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

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Carbon Solutions

Motivation

- Electricity generated from coal accounted for ~19% of total U.S. energy-related CO_2 emissions in 2022, representing 55% of total CO_2 emissions from the electric power sector (EIA, 2024)
- One approach: decarbonized coal-fired power through CCS and biomass co-firing
- Life Cycle Assessment aims to quantify the environmental impacts of a product or process, accounting for its entire life cycle → ensures carbon reduction
  - ISO 14040 Compliant
- Evaluate the **global warming impact of generating 1 kWh of electricity** with a co-fired **biomass, waste coal**, and **virgin coal** power facility that employs **CCS** for system optimization by industry partner **CONSOL Energy**. Determine the limits of biomass percentage to achieve carbon neutrality.

Scope

- Cradle-to-gate analysis for 1 kWh of electricity produced, including:
  - Production and transport of major raw materials
  - On-site emissions
  - Construction
  - Transport and sequestration of CO_2
- Not included: plant decommissioning & demolition → negligible impact
- Evaluated using openLCA 2.2 software, TRACI 2.1 impact assessment, GHG-100 CO_2e
- Data Sources: Industry Partner → NETL 45Q LCI & CO2U Database → GREET 2023, 1.3.0

System Diagram

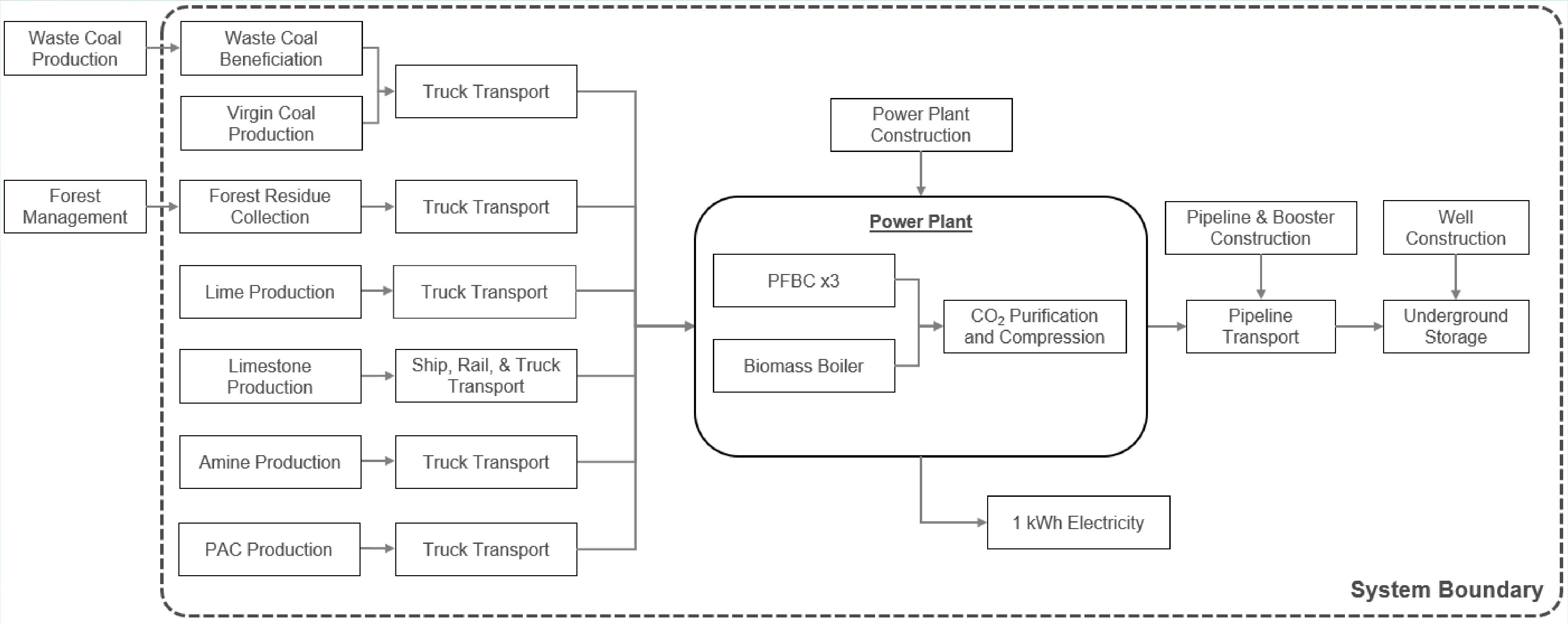
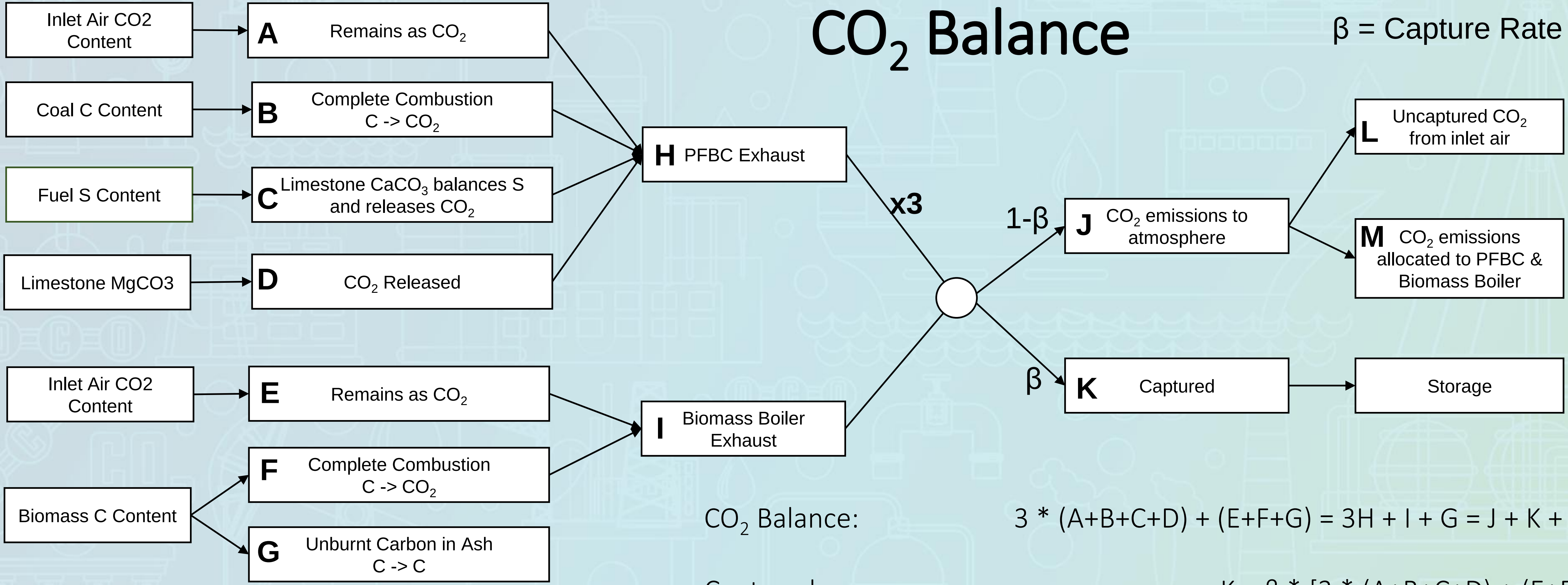


Figure 1. System boundary of the proposed 21 CPP BP2 design

CO_2 Balance

β = Capture Rate



CO_2 Balance: $3 * (A+B+C+D) + (E+F+G) = 3H + I + G = J + K + G$

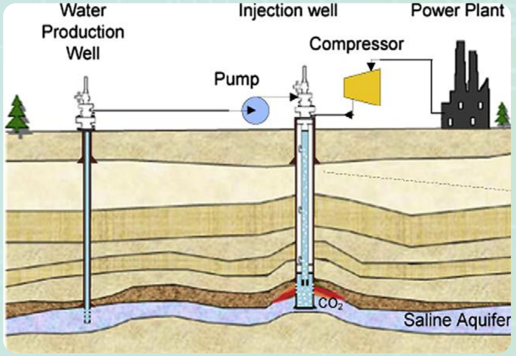
Captured: $K = \beta * [3 * (A+B+C+D) + (E+F)]$

CO_2 emissions to atmosphere: $J = (1-\beta) * [3 * (A+B+C+ D) + (E+F)]$

CO_2 emissions allocated to PFBC/Boiler: $M = (1-\beta) * [3 * (B+C+D) + (F)]$

Key model parameters

Coal Blend	Virgin & Beneficiated Waste Coal
Coal Blend Energy Content, wet	9,961 Btu/lb
Coal Blend Moisture Content	26.5 wt%
Percentage Waste Coal	50%
Biomass Type	**Forest Residue**
Biomass Energy Content, wet	5,030 Btu/lb
Biomass Moisture Content	30 wt%
Biomass in Feed (Energy-basis)	20%
Capture System and Transport	
CO_2 Capture Rate	97%
Number of CO_2 Compressors	2
CO_2 Pipeline Length	47 miles
Sequestration	
Number of Wells	11
Number of Well Head Compressors	1
Formation Leakage	0.5%



https://doi.org/10.1016/J.ENERGY.2012.07.002

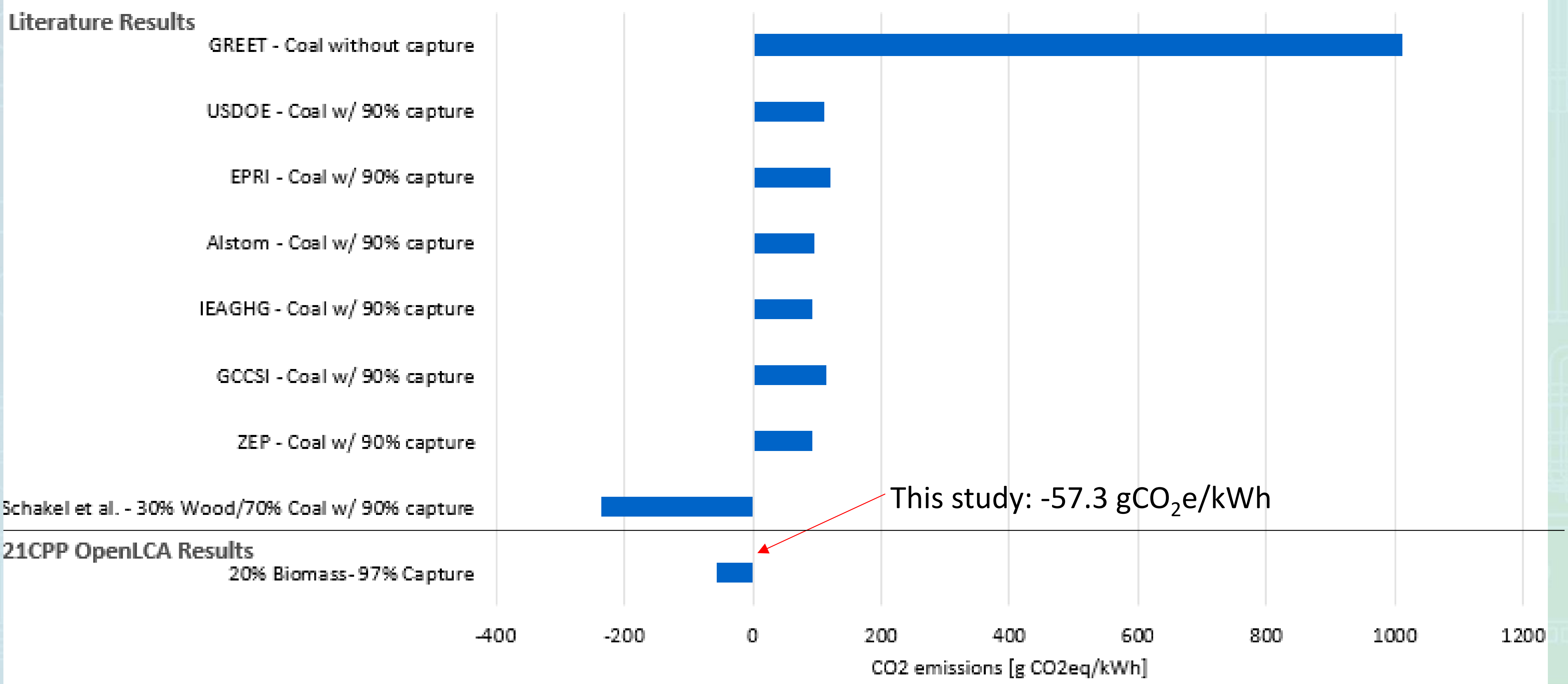
Model Output and Sensitivity Highlights

- Coal power generally produces ~1000 g CO_2e/kWh
- Biomass carbon uptake makes the plant's overall GWP negative
  - At least **14% biomass fraction** could achieve carbon neutrality
- Construction of the CO_2 pipeline and its operation have non-negligible effects
  - NETL CO2U transport and storage process: 17.6 g CO_2e/kWh
- Sensitivity to storage field formation leakage was modeled
  - 5.3% leakage rate over 100 years would risk the project's climate neutrality

Process impact contributions at baseline plant design.

Variable	Value [gCO_2e /kWh]
Biomass Carbon Uptake	-197.2
Virgin Coal Supply	67.1
Lime, Limestone, Amine, PAC Supply	4.2
Material Transportation	12.5
On-Site Emissions	36.6
Plant Construction	0.8
CO_2 Transport, Storage, and Construction	18.7
TOTAL	**-57.3**

Results Comparison



Conclusions

- A cradle-to-gate impact of -57.3 gCO_2e/kWh was calculated for the proposed 21CPP system
- 14% biomass must be combusted on an energy basis for this system to reach expected carbon neutrality
- Integrating LCA into a design process can improve overall system design by identifying key trade-offs and optimizing environmental performance

Questions?

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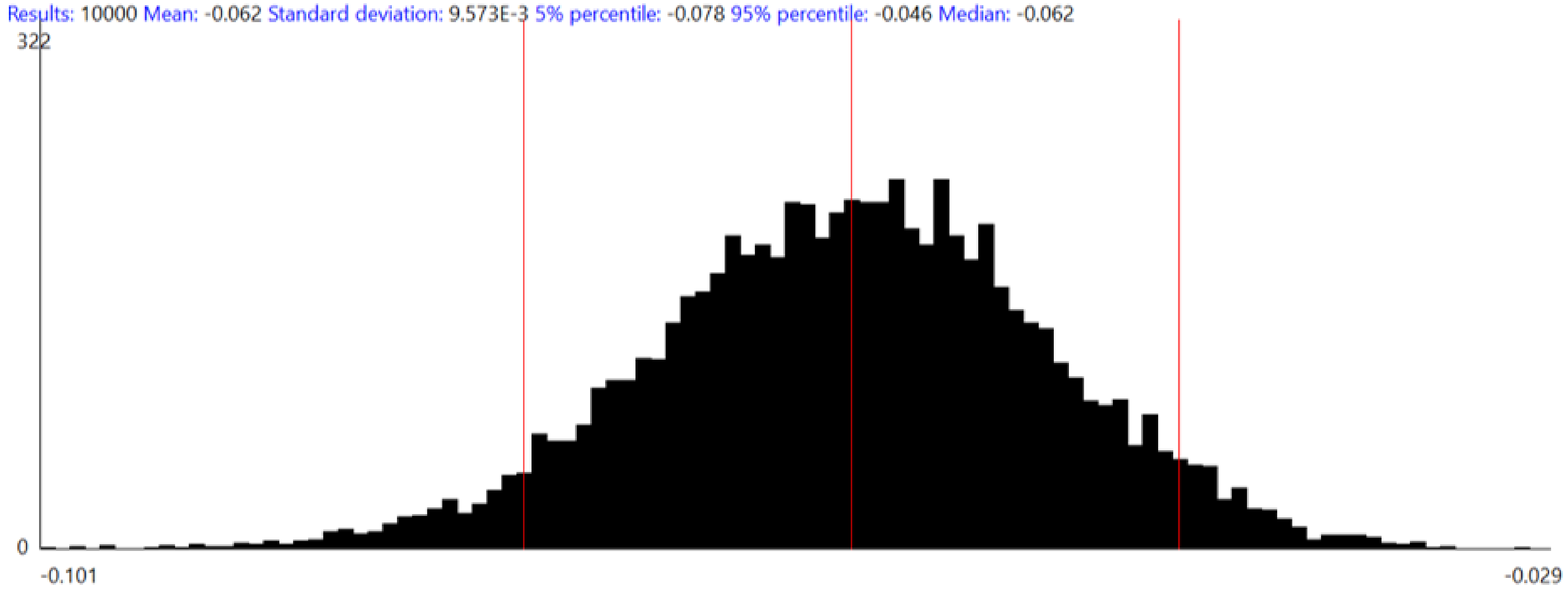
Monte Carlo Simulation



Inputs/Outputs - Plant Output

Inputs

Flow	Category	Amount	Unit	Uncertainty	Provider	Data qu	Description
Cargo	NETL flows	amine_kg_km	kg*km	lognorm...	Truck Transport - US	(2; 1; ...	Transport of amine, kg*km
Cargo	NETL flows	pac_kg_km	kg*km	lognorm...	Truck Transport - US	(2; 1; ...	Transported of PAC, kg*km
Cargo	NETL flows	lime_kg_km	kg*km	lognorm...	Truck Transport - US	(2; 1; ...	Transport of lime, kg*km
CO2_from_air	PI Data	CO2_inlet_flow_bio_kg...	kg	lognorm...	Biomass Boiler	(2; 1; ...	CO2 in biomass boiler from inlet air stream (k
CO2_from_air	PI Data	co2_inlet_flow_pfbc_k...	kg	lognorm...	PFBC x3	(2; 1; ...	CO2 in PFBC from inlet air stream (kg/kWh)
CO2_from_bio	PI Data	CO2_bio_C_kg_kWH	kg	lognorm...	Biomass Boiler	(2; 1; ...	CO2 output from Biomass boiler
CO2_from_coal	PI Data	CO2_coal_C_kg_kWh	kg	lognorm...	PFBC x3	(2; 1; ...	CO2 output from PFBC x3 coal
CO2_from_MgCO3	PI Data	CO2_coal_MgCO3_kg_...	kg	lognorm...	PFBC x3	(2; 1; ...	CO2 output from PFBC x3 Limestone
CO2_from_sulfur	PI Data	CO2_coal_S_kg_kWh	kg	lognorm...	PFBC x3	(2; 1; ...	CO2 output from PFBC x3 Limestone CaCO3
Lime	PI Data	m_lime_kg	kg	lognorm...	Lime Production	(2; 1; ...	Transported lime input
Monoethanolamine	PI Data	m_amine_kg	kg	lognorm...	MEA Production	(2; 1; ...	Transported MEA input
PAC	PI Data	m_PAC_kg	kg	lognorm...	PAC Production	(2; 1; ...	Transported PAC input
Plant Construction	PI Data	1.00000	Item(s)	lognorm...	Plant Construction	(2; 1; ...	Impacts of plant construction per kWh outpu

Outputs

Flow	Category	Amount	Unit	Uncertainty	Provider	Data c	Description
Electricity	**NETL flows/Energy ...**	**1.00000**	**kWh**	**lognorm...**		**(2; ...**	**1 kWh electricity output**
CO2_from_air	PI Data	released_co2_from_air	kg	lognorm...		(2; 1...	CO2 released originally from air
carbon_dioxide_seq...		sequestered_co2	kg	lognorm...	Field_C...	(2; 1...	
Carbon dioxide	../Emission to air/uns...	released_co2_from_liber...	kg	lognorm...			