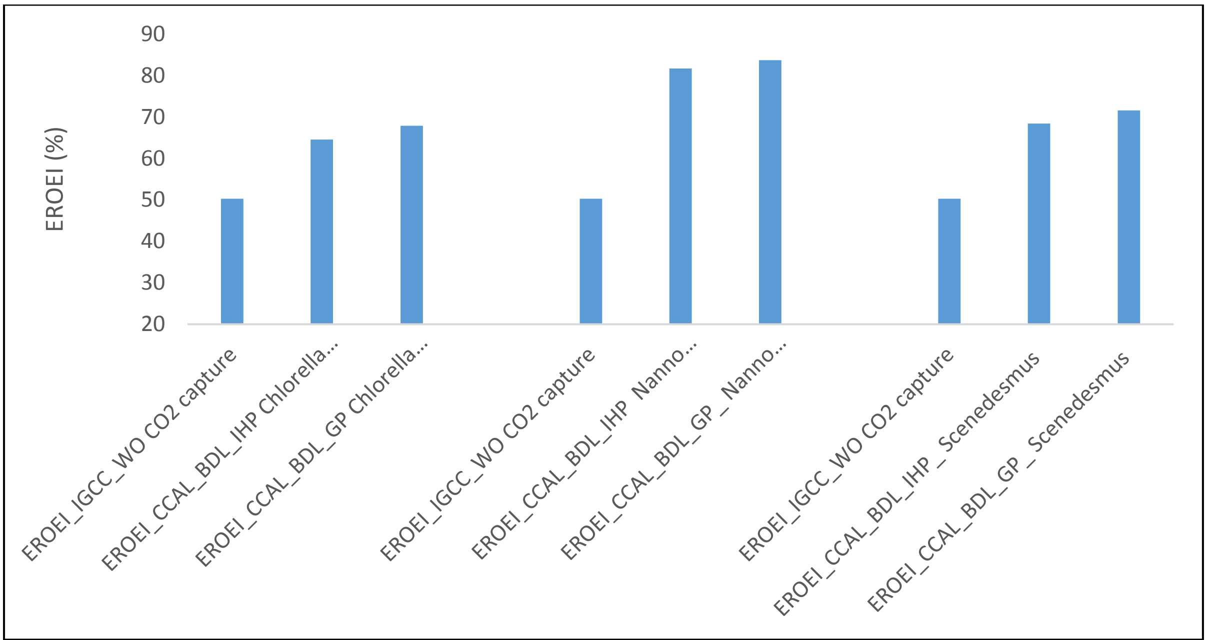


Figure 8.11. Comparison of EROEI of 30 TPD cofired IGCC plant for with and without CO_2 capture by algae including algae to biodiesel production use of in-house power and grid power.

Energy return on energy investment($EROEI_{CCALBDL}$) has been calculated using the data generated by ASPEN Plus®. The sample calculations and the ASPEN Plus® data are provided in the Appendix of this Chapter

8.3.5 Avoidance of CO_2 by algal CO_2 capture (ACE_{CCAL})

Considering the use of in-house power and grid power for algal CO_2 capture, the Avoidance in CO_2 emissions **(**ACE_{CCAL}) of 30 TPD IGCC plant has been compared for with and without CO_2 capture (70%) considering the use of in-house power and grid power. *Chlorella vulgaris, Nannochloropsis spp and Scenedesmus spp* have been used as the algal species and the comparison has been shown in Figure 8.12. From the analysis of the figure, it is clear that there is an increase in the value of ACE from 50.2% to 118.8%, 118.8% and 118.8% respectively, for Chlorella *vulgaris, Nannochloropsi*s *spp* and Scenedesmus *spp* when the algal CO_2 capture unit, run on in-house power, is integrated with the IGCC plant. When the algal capture unit is run using grid power, the value of ACE increases to 103.3%, 103.7%, and 102.5% for Chlorella *vulgaris, Nannochloropsi*s *spp* and *Scenedesmus spp* respectively. In both the cases, the observed increase in ACE is due to the capture of CO_2 by the algal capture unit.

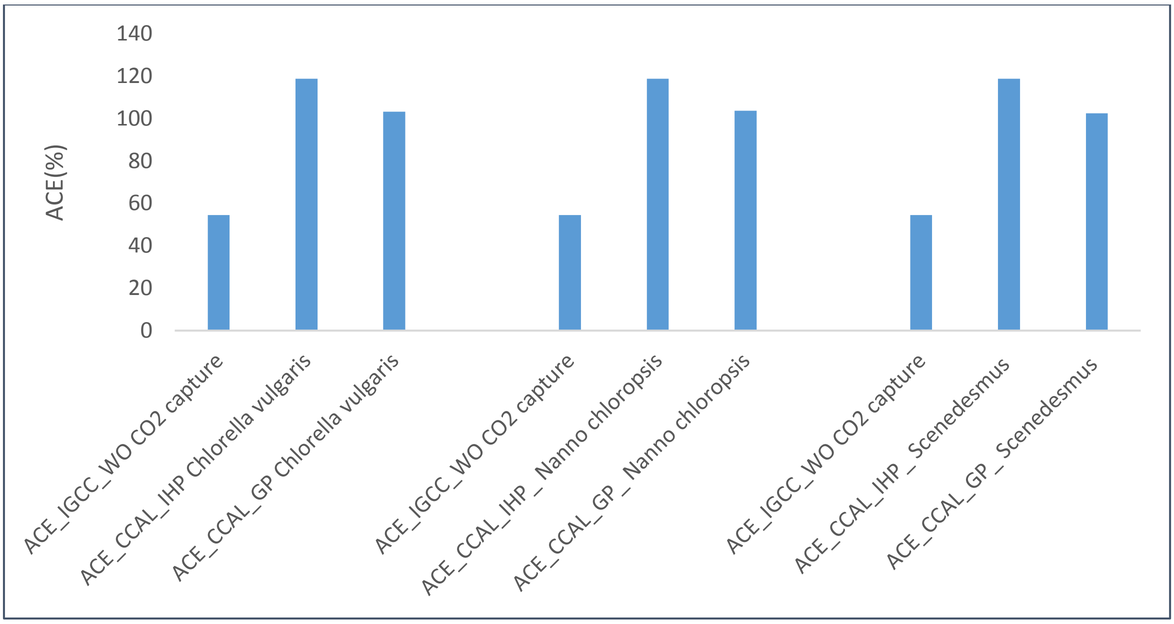


Figure 8.12. Comparison of Avoidance in CO_2 emissions (ACE) of 30 TPD IGCC plant for with and without CO_2 capture considering use of in-house power and grid power.

8.3.6 Avoidance of CO_2 by algal CO_2 capture (ACE_{CCAL_BDL}) including biodiesel production

In Figure 8.13, the values of ACE for IGCC plant integrated with algal CO_2 capture and biodiesel unit using in-house power, $ACE_{CCALBDL\_IHP}$ and grid power, $ACE_{CCALBDL_{GP}}$ have been compared with the values of ACE for the original IGCC plant, ACE_{WCC}. The comparison has been carried out for all three algal strains, *Chlorella Vulgaris*, *Nannochloropsis spp* and *Scenedesmus*. It has been observed that the values of $ACE_{CCALBDL\_IHP}$ *using Chlorella Vulgaris*, *Nannochloropsis spp* and *Scenedesmus* are 169 %, 208%, 179 % and are much higher than ACE_{WCC} *which is* 54.5%. Similarly the ACE values, $ACE_{CCALBDL_{GP}}$ for *Chlorella Vulgaris*, *Nannochloropsis spp* and *Scenedesmus* using grid power are 141.4%, 174.7%, and 150.4% . Also, these values clearly exceed the value of ACE_{WCC}, *i.e.* 54.5% . In both the cases, the increase in ACE is caused due to the consideration of substitution of a part of energy, required for algal CO_2 capture and biodiesel production, by the energy generated from the product biodiesel. From the comparison of the $ACE_{CCALBDL\_IHP}$ *and* $ACE_{CCALBDL_{GP}}$ of three algal strains, it is clear that *Nannochloropsis spp* gives the highest value, followed by *Scenedesmus* and *Chlorella Vulgaris*.

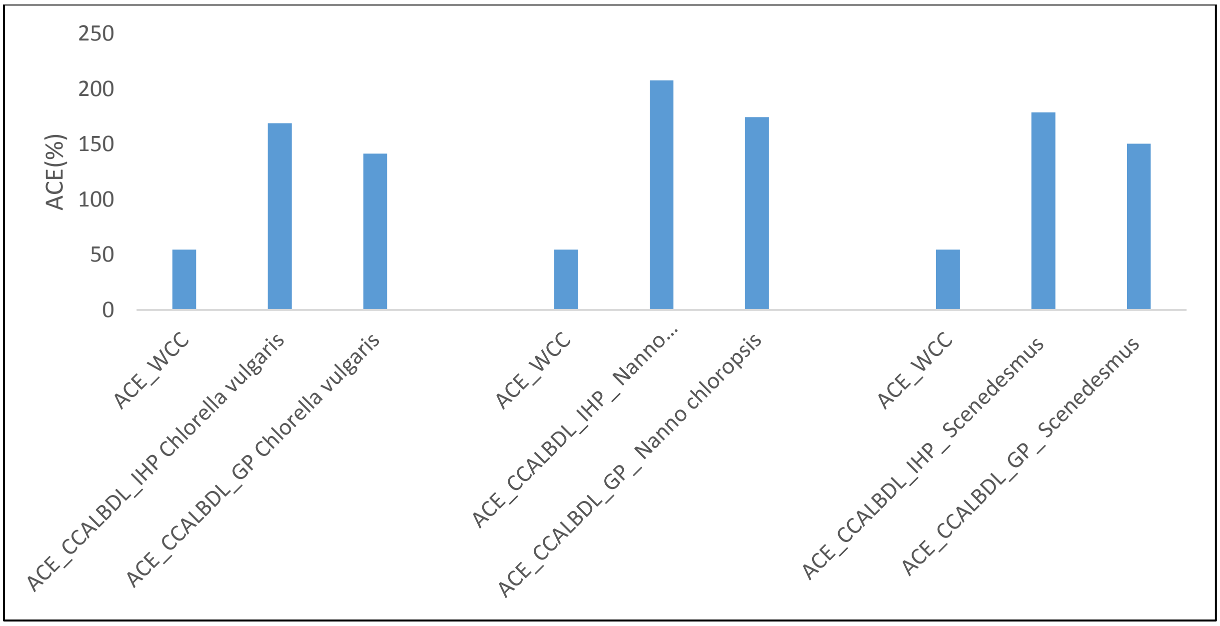


Figure 8.13. Comparison of Avoidance in CO_2 emissions (ACE) of 30 TPD IGCC plant for with CO_2 capture including algae to biodiesel production considering use of in-house power and grid power

8.3.7 Compared Energy requirement for different units/process of algal CO_2 capture and biodiesel production with literature

The requirement of the energy for different units/ process of the proposed model is also compared with literature data published by Cesar G 2014[[36]. As evident from the data provided in Table 8.11, most of the results are in good agreement. However, the energy requirement for extraction of algal oil, calculated using ASPEN Plus® model, is much higher than that reported in the literature.

Table 8.11 Energy requirement for various units/ processes of the proposed model with published literature data.

Operating parameters	literature data published by Cesar G 2014 [36].	This study
Name of Algae	*Chlorella Vulgaris*	*Chlorella Vulgaris*
Cultivated in openpond raceway	Openpond raceway	Openpond raceway
Energy required for CO2 delivery/pumping in cultivation, (kWh /ton of algae)	28.9	31.8

Energy required for stirring of cultivation, (kWh /ton of algae)	200	246.7
Energy required for water pumping in cultivation, (kWh /ton of algae)	153	61.7
Energy required for harvesting, (kWh /ton of algae)	26.5	30
Energy required for dewatering, (kWh /ton of algae)	167	191.7
Energy required for extraction (kWh /ton of algae)	130.7	413.3
Energy required for transesterification (kWh /ton of algae)	20.4	33.3

Symbols used

A_p	[g/ m^2/ d]	productivity of microalgae
X_f	[g/L]	algal biomass concentration at a time T_f (days)
X_0	[g/L]	initial algal biomass concentration at time T_0 (days).
T_f	[days]	Final days of cultivation
T_0	[days]	Initial days of cultivation
V	[L]	working volume of open raceway pond
A	[m^2]	carpet area of open raceway pond
MW_{CO_2}	[kg/kmol]	molecular weight of CO_2
MW_C	[kg/kmol]	molecular weight of carbon
EROEI	[%]	ratio of energy return on energy investment
ACE	[%]	avoidance of CO_2 emissions

Abbreviations

ASPEN Plus®	advanced system for process engineering
ACE	avoidance in CO_2 emissions
EROEI	energy return on energy investment
$EROEI_{WCC}$	*EROEI* for the IGCC power plant without CO_2 capture
$EROEI_{CCAL}$	*EROEI* with CO_2 capture using algal culture
$EROEI_{CCABSR}$	*EROEI* with CO_2 capture using absorption method with solvent recovery
ACE_{WCC}	*ACE* for the IGCC power plant without CO_2 capture
$CO_{2_{MSWBPH}}$	consumption of CO_2 during the production of Agri-MSW biomass through photosynthetic route
$CO_{2_{CCAL}}$	quantum of CO_2 captured by algae

ACE_{CCAL}	ACE for the IGCC power plant with algal CO_2 capture
ACE_{CCABSR}	ACE for the IGCC power plant with CO_2 capture through absorption with solvent recovery
$CO_{2_{CCABSR}}$	quantum of CO_2 captured by absorption
GHG	greenhouse gas
HRSG	heat recovery steam generator
HFC	hydro fluorocarbons
IPCC	intergovernmental panel on climate change
IGCC	integrated gasification combined cycle
LHV	lower heating value
MSW	municipal solid waste
MEA	monoethanol amine
TPD	ton per day

8.4 References

[1] Brennan, L.; Owende, P. 2010. Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products. *Renew. Sustain. Energy Rev*. 14, pp. 557–577.

[2] Tatyana Iglina, Pavel Iglin , Dmitry Pashchenko. 2022. Industrial CO2 Capture by Algae: A Review and Recent Advances, *Sustainability*, 14, pp. 3801.

[3] Saleh M.A. Mobin, Harun Chowdhury, Firoz Alam. 2019. Commercially important bioproducts from microalgae and their current applications – A review. *Energy Procedia*, 160 pp. 752-760.

[4] Gatamaneni Loganathan Bhalamurugan, Orsat Valerie, Lefsrud Mark. 2018. Valuable bioproducts obtained from microalgal biomass and their commercial applications: A review. *Environ Engg*. 23, pp. 229-241.

[5] Muhammad Imran Khan, Jin Hyuk Shin , Jong Deog Kim. 2018. The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. *Microbial Cell Factories*. 36 pp. 584–593.

[6] Esaam HobAllah , Mohamed Saber , Alaa Zaghloul. 2019.Commercial Bio- products from Algal Biomass. *IJEPEM* 2, pp. 90–104.

[7] Zhaohui Xue Yue Yu, Wancong Yu, Xin Gao, Yixia Zhang and Xiaohong Kou. 2020. Development Prospect and Preparation Technology of Edible Oil from Microalgae. *Front. Mar. Sci.*, 14, pp. 557–577.

[8] Michał Adamczyk, Janusz Lasek, and Agnieszka Skawińska, 2016. CO2 Biofixation and Growth Kinetics of Chlorella vulgaris and Nannochloropsis gaditana, *Appl Biochem Biotechnol* 179, pp. 1248–1261.

[9] Cheah, W.Y.; Show, P.L.; Chang, J.-S.; Ling, T.C.; Juan, J.C.2015. Biosequestration of atmospheric CO2 and flue gas-containing CO2 by microalgae. Bioresour. Technol. 184, pp. 190–201.

[10] Jin-Suk-Lee, Deog-Keun Kim, Jun-Pyo Lee. 2002. Effetcs of SO2 and NO on growth of Chlorella sp KR-1. *Bioresource technology*. 82, pp. 1–4.

[11] Sara P.Cuellar-Bermudez, Jonathan S.Garcia-Perez, Roberto Parra-Saldivar. 2015. Photosynthetic bioenergy utilizing CO2:. an approach on flue gases utilization for third generation biofuels. *Journal of Cleaner Production*; 98, pp 53-65

[12] M.Prathima Devi, G.Venkata Subhash, S.Venkata Mohan, 2012. Heterotrophic cultivation of mixed microalgae for lipid accumulation and wastewater treatment during sequential growth and starvation phases: Effect of nutrient supplementation *Renewable Energy*; 43, pp. 276-283.

[13] D.Manhaeghe, T.Blomme, S.W.H.Van Hulle, D.P.L.Rousseau. 2020. Experimental assessment and mathematical modeling of the growth of *Chlorella vulgaris* under photoautotrophic, heterotrophic and and mixotrophic conditions, *Water Reserach*.

[14] Rakesh R. Narala, Sourabh Garg, Kalpesh K. Sharma, Skye R. Thomas-Hall, Miklos Deme, Yan Li , Peer M. Schenk, M. 2016. Comparison of Microalgae Cultivation in Photobioreactor, Open Raceway Pond, and a Two-Stage Hybrid System.. *Energy Resource*, 27, pp. 128–148.

[15] Davis, R . 2016. Process design and economics for the production of algal biomass: algal biomass production in open pond systems and processing through dewatering for downstream conversion. *National Renewable Energy Laboratory*, Golden, CO (United States).

[16] Soheili, Marzieh; Khosravi-Darani, Kianoush. 2011. The Potential Health Benefits of Algae and Micro Algae in Medicine: A Review on Spirulina platensis. *Current Nutrition & Food Science*, 7, pp. 279–285.

[17] Helen Onyeaka, Taghi Miri, KeChrist Obileke, Abarasi Hart, Christian Anumudu, Zainab T.Al-Sharif. 2021. Minimizing carbon footprint via microalgae as a biological capture. *Carbon capture & science tech*.

[18] Worasaung Klinthong, Yi-Hung Yang, Chih-Hung Huang, Chung-Sung Tan. 2015. A Review: Microalgae and Their Applications in CO2 Capture and Renewable Energy. Aerosol & Air Quality Research, 15, pp. 712-742.

[19] de Morais MG; Costa JAV, 2007. Biofixation of carbon dioxide by Spirulina sp. and Scenedesmus obliquus cultivated in a three-stage serial tubular photobioreactor. Journal of biotechnology. 129, pp. 439-445.

[20] Adamczyk M; Lasek J; Skawińska A, 2016.CO2 Biofixation and Growth Kinetics of Chlorella vulgaris and Nannochloropsis gaditana. Applied Biochemistry and Biotechnology, 179, pp. 1248-1261

[21] Ryan Davis, Jennifer Markham, Christopher Kinchin, Nicholas Grundl, and Eric C.D. Tan, Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion, *National Renewable Energy Laboratory*

[22] Vincenzo Piemontea, Luisa Di Paolaa, Alessio Gentileb, Barbara Masciocchib,Valentina Russoa, Gaetano Iaquanielloc, Biodiesel Production from Microalgae: Ionic Liquid Process Simulation,

[23] *Geetanjali Yadav, Brajesh K Dubey, Ramkrishna Sen,* A comparative life cycle assessment of microalgae production by CO2 sequestration from flue gas in outdoor raceway ponds under batch and semi-continuous regime, https://doi.org/10.1016/j.jclepro.2020.120703

[24] Sukumar Roy, Snigdha Pal, Nabajit Chakravarty. 2016. Global solar radiation characteristics at Dumdum (West Bengal), Indian Journal of Radio & Space Physics, 45, pp. 148-153

[25] Erick M. Tejada Carbajal, Elías Martínez Hernández, Luis Fernández Linares, Eberto Novelo, Roberto Limas Ballesteros. 2020. Techno-economic analysis of Scenedesmus dimorphus microalgae biorefinery scenarios for biodiesel production and glycerol valorization, *Bioresource Technology Reports.*

[26] César G. Gutiérrez-Arriag, Medardo Serna-González,, JoséMaría Ponce-Orteg and Mahmoud M. El-Halwagi. 2014. Sustainable Integration of Algal Biodiesel Production with Steam Electric Power Plants for Greenhouse Gas Mitigation, ACS Sustainable Chem. Eng.,

[27] Dianne Luning Prak, Michael Hamilton , Rhea Banados , Jim Cowart. 2022. Density, viscosity, speed of sound, flash point, bulk modulus, and surface tension of mixtures of military jet fuel JP-5 and biodiesels dataset, Data in Brief , 41, pp. 107849

[28] Yuzuru Ued, Kosuke Kurokaw, *Member, IEEE,* Takayuki Tanabe, Kiyoyuki Kitamur, and Hiroyuki Sugihar, 2008. Analysis Results of Output Power Loss Due to the Grid Voltage Rise in Grid-Connected Photovoltaic Power Generation systems, IEEE transactions on industrial electronics, 55 (7).

[29] Moti L. Mitta, 2015. Estimates of Emissions from Coal Fired Thermal Power Plants in India

[29] S. Rezvani, N.R. Moheimani, P.A. Bahria, 2016.Techno-economic assessment of CO2 bio-fixation using microalgae in connection with three different state-of-the-art power plants, Computers and Chemical Engineering, 84, pp. 290–301

[30] Baral SS, Singh K; Sharma P, 2015. The potential of sustainable algal biofuel production using CO_2 from thermal power plant in India. Renewable and Sustainable Energy Reviews, 49, pp. 1061-1074.

[31] Gutiérrez-Arriaga CG; Serna-González M; Ponce-Ortega JM; El-Halwagi MM, 2014. Sustainable integration of algal biodiesel production with steam electric power plants for greenhouse gas mitigation. ACS Sustainable Chemistry & Engineering, 2, pp. 1388-1403.

[32] Aresta M; Dibenedetto A; Barberio G, 2005. Utilization of macro-algae for enhanced CO_2 fixation and biofuels production: development of a computing software for an LCA study. Fuel processing technology, 86, pp. 1679-1693.

[33] Leung DY; Caramanna G; Maroto-Valer MM, 2014. An overview of current status of carbon dioxide capture and storage technologies. Renewable and Sustainable Energy Reviews, 39, pp. 426-443.

[34] Chen CY; Chang HW; Kao PC; Pan JL; Chang J S, 2012. Biosorption of cadmium by CO_2-fixing microalga *Scenedesmus obliquus* CNW-N. Bioresource Technology, 105, pp. 74-80.

[35] Zhou D; Qiao B; Li G; Xue S; Yin J, 2017. Continuous production of biodiesel from microalgae by extraction coupling with transesterification under supercritical conditions. Bioresource Technology, 238, pp. 609-615.

[36] Taher H; Al-Zuhair S; Al-Marzouqi A; Haik Y; Farid M, 2015. Growth of microalgae using CO_2 enriched air for biodiesel production in supercritical CO_2. Renewable Energy. 82, pp. 61-70.

[37] Nautiyal P; Subramanian KA; Dastidar MG, 2014. Production and characterization of biodiesel from algae. Fuel Processing Technology, 120, pp. 79-88.

APPENDIX_Chapter 8

Table A.8.1 ASPEN Plus® generated data and the Calculation of $(EROEI_{CCAL})$ of IGCC Co-fired power plant with CO_2 capture using three algal species.

EROEI of IGCC without CO_2 capture		
Description	**Unit**	**Value**
IGCC Co-fired Power Plant Capacity	TPD	30
Cofiring ratio i.e. Agri-MSW to coal ratio (wt/wt)	%	50
Biomass i.e. Agri-MSW feed rate (M_{MSW})	Kg/hr (kg/s)	625 (0.1736)
HHV of Agri-MSW (HHV_{MSW})	kJ/kg	17600
Coal Feed rate(M_{COAL})	Kg/hr (kg/s)	625 (0.1736)
HHV of coal (HHV_{COAL})	kJ/kg	18840
Rate of Energy input (EI_{IGCC}) of IGCC co-fired power plant M_{MSW}x HHV_{MSW} + M_{COAL}x HHV_{COAL}	kw	$0.1736 \times 17600 + 0.1736 \times 18840$ =5815
Energy return $(ER_{wcc})$from IGCC co-fired power plant without CO_2 capture	kw	2922
EROEI without CO_2 capture $(EROEI_{WCC})$ has been calculated as per eqn (28) $EROEI_{WCC} = \frac{(ER_{wcc})}{EI_{IGCC}} = \frac{2922}{5815}$ *100 = 50.2		

EROEI of IGCC with CO_2 capture using three different type microalgae				
Description	**unit**	***Chlorella Vulgaris***	***Nannochloropsis***	***Scenedesmus***
Total energy requirement for CO_2 capture through algal route of (E_{CCAL}) as per eqn (30) $(E_{CO2\ blower} +$ $(E_{stirrer})$ +$((E_{water\ pump})$ +($E_{harvesting}) + E_{centrifuge})$	kw	19.1+141+ 37.3+17.9 7+114.6 = 329.97	19.1+139+ 36.5+17.6 7+110.2 = 322.47	19.1+148+ 39.4+18.7 8+121.3 = 346.58
EROEI with CO_2 capture using algal culture $(EROEI_{CCAL\_IHP})$ use of in-house power as per eqn. (31) $EROEI_{CCAL\_IHP} = \frac{ER_{wcc} - E_{CCAL}}{EI_{IGCC}}$	%	$\frac{2922 - 329}{5815} \times 100$ =44.57	$\frac{2922 - 322}{5815} \times 100$ =44.7	$\frac{2922 - 346}{5815} \times 100$ =44.3
EROEI with CO_2 capture using algal culture $(EROEI_{CCAL\_GP})$ use of grid power as per eqn. (32) $EROEI_{CCAL\_GP} = \frac{ER_{wcc}}{EI_{IGCC} + E_{CCAL}}$	%	$\frac{2922}{5815 + 329} \times 100$ =47.5	$\frac{2922}{5815 + 322} \times 100$ =47.6	$\frac{2922}{5815 + 346} \times 100$ =47.4

Table A.8.2 ASPEN Plus® generated data and the Calculation of $(EROEI_{CCALBDL})$ of IGCC Co-fired power plant with CO_2 capture using three algal species.

Description	Unit	Value		
Type of micro algae		*Chlorella vulgaris*	*Nannochloropsis*	*Scenedesmus*
Total energy required for algae to biodiesel production as per eqn. (33) $E_{BDL} = (E_{extraction} + (E_{esterification}) + E_{Dist\ I} + E_{Dist\ II})$	kw	248+3.5+18.4 = 269.9	376.8+5.4+27.9 = 410.1	275.2+3.8+19.4 = 298.4
Total energy required for CO2 capture with algal cultivation including algae to biodiesel production $(E_{CCALBDL}) = (E_{CCAL}) + (E_{BDL})$	kw	329.97+ 269.9 = 599.87	322.47+ 410.1 = 732.57	346.58+ 298.4 = 644.98
Energy return(ER_{BDL}) by biodiesel as per equation (36)	kw	42*1000*123/3600=1434.6	42*1000*219/3600= 2546.1	42*1000*146/3600=1703.6
Total Energy return for IGCC plant with CO2 capture and biodiesel production i.e. $ER_{wcc} + ER_{BDL}$		2922+ 1434.6 =4356.6	2922+ 2546.1 =5486.1	2922+ 1703.6 =4625.6
EROEI with CO_2 capture using algal culture including biodiesel production($EROEI_{CCALBDL\_IHP}$) considering use of in-house power as per eqn. (34) $EROEI_{CCALBDL\_IHP} = \frac{ER_{wcc} + ER_{BDL} - E_{CCAl}}{EI_{IGCC}}$	%	$\frac{4356.6 - 599.87}{5815} \times 100$ =64.6	$\frac{5486.1 - 732.5}{5815} \times 100$ =81.7	$\frac{4625.6 - 644.9}{5815} \times 100$ =68.4
EROEI with CO_2 capture using algal culture including biodiesel production($EROEI_{CCALBDL\_GP}$) considering use of grid power as per eqn. (35) $EROEI_{CCALBDL\_GP} = \frac{ER_{wcc} + ER_{BDL}}{EI_{IGCC} + E_{CCALBDL}}$	%	$\frac{4356.6}{5815 + 599.6} \times 100$ =67.9	$\frac{5486.1}{5815 + 732.5} \times 100$ =83.7	$\frac{4625.6}{5815 + 644.9} \times 100$ =71.6

Table A.8.3 ASPEN Plus® generated data and the Calculation of (ACE_{CCAL}) of IGCC Co-fired power plant with CO_2 capture using three algal species.

Calculation of ACE for 30 TPD IGCC without CO_2 capture		
Description	**Unit**	**Value**
Plant Capacity	TPD	30
CO_2 emission from coal fired power plant	Kg/hr	2120
CO_2 emissions from IGCC co-fired power plant	kg/hr	1950
Cofiring ratio i.e. Agri-MSW to coal ratio (wt/wt)	%	50
Agri-MSW biomass feed rate (M_{MSW})	kg/hr	625.00
Consumption of CO_2 during the production of Agri-MSW biomass through photosynthetic route ($CO_{2_{MSWBPH}}$) as per eqn. (10) $\mathrm{ACE}_{MSWBPH} = \frac{M_{MSWB} * w_{cMSWB} * MW_{\mathrm{CO_2}}}{MW_{\mathrm{C}}}$		
Weight fraction of carbon in the Agri-MSW biomass (w_{cMSWB})		0.43
Molecular weight of CO2 ($MW_{\mathrm{CO_2}}$)	Kg/kmol	44
Molecular weight of Carbon (MW_{C})	Kg/kmol	12
ACE_{MSWBPH}	Kg/hr	$\frac{625 \times 0.43 \times 44}{12}$ =985.42
CO_2 emissions from IGCC co-fired power plant ($CO_{2_{Cofiring}}$)	kg/hr	1950
Plant emissions avoidance due to switching over from coal fired to co-fired IGCC mode ($\mathrm{ACE}_{COAL\ to\ Cofiring}$) i.e. CO_2 emissions from coal fired power plant - CO_2 emissions from IGCC co-fired power plant	Kg/hr	2120-1950 =170
Total CO_2 emissions for IGCC co-fired plant without CO_2 capture has been calculated as per eq. no. (38)	Kg/hr	170+985.42 =1155.42
ACE for the IGCC power plant without CO_2 capture (ACE_{WCC}) as per eqn. (39) $ACE_{WCC} = \frac{\mathrm{ACE}_{COAL\ to\ Cofiring} + \mathrm{ACE}_{MSWBPH}}{CO_{2_{COAL}}}$	%	$\frac{1155.42}{2120} \times 100$ =54.5

Calculation of ACE for 30 TPD IGCC with formation algae including algae to biodiesel production using CO2 Capture				
Description	Unit	*Chlorella vulgaris*	*Nannochloropsis*	*Scenedesmus*
CO_2 capture by algae of IGCC co-fired power plant	%	70	70	70
CO_2 captured by algae (ACE_{CCAL})	Kg/hr	1950×0.7 =1365	1950×0.7 =1365	1950×0.7 =1365
Total CO_2 emissions for IGCC co-fired plant with CO_2 capture	Kg/hr	170+985.42+ 1365 =2520.4	170+985.42 +1365 =2520.4	170+985.42+ 1365 =2520.4

considering use of in-house power has been calculated as per eqn. (41)				
ACE for the IGCC power plant with algal CO_2 capture (ACE_{CCAL_IHP})as per eqn. (39) considering use of in-house power $$ACE_{CCAL\_IHP} = \frac{\text{ACE}_{COAL\ to\ Cofiring} + \text{ACE}_{MSWBPH} + \text{ACE}_{CCAL}}{CO_{2_{COAL}}}$$				
ACE_{CCAL_IHP}	%	$\frac{2520.42}{2120} \times 100 = 118.8$	$\frac{2520.42}{2120} \times 100 = 118.8$	$\frac{2520.42}{2120} \times 100 = 118.8$
Energy required for formation of algal biomass through CO2 capture, E_{CCAL}	K W	329.97	322.47	346.58
CO_2 emissions due to energy supplied from grid power as per eqn. (44) $CO_{2_{EGP}}$ = E_{CCAL}*(1+0.05)* 0.95	Kg/ hr	329.67*(1+0.05)*0.95 = 328.8	322.47*(1+0.05)*0.95 = 321.6	346.58*(1+0.05)*0.95= 345.7
Total CO_2 emissions avoidance for IGCC co-fired plant with CO_2 capture considering use of grid power has been calculated as per eqn. (43)	kg/ hr	170+985.42+ 1365 -328.8 =2191.6	170+985.42+ 1365 -321.6 =2198.8	170+985.42+ 1365 -345.7 =2174.7
ACE for the IGCC power plant with algal CO_2 capture (ACE_{CCAL_GP})as per eqn. (42) considering use of grid power $$ACE_{CCAL\_GP} = \frac{\text{ACE}_{COAL\ to\ Cofiring} + \text{ACE}_{MSWBPH} + \text{ACE}_{CCAL} - CO_{2_{EGP}}}{CO_{2_{COAL}}} * 100$$				
ACE_{CCAL_GP}	%	$\frac{2191.6}{2120} \times 100 = 103.3$	$\frac{2198.8}{2120} \times 100 = 103.7$	$\frac{2174.7}{2120} \times 100 = 102.5$

Table A.8.4 ASPEN Plus® generated data and the Calculation of $(ACE_{CCALBDL})$ of IGCC Co-fired power plant with CO_2 capture using three algal species.

Biodiesel production from 30 TPD IGCC plant (m_{BDL})	Kg/hr	122.9	219.7	146.1
Energy return(ER_{BDL}) by biodiesel as per equation (36)	kw	42*1000*123/3600=1434.6	42*1000*219/3600=2546.1	42*1000*146/3600=1703.6
CO2 emissions (ACE_{BDL})avoidance due to use of biodiesel inplace of conventional diesel for diesel engine as per eqn. (53)	Kg/hr	1434.6*0.75 =1075.9	2546.1*0.75 =1909.5	1703.6*0.75 =1277.7
Total CO_2 emissions avoidance for IGCC co-fired plant with CO_2 capture including algae to biodiesel production considering use of in-house power has been calculated as per eq. no. (46)	Kg/hr	170+985.42+1365 +1075.9 =3596.3	170+985.42+1365 +1909.5 =4429.5	170+985.42+1365 +1277.7 =3798.1
ACE for the IGCC power plant with algal CO_2 capture including biodiesel production $(ACE_{CCALBDL_IHP})$as per eqn. (45) considering use of in-house power $ACE_{CCALBDL\_IHP} = \frac{ACE_{COAL\ to\ Cofiring} + ACE_{MSWBPH} + ACE_{CCAL} + ACE_{BDL}}{CO_{2\,COAL}}$				
$ACE_{CCALBDL\_IHP}$	%	$\frac{3596.3}{2120} \times 100$ =169.6	$\frac{4429.5}{2120} \times 100$ =208	$\frac{3798.1}{2120} \times 100$ =179
Energy required for algae formation including biodiesel production using CO2 capture, $(E_{CCALBDL})$	KW	599.87	732.57	644.98
CO_2 emissions due to energy supplied from grid power as per	Kg/hr	599.87*1.05*0.95 =598.3	732.57*1.05*0.95 =730.7	644.98*1.05*0.95 =609.5

eqn. (52) $CO_{2_{EGPBDL}}$ = $(E_{CCALBDL})$*(1+0.05)*0.95				
Total CO_2 emissions avoidance for IGCC co-fired plant with CO_2 capture including algae to biodiesel production considering use of grid power has been calculated as per eqn. (51)	Kg/hr	170+985.42+1365 +1075.9 -598.3 =2998	170+985.42+1365 +1909.5 -730.7 =3698.8	170+985.42+1365 +1277.7 -609.5 =3188.6

ACE for IGCC power plant with algal CO2 capture including algae to biodiesel production considering use of grid power as per eqn. (50)

$$ACE_{CCALBDL\_GP} = \frac{\mathrm{ACE}_{COAL\ to\ Cofiring} + \mathrm{ACE}_{MSWBPH} + \mathrm{ACE}_{CCAL} + \mathrm{ACE}_{BDL} - CO_{2_{EGPBDL}}}{CO_{2_{COAL}}}$$

$ACE_{CCALBDL\_GP}$	%	$\frac{2998}{2120} \times 100$ =141.4	$\frac{3698.8}{2120} \times 100$ =174.7	$\frac{3188.6}{2120} \times 100$ =150.4

CHAPTER 9

IGCC WITH HYBRID (ABSORPTION-ALGAL) CO_2 CAPTURE

9.1 Introduction

Standalone post-combustion CO_2 capture by absorption has challenges, particularly, high energy consumption for solvent regeneration. On the other hand, post-combustion CO_2 capture by a biological system through algal cultivation has challenges. The challenges are low CO_2 solubility and low CO_2 fixation efficiency. To overcome the above issues for standalone post-combustion CO_2 capture methods, the absorption-microalgae hybrid systems for CO_2 capture are gaining interest [1-7]. From the literature review, presented in Chapter 2, it is evident that most of the research studies are focused on lab- scale experimental studies on the growth of algal species. Hybrid CO_2 capture systems integrated with conventional/ IGCC power plants have not yet been reported. Under the present study, the energy and environmental analysis of IGCC power plant, integrated with a hybrid CO_2 capture system has been studied and the performance has been compared with combined IGCC-absorption CO_2 capture system, based on ASPEN Plus® simulation data.

9.2 Methodology

ASPEN Plus® software has been used to develop a process simulation model for a solvent-based Absorption followed by algal cultivation hybrid CO2 capture.

9.2.1 30 TPD cofired IGCC Power plant

Table 9.1 summaries the operating parameters, output energy, and CO_2 emissions information of the 30 TPD co-fired IGCC power plant without a CO_2 capturing facility as described in Chapter 6. The data were determined through process simulation modeling using the ASPEN Plus® engineering tool.

Table 9.1 Technical information of 30 TPD co-fired IGCC plant without CO_2 capture

Parameter	Unit	Value
Cofiring (biomass:coal)	:	Inidan Agri- MSW based biomass: Coal
Feed composition (mass basis)	:	50:50
Gasifier Temperature	^oC	900
Indian Agri-MSW based Biomass feed flow rate as per cofired mass basis	Kg/h	625

Parameter	**Unit**	**Value**
Coal feed flow rate as per cofired mass basis	Kg/h	625
Higher heating value of Indian Agri-MSW based Biomass	MJ/kg	17.6
Higher heating value of Coal	MJ/kg	18.84
Energy return on Eenrgy Investment (EROEI)	%	50.25
Avoidance in CO_2 emissions (ACE)	%	49.4

The flue gas of original IGCC power plant, as described in Chapter 6, is the input for CO_2 capture by Absorption-algal hybrid system. The flue gas composition is provided in Table 9.2.

Table 9.2. Flue gas composition of 30 TPD cofired IGCC Power plant

Parameter	**Unit**	**Value**
CO_2	(mol/mol)%	10.14
H_2O	(mol/mol)%	6.76
O_2	(mol/mol)%	9.02
N_2	(mol/mol)%	74.08

9.2.2 Processes for CO_2 capture by Absorption-microalgae hybrid CO_2 capture

This hybrid system consists of an absorption system followed by a cultivation unit. The process flow diagram is shown in Figure 9.1.

Solvent Absorption Process

According to the process model of the IGCC plant, the flue gas temperature after gas cleaning is 58^{o}C. As the exit temperature of the flue gas is too high to be introduced to the CO_2 capture unit, a direct contact cooler is incorporated into the process flow sheet to decrease the flue gas temperature to 30^{o}C. Carbon dioxide in the flue gas gets scrubbed through the contact with amine during the counter flow through the absorber. CO_2-free flue gas leaves from the top of the absorber while CO_2 -rich amine solution exits from the bottom of the absorber.

Cultivation Process

The output product of the absorption unit is fed to the cultivation unit where the product of the absorption reaction unit has a potential nutrient source for micro-algal growth. Microalgae have the potential to avoid a huge amount of energy demand for regeneration of solvent from rich solution stream of absorption unit by consuming the dissolved CO_2 from the solvent of absorption unit with the help of solar energy by photosynthesis process. The ASPEN Plus® simulation flow sheet for the Absorption-microalgae hybrid system is shown in Figure 9.2.

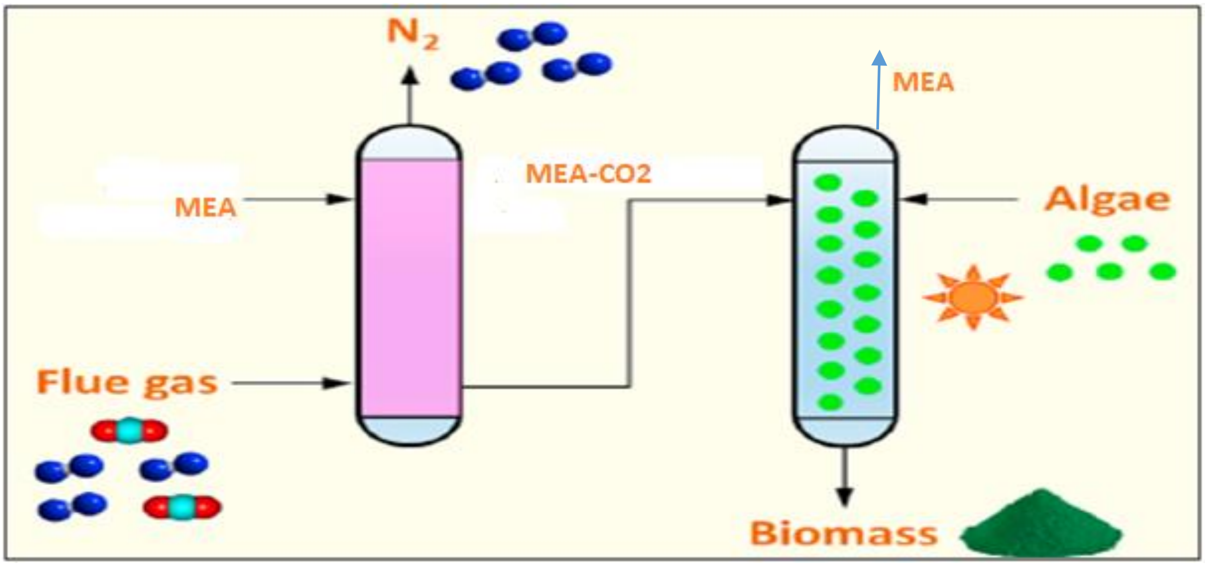


Figure 9.1: Process Flow Diagram of Absorption-microalgae hybrid CO_2 capture

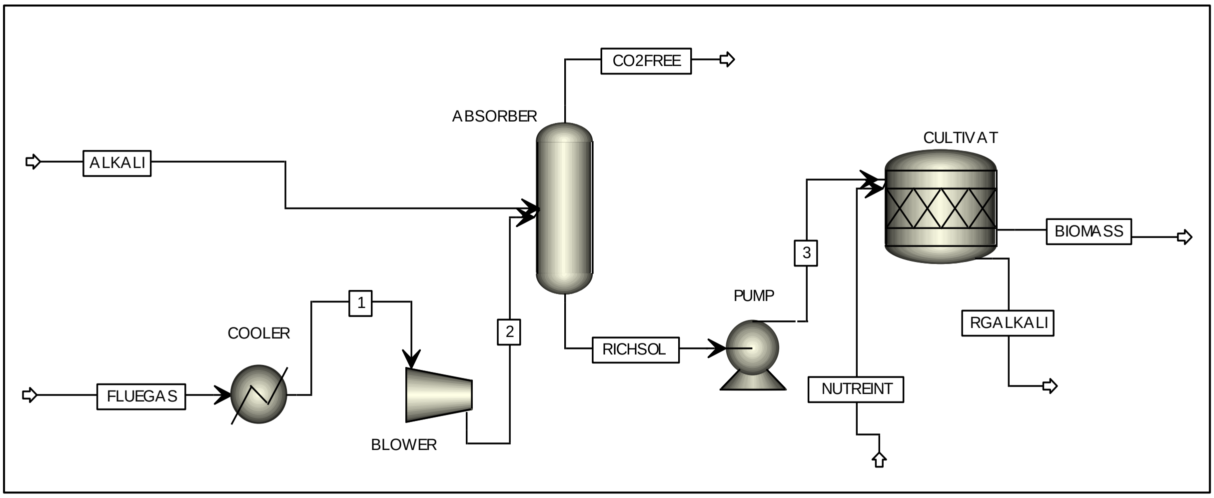
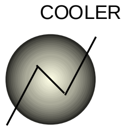
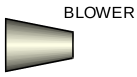
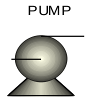
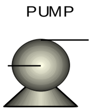
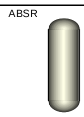


Figure 9.2. ASPEN Plus® simulation flow sheet for Absorption-microalgae hybrid CO_2 capture

All the blocks and components, used in the ASPEN Plus® flow sheet (Figure 9.2), are briefly described in Tables 9.3 and 9.4

9.2.3 Block Specification for Absorption-microalgae hybrid CO_2 capture

Table 9.3. Description of the blocks used in the modeling

Block ID	Module selected	Scheme	Description
COOLER	HEAT EXCHANGER		In this simulation Cooler has been used for the reduction of flue gas temperature from 95ºC to 30 degree C.
BLOWER	COMPRESSOR		Blower has been used for the supply of CO_2 to Absorber unit.
PUMP_RICHSOL	PUMP		Pump has been used for the supply of rich solvent to cultivation unit for solvent regeneration as well as biomass algae production.
PUMP_LEANSOL	PUMP		Pump has been used for the supply of lean solvent to absorption unit for CO_2 absorption
ABSORBER	RADFRAC		RADFRAC unit used as Absorber for absorption of CO_2 by mano ethylene amine (MEA) solvent. Absorber Pressure : 1 atm
CULTVAT	RSTOIC		Models stoichiometric reactor with specified reaction extent or conversion. In this simulation, Cultivation unit has been used for modeling the photosynthesis reaction between CO_2, H_2O for production of biomass. Nitrogen source. NH_3 has been fed to reactor for start the cultivation process.

9. 2.4. Components for Absorption-microalgae hybrid CO_2 capture

The components involved in the overall system have been classified as per the requirement of ASPEN Plus® software. In Table 9.4, all the components have been classified.

Table 9.4. Classification of all the components

Component ID	Type	Component name	Formula
CO_2	Conventional	CARBON-DIOXIDE	CO_2
H_2O	Conventional	WATER	H_2O
O_2	Conventional	OXYGEN	O_2
MEA	Conventional	MANOETHYLENE AMINE	C_2H_7NO
NH_3	Conventional	AMMONIA	H_3N
ALGAE	Conventional	LIPID	$C_{57}H_{104}O_6$
	Conventional	PROTEIN	$C_9H_{11}NO_2$
	Conventional	CARBOHYDRATE	$C_{12}H_{22}O_{11}$

9.2.5 Simulation by using ASPEN Plus®

In the ASPEN Plus® model, the stream class has been set as MIXCINC which represents all the streams such as MIXED, CONVENTIONAL, and NON-CONVENTIONAL.

9.2.5.1 Solvent Absorption Process

Aqueous monoethyl amine (MEA) has been selected as a solvent for the post-combustion CO_2 capture process [8-10]. Electrolyte Non-Random Two-Liquid (ELECNRTL) property method [11] has good accuracy to estimate the thermo-physical properties of the carbon capture process. The operating parameters for the amine-based CO_2 capture system have been provided in Table 9.5.

Table 9.5. Operating parameters for simulation of CO_2 capture by absorption.

Configurations	Parameters	Value
Flue Gas	Temperature	30^0C
	Pressure	1.7 bar
	CO_2 concentration	10.14 % by mole
	Flowrate	450 kmol/hr
Leam amine solution	Temperature	30^0C
	Pressure	1.1 bar
	Amine concentration	30 % by mass
	Lean amine solution flowrate	1000 – 2000 kmol/hr
Lean loading	CO_2 / amine (mole basis)	23%
Absorber column	Calculation type	Equilibrium
	No. of stages	10
	Condensor pressure	0.9 – 1.2 atm

The electrolyte reactions has been used in absorption-microalgae hybrid system are given in Table 9.6.

$$\boldsymbol{In(K_{eq}) = A + \frac{B}{T} + CIn(T) + DT}$$

Where, **T** in Kelvin, used by ASPEN Plus®

Table 9.6. Equilibrium constant for reactions of CO_2 with aqueous MEA solution.

Reactions	A	B	C	D
$2H_2O \leftrightarrow H_3O^+ + OH^-$	132.89888	-13445.9	-22.477301	0
$CO_2 + 2H_2O \leftrightarrow H_3O^+ + HCO_3^-$	231.465439	-12092.1	-36.781601	0
$HCO_3^- + H_2O \leftrightarrow H_3O^+ + CO_3^{2-}$	216.050446	-12431.7	-35.481899	0
$MEACOO^- + H_2O \leftrightarrow MEA + HCO_3^-$	-0.52135	-2545.53	0	0
$MEAH^+ + H_2O \leftrightarrow MEA + H_3O^+$	-3.038325	-7008.3569	0	-0.003135

9.2.5.2 Cultivation of Algae for regeneration of amine solvent

Open raceway pond (ORP) has been selected for the cultivation of *Scenedesmus* [12,13] to utilize the bicarbonate present in rich MEA solvent as a carbon source for algae culture and the regenerated solvent is recycled back to the absorption column. The cultivation has been initiated by inoculation with a stock culture having a concentration of biomass of 1.5g/L.

As algae are non-conventional feedstocks for ASPEN Plus® software, their physical properties are not available in the built-in database. In a technical report of NREL [14], the early, mid and late phase composition of *Scenedesmus spp*, with respect to carbohydrates, lipids, and proteins, has been provided. Under this study, the late phase composition of these micro algal species, as represented in Table 9.7, have been used in the ASPEN Plus® simulation. As reported by previous researchers, sucrose, triolein and L-phenylalanine have been used to represent carbohydrates, lipids and proteins respectively [15].

Table 9.7 Composition of *Scenedesmus spp*

Algal Species	Carbohydrate Sucrose ($C_{12}H_{22}O_{11}$) MW*: 342		Lipids Triolein ($C_{57}H_{104}O_6$) MW*: 884		Proteins L-phenylalanine ($C_9H_{11}NO_2$) MW*: 165	
	% (w/w) (dry basis)	% (molar)	% (w/w) (dry basis)	% (molar)	% (w/w) (dry basis)	% (molar)
Scenedesmus spp	35	27	25	8	40	65

Based on the composition of the algal species, the empirical formulae of *Scenedesmus spp* is assigned to be $C_{23.91}H_{43.26}O_{8.93}N_{0.08}$.

Biochemical Reaction for formation of *Scenedesmus spp*

The stoichiometric equations of biochemical reaction for the formation of the algal biomass from HCO_3^- can be written as follows:

Scenedesmus spp

$$12.21HCO_3^- + 36.466H_2O + 0.8\,NH_3 \xrightarrow{Light\ energy\ (h\gamma)} 0.058\,C_{57}H_{104}O_6 + 0.8\,C_9H_{11}NO_2 + 0.142C_{12}H_{22}O_{11} + 69.586OH^- \quad (1)$$

$$\Delta H^o_{R(Scenedesmus\ spp.)} = 2425\text{kJ/mol}$$

The area and the volume of the raceway pond have been determined with the following assumptions as discussed in Chapter 8.

1. The raceway pond operates under semi batch mode; the gas is fed and discharged continuously, and the liquid and solid phases are in batch mode.
2. Batch time (t_B) of six days has been assumed [13, 15]. This signifies that the algal biomass is harvested at an interval of six days.
3. Percentage conversion of inlet CO_2 to algal biomass is 70%. [16].
4. The productivity (P_B) of algal biomass is 25 g/m^2/day or, 0.001kg/m^2/h [15.16].
5. The biomass concentration (Cx) at the end of six days is 0.5 g/L [13, 15, 16].
6. Light energy required for the photosynthesis is supplied by natural sunlight.
7. The solar flux, of Eastern India, is in a range of 5-30Wh/m^2/d.[17]

According to above assumption, the area ($A_{ORP\_Scenedesmus}$) and volume ($V_{ORP\_Scenedesmus}$) of raceway ponds for the cultivation of algal biomass of Scenedesmus *spp*. can be determined as follows:

$$A_{ORP\_Scenedesmus}(m^2) = \frac{\dot{m}_{HCO3(\frac{kg}{h})} * 0.7}{P_B(\text{kg/m2/h}) * 3.22(\frac{kg}{kg})} \quad (2)$$

$$V_{ORP\_Scenedesmus} = \frac{P_{B\_Scenedesmus}\, t_B * A_{ORP\_Scenedesmus}}{(C_{X\ t=t_B} - C_{X\ t=0})} \quad (3)$$

9.2.5.3 Energy consumption for the cultivation of algae

There are two energy components involved in the cultivation process a) light energy consumed for photosynthesis reaction to occur and b) auxiliary energy consumed for running the paddles, for CO_2 delivery, for water pumping in cultivation unit.

Based on the stoichiometric equations, the energy (light energy) required for the biochemical reaction is computed using the ASPEN Plus® software. As per assumption 6, all light energy is supplied by natural sunlight. The required light conversion efficiency (LCE) is calculated using the literature data on solar flux, $E_{Solar\ flux}$ of Eastern India (5-30Wh/m^2/d), and required energy per unit time ($\dot{E}_R$) for the biochemical conversion, as calculated from the ASPEN Plus®. LCE for Scenedesmus *spp*. can be defined as follows:

$$LCE_{Scenedesmus\ spp}\ (\%) = \frac{\dot{E}_{R,Scenedesmus\ spp} * t_b}{E_{Solar\ flux} * A_{ORP\_Scenedesmus} * t_B} * 100 \qquad (4)$$

Scenedesmus spp.

Considering $E_{Solar\ flux}$ of 5 Wh/m^2/d, $LCE(\%) = \frac{2425*3600*1000*100}{5*3600*567000*6} = 14.2$

Considering $E_{Solar\ flux}$ of $30\text{Wh/m2/d}, LCE(\%) = \frac{2425*3600*1000*1000}{30*3600*590270*6} = 2.37$

The stirring energy is calculated using literature data, keeping the power per unit volume (P/V) constant [McCabe]. The value of P/V, as reported in the literature is 0.02kWh/m^3/d [14, 16]. The power consumption for stirring is calculated by multiplying P/V by the present reactor volume. The energy consumption for CO_2 delivery/pumping i.e. BkW of CO_2 delivery pump is calculated by ASPEN Plus®. The energy consumption for water pumping in cultivation unit i.e. BkW of water supply pump is also calculated by ASPEN Plus®.

9.2.6 Energy and environmental analysis

The energy and CO_2 emissions components used for the Energy Return on Energy Investment (*EROEI*) and Avoidance in CO_2 Emissions (*ACE*) are schematically explained in the following Figure 9.3a, and 9.3b schematic diagram

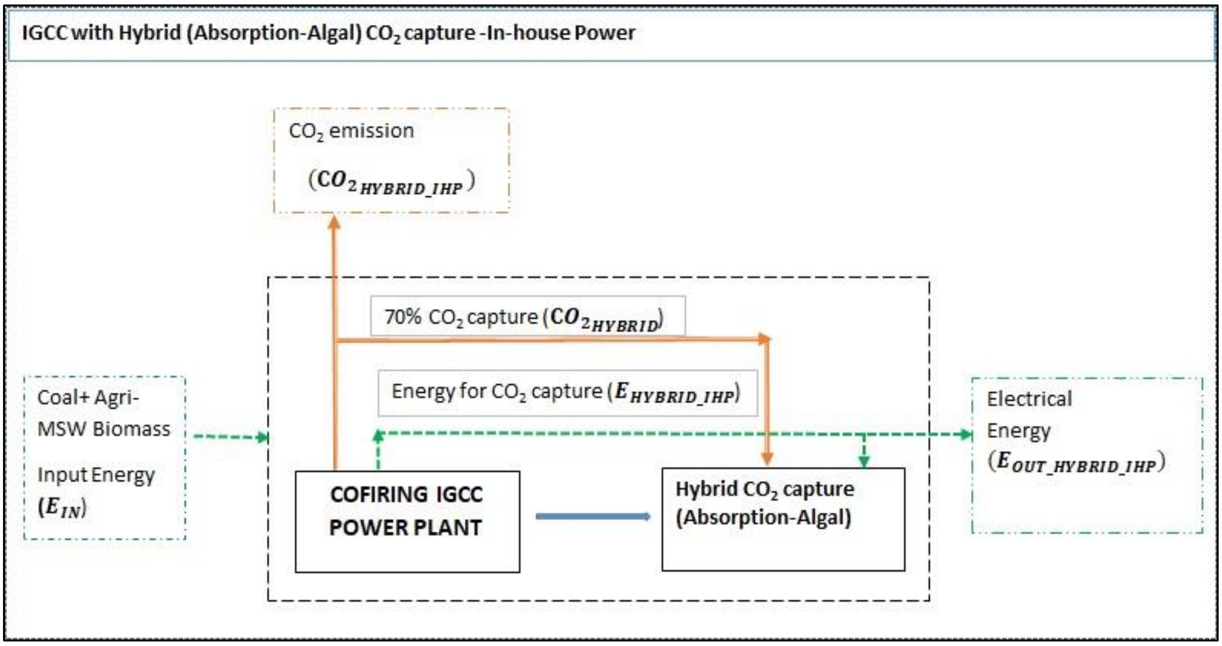


Figure 9.3a Schematic diagram of the energy and CO_2 emissions for Cofiring IGCC Power Plant and CO_2 capture by Hybrid Process considering the use of in-house power

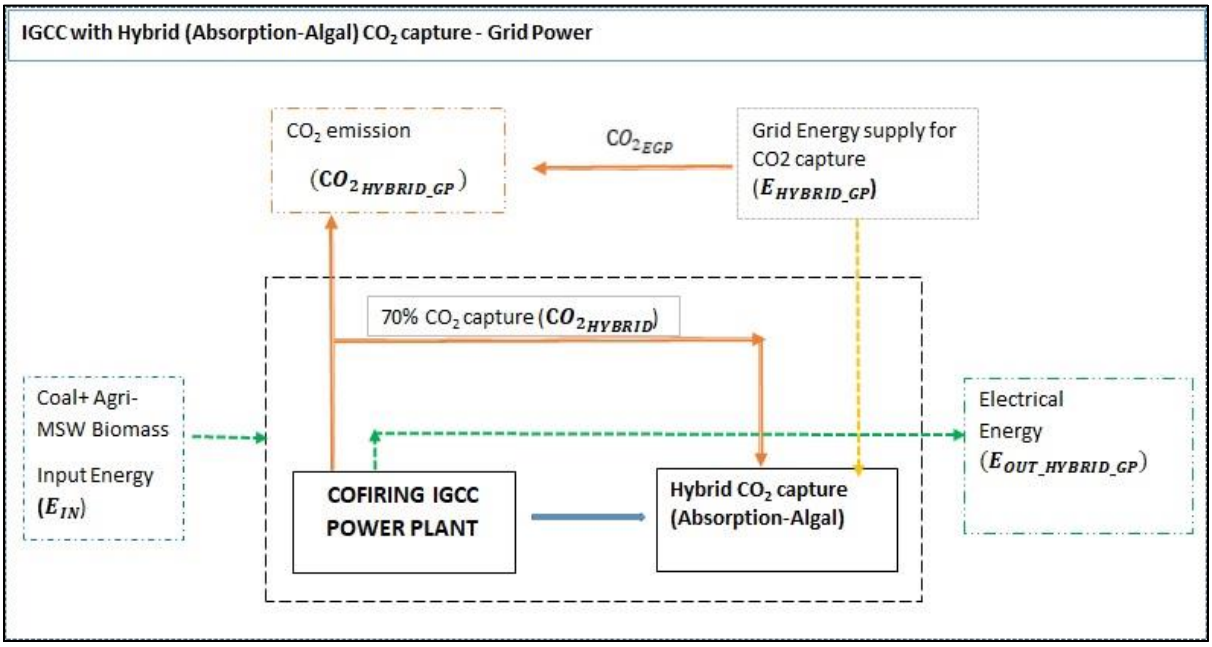


Figure 9.3b Schematic diagram of the energy and CO_2 emissions for Cofiring IGCC Power Plant and CO_2 capture by Hybrid Process considering the use of grid power

9.2.6.1 Energy Return on Energy Investment (*EROEI*) for standalone CO_2 absorption system

Based on the simulation results using the ASPEN Plus®**,** the energy return on energy investment (*EROEI*) for the IGCC plant with and without CO_2 capture using hybrid process have been calculated.

EROEI without CO_2 capture ($EROEI_{WCC}$) has been calculated as follows:

$$EROEI_{WCC} = \frac{\text{Energy return from cofired IGCC plant } (ER_{wcc})}{\text{Energy Inpu of Cofired IGCC plant } (EI_{IGCC})} * 100 \quad (5)$$

During the calculation of *EROEI* with CO_2 capture by hybrid process, $EROEI_{HYBRID}$, the total energy requirement, E_{HYBRID}, has been calculated. E_{HYBRID} includes the, pumping energy for the CO_2 delivery, $E_{CO2\ blower}$, the energy consumption for the generation of algae through the photosynthesis reaction, E_R, stirring energy utilized in the ORP, $E_{stirrer}$, pumping energy for the water supply, $E_{water\ pump}$,. The values of $EROEI_{HYBRID}$ have been calculated for two possible cases, I: E_{HYBRID} is derived from the in-house energy generated by the IGCC plant ; II: E_{HYBRID} is derived from the grid. The *EROEI* for case-I, and case-II are designated by E_{HYBRID_IHP}, and E_{HYBRID_GP}, The definitions of E_{HYBRID_IHP} and E_{HYBRID_GP} are as follows

$$E_{HYBRID}=E_{CO2\ blower} + E_R + E_{stirrer} + E_{water\ pump} \quad (6)$$

Energy consumption for the generation of algae through the photosynthesis reaction, E_R, is supplied neither from in-house power nor grid power. Sunlight is providing the energyE_R. Therefore, E_R has not been considered in E_{CCAL} for determination of $EROEI_{CCAL}$.

Therefore,

$$E_{CCAL}=E_{CO2\ blower}+E_{stirrer}+ E_{water\ pump} \quad (7)$$

EROEI for Absorption-microalgae hybrid CO_2 capture considering use of in-house power ($EROEI_{HYBRID\_IHP}$) has been calculated as follows

$$EROEI_{HYBRID\_IHP} = \frac{\text{Energy output from cofired IGCC plant} - \text{Energy requirement for } CO_2 \text{ capture through absorption} - \text{microalgae hybrid process}}{\text{Energy Input of Cofired IGCC plant}} *100 \quad (8)$$

EROEI for Absorption-microalgae hybrid CO_2 capture considering use of grid power ($EROEI_{HYBRID\_GP}$) has been calculated as follows

$$EROEI_{HYBRID\_GP} = \frac{\text{Energy output from cofired IGCC plant}}{\text{Energy Input of Cofired IGCC plant} + \text{Energy supply from grid for } CO_2 \text{ capture through absorption} - \text{microalgae hybrid process}} * 100 \quad (9)$$

9.2.6.2 Avoidance in CO_2 Emissions (*ACE*) for) for Absorption-microalgae hybrid CO_2 capture

For the IGCC power plant with CO_2 capture through absorption-microalgae hybrid system, total CO_2 emissions avoidance has been calculated considering use of in-house power as follows:

$$\begin{aligned}&\text{Total } CO_2 \text{ emission avoidance for the IGCC power cofired power plant with } CO_2 \text{ capture}\\&= \text{Plant emission avoidance due to switching over from coal fired to Cofired IGCC mode}\\&+ CO_2 \text{ consumed during the production of Agri\_MSW Biomass } (\text{ACE}_{MSWBPH})\\&+ \text{CO2 captured by Absorption algae hybrid system } (\text{ACE}_{HYBRID})\end{aligned} \quad (10)$$

The calculation of ACE for the IGCC power plant with CO_2 capture through absorption-microalgae hybrid system (ACE_{HYBRID_IHP}) use of in-house power.

$$ACE_{CCABSR\_WOS\_GP} = \frac{\text{Total } CO_2 \text{ emission avoidance for the IGCC power cofired power plant with } CO_2 \text{ capture hybrid system use inhouse power}}{CO_2 \text{ emission from coal plant}} * 100 \quad (11)$$

For the IGCC power plant with CO_2 capture through absorption-microalgae hybrid system, total CO_2 emissions avoidance has been calculated considering use of of grid power as follows:

$$\begin{aligned}&\text{Total } CO_2 \text{ emission avoidance for the IGCC power cofired power plant with } CO_2 \text{ capture}\\&= \text{Plant emission avoidance due to switching over from coal fired to Cofired IGCC mode}\\&+ CO_2 \text{ consumed during the production of Agri\_MSW Biomass } (\text{ACE}_{MSWBPH})\\&+ \text{CO2 captured by absorption}_{\text{microalgae}} \text{ hybrid system } \left(ACE_{\ HYBRID}\right)\\&- CO_2 \text{emission due to grid power requirement for } CO_2 \text{ capture by hybrid system} \left({CO_2}_{EGP}\right)\end{aligned} \quad (12)$$

The calculation of ACE for the IGCC power plant with CO_2 capture through absorption-microalgae hybrid system (ACE_{HYBRID_GP}) use of grid power.

$$ACE_{HYBRID\_GP} = \frac{\text{Total } CO_2 \text{ emission avoidance for the IGCC power cofired power plant with } CO_2 \text{ capture hybrid system use grid power}}{CO_2 \text{ emission from coal plant}} * 100 \quad (13)$$

CO_2 emissions due to the use of grid power (${CO_2}_{EGP}$), supplied for CO2 capture by algae process, has been calculated with due consideration of distribution losses of around 5%[28]. Therefore, ${CO_2}_{EGP}$ can be defined as follows:

$${CO_2}_{EGP} = \text{Total power demand for } CO_2 \text{ capture by algae culture process} * 1.05 * CO_2 \text{ emissions factor } \left(\frac{\text{kg}}{\text{kWh}}\right) \quad (14)$$

Where, CO_2 emissions factor signifies the CO_2 emissions per unit energy generated by a coal-fired power plant. The value of CO_2 emissions factor is 0.95kg/kWh for conventional Indian power plant [29].

Therefore,

$$CO_{2_{EGP}} = 1.05 * E_{CCAL} * 0.95 \quad (15)$$

9.3 Results and discussion

9.3.1 Energy demand for Absorption-microalgae hybrid CO_2 capture process

In the process of CO_2 capture by absorption-microalgae hybrid method, the Aspen Plus® simulation tool shows the main energy component is that required by the photosynthesis process, occurring through the assimilation of dissolved inorganic carbon (DIC), mainly the bicarbonate (HCO_3^-). This light energy is, however, supplied by sunlight.

Table 9.8 summarizes some results with consideration of 70% CO_2 capture.

The corresponding data sheet of ASPEN Plus® has been provided in the Appendix.

Table 9.8. Results of Absorption & microalgae cultivation hybrid process

Variable	Unit	Value	%
Rate of Electricity consumption for CO_2 delivery by blower & auxiliaries for Absorption unit, $E_{CO2\ blower}$	kW	87.2	3.2
Rate of Light Eenrgy consumption for photosynthesis of cultivation unit E_R	kW	2425	90.1
Rate of Electricity consumption in cultivation by paddle wheel, $E_{stirrer}$	kW	142	5.3
Rate of Electricity consumption for water pumping in cultivation unit$E_{water\ pump}$	kW	37.3	1.4
Rate of Total Energy consumption	kW	2691.5	

9.3.2 Study on EROEI for Absorption-microalgae hybrid CO_2 capture process

Energy return on energy investment (*EROEI)* has been compared for 70 % CO_2 capture from the 30 TPD co-fired IGCC plant with CO_2 capture by solvent absorption ($EROEI_{ABBSR\_WS}$), algal CO_2 capture ($EROEI_{CCAL}$), and Absorption-Algal Hybrid CO_2 capture ($EROEI_{HYBRID}$)

considering use of in-house power and grid power, as shown in Figure 9.4. From Figure 9.4, it can be inferred that the $EROEI_{HYBRID)}$ is the highest and $EROEI_{ABBSR\_WS)}$ is the lowest among all three CO_2 capture plant integrated with IGCC power plant considering the use of in-house power. It can also be reported that considering the use of grid power, the $EROEI_{HYBRID)}$is the highest, and $EROEI_{ABBSR\_WS)}$ is the lowest among all three CO_2 capture plants integrated with IGCC power plant. From the result, it can be inferred that the energy penalty of CO_2 capture can be minimized by using Absorption-algal hybrid system.

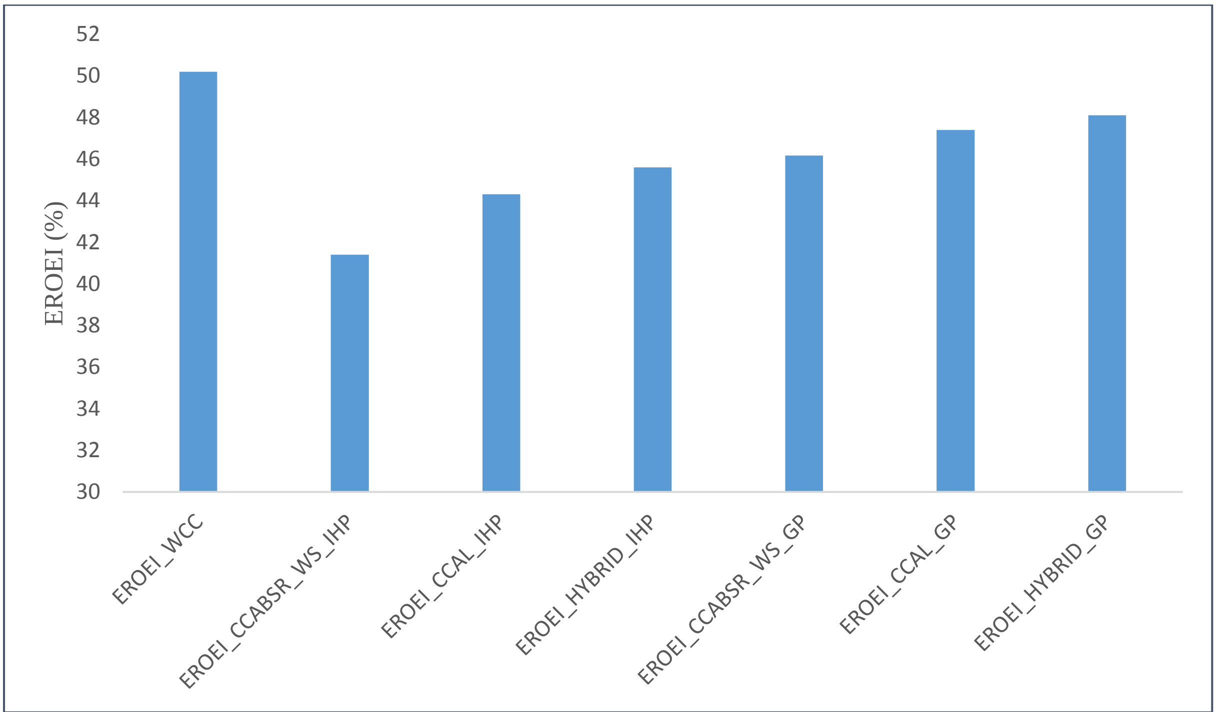


Figure 9.4. **Comparison of EROEI of 30 TPD cofired IGCC plant with CO_2 capture by three different CO_2 capture plant**

Energy return on energy investment ($EROEI_{HYBRID}$) has been calculated using the data generated by ASPEN Plus®. The sample calculations and the ASPEN Plus® data are provided in the Appendix of this Chapter.

9.3.3 Study on ACE for Absorption-microalgae hybrid CO_2 capture process

Avoidance in CO_2 emissions (*ACE)* has been studied for 70 % of CO_2 capture of 30 TPD co-fired IGCC plant with CO_2 capture by solvent absorption ($ACE_{ABBSR\_WS)}$, algal CO_2 capture ($ACE_{CCAL)}$,, and Absorption-Algal Hybrid CO_2 capture ($ACE_{HYBRID)}$ considering use of only grid power as shown in Figure 9.5. As the ACE for all three CO2 capture system are the same when the use of in-house power is considered. Therefore the values of ACE for three CO2 capture plants considering the use of grid power have been compared. From Figure 9.5, it can be inferred that the $ACE_{HYBRID)}$ is the highest and $ACE_{ABBSR\_WS)}$ is the lowest among all three CO_2 capture plant integrated with IGCC power plant considering the use of grid power. This variation of ACE is only due to CO_2 emissions due to grid power requirement for CO_2 capture of individual CO2 capture plant

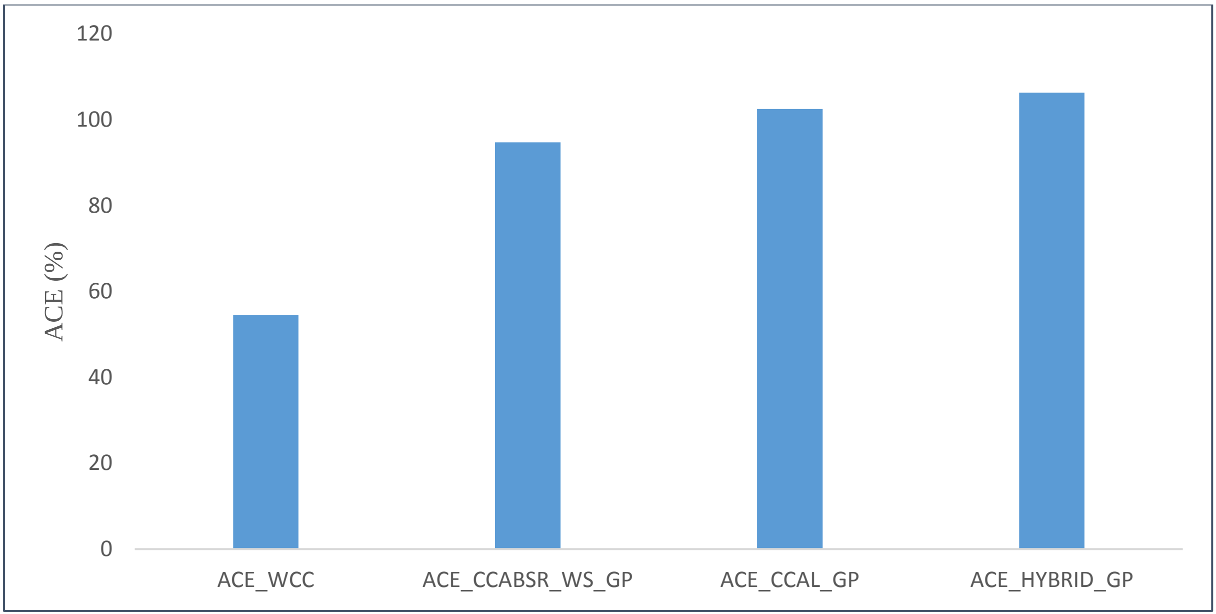


Figure 9.5. Comparison of Avoidance in CO_2 emissions (ACE) of 30 TPD cofired IGCC plant with CO_2 capture by three different CO_2 capture plant

Avoidance in CO_2 emissions has been analyzed for the above plant using the data generated by ASPEN Plus®. The calculations and the data are provided in the Appendix of this chapter.

Conclusion

Overall, it can be inferred that both EROEI and ACE values are improved over solvent-based and algal CO_2 capture if the hybrid system is used. Under this strategy for hybrid system, although the solvent can be regenerated, for the recovery of algal biomass, additional harvesting and de-watering energy have to be spent.

9.4 References

[1] Zemin Tu1, Liangting Liu1, Weitie Lin1, Zhangzhang Xie, Jianfei Luo. 2018. Potential of using sodium bicarbonate as external carbon source to cultivate microalga in non-sterile condition, Bioresource Technology, 266 , pp.109–115

[2] Bruna Barcelos Cardias, Michele Greque de Morais, Jorge Alberto Vieira Costa. CO2 conversion by the integration of biological and chemical methods: Spirulina sp. LEB 18 cultivation with diethanolamine and potassium carbonate addition, Bioresource Technology

[3] Gabriel Martins da Rosa, Luiza Moraes, Bruna Barcelos Cardias, Michele da Rosa Andrade Zimmermann de Souza, Jorge Alberto Vieira Costa. 2015. Chemical absorption and CO2 biofixation via the cultivation of Spirulina in semicontinuous mode with nutrient recycle, Bioresource Technology, 192, pp.321–327

[4] Garam Kim, Wookjin Choi, Chang-Hee Lee, Kisay Lee. 2013. Enhancement of dissolved inorganic carbon and carbon fixation by green alga Scenedesmus sp. in the presence of alkanolamine CO2 absorbents, Biochemical Engineering Journal, 78, pp.18– 23

[5] Zhanyou Chi , Yuxiao Xie , Farah Elloy , Yubin Zheng , Yucai Hu, Shulin Chen. 2013. Bicarbonate-based Integrated Carbon Capture and Algae Production System with alkalihalophilic cyanobacterium, Bioresource Technology, 133, pp. 513–521

[6] Choi, W., Kim, G., Lee, K., 2012. Influence of the CO2 absorbent monoethanolamine on growth and carbon fixation by the green alga Scenedesmus sp. Bioresour. Technol. 120, pp. 295–299.

[7] Choi, W., Kim, G., Lee, K., 2012. Influence of the CO2 absorbent monoethanolamine on growth and carbon fixation by the green alga Scenedesmus sp. Bioresour. Technol. 120, 295–299.

[8] Bo Yang, Yi-MingWei, Lan-Cui Liue, Yun-Bing Hou , Kun Zhang, Lai Yang, Ye Feng. 2021. Life cycle cost assessment of biomass co-firing power plants with CO2 capture and storage considering multiple incentives, Energy Economics, 96, pp. 105173

[9] Woo-Sung Lee , Hyun-Taek Oh, Jae-Cheol Lee, Min Oh, Chang-Ha Lee. 2019. Performance analysis and carbon reduction assessment of an integrated syngas purification process for the co-production of hydrogen and power in an integrated gasification combined cycle plant, Energy, 171, pp. 910-927

[10] NETL. Cost and performance baseline for fossil energy plants. Volume 3b: Low rank coal to electricity: Combustion cases. DOE/NETL-2011/1463; March 2011

[11] Lars Erik Øia, Stian Holst Pedersen Kvama, Energy Procedia. 2014, 63, 18–26. DOI:10.1016/j.egypro.2014.11.003

[12] de Morais MG; Costa JAV, 2007. Biofixation of carbon dioxide by Spirulina sp. and Scenedesmus obliquus cultivated in a three-stage serial tubular photobioreactor. Journal of biotechnology. 129, pp. 439-445.

[13] Adamczyk M; Lasek J; Skawińska A, 2016.CO2 Biofixation and Growth Kinetics of Chlorella vulgaris and Nannochloropsis gaditana. Applied Biochemistry and Biotechnology, 179, pp. 1248-1261

[14] Ryan Davis, Jennifer Markham, Christopher Kinchin, Nicholas Grundl, and Eric C.D. Tan, Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion, *National Renewable Energy Laboratory.*

[15] Vincenzo Piemontea, Luisa Di Paolaa, Alessio Gentileb, Barbara Masciocchib,Valentina Russoa, Gaetano Iaquanielloc, Biodiesel Production from Microalgae: Ionic Liquid Process Simulation,

[16] *Geetanjali Yadav, Brajesh K Dubey, Ramkrishna Sen,* A comparative life cycle assessment of microalgae production by CO2 sequestration from flue gas in outdoor raceway ponds under batch and semi-continuous regime, https://doi.org/10.1016/j.jclepro.2020.120703

[17] Sukumar Roy, Snigdha Pal, Nabajit Chakravarty. 2016. Global solar radiation characteristics at Dumdum (West Bengal), Indian Journal of Radio & Space Physics, 45, pp. 148-153

APPENDIX_Chapter 9

Table A.9.1 ASPEN Plus® generated data and the Calculation $of\ (EROEI_{HYBRID})$ of IGCC Co-fired power plant with CO_2 capture using hybrid

Total energy demand for CO_2 capture through hybrid (E_{HYBRID})i.e. $(E_{CO2\ delivery} + (E_{puddile\ wheel}) + (E_{water\ delivery})$	kw	87+142+37.3 =266.3
EROEI with CO_2 capture using hybrid system ($EROEI_{HYBRID\_IHP}$) has been calculated consideration of use of in-house power as per eqn. (4) $EROEI_{HYBRID\_IHP} = \frac{\text{Energy output from cofired IGCC plant} - \text{Energy demand for } CO_2 \text{ capture through hybrid process}}{\text{Energy Input of Cofired IGCC plant}} * 100$		
EROEI with CO_2 capture using hybrid system ($EROEI_{HYBRID\_IHP}$)	%	$\frac{2922 - 266.3}{5815} \times 100$ =45.6
EROEI with CO_2 capture using hybrid system ($EROEI_{HYBRID\_GP}$) has been calculated consideration of use of grid power as per eqn. (5) $EROEI_{HYBRID\_GP} = \frac{\text{Energy output from cofired IGCC plants}}{\text{Energy Input of Cofired IGCC plant} + \text{Energy demand for } CO_2 \text{ capture through hybrid proces}} * 100$		
EROEI with CO_2 capture using hybrid system ($EROEI_{HYBRID\_GP}$)	%	$\frac{2922}{5815 + 266.3} \times 100$ =48.1

Table A.9.2 ASPEN Plus® generated data and the Calculation $of\ (ACE_{CHYBRID})$ of IGCC Co-fired power plant with CO_2 capture using hybrid system

Total CO_2 emissions for IGCC co-fired plant with CO_2 capture by hybrid system considering use of in-house power calculated as per eq. no. 19	kg/hr	170+985.42+1365 =2520.42
ACE for the IGCC power plant with CO_2 capture by hybrid system (ACE_{HYBRID_IHP})as per eqn.(18) of manuscript considering use of in-house power $ACE_{HYBRID\_IHP} = \frac{\text{Total } CO_2 \text{ emissions avoidance for the IGCC plant with } CO_2 \text{ capture by hybrid system considering use of in} - \text{house power}}{CO_2 \text{ emissions from coal plant}} * 100$		
ACE_{HYBRID_IHP}	%	$\frac{2520.42}{2120} \times 100$ =118.8
CO_2 emissions due to energy supplied from grid power i.e. 1.05*0.95* Energy demand for CO2 capture by hybrid system as per eq. no. 16	Kg/hr	1.05*0.95*266.3= 265.6
Total CO_2 emissions avoidance for IGCC co-fired plant with CO_2 capture by hybrid system considering use of grid power has been calculated as per eq. no. 13	kg/hr	170+985.42+1755-265.6 =2254.82
ACE for the IGCC power plant with CO_2 capture (ACE_{HYBRID_GP}) by hybrid system as per eqn. 12 of manuscript considering use of grid power $ACE_{HYBRID\_GP} = \frac{\text{Total } CO_2 \text{ emissions avoidance for the IGCC plant with } CO_2 \text{ capture by hybrid system considering use of grid power}}{CO_2 \text{ emissions from coal plant}} * 100$		
ACE_{HYBRID_GP}	%	$\frac{2254.82}{2120} \times 100$ =106.3

CHAPTER 10

CONCLUSIONS

To assess the energy and environmental impacts of the combining agricultural and MSW derived lignocellulosic biomass with coal in the Indian power sector, the present research was focused on the following topics: (I) optimization and energy and environmental analysis of an IGCC power plant co-fed with mixture of Indian coal and Agri-MSW-based biomass; (II) optimization and energy and environmental analysis of the mixed-fuel IGCC plant integrated with CO_2 capture through absorption using solvent; (III) design of algal CO_2 capture and utilization system for the mixed-fuel IGCC plant and energy and environmental analysis of the integrated system; (IV) energy and environmental analysis of the mixed-fuel IGCC plant integrated with algal CO_2 capture and biodiesel production. (V) energy and environmental analysis of for the mixed-fuel IGCC plant integrated with hybrid system of solvent based CO_2 capture and algal CO_2 and utilization. The following conclusions can be drawn on different topics (I-V):

Topic I

- A systematic process model using ASPEN Plus® has been developed for a 30 TPD IGCC power plant co-fired by Indian coal and Agri-MSW-biomass mixture.
- Analyzed the parametric sensitivity of Energy Return on Energy Investment (EROEI) and avoidance in CO2 emissions (ACE) of the above plant with respect to the input variables, Agri-MSW -coal ratio, gasifier temperature and the ratio of supplied air to that required for complete combustion. The values of EROEI and ACE have been calculated using ASPEN Plus® simulation data obtained at the pre-determined set of values of input variables decided through the design of experiments using Box-Behnken design of experiments (DOE) method.
- Obtained second order polynomial equations with respect to input variables for both the responses, i.e. EROEI and ACE through Response surface methodology.
- Optimization of EROEI and ACE the Co-fired IGCC power plant has been performed using Design Expert software. For the values of Gasifier temperature = 900oC; Agri-MSW Biomass-coal ratio of 1:1, and the supplied air flow rate =20% of air flowrate required for complete combustion, the optimum values of EROEI of 50.2% and ACE of 54.5% have been obtained.

Topic II

- A systematic process model using ASPEN Plus® has been developed for the optimally operated 30 TPD IGCC power plant co-fired by Indian coal and Agri-MSW-biomass mixture, integrated with MEA-based post-combustion CO_2 capture with and without regeneration of solvent.
- Studied the effect of individual process parameters i.e. CO2 loading in lean amine solution; amine concentration; solvent temperature on CO2 absorption. With the increase of solvent loading and in turn, with the decrease in CO2 loading in the lean amine solution and with the increase in temperature there is an increase the CO2 capture.
- Analyzed the parametric sensitivity of Energy Return on Energy Investment (EROEI) with regeneration of solvent and CO2 capture of the above plant with respect to CO2 loading in lean amine solution; amine concentration; solvent temperature. The values of EROEI and CO2 capture have been calculated using ASPEN Plus® simulation data obtained at the pre-determined set of values of input variables decided through the design of experiments using Box-Behnken DOE method. The analysis has been performed considering the in-house energy consumption for CO2 capture.
- Obtained second order polynomial equations with respect to input variables for both the responses, i.e. EROEI and CO2 capture through Response surface methodology.
- Optimization of EROEI and CO2 capture of the Co-fired IGCC power plant, integrated with MEA-based post-combustion CO2 capture with solvent regeneration, has been performed using Design Expert software. The Optimization has been performed considering the in-house energy consumption for CO2 capture. For the solvent temperature = 30oC; solvent concentration = 22 wt% and lean loading of solvent = 0.15 are required to capture the CO2 of 90%. The optimum values of EROEI of 40% and CO2 capture of 90% have been obtained. Considering in-house power.
- Energy return on energy investment (*EROEI)* has been calculated at 90 % CO_2 capture of 30 TPD co-fired IGCC plant with and without solvent regeneration considering the use of a) in-house power and b) grid power. With solvent regeneration facility, EROEI of the above plant has decreased to 39.3 % and 45.3%

with respect to 50.2 %, obtained for the original IGCC plant when in-house and grid power consumption for the CO_2 capture unit has been considered respectively. EROEI of the IGCC plant integrated with CO2 capture by solvent absorption without solvent regeneration, has decreased to 48.75 %, and 49.5% considering the use of in-house power and grid power respectively.

- The values of ACE have been calculated at 90 % of CO_2 capture for the 30 TPD co-fired IGCC plant with and without solvent regeneration considering the use of a) in-house power and b) grid power. With solvent regeneration, the values of ACE of 137% and 111.8% have been obtained when in-house and grid power consumption is considered respectively. In the case of CO_2 capture without solvent regeneration, the values of ACE of 137% and 133.7% have been obtained when in-house and grid power consumption is considered respectively. This drop in ACE in case of grid power consumption is due to CO_2 emissionss for the use of the grid power.

Topics III and IV

- Design of algal CO_2 capture and utilization system for the mixed-fuel 30 TPD IGCC plant, separately using three algal strains, *Chlorella Vulgaris*, *Nannochloropsi*s *spp* and *Scenedesmus* has been carried out. The energy and environmental analysis of the integrated system, based on each algal strain, has been performed for the first time based on process modeling using ASPEN Plus®.

- Studied the CO_2 fixation, algal biomass productivity, and energy demand for algal CO2 capture using three algal strains *Chlorella Vulgaris*, *Nannochloropsi*s *spp* and *Scenedesmus* integrated with a 30 TPD co-fired IGCC power plant. *Scenedesmus spp.* producing the highest quantity of biomass, require the largest volume of open raceway pond. among the three algal strains. The energy consumption for the generation of algae through the photosynthesis reaction, E_R of algal culture process has also been calculated by the ASPEN Plus. The higher value of E_R for *Nannochloropsi*s *spp* is required compared to the other two microalgae i.e. *Chlorella Vulgaris*, and *Scenedesmus spp* due to the high weight fraction of carbon in *Nannochloropsi*s *spp* . The light conversion efficiency (LCE) has been calculated based on E_R for each algal strain, area of open raceway pond and insolation (i.e., solar flux). Value of LCE for *Nannochloropsi*s *spp* is the highest among others. The energy required for photosynthesis is assumed to be derived from solar energy, the high value of E_R is not reflected in the overall energy demand. The total energy demand for algal CO_2 capture is also the highest for *Scenedesmus* compared to other algal strains.

- Energy return on energy investment (*EROEI)* has been calculated for the 30 TPD co-fired IGCC plant integrated with algal CO2 capture considering the use of a) in-house power and b) grid power for each algal species. When in-house power is utilized for CO2 capture, the values of EROEI become 44.5 %, 44.7% and 44.3% respectively for *Chlorella vulgaris, Nannochloropsi*s *spp* and Scenedesmus *spp*. compared to 50.2% for the original IGCC plant. It has been observed that there is an increase of EROEI by about 3% for the integrated system using any one of the three algae when the use of grid power is considered.

- The values of ACE have been calculated for the 30 TPD co-fired IGCC plant integrated with algal CO2 capture considering the use of a) in-house power and b) grid power for each algal species. When in-house power is utilized for CO2 capture, the values of ACE become 118.8 %, for *Chlorella vulgaris, Nannochloropsi*s *spp* and Scenedesmus *spp*. each compared to 54.5% for the original IGCC plant. It has been observed that there is a decrease of ACE by about 15% for the integrated system using any one of the three algae when the use of grid power is considered

- Studied the energy demand for biodiesel production from algae using three algal strains *Chlorella Vulgaris*, *Nannochloropsi*s *spp* and *Scenedesmus* combined with the above integrated system of IGCC plant and algal CO2 capture. The energy demand for the overall system is the highest for *Nannochloropsi*s *spp,,*. The system using *Nannochloropsi*s *spp,,*. also produces the highest quantity of biodiesel among the three due to the highest lipid content (40 wt%) of the algal biomass of this strain.

- Evaluated the EROEI for IGCC plant integrated with algal CO_2 capture and biodiesel unit using in-house power and it has been observed that EROEI values increase from 50.2% of original IGCC to 64.6 %, 81.7%, 68.4 % for *Chlorella vulgaris, Nannochloropsi*s *spp* and Scenedesmus *spp* respectively. This is due to the consideration of substitution of a part of energy from product biodiesel. Similar to the case of integrated system of IGCC power plant and algal CO_2 capture, there is an increase of EROEI by about 3% for the integrated system using any one of the three algae when the use of grid power is considered.

- Evaluated the ACE for IGCC plant integrated with algal CO_2 capture and biodiesel unit using in-house power and it has been observed that ACE values increase from 54.5% of original IGCC to 169.6 %, 208%, 179 % for *Chlorella vulgaris, Nannochloropsi*s *spp* and Scenedesmus *spp* respectively. This is due to the consideration of substitution of a part of energy from product biodiesel. Similar to the case of integrated system of IGCC power plant and algal CO_2 capture, there is a decrease of ACE by about 30% for the integrated system using any one of the three algae when the use of grid power is considered.

Topics V

- A systematic process model using ASPEN Plus® has been developed for the first time for the optimally operated 30 TPD IGCC power plant co-fired by Indian coal and Agri-MSW-biomass mixture, integrated with hybrid system of solvent based CO_2 capture and algal CO_2 and utilization.
- Energy return on energy investment (*EROEI)* has been calculated for the 30 TPD co-fired IGCC plant integrated with a hybrid system of solvent based CO2 capture and algal CO2 and utilization. In this analysis, 70% CO_2 capture has been considered. and it has been observed that $EROEI_{HYBRID}$ is the highest among other two CO2 capture plant for both the cases i.e. considering use of in-house power and grid power.
- The values of ACE have been calculated for the same integrated system of IGCC plant and hybrid system of solvent based CO_2 capture and algal CO_2 and utilization. Similar to EROEI, the values of ACE are the highest among all three integrated systems considering the options of CO_2 capture.

The outcome of this research is expected to be useful in taking strategic decisions on running IGCC power plants using a combination of coal and Agri-MSW based biomass as feed. It is expected that the assessment of performance of energy return and CO_2 avoidance of different CO_2 capture and utilization units will further facilitate the implementation of the plan of Government of India to use biomass along with coal in the power generation sector. However, there are further scopes for research in this area for the ultimate integration of biomass with coal for energy generation.

The present research study has thoroughly assessed the energy and environmental performance of stand-alone IGCC power plants co-fired with a particular Indian biomass and coal and integrated systems of IGCC plant and CO_2 capture and utilization facilities. on the basis of process modeling and simulated data,. Although it is expected that a preliminary roadmap on the combined utilization of biomass and coal can be drawn using the outcome of the knowledge-base generated through this research study, further research studies should be conducted to generate more insights in the following areas:

1. The techno-economic viability of the different integrated systems, studied under this research, should be tested.
2. Pilot-plant studies should be conducted using coal and different Indian biomass mixture for power generation through IGCC route.
3. Life-cycle analysis should be conducted for the power plants co-fired by coal and biomass and integrated with different CO_2 capture and utilization facilities.
4. The scope for polygeneration should be explored to popularize the low carbon power generation using a biomass-coal cocktail.

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Parametric Sensitivity of Municipal Solid Waste Integrated Power Plant: CO_2 Footprint and Energy Analysis

The performance of an integrated gasification combined cycle based power plant using a mixture of municipal solid waste (MSW) and coal was evaluated. The parametric sensitivities of avoidance in CO_2 emission (ACE) and the energy return on energy investment (EROEI) were analyzed by MSW-coal ratio, gasifier temperature, and the air supplied for gasification as the independent variables. The data on ACE and EROEI simulated by Aspen Plus at different combinations of input parameters, pre-set using the Box-Behnken type design of experiments, were employed. Through response surface methodology, a valid model demonstrating the strong influence of MSW-coal ratio and gasifier temperature on both the ACE and EROEI was developed.

Keywords: Carbon footprint reduction, Municipal solid waste, Power plant, Process simulation, Response surface methodology

Supporting Information available online

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1 Introduction

Current global energy supply is to a large extent based on fossil fuels (oil, natural gas, coal), of which the reserves are finite [1]. Given the growing world population, the increasing energy consumption per capita and the evidence of global warming, the necessity for long-term alternative energy sources is obvious. For these twin crises of fossil fuel depletion and environmental degradation, energy planning and technology improvement has become an important public agenda of most developed and developing countries. Biomass is a promising eco-friendly alternative source of renewable energy [2–5] in the context of current energy scenarios. It is also regarded as being both CO_2-neutral and multifaceted in its application [6, 7].

The IPCC (Intergovernmental Panel on Climate Change) has identified six anthropogenic gases with climate change potential, i.e., CO_2, CH_4, N_2O, SF6, chlorofluorocarbons, and hydrofluorocarbons (HFCs). CO_2 has the largest global climate change impact because its total emissions are much greater than that of others [8–11]. The main source of immobile CO_2 emissions is the power generation sector. Thus, more research efforts preventing climate change should focus on strategies for reduction of CO_2 emissions [12–14]. The substitution of coal with carbon-neutral waste biomass for power generation is one of the routes for mitigation of CO_2 emission [15–17]. Biomass co-firing also provides other benefits. It requires a lower initial investment with minor modifications compared with other lower-emission technologies [18, 19]. This is due to the fact that the most common technology used in this integration is basically gasification followed by combustion and can be incorporated in any existing coal-fired power plant.

Although agricultural residues are the major source of biomass, Indian municipal solid wastes (MSWs) are also rich in biomass. The quantity of MSW is increasing at an alarming rate in India due to rapid urbanization and high population growth [20]. The strategy of using MSW as a feedstock for co-fired power plants can open up a new direction to solve the challenges faced in handling mixed solid waste in urban and rural areas. This can also provide a way to eliminate emissions of methane and scarcity of space caused by presently practiced MSW management technology, namely, landfilling [21, 22].

Different reports are available on biomass-integrated power plants [23–26]. From the literature review, it is clear that for the purpose of efficient waste management and environmental protection the conversion of MSWs to energy, either alone or with coal, is being researched by several groups [27–45]. Electricity generation and district heating were possible using MSW incineration plants [31]. Some studies reported on the generation of electric, thermal or mechani cal energy as an alternative energy source in urban areas through the production of biogas from MSW by anaerobic digestion process [32, 35]. Biological treatment of leachate of landfill MSW, meant for establishment of a sustainable system of solid waste managemnt, was also described by a research group [33].

An Aspen Plus model of co-gasification of MSW and coal was developed for the evaluation of the potential for hydrogen

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production [34]. The co-combustion of MSW with additional fuel in a rotary kiln of cement plant was used efficiently for cement production and electricity generation [36]. Conversion of a biogenic fraction of MSW to energy was proposed to solve the waste management issue as well as the crisis of energy demand [37]. A recent publication assessed the conversion of MSW to energy using three models, namely, (i) MSW to thermal energy, (ii) MSW to electricity on 1500 MSW tons per day, and (iii) 750 MSW tons per day scales. On the basis of this assessment, electricity generation from MSW on both the scales was recommended showing the potential of energy generation and reduction of CO_2 emission [38].

A life cycle analysis (LCA) of MSW to energy through conventional gasification processes showed attractive findings with respect to environmental impacts, namely, eutrophication, acidification, marine aquatic ecotoxicity, and human toxicity potentials. Plasma gasification turned out to be more advantageous with respect to all environmental impacts. Based on the LCA analysis, MSW was projected to be a sustainable energy feedstock globally [39]. According Mazzoni et al. [42], both the integrated plasma gasification combustion cycle (IPGCC) and and the integrated gasification combustion cycle (IGCC) were established to be viable for the conversion of a mixture of petroleum coke and MSW to electricity [42].

In another report, IGCC using co-gasification of refused derived fuel (RDF) and lignite on different scales was assessed and setting up of such projects was advocated for environmental protection [45]. However, no assessment is available on such efforts using an Indian MSW-coal mixture. The main focus of this paper is to develop a process model of an IGCC plant using a mixture of Indian MSW and coal by means of the Aspen Plus engineering tool. Statistical modeling using response surface methodology was applied to analyze the parametric sensitivity on energy return and avoidance of CO_2 emission. In order to investigate the parametric sensitivity of the plant, the MSW-coal ratio, the gasifier temperature, and the ratio of supplied air to that required for complete combustion were selected as input variables.

2 Materials and Methods

2.1 Design of Experiments

A statistical model is developed under the situation where the deterministic modeling is out of question due to lack of information on the physical and thermodynamic laws correlating the response variable with the input variables of a complex system. The statistical model connects any response variable Y with the input variables, X_1, X_2, ...X_k by a function $Y = \phi(X_1, X_2, ...X_k)$. Response surface methodology is particularly suitable when the response variable is influenced by several variables and the ultimate objective is to optimize the response.

The independent variables are called factors. The space with the coordinates X_1, X_2, ...X_k is called the factorial space. The geometric portrait of the response function in the factorial space is named the response surface which may be depicted by contour diagrams. One of the most important aspects of statistical modeling is the design of experiments which is the strategy to obtain an adequate model with minimum number of experiments. In this work, the three-factor Box-Behnken design (BBD) was applied to examine the interaction effect of factors, namely, gasifier temperature (X_1), MSW-coal ratio (X_2), and the ratio of supplied air to that required for complete combustion (X_3) on response variables, namely, total CO_2 emission avoidance (Y_1) and the energy return on energy investment (Y_2).

When experiments are planned to correlate a dependent variable with multiple independent factors, the BBD under RSM, based on the evenly spaced three-level fractionate factorial principle, can be followed [46, 47]. A quadratic model is estimated by creating the experimental planning according to BBD. This design is highly rotatable and generates strong coefficients at the center of the cube. BBD does not involve corner points on the hypercube and hence the experiments under extreme conditions can be avoided without missing any adequacy of the model. As the experimental runs signifiy the investment, the BBD is more cost-effective than the plan of experiments following the central composite design (CCD) [47–50].

For the present study, the combination of independent variables was chosen following the BBD. However, the accuracy of the model is also compared with that obtained using CCD. The details of design of experiments (Tab. S1), the predicted model equations (Eqs. (S2) and (S3)), and correlation coefficients (Tabs. S2 and S3), obtained through CCD are described in the Supporting Information (SI) [42].

The values of response variables were generated using the Aspen Plus model at the conditions pre-set by the BBD of experiments. A second-degree polynomial Eq. (1) was attempted:

$$Y = A_0 + A_1X_1 + A_2X_2 + A_3X_3 + A_{12}X_1X_2 + A_{13}X_1X_3 + A_{23}X_2X_3 + A_{11}X_1^2 + A_{11}X_1^2 + A_{22}X_2^2 + A_{33}X_3^2 \quad (1)$$

The values of Y at different combinations of X_1, X_2, and X_3, pre-set by BBD of experiments were generated using Aspen Plus software. The Design Expert (Version 8.0.6, Stat-Ease Inc., Minneapolis, USA) software package was employed for experimental design, regression, and response surface analysis.

2.2 Simulation Model Development Using ASPEN Plus

The block diagram of the IGCC is displayed in Fig. 1. The process simulation model of the IGCC with a mixture of MSW and coal as feedstocks was developed by means of Aspen Plus. The simulation flow sheet for the IGCC is presented in Fig. 2.

The overall IGCC-based co-generative power plant consists of four main parts: drying, gasification by stoichiometric air, power generation by a gas turbine, and power generation by a steam turbine using steam generated through waste heat recovery. The thermochemical properties of Indian MSW and coal are given in Tab. 1.

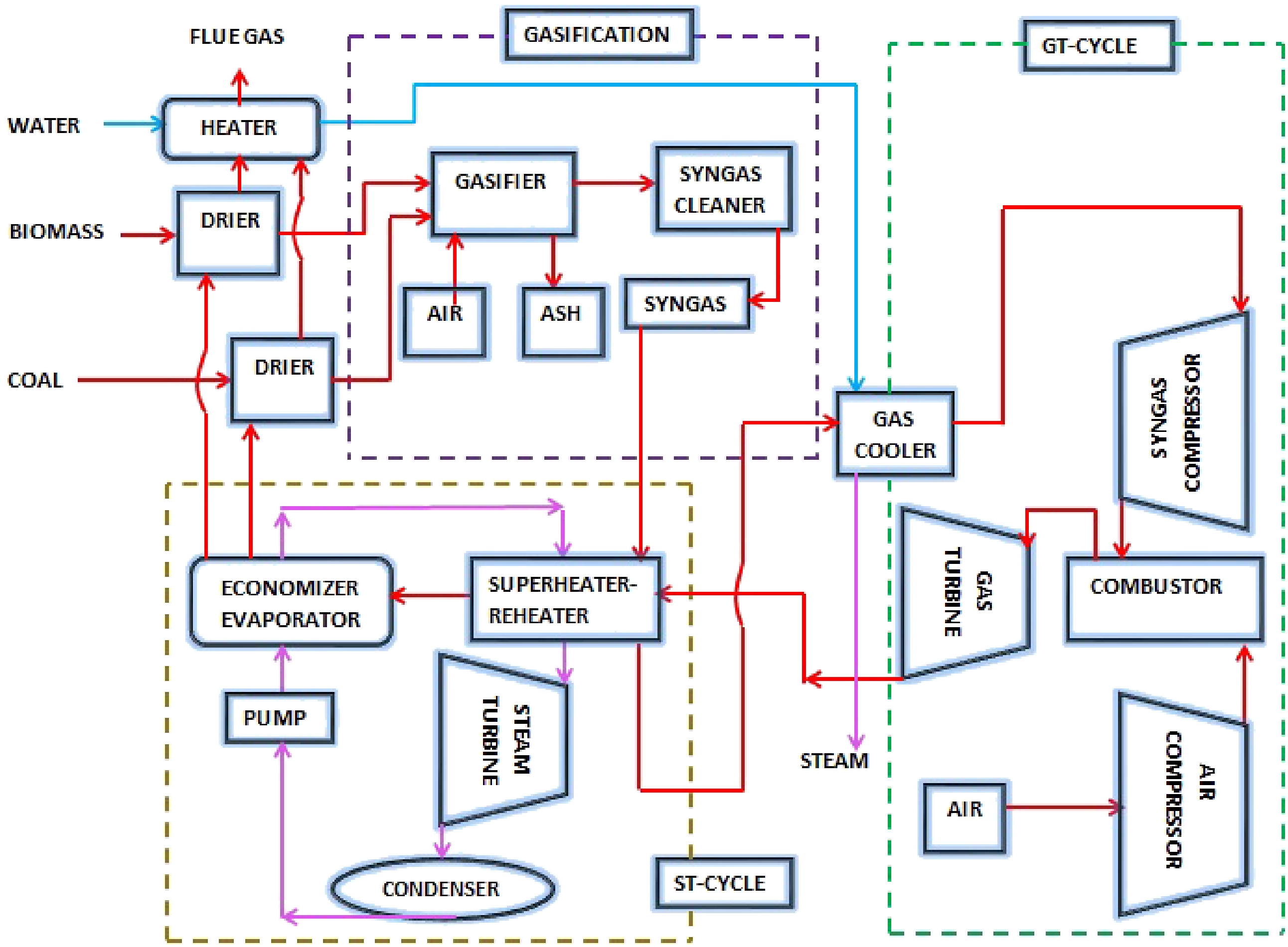

Figure 1. Block diagram of the IGCC.

2.3 Unit Operations and Processes

2.3.1 Drying

The moisture content of the MSW and coal was primarily reduced by the drying process using RStoic reactors of the Aspen Plus block. The separated water vapor was drained out from the process, and the solid stream consisting of dry MSW and coal goes on to the next unit for the decomposition of dried feed.

2.3.2 Gasification

The gasification process was modeled with two reactors. The first reactor is the decomposer reactor (RYield), which converts the non-conventional MSW and coal into conventional components including hydrogen (H_2), oxygen (O_2), carbon (C), sulfur (S), N_2, and ash by specifying the yield distribution according to the feedstock's proximate and ultimate analysis.

The outlet stream from the decomposer reactor is fed to the second reactor (RGibbs). Gasification is modeled for MSW and coal with stoichiometric air in a gasifier according to the following reactions:

Partial combustion of char

$$C + O_2 \rightleftharpoons CO_2 \tag{2}$$

Hydrogen combustion

$$2H_2 + O_2 \rightleftharpoons 2H_2O \tag{3}$$

Water gas reaction

$$C + H_2O \rightleftharpoons H_2 + CO \tag{4}$$

Boudouard reaction

$$CO_2 + C \rightleftharpoons 2CO \tag{5}$$

CO shift conversion

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \tag{6}$$

Methanation reaction

$$C + 2H_2 \rightleftharpoons CH_4 \tag{7}$$

Steam reforming of methane

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2 \tag{8}$$

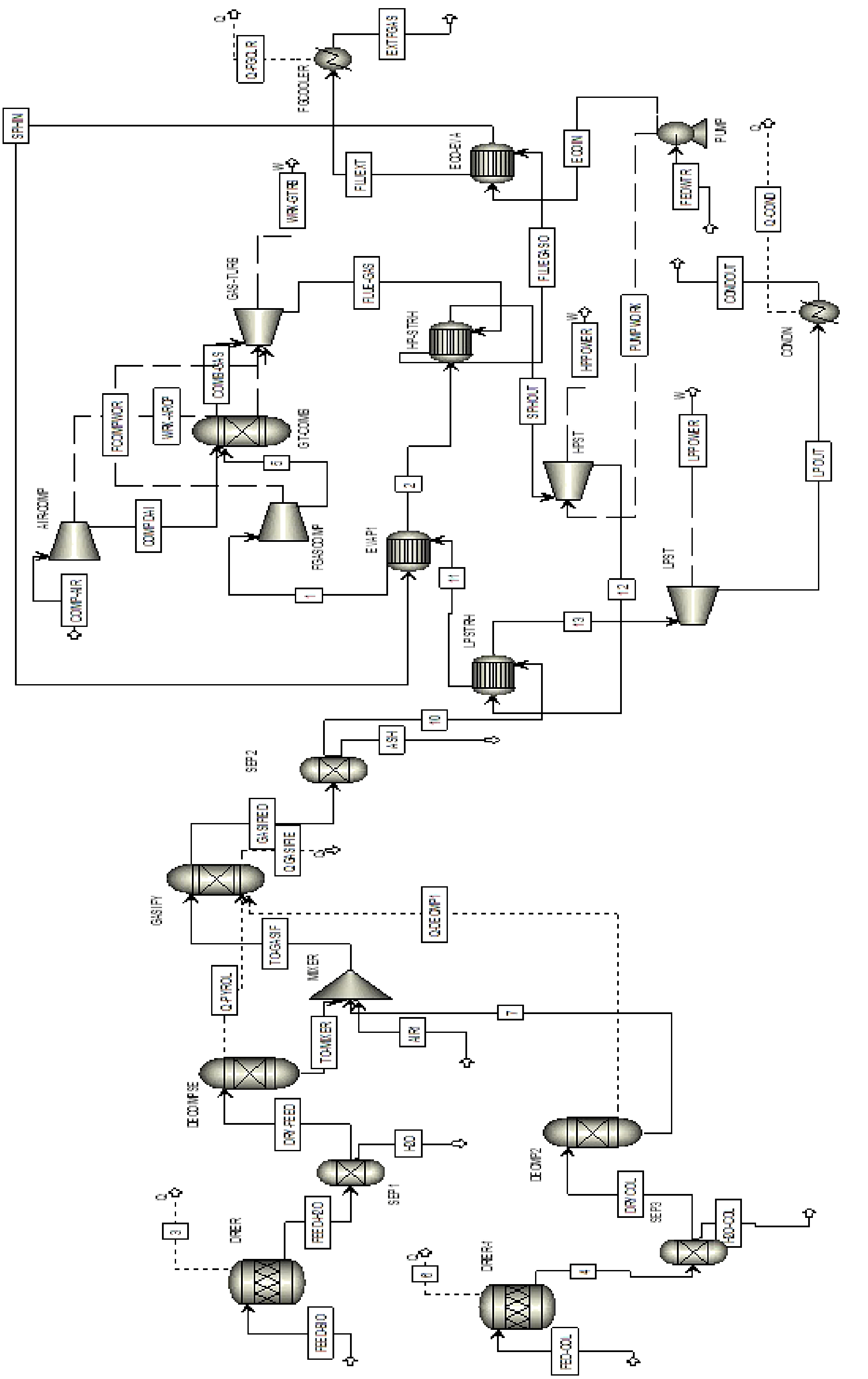

Figure 2. ASPEN Plus simulation flow sheet for the IGCC.

Table 1. Feedstock properties and their proximate and ultimate analysis.

	MSW	Coal
Proximate analysis (dry basis) [wt %]		
Volatile matter	83.1	28.7
Fixed carbon	12.4	29.1
Ash	4.5	33.2
Ultimate analysis (dry basis) [wt %]		
C	42.9	46.86
H	6.7	2.94
O	35.5	6.31
N	1.84	1.22
S	0.46	0.47
Ash	4.5	33.2
Moisture content [wt %]	8.4	9.0
Lower heating value [MJ kg^{-1}]	15.9	17.6

The outlet stream from the gasification unit is sent to the cleaning unit for removal of dust particles and ash. The clean syngas is directed to the superheater-reheater to reheat the steam in the power cycle as well as to remove NH_3 and H_2S from syngas by means of a syngas cooler for improved efficiency of the gas turbine of the combined cycle.

2.3.3 Power Generation Using Gas Turbine and Steam Turbine

The clean syngas was then utilized for power generation in a combined cycle which consists of syngas compressor, air compressor, and gas turbine. The clean syngas was fed to a combustion chamber via a syngas compressor with compressed air. In the combustion chamber, unreacted char and CO in the syngas were oxidized to flue gas by compressed air. The highly pressurized flue gas was then expanded in the gas turbine for power generation. Steam was generated in a heat recovery steam generator (HRSG), by the recovery of waste heat in the flue gas of the gas turbine.

2.4 Simulation by Aspen Plus: Physical Property Method

In the Aspen Plus model, the stream class was set as MIXCINC which represents all the streams such as MIXED, CONVENTIONAL, and NON-CONVENTIONAL. To estimate all physical properties of the conventional components for the IGCC-based co-generative power plant, the Redlich-Kwong-Soave ubic equation-of-state with Boston-Mathias alpha function (RKS-BM) were applied. Initial conditions of feedstocks and primary parameters in the model are summarized in Tab. S4 (see SI).

3 Results and Discussion

The results obtained by process simulation using Aspen Plus software as per Box-Behnken design of experimemts (DOE) are presented in Tab. 2. The results are given as input to the Design Expert Software for further analysis. Examining the fit summary, it is clear that the quadratic model is statistically significant for both responses, i.e., CO_2 emission avoidance (Y_1) and energy return on energy investment (Y_2).

Table 2. Box-Behnken design matrix.

Run	X_1 [°C]	X_2 [%]	X_3 [%]	Y_1 [%]	Y_2 [%]
1	750.00	20.00	60.00	19.7	17.4
2	750.00	50.00	40.00	49.3	31.2
3	900.00	50.00	20.00	49.4	50.25
4	900.00	20.00	40.00	19.7	36.8
5	600.00	80.00	40.00	79.8	31.2
6	750.00	80.00	60.00	78.9	12.7
7	750.00	50.00	40.00	49.3	31.2
8	900.00	80.00	40.00	78.9	37.5
9	600.00	20.00	40.00	19.7	30.8
10	600.00	50.00	20.00	49.3	42.6
11	750.00	50.00	40.00	49.3	31.2
12	600.00	50.00	60.00	49.3	13.4
13	750.00	50.00	40.00	49.3	31.2
14	750.00	50.00	40.00	49.3	31.2
15	750.00	80.00	20.00	78.9	41.2
16	900.00	50.00	60.00	49.3	20.1
17	750.00	20.00	20.00	19.8	46.1

3.1 ANOVA for Response on CO_2 Emission Avoidance

Analysis of variance (ANOVA) is a proficient statistical decision-making tool that is used to test the satisfactoriness of a model for the responses in data obtained from Aspen Plus. Tab. S5 (see SI) summarizes the ANOVA data for the response surface quadratic model for CO_2 emission avoidance of the IGCC process. The variables X_1 (gasifier temperature), X_2 (MSW-coal ratio), and X_3 having a P-value of < 0.05 are statistically significant in the regression model with 95 % confidence level. Hence, it can be inferred that X_1 and X_2 are major contributing factors in CO_2 emission avoidance in comparison to X_3, i.e., the ratio of supplied air to that required for complete combustion.

The model F-value of 21955.57 implies that the model is significant. In the model, X_2, X_1X_2 are significant model terms. Fig. 3 illustrates the three-dimensional response surface which

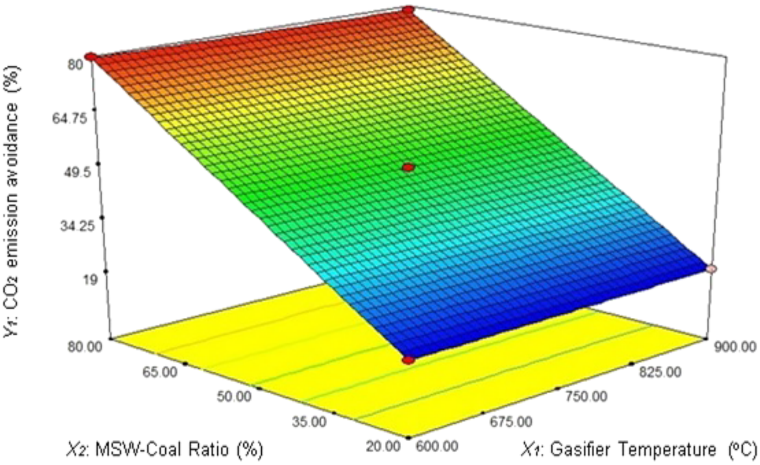

Figure 3. Three-dimensional response surface plot of CO_2 emission avoidance (effect of gasifier temperature and the MSW-Coal ratio) of the IGCC.

was constructed to show the interaction effect of X_1 and the X_2 on CO_2 emission avoidance.

A second-order polynomial model equation was obtained to represent the functional relationship between the process parameters and response, i.e., CO_2 emission avoidance. The predicted influence on CO_2 emission avoidance (Y_1) obtained in terms of coded factor excluding terms containing X_3 is as follows:

$$Y_1 = 49.03 - 0.1X_1 + 29.7X_2 - 0.23X_1X_2 + 0.11X_1^2 + 0.11X_2^2 \quad (9)$$

The value of R^2 of unity indicates good agreement between the data as obtained from Aspen Plus and values of the response predicted by the RSM model. The obtained ratio of 413.784 can be noted as adequate signal which is greater than 4 as indicated in Tab. S6 (see SI).

In addition, Fig. S1 (in SI) presents the predicted values versus actual values as obtained from Aspen Plus for CO_2 emission avoidance.

3.2 ANOVA of Energy Returns on Energy Investment (EROEI)

From the ANOVA for the three-factor interaction model for EROEI (Tab. S7 in SI), an F-value of 92.92 and a P-value of < 0.05 are indicated, implying the significance of the model. In this case, X_1, X_3, X_1^2, and X_3^2 factors are significant model terms. Fig. 4 displays the three-dimensional response surface which was constructed to show the interaction effect of X_1 and X_2 on EROEI.

A second-order polynomial model equation of the following form was got to demonstrate the influence on EROEI. The predicted response on EROEI (Y_2) obtained in terms of a coded factor is as follows:

$$Y_2 = 31.2 + 3.33X_1 - 1.06X_2 - 14.57X_3 + 0.075X_1X_2 - 0.24X_1X_3 + 0.05X_2X_3 + 2.56X_1^2 + 0.32X_2^2 - 2.17X_3^2 \quad (10)$$

The value of R^2 (0.9917) close to 1 indicates a good fitness of the data predicted by the quadratic model with those data obtained with Aspen Plus. The Adeq. Precision of 31.593 > 4.0 again indicates the goodness of fit as presented in Tab. S8 (in SI). In addition, Fig. S2 (in SI) shows the predicted values versus actual values as obtained from Aspen Plus for EROEI.

Tab. S2 (in SI) depicts the statistical values from ANOVA analysis of CCD for the CO_2 emission avoidance-based models. Tab. S3 (SI) presents the statistical values from ANOVA analysis using CCD for the EROEI-based models. While the values of R^2 for CO_2 emission avoidance and EROEI using BBD were determined to be 1.000 and 0.9917, respectively, those using CCD were 0.9969 and 0.9620, respectively, for CCD. Thus, the BBD-based models are superior to the CCD ones for the present analysis. This is also true with respect to the values of adj R^2, and pred R^2.

3.3 Comparison with Experimental Data

The performance of the proposed model was also compared with operating plant data published by Kumar et al. [29] and experimental data published by Surroop and Juggurnath [30]. As is evident from data provided in Tabs. 3 and 4, most of the results are in good agreement.

EROEI and CO_2 emission avoidance of Run 3 are 90.0 % and 91.5 % accurate, respectively, with experimental data published by Surroop and Juggurnath [30]. From the optimum values of EROEI and CO_2 emission avoidance it appears that the IGCC of the mixture of Indian MSW and coal can serve as a potential process for efficient waste management and alternative energy. However, different challenges were identified by

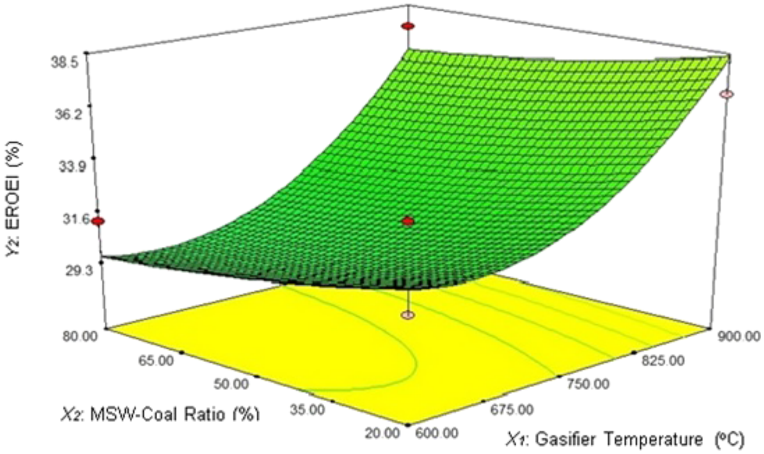

Figure 4. Three-dimensional response surface plot of energy return on energy investment (effect of gasifier temperature and the MSW-coal ratio) of the IGCC.

Table 3. Performance of the proposed model with operating plant data.

Operating parameters	Operating plant data [29]	Prediction of the model developed in Run 17, Tab. 2 of the present work
Cofiring (biomass:coal)	Rice husk:coal	Municipal solid waste:coal
Fuel feed rate [$t\,h^{-1}$]	11	1.25
Fuel composition (mass basis)	30:70	20:80
Gasifier temperature [°C]	750–800	750
Energy return on energy investment [%]	49	46.1

Table 4. Performance of the proposed model with published experimental data.

Operating parameters	Experimental data from [30]	Prediction of the model developed in Run 3, Tab. 2 of the present work
Cofiring (biomass:coal)	Municipal solid waste: coal	Municipal solid waste:coal
Fuel feed rate [$t\,h^{-1}$]	58.29	1.25
Fuel composition (mass basis)	80:20	80:20
Gasifier temperature [°C]	900	900
Energy return on energy investment [%]	55.92	50.25
CO_2 emission avoidance [%]	45.5	49.4

several investigators and some recommendations were made. According to a scientific group, for the economic feasibility of the MSW-to-electricity (WTE) plants, introduction and implementation of some government policies are required [38, 41, 44]. These are policies ensuring the government's responsibility of MSW collection and transportation to WTE plants, purchasing the generated electricity at the same price as that of the existing supplies and tax exemption on the income of the owners of WTE plants for ten years [38].

In a recent article, it was reported that although distributed electrical power generation through gasification of MSW is a potential option for renewable energy, there are some challenges like increase of efficiency of gasification, reduction in the contaminant level of syngas, and improvement of the conversion efficiency of electrical power from syngas [41]. Different MSW management models encompassing efficient collection, transportation, material recovery, and generation of energy were recommended in another investigation [44]. These challenges should be addressed and the recommendations should be considered before taking any strategic decision regarding utilization of MSW in India.

4 Conclusions

A systematic process model using Aspen PLUS was developed for an IGCC-based power plant based on the mixture of Indian MSW and coal. Based on the data simulated by the process model, statistical modeling was performed to correlate the energy and environmental impacts of the power plant with important input parameters. The energy efficiency of the MSW gasification decreases with higher temperature. At lower temperatures, the equilibrium of the exothermic carbonation and water-gas shift (WGS) reactions is shifted forward to increase hydrogen production and thereby enhancing the energy efficiency of the system.

The gasifier temperature, MSW-coal ratio, and air fed to the gasifier were found to have significant effects on the reduction of the carbon footprint and energy return from the power plant. The outcome of this research is expected to be useful in taking strategic decisions on running IGCC power plants using a combination of coal and MSW as feed.

Supporting Information

Supporting Information for this article can be found under DOI: https://doi.org/10.1002/ceat.202000230.

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Symbols used

X_1	[°C]	gasifier temperature
X_2	[%]	ratio of municipal solid waste to coal

X_3	[%]	ratio of supplied air to that required for complete combustion
Y_1	[%]	CO_2 emission avoidance
Y_2	[%]	ratio of energy return on energy investment

Abbreviations

ANOVA	analysis of variance
ASPEN	advanced system for process engineering
ACE	avoidance in CO_2 emission
BBD	Box-Behnken design
DOE	design of expert
EROEI	energy return on energy investment
GHG	greenhouse gas
HRSG	heat recovery steam generator
HFC	hydrofluorocarbons
IPCC	intergovernmental panel on climate change
IGCC	integrated gasification combined cycle
MSW	municipal solid waste
RSM	response surface methodology
SR	stoichiometric ratio
WGS	water-gas shift

References

[1] A. M. Omer, *Int. J. Waste Resour.* **2017**, *7 (3)*, 1–11. DOI: https://doi.org/10.4172/2252-5211.1000292
[2] H. K. Jeswani, A. Azapagic, *Waste Manage.* **2016**, *50*, 346–363. DOI: https://doi.org/10.1016/j.wasman.2016.02.010
[3] J. M. Fernández-González, A. L. Grindlay, F. Serrano-Bernardo, M. I. Rodríguez-Rojas, M. Zamorano, *Waste Manage.* **2017**, *67*, 360–374. DOI: https://doi.org/10.1016/j.wasman.2017.05.003
[4] P. N. Mabalane, B. O. Oboirien, E. R. Sadiku, M. Masukume, *Waste Biomass Valor.* **2020**, in press. DOI: https://doi.org/10.1007/s12649-020-01043-z
[5] P. Stehlík, Q. Smejkal, R. Štulíř, *Chem. Eng. Technol.* **2008**, *31 (5)*, 788–791. DOI: https://doi.org/10.1002/ceat.200800080
[6] B. Patel, B. Gami, *Iran. J. Energy Environ.* **2012**, *3 (2)*, 123–128. DOI: https://doi.org/10.5829/idosi.ijee.2012.03.02.0071
[7] M. Ozturk, I. Dincer, *J. Soc. Chem. Ind.* **2020**, *10 (4)*, 855–864. DOI: https://doi.org/10.1002/ghg.1955
[8] C. Strazza, A. Del Borghi, M. Gallo, *Energies* **2013**, *6 (3)*, 1250–1265. DOI: https://doi.org/10.3390/en6031250
[9] S. Shirazian, A. Moghadassi, S. Moradi, *Simul. Modell. Pract. Theory* **2009**, *17 (4)*, 708–718. DOI: https://doi.org/10.1016/j.simpat.2008.12.002
[10] M. R. Sohrabi, A. Marjani, S. Moradi, M. Davallo, S. Shirazian, *Appl. Math. Modell.* **2011**, *35 (1)*, 174–188. DOI: https://doi.org/10.1016/j.apm.2010.05.016
[11] M. Ghadiri, A. Marjani, S. Shirazian, *Int. J. Greenhouse Gas Control* **2013**, *13*, 1–8. DOI: https://doi.org/10.1016/j.ijggc.2012.11.030
[12] S. M. R. Razavi, S. Shirazian, M. Nazemian, *Arab. J. Chem.* **2016**, *9 (1)*, 62–71. DOI: https://doi.org/10.1016/j.arabjc.2015.06.006
[13] C. Dong, B. Jin, J. Lan, *Dev. Chem. Eng. Miner. Process.* **2008**, *10 (5–6)*, 639–646. DOI: https://doi.org/10.1002/apj.5500100613
[14] I. Hernandez-Mireles, R. van der Stel, E. Goetheer, *Energy Procedia* **2014**, *63*, 7954–7958. DOI: https://doi.org/10.1016/j.egypro.2014.11.830
[15] M. K. Mann, P. L. Spath, *Clean Technol. Environ. Policy* **2001**, *3 (2)*, 81–91. DOI: https://doi.org/10.1007/s100980100109
[16] K. R. Rathnam, J. Kärki, M. Nieminen, A. Leinonen, P. Jain, T. N. Raju, *Energetica India* **2013**, *8*, 68–73.
[17] D. Loeffler, N. Anderson, *Appl. Energy* **2014**, *113*, 67–77. DOI: https://doi.org/10.1016/j.apenergy.2013.07.011
[18] P. Basu, J. Butler, M. A. Leon, *Renewable Energy* **2011**, *36 (1)*, 282–288. DOI: https://doi.org/10.1016/j.renene.2010.06.039
[19] H. Mikulčić, D. Cerinski, J. Baleta, X. Wang, *Chem. Eng. Technol.* **2019**, *42 (12)*, 2539–2545. DOI: https://doi.org/10.1002/ceat.201900086
[20] A. Liu, F. Ren, W. Y. Lin, J.-Y. Wang, *Int. J. Sustainable Built Environ.* **2015**, *4*, 165–188. DOI: https://doi.org/10.1016/j.ijsbe.2015.11.002
[21] S. Tana, H. Hashima, C. Leea, M. R. Taiba, J. Yanb, *Energy Procedia* **2014**, 704–708. DOI: https://doi.org/10.1016/j.egypro.2014.11.947
[22] N. Scarlat, F. Fahl, J. Dallemand, *Waste Biomass Valor.* **2019**, *10*, 2425–2444. DOI: https://doi.org/10.1007/s12649-018-0297-7
[23] S. Addai-Asante, T. Hao, *Int. J. Eng. Sci.* **2017**, *6 (3)*, 21–31. DOI: https://doi.org/10.9790/1813-0603022131
[24] www.coalcontroller.gov.in (2016-17)
[25] G. Guest, R. M. Bright, F. Cherubini, O. Michelsen, A. Hammer Strømman, *J. Ind. Ecol.* **2011**, *15 (6)*, 908–921. DOI: https://doi.org/10.1111/j.1530-9290.2011.00375.x
[26] K. V. Narayanan, E. Natarajan, *Renewable Energy* **2007**, *32 (15)*, 2548–2558. DOI: https://doi.org/10.1016/j.renene.2006.12.018
[27] D. Moyaa, C. Aldás, G. López, P. Kaparaju, *Energy Procedia* **2017**, *134*, 286–295. DOI: https://doi.org/10.1016/j.egypro.2017.09.618
[28] B. Patel, B. Gami, *Iran. J. Energy Environ.* **2012**, *3 (2)*, 123–128. DOI: https://doi.org/10.5829/idosi.ijee.2012.03.02.0071
[29] H. Kumar, S. K. Mohapatra, R. Singh, *Ind. Acad. Sci.* **2015**, *40*, 1283–1299. DOI: www.ias.ac.in/article/fulltext/sadh/040/04/1283-1299
[30] D. Surroop, A. Juggurnath, *Univ. Mauritius Res. J.* **2011**, 17. DOI: https://doi.org/10.4314/umrj.v17i1.70732
[31] M. Ozturk, I. Dincer, *Greenhouse Gases Sci. Technol.* **2020**, *10 (4)*, 855–864. DOI: https://doi.org/10.1002/ghg.1955
[32] N. Harun, Z. Hassan, N. Zainol, W. H. W. Ibrahim, H. Hashim, *Chem. Eng. Technol.* **2019**, *42 (9)*, 1834–1839. DOI: https://doi.org/10.1002/ceat.201800637
[33] D. Bove, S. Merello, D. Frumento, S. Al Arni, B. Aliakbarian, A. Converti, *Chem. Eng. Technol.* **2015**, *38 (12)*, 2115–2126. DOI: https://doi.org/10.1002/ceat.201500257
[34] W. Gao, L. Yan, M. Tahmoures, A. H. A. Safdar, *Chem. Eng. Technol.* **2017**, *41 (3)*, 447–453. DOI: https://doi.org/10.1002/ceat.201700272

[35] L. C. Martins das Neves, A. Converti, T. C. Vessoni Penna, *Chem. Eng. Technol.* **2009**, *32 (8)*, 1147–1153. DOI: https://doi.org/10.1002/ceat.200900051
[36] W. H. Cheung, K. K. H. Choy, D. C. W. Hui, J. F. Porter, G. Mckay, *Dev. Chem. Eng. Miner. Process.* **2008**, *14 (1–2)*, 193–202. DOI: https://doi.org/10.1002/apj.5500140117
[37] S. J. Dabe, P. J. Prasad, A. N. Vaidya, H. J. Purohit, *Environ. Prog. Sustainable Energy* **2018**, *38 (2)*, 654–671. DOI: https://doi.org/10.1002/ep.12981
[38] R. A. Tayeh, M. F. Alsayed, Y. A. Saleh, *J. Cleaner Prod.* **2021**, *279*, 123753. DOI: https://doi.org/10.1016/j.jclepro.2020.123753
[39] A. Ramos, A. Rouboa, *Environ. Impact Assess. Rev.* **2020**, *85*, 106469. DOI: https://doi.org/10.1016/j.eiar.2020.106469
[40] C. Smith Lewin, A. R. Fonseca de Aguiar Martins, F. Pradelle, *Energy* **2020**, *210*, 118498. DOI: https://doi.org/10.1016/j.energy.2020.118498
[41] N. Indrawan, A. Kumar, M. Moliere, K. A. Sallam, R. L. Huhnke, *J. Energy Inst.* **2020**, *93 (6)*, 2293–2313. DOI: https://doi.org/10.1016/j.joei.2020.07.001
[42] L. Mazzoni, I. Janajreh, S. Elagroudy, C. Ghenai, *Energy* **2020**, *196*, 117001. DOI: https://doi.org/10.1016/j.energy.2020.117001
[43] J. Wei, Q. Guo, L. Ding, K. Yoshikawa, G. Yu, *Appl. Energy* **2017**, *206*, 1354–1363. DOI: https://doi.org/10.1016/j.apenergy.2017.10.005
[44] G. Ionescu, E. C. Rada, M. Ragazzi, C. Marculescu, A. Badea, T. Apostol, *Energy Convers. Manage.* **2013**, *76*, 1083–1092. DOI: https://doi.org/10.1016/j.enconman.2013.08.049
[45] N. Koukouzas, A. Katsiadakis, E. Karlopoulos, E. Kakaras, *Waste Manage.* **2008**, *28*, 1263–1275. DOI: https://doi.org/10.1016/j.wasman.2007.04.011
[46] *Response Surface Methodology*, 4th ed. (Eds: R. H. Myers, D. C. Montgomery, C. M. Anderson-Cook), Wiley Series in Probability and Statistics, John Wiley & Sons, Inc., Hoboken, NJ **2016**.
[47] I. Martins Fukuda, C. Francini Fidelis Pinto, C. dos Santos Moreira, A. Morais Saviano, F. Rebello Lourenço, *Braz. J. Pharm. Sci.* **2018**, *54*, e01006. DOI: https://doi.org/10.1590/s2175-97902018000001006
[48] M. A. Bezerra, R. E. Santelli, E. P. Oliveira, L. S. Villar, L. A. Escaleira, *Talanta* **2008**, *76 (5)*, 965–977. DOI: https://doi.org/10.1016/j.talanta.2008.05.019
[49] L. V. Candioti, M. M. De Zan, M. S. Cámara, H. C. Goichoechea, *Talanta* **2014**, *124*, 123–138. DOI: https://doi.org/10.1016/j.talanta.2014.01.034
[50] S. N. Politis, P. Colombo, G. Colombo, D. M. Rekkas, *Drug Dev. Ind. Pharm.* **2017**, *43 (6)*, 889–901. DOI: https://doi.org/10.1080/03639045.2017.1291672

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Ekta Tayal[1], Ankita Kaushal[2]
[1,2]Panjab Univerity Chandigarh

PR00572 Extended Dynamic Matrix Controller for a Pilot Plant Binary Distillation Column
Bharath K. Udupa[1], Vinayambika S. Bhat[2], I. Thirunavukkarasu[3], Dayananda Nayak[4]
[1,2,3,4]Department of Instrumentation and Control Engineering, MIT, Manipal University, Karnataka,

Renewable Energy (RE)

Oral Presentation

RE007 Fuel Oil Production From Waste Electrical and Electronic equipment
Vaibhav Pandere[1] Alok Gautam and **Shina Gautam**[3]
[1, 2, 3] Department Of Chemical Engineering, Shroff S R Rotary Institute of Chemical Technology, Ankleshwar, Gujarat, 393001, India

RE0074 Ethanol Steam Reforming Over BICUVOX Catalyst for Hydrogen Production
Shweta Sharma[1], Bhagyesha Patil[1], H.K. Mohanta[1] and **Banasri Roy**[1]
[1]Department of Chemical Engineering, BITS-PILANI, Pilani, 333031, India

RE00102 Molecular Modelling of Electrolytes for Lithium-Ion Batteries
Bharath Ravikumar[1], Mahesh Mynam[2], Beena Rai[3]
[1,2,3]TRDDC, TCS Innovation Labs, Hadapsar Industrial Estate, Pune

RE00104 Parametric Sensitivity of MSW Integrated Power Plant: CO_2 Footprint and Energy Analysis
Ashim Kumar Khan[1]and Prof. Ranjana Chwodhury[2]
[1,2]Department of Chemical Engineering, Jadavpur University, Kolkata – 700032, India

RE00127 A Review on Different Correlations of Heat Transfer in Helical Coil Heat Exchangers
Vandana Kumari Jha[1], Nishtha Shrivastava[2] and Soubhik Kumar Bhaumik[3]
[1,2,3] Department of Chemical Engineering, IIT (ISM), Dhanbad, India, 826004

RE00139 Efficiency Enhancement of Perovskite Based Chlorophyll Dye Sensitized Thin Film Solar Cells
Argha dey[1], Subhasis Roy[2] and Bhaskar chandra Das[3]
[1,2,3] Department Of Chemical Engineering, University Of Calcutta, Kolkata, India.

RE00142 Synthesis of Cost-Effective Graphene Based Ferritic Photocatalyst for Hydrogen Generation from Water
Arundhati Sarkar[1], Anjik Chowdhury[2] and Kajari Kargupta[3]
[1,2,3]Chemical Engineering Department, Jadavpur University, Kolkata 700032, India

RE 0217 Efficient Conversion of Cellulose to HMF Catalyzed By Solid Acid Catalyst
Uplabdhi Tyagi, **Neeru Anand**[1] and Dinesh Kumar[2]
[1,2]University School of Chemical Technology, Guru Gobind Singh Indraprastha University, India

RE00242 A Study on the Solar Hydrogen Production by Different Hetero Structured Photocatalys: A State-of-The-Art Review
S. Sai Praneeth Tej[1], I. Joy Madhuri[2] and Moola.Karthik[3]
[1,2] Department Of Chemical Engineering, Gmr Institute Of Technology, Rajam
[3]Process Control Department, Kanoria Chemicals, Parawada.

RE00346 Slow Pyrolysis of Dried Maize Cob in a Fixed Bed Reactor: Characterization Of Bio-Oil, Bio-Char And Pyrolytic Gas
Goutam Kishore Gupta[1], Mahendra Ram[2] and Monoj Kumar Mondal[3]
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Biomass is a renewable energy source not only because the energy it comes from the sun, but also because biomass can re-grow over a relatively short period of time. Through the process of photosynthesis, chlorophyll in plants captures the sun's energy by converting carbon dioxide from the air and water from the ground into carbohydrates—complex compounds composed of carbon, hydrogen, and oxygen. When these carbohydrates are burned, they turn back into carbon dioxide and water and release the energy they captured from the sun. In this way, biomass functions as a sort of natural battery for storing solar energy. As long as biomass is produced sustainably—meeting current needs without diminishing resources or the land's capacity to re-grow biomass and recapture carbon—the battery will last indefinitely and provide sources of low-carbon energy.The present deliberation will provide an insight into the viability of the term 'BIOMASS' under proper condition to benefit us all and it's future perspective.

Key Words: Biomass; Renewable energy; Sustainably; Low-carbon energy

References:

[1]Tilman, D. et al. Science, 2009, July 17: 270-271.
[2]Campbell, J.E., Lobell, D.B., Genova, R.C., Field, C.B. Environ. Sci. Technol.,2008, 42: 5791–5794.

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HYBRID PROCESSING OF BIOMASS AND COAL FOR LOW CARBON POWER GENERATION

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Abstract

Current global energy supply is to a large extent based on fossil fuels (oil, natural gas, coal), of which the reserves are finite. Given the growing world population, the increasing energy consumption per capita and the evidence of global warming, the necessity for long-term alternative energy sources is obvious. For these twin crises of fossil fuel depletion and environmental degradation, energy planning and technology improvement have become the important public agenda of most developed and developing countries. Biomass is a promising eco-friendly alternative source of renewable energy in the context of current energy scenarios. Biomass, an abundant agricultural and municipal waste of India, also represents the class of hydrocarbon with much lower carbon intensity than coal. If coal is replaced by biomass the actual fuel combustion will be carbon neutral. All associated carbon emission will be caused from the ancillary collection, processing, transportation etc. Life cycle assessment is necessary to determine whether the fuel switching mechanism is beneficial in the long run r not. A life cycle assessment has been conducted on a coal-fired power system that cofires sewage sludge. The assessment has been conducted on green house gas emissions and decrease in non-renewable energy consumption. Cofiring has been found to significantly reduce the environmental footprint of the average coal-fired power plant. Net energy consumption is lowered by 4.1% and 12.75% for the 5% and 15% cofiring cases, respectively. At the replacement levels of 5 % and 15 % of fossil fuél by biomass, the emission of green house (CO_2 equiv.) gas as reduced by 6.1% and 19.2% respectively. Emissions of SO_2, NO_x, non-methane hydrocarbons, particulates and carbon monoxide are also reduced with cofiring. Finally, resource consumption and solid waste generation were found to be much lesser for cofire system.

Key Words: *Indian Sewage Sludge, Greenhouse gas emission, Net energy consumption etc...*