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Utilizing Life Cycle Assessment to Design a Novel Carbon-Negative Power Plant in Appalachia, USA

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Abstract

In the United States, sixteen states and Puerto Rico have legislation establishing greenhouse gas (GHG) emissions reduction requirements, while other states have announced executive action to develop GHG reduction goals. In response, companies are evaluating their facilities and process designs to identify ways to meet these targets without disrupting the essential products and services they provide. For example, coal-fired power plants are exploring options to reduce CO_2 emissions by adding carbon capture and storage (CCS) or converting to co-firing with biomass.

In Appalachia, CONSOL Energy is leading a USDOE-funded 21st Century Power Plant Project to develop the world's first carbon-negative power plant fueled by a blend of biomass, waste coal products, and virgin coal in a novel pressurized fluidized bed combustor system. The objective of this study is to provide critical inputs to the Front-End Engineering Design process to ensure carbon-negative performance. The scope expands on preliminary work published in 2023 by developing a novel LCA model created in openLCA that covers both the total impacts of the system design and hotspot analysis.

Introduction

Electricity generation from coal accounted for about 19% of total U.S. energy-related CO_2 emissions in 2022, representing 55% of total CO_2 emissions from the electric power sector.[1] Bioenergy with carbon capture and storage (BECCS), a subset of carbon capture and storage (CCS) technologies, is expected to serve as a crucial negative energy technology in meeting Paris Agreement targets. Bioenergy comprises energy generated from biomass combustion. Biomass absorbs atmospheric CO_2 during growth, which is then sequestered after combustion.[2] This allows for a carbon negative system.

The U.S. coal-fired power fleet employs several combustion technologies to generate power, including pulverized coal (PC), circulating fluidized bed (CFB), bubbling fluidized bed (BFB), and integrated gasification combined cycle (IGCC) designs. PC plants burn finely pulverized coal, while CFB and BFB plants combust coal in fluidized beds of limestone or dolostone, allowing for greater flexibility in fuel specifications. IGCC plants gasify coal to produce syngas, which is then combusted in a gas turbine and paired with a steam turbine for additional power generation. While PC and CFB/BFB plants achieve efficiencies of around 36%, IGCC plants can operate with efficiencies of up to 39%; however, the adoption of IGCC technology has been limited due to its higher costs and technical complexities.[3]

Pressurized fluidized bed combustion (PFBC) offers an advanced alternative to conventional fluidized bed technologies by generating power in both turbomachinery and conventional steam turbine cycles like IGCC cycles, offering higher efficiencies and environmental performance than CFB and BFB designs. By utilizing waste coal or biomass, PFBC designs can reduce emissions through in-bed desulfurization, operate at lower temperatures to limit thermal NO_x formation, and reduce the need for virgin coal mining. This study provides an update to a preliminary life cycle assessment (LCA) of a PFBC plant designed by CONSOL Energy, reflective of its latest design iteration. This study evaluates the global warming potential of a coal and biomass power generation system, termed the 21st-Century Power Plant (21CPP).

Methods

This study aimed to evaluate the parameters within which the 21CPP design can deliver carbon-negative electricity. The system under consideration utilizes three PFBCs in parallel, co-firing waste coal and virgin coal. Limestone is consumed within the PFBCs to mitigate sulfur emissions. Additionally, a biomass boiler combusts forest waste, wherein all generated emissions are combined with emissions from the PFBCs, fed to a circulating dry scrubber and fabric filter, then to an amine carbon capture unit. CO_2 is captured and compressed to pipeline standards, then transported via pipeline and injected underground. This LCA performed a cradle-to-grave analysis, including the production and transport of all major inputs, construction of the power plant and CCS infrastructure, power plant operation, and CO_2 pipeline and storage impacts. Waste coal production and forest management were assumed to be outside of the system boundary. Infrastructure demolition and disposal were not evaluated. The system diagram and system boundary are shown in Figure 1.

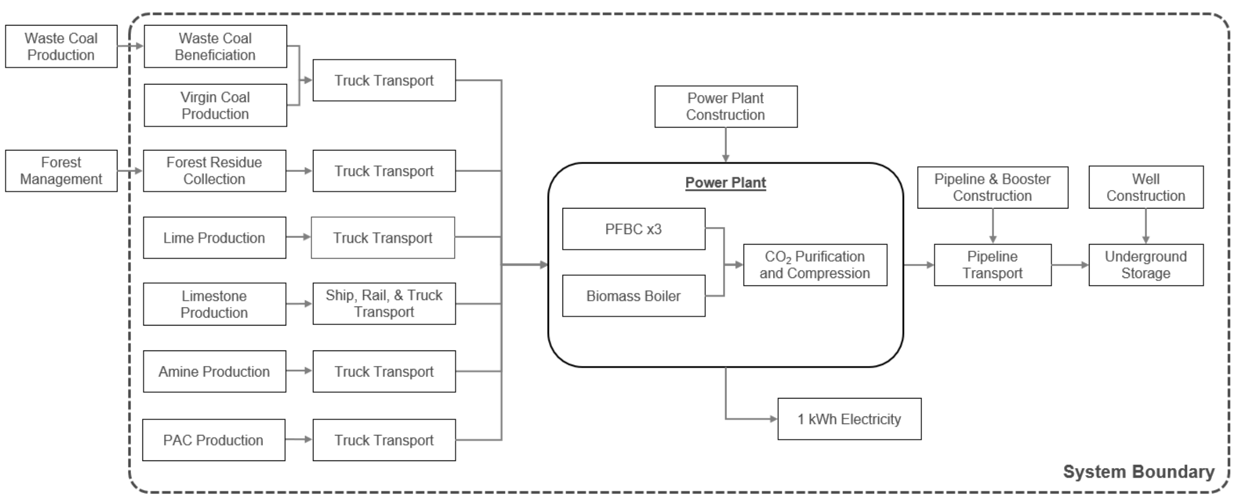

Figure 1. System diagram.

CARBON SOLUTIONS modeled the proposed system in openLCA to evaluate global warming potential, evaluating impacts using the TRACI 2.1 assessment method.[4] The functional unit for this analysis is the global warming potential over 100 years in g CO_2eq per 1 kWh of electricity produced, with lFigure 1ife cycle inventory data provided by CONSOL and its engineering design team. Additional life cycle impacts and unknown inventory values were collected from Argonne National Lab's GREET 2023 model and NETL's CO2U and 45Q LCI average databases.[5,6,7] NETL's gate-to-grave LCA of saline aquifer sequestration of CO_2 was updated for a pipeline modeled by the project's design team, inclusive of a grid-powered compressor and the construction of 11 wells for injection and plume monitoring.[8] The model was verified with heat and mass balance calculations provided by the project engineering design team, with key model parameters shown below in Table 1. Other assumptions made in this study in consultation with the engineering design team include:

- *Energy required for waste coal beneficiation is provided by the proposed 21st century power plant.*
- *Collected forest waste biomass does not require additional drying beyond desiccation during transport and on-site storage.*
- *Coal mining and cleaning impacts are not allocated to using waste coal as a fuel.*
- *The CO_2 pipeline compressor at the storage site is powered by the U.S. average grid mix, and wells are drilled with a diesel-powered rig.*

Table 1. Relevant model parameters. Fuel parameters are for fuel, as fired.

Variable	*Value*	*Source*
Biomass Energy Content, wet	*6,084 Btu/lb*	*CONSOL*
Biomass Moisture Content	*30 wt%*	*CONSOL*
Coal Blend Energy Content, wet	*9,961 Btu/lb*	*CONSOL*
Coal Blend Moisture Content	*26.5 wt%*	*CONSOL*
Waste Coal Percentage (in Blend)	*50 wt%*	*CONSOL*
Biomass Percentage (Energy-Basis)	*20%*	*CONSOL*
Number of PFBCs	*3*	*CONSOL*
Number of Biomass Boilers	*1*	*CONSOL*
CO_2 Capture Rate	*97%*	*CONSOL*
Number of CO_2 Compressors	*2*	*CONSOL*
CO_2 Pipeline Length	*47 miles*	*CONSOL*
Number of Wells	*11*	*CONSOL*
Number of Well Head Compressors	*1*	*CONSOL*
Formation Leakage	*0.5%*	*NETL[8]*

Results and Discussion

Table 2. Process impact contributions at baseline plant design.

GWP		
Variable	Value	Unit
Biomass Carbon Uptake	-190.2	[gCO_2e /kWh]
Virgin Coal Supply	67.1	[gCO_2e /kWh]
Lime, Limestone, Amine, PAC Supply	4.2	[gCO_2e /kWh]
Material Transportation	12.2	[gCO_2e /kWh]
Power Plant, Pipeline, and Storage Field Construction	12.2	[gCO_2e /kWh]
Storage Compression and Injection	7.3	[gCO_2e /kWh]
Total GWP	-87.2	[gCO_2e /kWh]

The impact contribution of each life cycle stage for the baseline plant design is included in Table 2, showing that the carbon uptake of biomass contributes significantly to the overall negative global warming potential of the power plant. The production and cleaning of virgin coal has the highest impact. Outside of biomass growth, plant construction and material transportation were determined to have the next largest impact on global warming potential. Additionally, the model was iteratively solved to determine that a minimum of 10% biomass on an energy basis is required to achieve carbon neutrality.

To validate the openLCA model, it was benchmarked against other relevant studies as shown in Table 3. Comparisons were made with 1) life cycle emissions from a coal-fired power plant without carbon capture as reported by GREET[5], 2) point-source emissions (excluding life cycle emissions) from power plant designs described in Rubin et al.[9], and 3) life cycle emissions from a coal plant co-fired with biomass as presented in Schakel et al.[10] It is important to note that the system boundaries of these studies vary, in addition to the reference plant net power output and capacity factor, among other factors.

The PFBC plant under evaluation (Entry 9 in Table 3) adopts a similar cradle-to-gate boundary to Entry 1 (fuel collection through electricity generation); however, its design differs significantly from those in benchmark studies. Therefore, the objective was not to replicate results but to ensure the custom model produced results within a comparable range, particularly for scenarios co-firing coal and biomass. The comparisons in Table 3 demonstrate that the custom model yields a result consistent with literature-reported values. In comparison to a system with no biomass or capture, the system under evaluation has a -1,097 g CO_2e/kWh GWP difference. In comparison to a system with just capture and no biomass, the system has a GWP difference ranging from -179 to -207 g CO_2e/kWh.

Lastly, the sensitivity of the process to storage field formation leakage was modeled, and it was determined that a leakage rate of 8% would risk the project's climate neutrality. An 8% leakage rate is significantly higher than NETL's expected estimate of 0.5% and high-end estimate of 1% over 100 years, demonstrating that the project is well-situated to provide net-negative electricity.[8]

Table 3. Comparison of openLCA model to literature.

Entry	Source	Case	Coal % / Biomass %	Capture Rate %	gCO_2e / kWh
1	GREET[3]	N/A	100/0	0%	1010
2	Rubin et al.[9]	USDOE	100/0	90%	111
3	Rubin et al.[9]	EPRI	100/0	90%	120
4	Rubin et al.[9]	Alstom	100/0	90%	95
5	Rubin et al.[9]	IEAGHG	100/0	90%	93
6	Rubin et al.[9]	GCCSI	100/0	90%	116
7	Rubin et al.[9]	ZEP	100/0	90%	92
8	Schakel et al.[10]	N/A	70/30	90%	-237
9	This study	N/A	80/20	97%	-87
10	This study	N/A	70/30	97%	-178
11	This study	N/A	100/0	97%	96

Conclusions

This study evaluated the global warming potential of a net-negative pressurized fluidized bed combustion plant being designed to fire forest residue, waste coal, and virgin coal. From cradle-to-grave, the evaluated system was determined to have a -87 g CO_{2e}/kWh global warming impact. The developed openLCA model results compare well against literature values of similar coal and biomass fractions and CO_2 capture rates. Further, we found that a minimum of 10% biomass must be combusted on an energy basis to reach carbon neutrality, and the storage formation leakage rate must stay under 8% over 100 years. For the baseline system, we found that outside of biomass growth and primary combustion, plant construction and material transportation had the largest impacts on global warming potential. Ultimately, this work demonstrates how a life cycle assessment can be a powerful support tool to inform engineering decision-making that can encourage system design alterations to achieve the project's net-negative goals.

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References

[1] Energy Information Administration. 2024. Coal and the Environment. (last updated 17 April 2024). https://www.eia.gov/energyexplained/coal/coal-and-the-environment.php.

[2] European Academies Science Advisory Council. 2018. Negative Emissions Technologies—What Role in Meeting Paris Agreement Targets? https://easac.eu/publications/details/easac-net.

[3] 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

[4] Bare, J. Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) TRACI version 2.1 User's Guide. U.S. EPA Office of Research and Development, Washington, DC, EPA/600/R-12/554, 2014. https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NRMRL&dirEntryId=274755.

[5] Wang M, Elgowainy A, Lee U, Bafana A, Banerjee S, Benavides P, et al. Summary of Expansions and Updates in GREET® 2023. https://www.osti.gov/servlets/purl/2278803.

[6] Skone T, Krynock M, Jamieson, M. NETL CO2U openLCA LCI Database (Version 2.1) [Data set]. Pittsburgh, PA: National Energy Technology Laboratory, U.S. Department of Energy. https://www.netl.doe.gov/energy-analysis/details?id=5d3ec761-3671-46e1-9262-1b227a8715a1.

[7] Krynock, M. NETL 45Q US Average LCI (Version 1) [Data set]. Pittsburgh, PA: National Energy Technology Laboratory, U.S. Department of Energy. https://www.netl.doe.gov/energy-analysis/details?id=c0af018e-fd60-44c8-97ce-ee931b82c728.

[8] National Energy Technology Laboratory. 2013. Gate-to-Grave Life Cycle Analysis Model of Saline Aquifer Sequestration of Carbon Dioxide. https://www.netl.doe.gov/energy-analysis/details?id=813.

[9] Rubin ES, Davison JE, Herzog HJ. The Cost of CO_2 Capture and Storage. Int J Greenh Gas Control 2015; 40:378–400. https://doi.org/10.1016/j.ijggc.2015.05.018.

[10] 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.