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ScienceDirect

Procedia CIRP 116 (2023) 19–22

www.elsevier.com/locate/procedia

30th CIRP Life Cycle Engineering Conference.

Preliminary Life Cycle Assessment of a Net-zero Power Plant Co-fired with Waste Coal and Biomass

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Abstract

In this study, we apply life cycle assessment (LCA) to a novel power plant being designed to run on waste coal and biomass. LCA is critical in helping guide the plant engineering design towards net neutral or net negative emissions. The power plant will utilize an advanced power generation technology, Pressurized Fluidized Bed Combustion (PFBC) to co-fire waste coal and biomass. The ability of PFBCs to combust fine, wet, waste coal with a high efficiency helps deliver low emissions while avoiding the need to mine new coal.. The objective of this study is to identify the ratio of biomass required to achieve net neutrality so that the power plant can be designed with the necessary infrastructure. Our results show that firing with 4–13% biomass by mass is expected to achieve net-zero emissions.

Keywords: LCA; co-firing; carbon capture and storage; CCS

1. Introduction

Mitigating climate change requires substantial reductions in carbon dioxide emissions. In the United States, the electric power sector was responsible for 32% of carbon dioxide emissions in 2021 [1]. Pairing fossil fuel fired power plants with carbon capture and storage (CCS) is a promising way of reducing emissions. To further reduce emissions, coal-fired power plants can be co-fired with biomass.

Coal-fired power plants can utilize several core combustion technologies, including pulverized coal (PC), circulating fluidized or bubbling fluidized bed (CFB or BFB), and integrated gasification with combined cycle (IGCC). PC power plants fire finely atomized pulverized coal. Circulating and bubbling fluidized beds combust coal within a fluidized bed of limestone or dolostone. With each of these technologies, power is generated via a steam turbine operating under either a subcritical or supercritical cycle depending on the operating temperature. Conversely, IGCC power plants gasify coal to produce syngas which in turn is combusted in a gas turbine. Also, within an IGCC plant, steam is generated and paired with a steam turbine [2] in a conventional steam cycle to produce additional power. PC boilers are designed to fire ground coal. CFB/BFB and IGCC plants are designed with fuel flexibility and can fire several types of fuel including coal, biomass, and a blend of coal/biomass. PC and CFB/BFB power plants can realize efficiencies of approximately 36%, while IGCC plants are more efficient due to their combined steam and gas cycles. The GREET database estimates that IGCC power plants can achieve efficiencies of about 39% [3]. However, IGCC technology has not been readily deployed due to its higher cost and technical challenges [4].

Pressurized Fluidized Bed Combustion (PFBC) is a variation of conventional fluidized bed technology and combusts fuel in a fluidized limestone or dolostone bed,

10.1016/j.procir.2023.02.004

however, it combusts at elevated pressures to extract additional power. PFBC realizes higher efficiency than conventional atmospheric fluidized bed technologies by generating power similar to an IGCC plant with both a conventional steam turbine and gas turbomachinery technology. Due to the controlled bed fluidization and the ability to handle fuels with high moisture as well as fine particle sizes, PFBC is ideal for fuels such as waste coal or biomass. As a result, new coal is not required to be mined helping to minimize the PFBC environmental footprint. Additionally, PFBC technology generates lower air emissions due to limestone injection into the boiler for desulfurization and a lower operating temperature which helps to inhibit thermal NOx generation. PFBC plants have operated in Sweden, Germany, and Japan [5].

This study presents a preliminary life cycle assessment (LCA) of a PFBC plant being designed by CONSOL Energy to provide carbon neutral or carbon negative electricity. LCA was incorporated early in the design process to ensure that the final design can meet the net-zero carbon target. The design team was investigating a variety of carbon capture targets and needed to understand the amount of biomass required to achieve carbon-neutrality for each target.

Nomenclature

CCS	Carbon capture and storage
BFB	Bubbling Fluidized Bed
CFB	Circulating Fluidized Bed
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model
GWP	Global Warming Potential
IGCC	Integrated Gasification with Combined Cycle
LCA	Life Cycle Assessment
PC	Pulverized Coal
PFBC	Pressurized Fluidized Bed Combustion

2. Methodology

We present an attributional midpoint LCA of the PFBC plant co-firing waste coal with biomass in the form of forestry waste. This preliminary study was focused on achieving net zero carbon emissions, so global warming potential (GWP) was selected as the sole environmental impact metric. We used a functional unit of 1 kWh to be comparable with similar studies [6].

2.1. System boundary and diagram

We applied a cradle-to-gate system boundary to quantify the impact of producing electricity at the power plant, excluding the transmission and distribution processes. In particular, the system boundary includes the production and gathering of materials upstream, transportation of those material flows, electricity generation, and capture of carbon dioxide. The project is being planned to run on waste coal and forestry waste, so the burden of producing the initial coal and lumber products was excluded from the system boundary. An overview of the system is shown in Fig. 1.

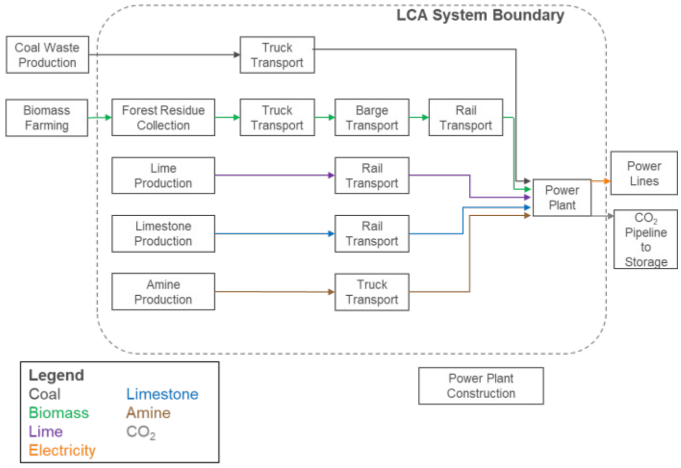

Fig. 1. System diagram.

2.2. Data collection, software, and assumptions

A custom LCA model was created in Excel and paired with Oracle Crystal Ball for Monte Carlo simulations and to enable uncertainty analysis. The model used life cycle inventory data from GREET 2021 [3], and combined it with estimates of the plant design and operation from the expert project team. Fuel model inputs are shown below in Table 1.

This study made several assumptions including:

- *CO_2 compression at power plant is sufficient for transport and injection.*
- *Biomass is collected forest waste and does not need to be dried.*
- *Waste coal beneficiation occurs outside of the system boundary in the coal waste production step.*
- *Coal conveyer has similar emissions as truck transport.*
- *Coal mining/cleaning impacts are not allocated to using waste coal as a fuel.*
- *Power plant construction does not have a major impact on the total life cycle emissions.*
- *Carbon content of fuel is fully combusted to CO_2.*

Table. 1. Fuel model inputs.

Variable	*Value*	*Source*
Biomass Type	*Forest Waste*	-
Biomass Energy Content	*8,953 Btu/lb*	GREET [3]
Waste Coal Energy Content	*10,270 Btu/lb*	*CONSOL*
Biomass Carbon Content	*50%*	GREET [3]
Waste Coal Carbon Content	*57%*	*CONSOL*

2.3. Scenarios

Four scenarios were developed based on amine-based carbon capture rates being considered by the team: 90%, 93%, 97%, and 98%. Model instances were run for a range of biomass co-firing fractions under each scenario to provide insight into the plant design process.

3. Results and discussion

3.1. Benchmark

After the custom model was created, it was benchmarked to gain confidence in the results. We compared it against 1) life cycle emissions of a coal plant without capture from GREET [3], 2) power plant point-source emissions (not across the life cycle) based on designs presented in Rubin et al. [7], and 3) life cycle emissions of a coal plant co-fired with biomass from Schakel et al. [2]. The system boundary of each of these studies is slightly different. Entry 1 in Table 2 includes fuel collection through electricity generation at the power plant (cradle-to-gate). Entries 2–7 in Table 2 only include the power plant. Entry 8 in Table 2 includes fuel collection, electricity generation at the power plant, and transportation of the CO_2.

The PFBC plant we are analyzing (entries 9–13 in Table 2) is also cradle-to-gate (fuel collection through electricity generation at the power plant), but its design is distinct from our benchmark studies, so we were not looking to match results. Instead, we were aiming to check that the custom model provided results in a similar range based on the biomass co-firing. The comparison in Table 2 shows that the custom model aligns well with the select studies from literature.

Table. 2. Benchmark of custom model against literature.

#	Source	Case	Coal % / Biomass %	Capture Rate %	g CO_2 / kWh
1	GREET [3]	N/A	100 / 0	0%	1010
2	Rubin et al. [7]	USDOE	100 / 0	90%	111
3	Rubin et al. [7]	EPRI	100 / 0	90%	120
4	Rubin et al. [7]	Alstom	100 / 0	90%	95
5	Rubin et al. [7]	IEAGHG	100 / 0	90%	93
6	Rubin et al. [7]	GCCSI	100 / 0	90%	116
7	Rubin et al. [7]	ZEP	100 / 0	90%	92
8	Schakel et al. [8]	N/A	70 / 30	90%	-237
9	This study	N/A	100 / 0	90%	105
10	This study	N/A	100 / 0	97%	34
11	This study	N/A	90 / 10	90%	26
12	This study	N/A	90 / 10	97%	-43
13	This study	N/A	70 / 30	90%	-143

3.2. Monte Carlo analysis

After benchmarking the model, we performed a Monte Carlo analysis for the four scenarios. Each scenario was run 100 times uniformly distributed with a biomass fraction between 0 (no biomass) and 1 (all biomass). Fig. 2A gives an overview of the simulations, and Fig. 2B zooms in on the regions where neutral emissions are achieved.

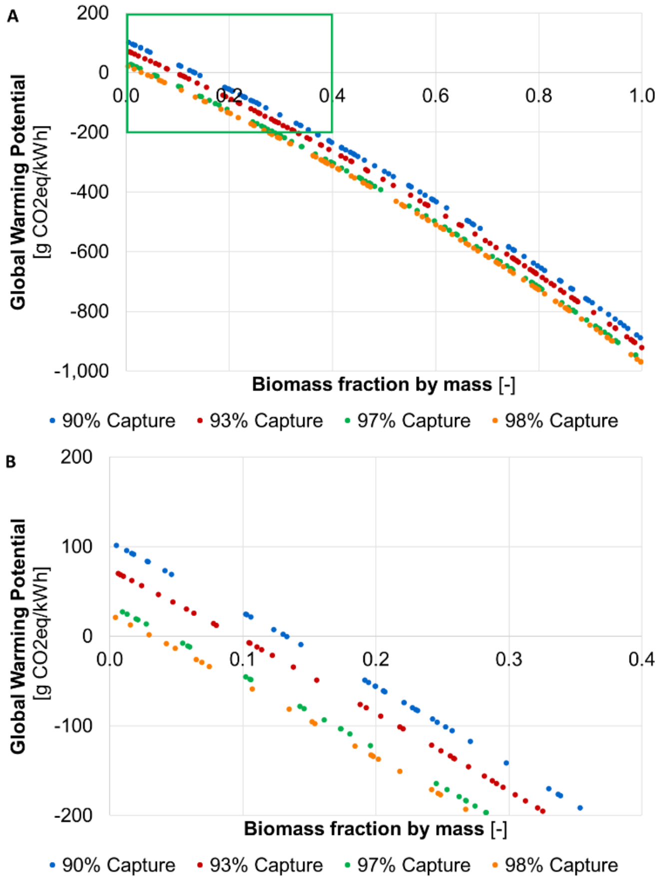

Fig. 2. A) Monte Carlo results and b) zoom-in in area of interest.

3.3. Carbon neutral design points

The model was then iteratively solved to determine the biomass fraction required to achieve carbon neutrality for each scenario. Results are shown in Table 3. We see that varying the capture rate by 8% (from 90% to 98%) results in changing the biomass fraction by 10% (13.3% to 3.2%) to achieve carbon neutrality.

Table. 3. Carbon neutral design points.

Capture Rate [%]	Biomass Fraction [-]
90	0.133
93	0.096
97	0.045
98	0.032

3.4. Hot spot analysis

Next, we performed a hot spot analysis to identify which processes created the largest impacts. Table 4 shows the impact of each life cycle stage for a 97% capture rate and 3.9% biomass blend that achieves carbon neutral emissions. As expected, the only source of negative emissions is the carbon uptake of the biomass while growing, and the major emissions are from combustion products that are released to the atmosphere. Lime production is the next major impact.

The use of hydrated lime in the plant's circulating dry scrubber system helps to further reduce acid gases beyond desulfurization in the PFBC boiler, however, we see that it comes with a carbon impact.

Table. 4. Hot spot analysis.

GWP		
Variable	Value	Unit
GWP - Biomass Carbon Uptake	**-34.678**	[g CO2eq / FU]
GWP - Biomass Farming	**0.307**	[g CO2eq / FU]
GWP - Lime Production	**3.287**	[g CO2eq / FU]
GWP - Limestone Production	**0.119**	[g CO2eq / FU]
GWP - Amine Production	**0.251**	[g CO2eq / FU]
GWP - Coal Transport	**0.056**	[g CO2eq / FU]
GWP - Biomass Truck Transport	**0.040**	[g CO2eq / FU]
GWP - Lime Truck Transport	0.000	[g CO2eq / FU]
GWP - Limestone Truck Transport	0.000	[g CO2eq / FU]
GWP - Amine Truck Transport	**0.004**	[g CO2eq / FU]
GWP - Biomass Train Transport	**0.012**	[g CO2eq / FU]
GWP - Lime Train Transport	**0.016**	[g CO2eq / FU]
GWP - Limestone Train Transport	**0.357**	[g CO2eq / FU]
GWP - Amine Train Transport	0.000	[g CO2eq / FU]
GWP - Biomass Barge Transport	**0.056**	[g CO2eq / FU]
GWP - Lime Barge Transport	0.000	[g CO2eq / FU]
GWP - Limestone Barge Transport	0.000	[g CO2eq / FU]
GWP - Amine Barge Transport	0.000	[g CO2eq / FU]
GWP - Power Plant Emission	**30.172**	[g CO2eq / FU]
Total GWP	**0.000**	[g CO2eq / FU]

4. Conclusions

This study evaluated the global warming potential of a first-of-a-kind pressurized fluidized bed combustion power plant being designed to fire waste coal and forest waste. The goal of the project is to achieve carbon neutrality. We demonstrated that the custom LCA model compares well against similar studies. Further, we investigated the impact of the biomass co-firing fraction, identified carbon neutral design points, and performed a hot spot analysis. Our results show that firing with 4–13% biomass by mass is expected to achieve net-zero emissions depending on the CO_2 capture rate of the flue gas emissions. We also found that outside of biomass growth and primary combustion, the production of lime had the largest impact on global warming potential.

5. Future Work

The LCA will continue to be updated as the project develops. Once the plant design is more established, a more detailed LCA will be performed to quantify additional environmental impacts such as land and water use.

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy National Energy Technology Laboratory under Award Number DE FE0031998.

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References

[1] Lawrence Livermore National Laboratory. United States Energy-related Carbon Dioxide Emissions in 2021 2021. https://flowcharts.llnl.gov/commodities/carbon (accessed October 21, 2022).

[2] Schakel W, Meerman H, Talaei A, Ramírez A, Faaij A. Comparative life cycle assessment of biomass co-firing plants with carbon capture and storage. Appl Energy 2014;131:441–67. https://doi.org/10.1016/j.apenergy.2014.06.045.

[3] Wang M, Elgowainy A, Lee U, Bafana A, Banerjee S, Benavides P, et al. Summary of Expansions and Updates in GREET ® 2021 2021.

[4] Bennett JA, Abotalib M, Zhao F, Clarens AF. Life cycle meta-analysis of carbon capture pathways in power plants: Implications for bioenergy with carbon capture and storage. Int J Greenh Gas Control 2021;111:103468. https://doi.org/10.1016/j.ijggc.2021.103468.

[5] Connell D. Advanced Pressurized Fluidized Bed Coal Combustion with Carbon Capture Conceptual Design Report. Canonsburg, PA: 2019.

[6] Bennett JA, Jasmin Melara A, Colosi LM, Clarens AF. Life cycle analysis of power cycle configurations in bioenergy with carbon capture and storage. Procedia CIRP 2019;80:340–5. https://doi.org/10.1016/j.procir.2018.12.014.

[7] Rubin ES, Davison JE, Herzog HJ. The cost of CO2 capture and storage. Int J Greenh Gas Control 2015;40:378–400. https://doi.org/10.1016/j.ijggc.2015.05.018.