Life Cycle Greenhouse Gas Emissions of Coal-Biomass Co-firing Power Plants without and with Carbon Capture and Storage

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Introduction

- The United States has set a goal of net-zero emissions by no later than 2050 (The White House, 2021).
- The United States aims for 100% clean electricity in 2035 (The White House, 2021).
- In 2022, electricity generation from coal occupied 19.7% of the U.S. electricity mix, falling from 51.7% in 2000 (EPA, 2023).
- Technology development and deployment for mitigating the environmental impacts of legacy coal-based generation plants is necessary.
  - Co-firing biomass with coal is a feasible and competitive option, but the carbon mitigation potential is affected by several critical factors (The White House, 2021; National Academy of Science, 2019);
  - Carbon capture and storage (CCS) is an environmental pollutants control technology that can help in reducing the stack emissions of power plants.

Objectives

The study has four objectives.

- To characterize and estimate the technological performance and life cycle greenhouse gas (GHG) emissions of the coal-biomass co-firing power plants with and without CCS;
- To identify the critical factors that impact the technological performance and life cycle emissions at a plant;
- To determine the breakeven co-firing level for co-firing power plants to achieve net-zero emissions on a life cycle basis;
- To quantify the variability and uncertainty of the life cycle emissions.

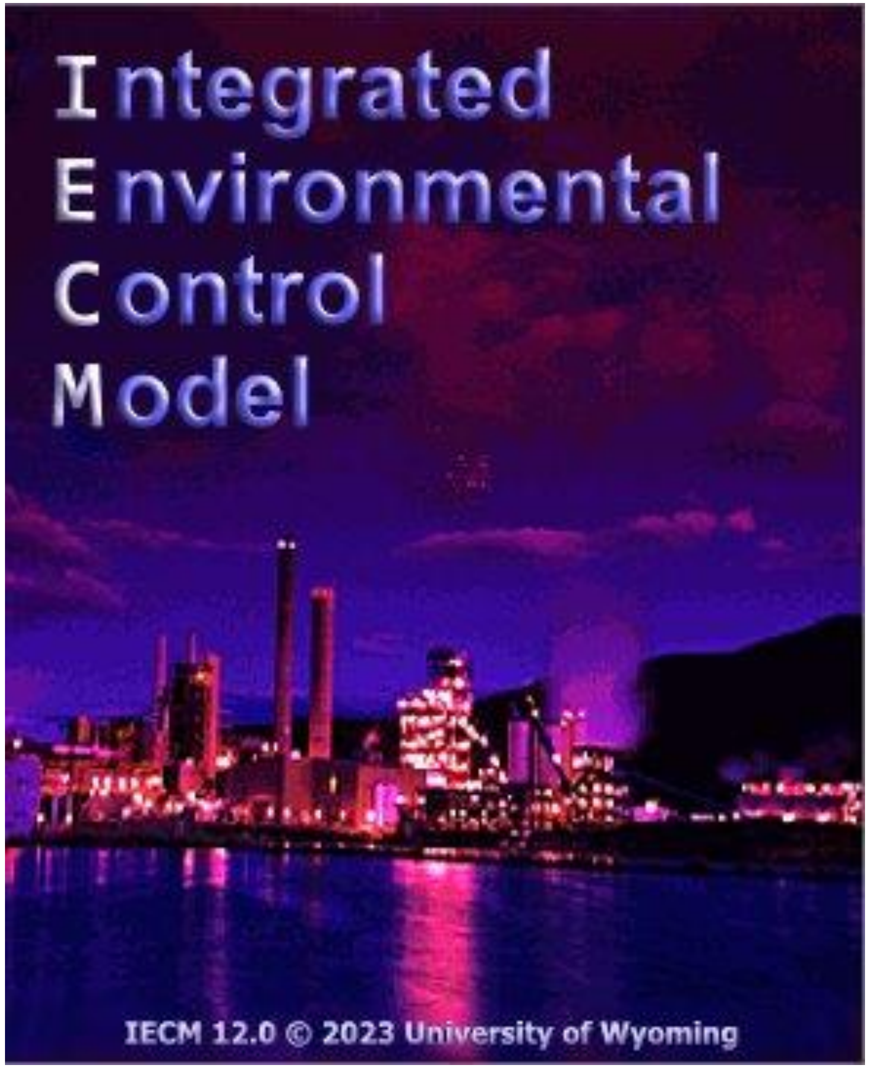
Methodology

- To evaluate the life cycle emissions of a co-firing power plant, this study:
  - Develops a fuel-based life cycle module,
  - Embeds the life cycle module to a power plant modeling tool, namely the Integrated Environmental Control Model (IECM), and then
  - Conducts the process-based performance analysis and life cycle assessment using the enhanced IECM.

Integrated Environmental Control Model (IECM) for Power Plant Assessment

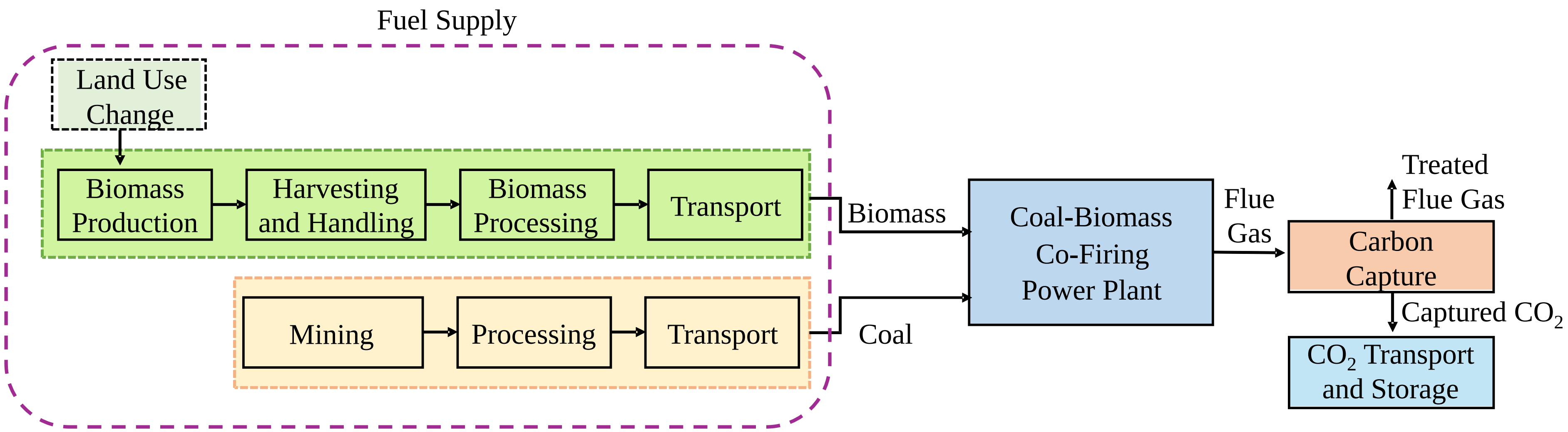
- A desktop/laptop computer model developed previously by CMU and now by UWyo for DOE/NETL; free and publicly available at:
  - https://www.iecm-online.com

- Provides systematic estimates of performance, emissions, costs, and uncertainties for the preliminary design of
  - Conventional and advanced power plants
  - Flue/fuel gas treatment systems
  - CO_2 capture and storage



Life Cycle GHG Emissions Analysis

- The Fuels of Interest.
  - Coal Resources: bituminous and sub-bituminous coal, and
  - Biomass Resources: energy crops, agricultural residues, and forestry residues.
- The scope of the life cycle assessment (LCA) includes fuel supply, electricity generation via combustion, and CO_2 transport and storage.
- The functional unit of LCA is 1 MWh of electricity delivered to the power grid.



Life Cycle GHG Emissions Estimation

$$EF_{LCA} = \underbrace{EF_{coal} \times \frac{FR_{coal}}{MW_{net}}}_{\text{Coal}} + \underbrace{EF_{bio} \times \frac{FR_{bio}}{MW_{net}}}_{\text{Biomass}} + \underbrace{\frac{EF_{plant}}{MW_{net}}}_{\text{Power Generation}} + \underbrace{EF_{T\&S} \times \frac{FR_{CO_2Cap}}{MW_{net}}}_{CO_2\text{ Transport \& Storage}}$$

where,

EF_{LCA}: life cycle GHG emissions for co-firing power plant with CCS (kg_{CO2e}/MWh_{net})

EF_{coal}: coal supply GHG emissions (kg_{CO2e}/kg_{coal})

FR_{coal}: coal flow rate for co-firing power plant with CCS (kg_{coal}/hour)

MW_{net}: net electricity output of co-firing power plant with CCS (MW_{net})

EF_{bio}: biomass supply GHG emissions (kg_{CO2e}/kg_{bio})

FR_{bio}: biomass flow rate for co-firing power plant with CCS (kg_{bio}/hour)

EF_{plant}: stack emissions of co-firing power plant with CCS (kg_{CO2e}/hour)

$EF_{T\&S}$: CO_2 transport and storage GHG emissions ($kg_{CO2e}/kg_{CO2\text{-}captured}$)

FR_{CO_2Cap}: captured CO_2 flow rate for co-firing power plant with CCS ($kg_{CO2\text{-}captured}$/hour)

Coal Supply Emissions Estimation Method

$$EF_{coal} = EF_{coal}^{mining} + EF_{coal}^{process} + EF_{coal}^{transport}$$
$$EF_{coal}^{transport} = EF_{train}^{transport} \times D_{coal}^{train} + EF_{truck}^{transport} \times D_{coal}^{truck} + EF_{barge}^{transport} \times D_{coal}^{barge}$$

where,

EF_{coal}: coal supply GHG emission factor (kg_{CO2e}/kg_{coal})

EF_{coal}^{mining}; $EF_{coal}^{process}$; $EF_{coal}^{transport}$: emissions of coal mining; processing; transport (kg_{CO2e}/kg_{coal})

$EF_{train}^{transport}$; $EF_{truck}^{transport}$; $EF_{barge}^{transport}$: transport emissions of train; truck; barge ($kg_{CO2e}/kg_{coal}/km$)

D_{coal}^{train}; D_{coal}^{truck}; D_{coal}^{barge}: coal transport distance of train; truck; barge (km)

- The emissions of coal supply associated with (NETL, 2022, 2023):
  - Coal Mining: coal mine methane, extraction process, facility construction, ventilation (if applicable), overburden removal and mine reclamation (if applicable);
  - Coal Processing: handling and cleaning;
  - Coal Transport: train, truck, or barge.

Biomass Supply Emissions Estimation Method

$$EF_{bio} = EF_{bio}^{luc} + EF_{bio}^{production} + EF_{bio}^{harvest} + EF_{bio}^{process} + EF_{bio}^{transport}$$

$$EF_{bio}^{transport} = EF_{train}^{transport} \times D_{bio}^{train} + EF_{truck}^{transport} \times D_{bio}^{truck}$$

where,

EF_{bio}: biomass supply GHG emission factor (kg_{CO2e}/kg_{bio})

EF_{bio}^{luc}; $EF_{bio}^{production}$; $EF_{bio}^{harvest}$; $EF_{bio}^{process}$; $EF_{bio}^{transport}$: emissions of land use change; biomass production; biomass harvesting; biomass processing; biomass transport (kg_{CO2e}/kg_{bio})

$EF_{train}^{transport}$; $EF_{truck}^{transport}$: transport emissions of train; truck ($kg_{CO2e}/kg_{bio}/km$)

D_{bio}^{train}; D_{bio}^{truck}: biomass transport distance of train; truck (km)

- The emissions of biomass supply associated with * (NETL, 2022, 2023; Bush et al., 2001; EPRI, 2010, 2012; Zygarlicke et al., 2001; Kopczyński et al., 2017; ECN, 2022):
  - Land Use Change: direct and indirect land use change;
  - Biomass Production: CO_2 uptake, biomass cultivation, herbicide and fertilizer;
  - Biomass Harvesting: harvesting and handling;
  - Biomass Processing: grinding and torrefaction (if needed);
  - Biomass Transport: train, truck, or barge.

*Details are provided in Appendix.

Plant Operation Emissions Estimation Method

- The combustion-based power plant burns fuel and consumes natural resources to generate electricity for the grid, and it also emits stack emissions into the atmosphere.
- GHG emissions of the power plant operation refer to the plant-level CO_2 stack emissions ($\mathrm{EF_{plant}}$).
- The GHG emissions for the electricity generation plant can be estimated by enhanced IECM.
    - Enhancements to the IECM model, including*:
        - Addition of fuel blend option
        - Addition of biomass database
        - Improvement of boiler efficiency
        - Development of a fuel-based life cycle module

*Details are provided in the Appendix.

CO_2 Transport and Storage Emissions-Estimation Method

$$EF_{T\&S} = EF_{T\&S}^{Pipeline} + EF_{T\&S}^{geostorage}$$

where,

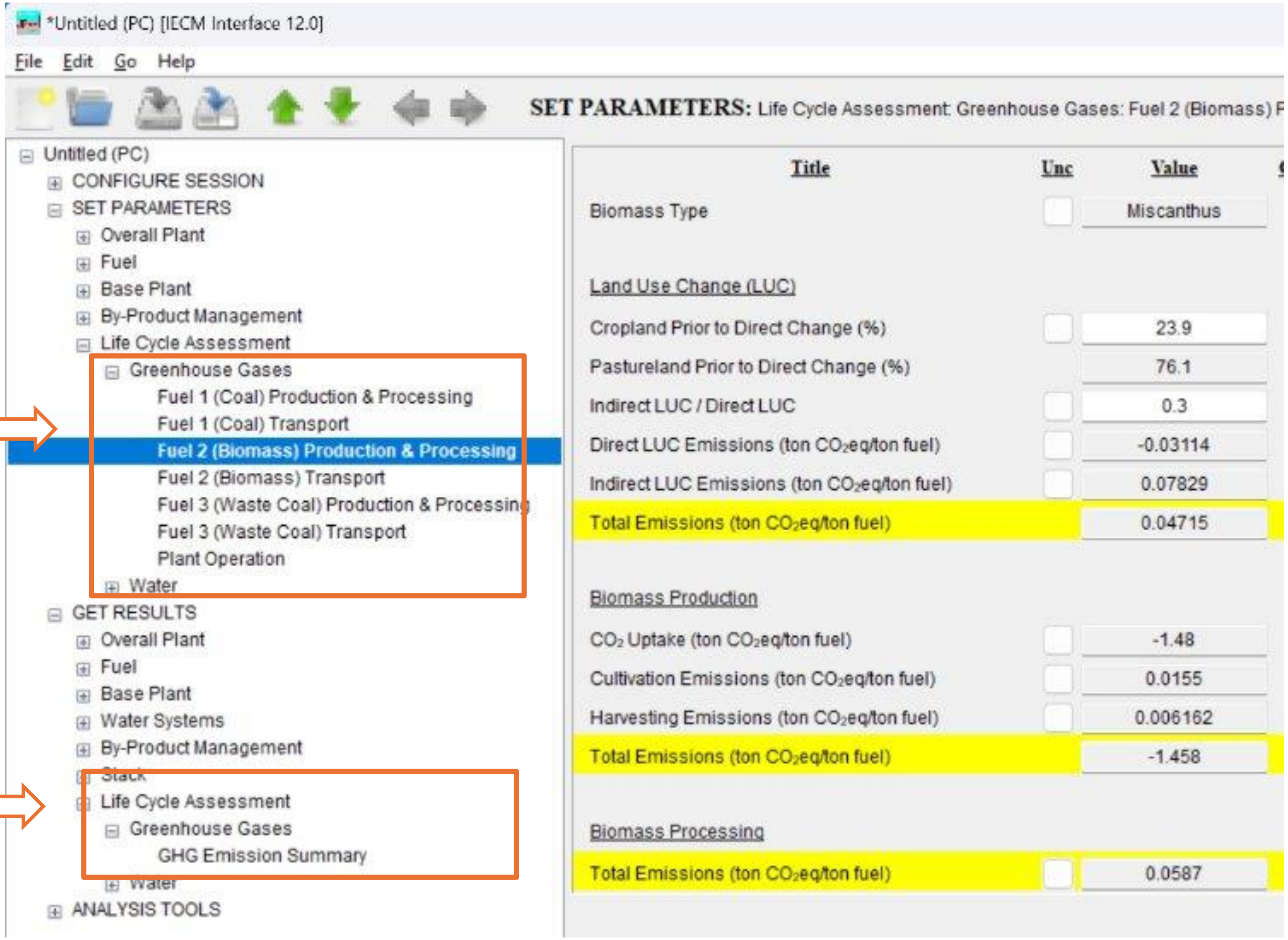
$EF_{T\&S}$: CO_2 transport and storage GHG emission factor ($kg_{CO2e}/kg_{CO2\text{-}captured}$)
$EF_{T\&S}^{Pipeline}$: emissions of CO_2 pipeline transport ($kg_{CO2e}/kg_{CO2\text{-}captured}$)
$EF_{T\&S}^{geostorage}$: emissions of CO_2 geological storage ($kg_{CO2e}/kg_{CO2\text{-}captured}$)

- The GHG emissions of CO_2 transport and storage associated with (NETL, 2022, 2023):
  - CO_2 Transport: pipeline fugitive, pigging, pipeline construction, injection pump leakage.
  - CO_2 Storage: site operation and brine management, formation leakage, seismic site preparation and monitoring, saline aquifer well assembly.

Life Cycle GHG Emission Model in IECM

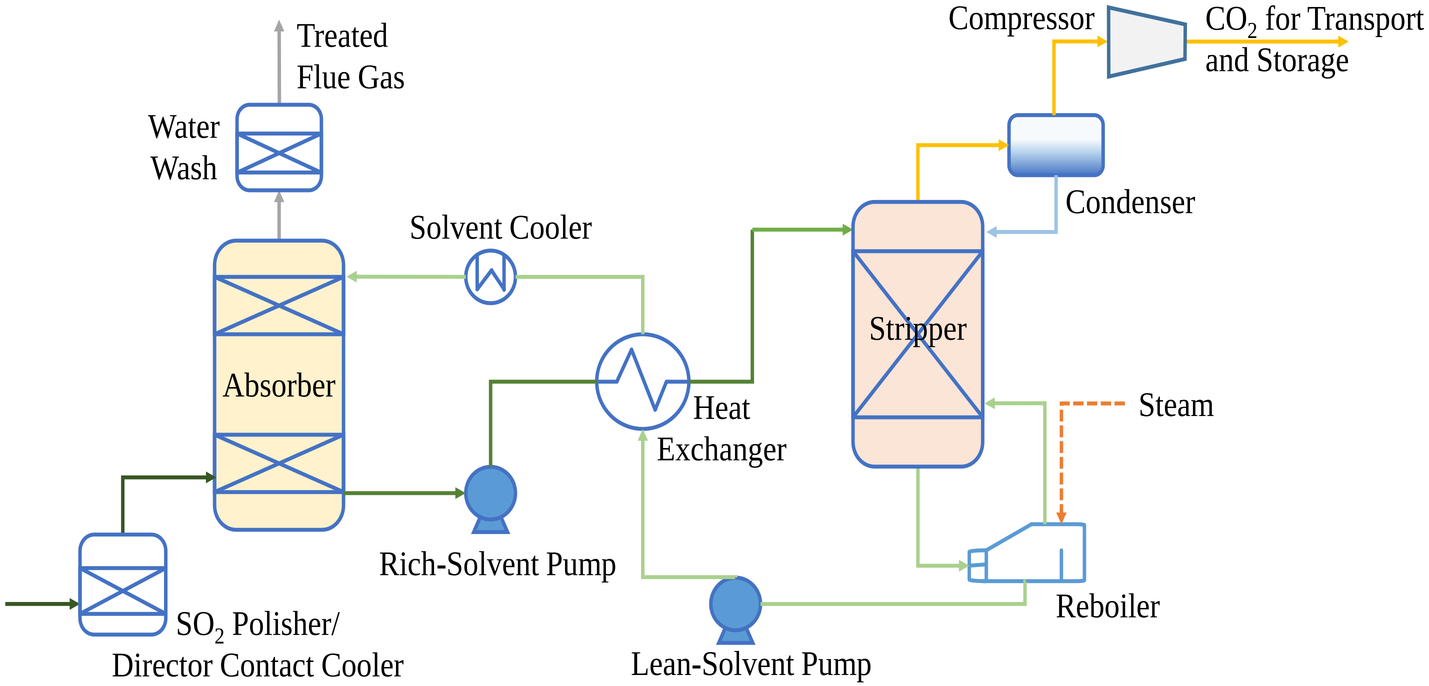
LCA Module
Set Parameters

LCA Module
Get Results



Life Cycle GHG Emissions Analysis: Case Studies

- Configuration of Co-Firing Power Plants:
  - 0–20% co-firing rate of biomass at a coal-fired power plant;
  - with or without amine-based post-combustion capture using monoethanolamine (MEA).

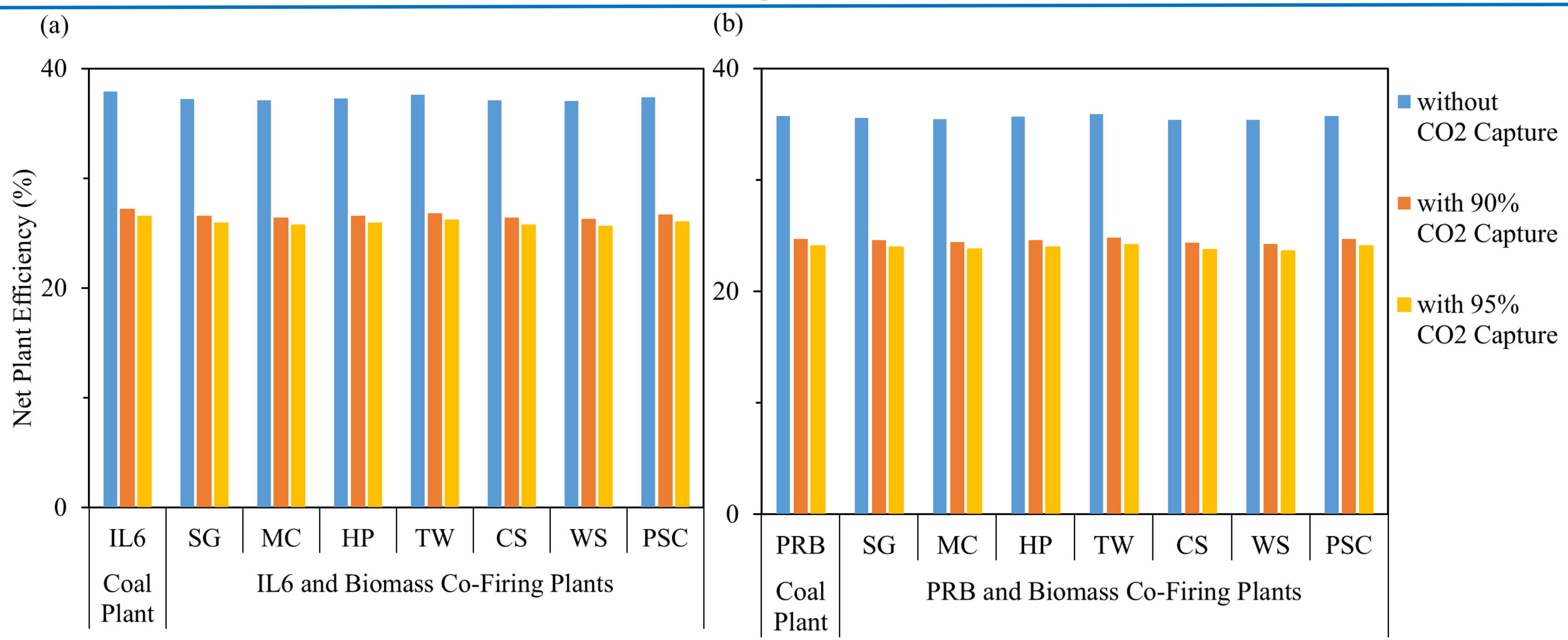


Major Parameters and Assumptions for Coal-Biomass Co-Firing Power Plants

Parameter	Value
Plant Type	Supercritical
Gross Capacity (MW_g)	650
Capacity Factor (%)	75
Co-Firing Level (%, Energy Basis)	20
Plant Location	Illinois State and Wyoming State
Primary Fuel Option	Bituminous and Subbituminous Coal
Coal Type	Illinois No. 6 Coal (IL6), Powder River Basin Coal (PRB)
Coal Transport Method and Distance	Train (644 km)
Secondary Fuel Option	Biomass
Biomass Type	Switchgrass (SG), Miscanthus (MC), Hybrid Poplar (HP), Torrefied Wood (TW), Corn Stover (CS), Wheat Straw (WS), Pine Spruce Chip (PSC)
Biomass Transport Method and Distance	Truck (200 km in IL State, 1000 km in WY State)
Environmental Control Systems	
NO_x Control	Hot-Sided Selective Catalytic Reduction
Particulate Control	Cold-Sided Electrostatic Precipitator
SO_2 Control	Wet Flue Gas Desulfurization
CO_2 Capture Technology (If Applicable)	Econamine FG+
CO_2 Capture Rate (%, If Applicable)	90, 95
Cooling System	Wet Cooling Tower

Performance and Life Cycle Emissions of Base Cases

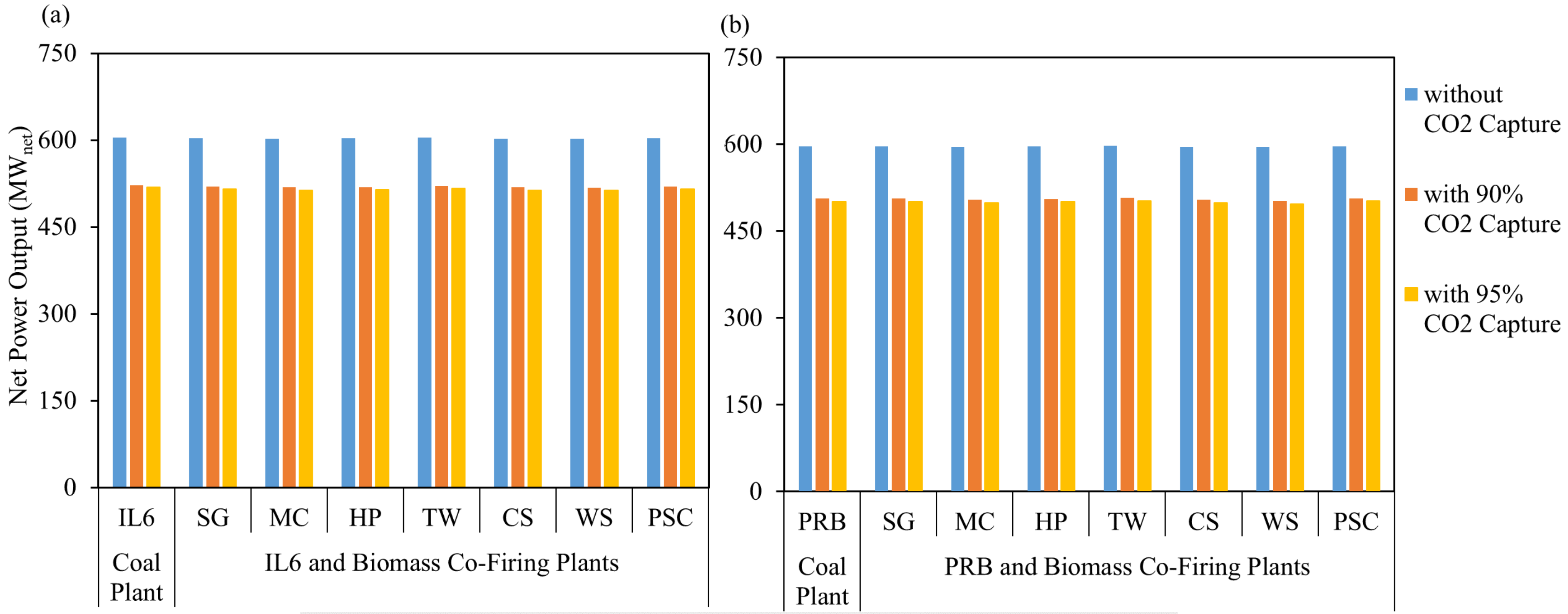
Net Plant Efficiency of 20% Co-Firing Power Plants



IL6: Illinois No.6 Coal; PRB: Powder River Basin Coal; SG: Switchgrass; MC: Miscanthus; HP: Hybrid Poplar; TW: Torrefied Wood; CS: Corn Stover; WS: Wheat Straw; PSC: Pine Spruce Chip

- Co-firing power plants have a less net efficiency (1% on average) than that of coal-fired power plants.
- Deployment of CCS for 90% and 95% CO_2 capture decreases the net plant efficiency by 30% and 32%, compared to the cases without CCS, respectively.

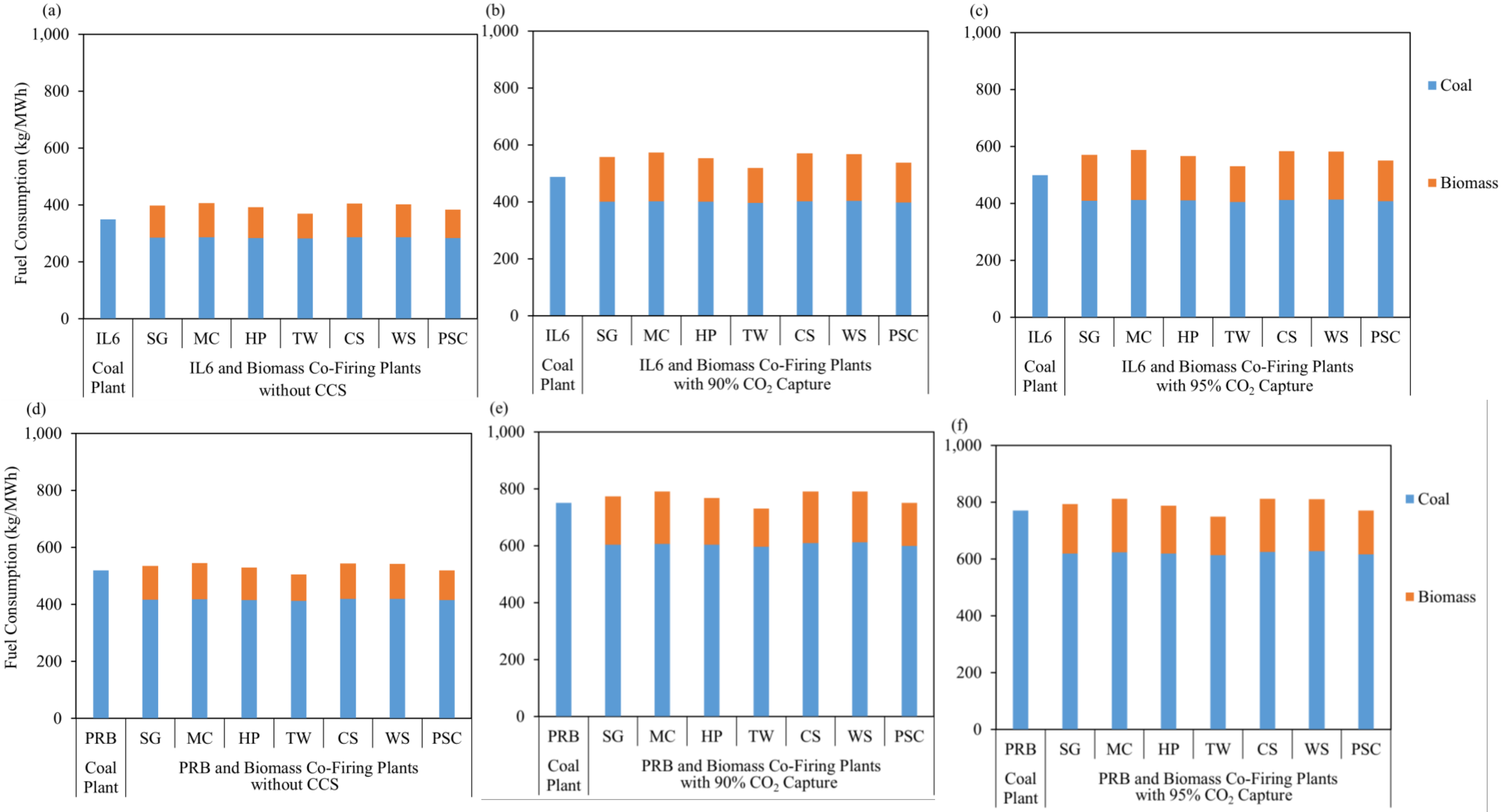
Net Power Output of 20% Co-Firing Power Plants



IL6: Illinois No.6 Coal; PRB: Powder River Basin Coal; SG: Switchgrass;
MC: Miscanthus; HP: Hybrid Poplar; TW: Torrefied Wood;
CS: Corn Stover; WS: Wheat Straw; PSC: Pine Spruce Chip

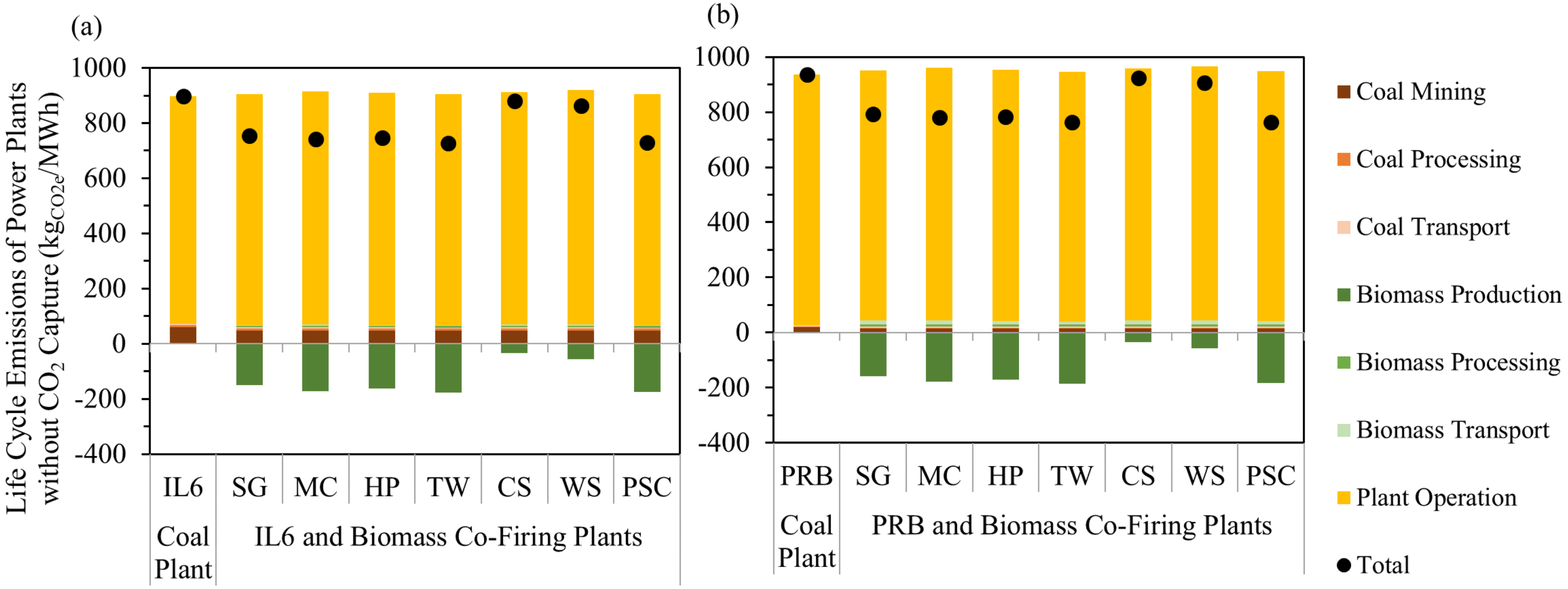
- The net power output of co-firing power plants is 0.2% less on average than that of coal-fired power plants.
- The net power outputs of plants with CCS of 90% and 95% CO_2 capture are 14.6% and 15.3% lower on average than that of the cases without CCS, respectively.

Fuel Consumption of 20% Co-Firing Power Plants



- Co-firing with biomass (excluding torrefied wood) and implementing CCS increase the fuel consumption.

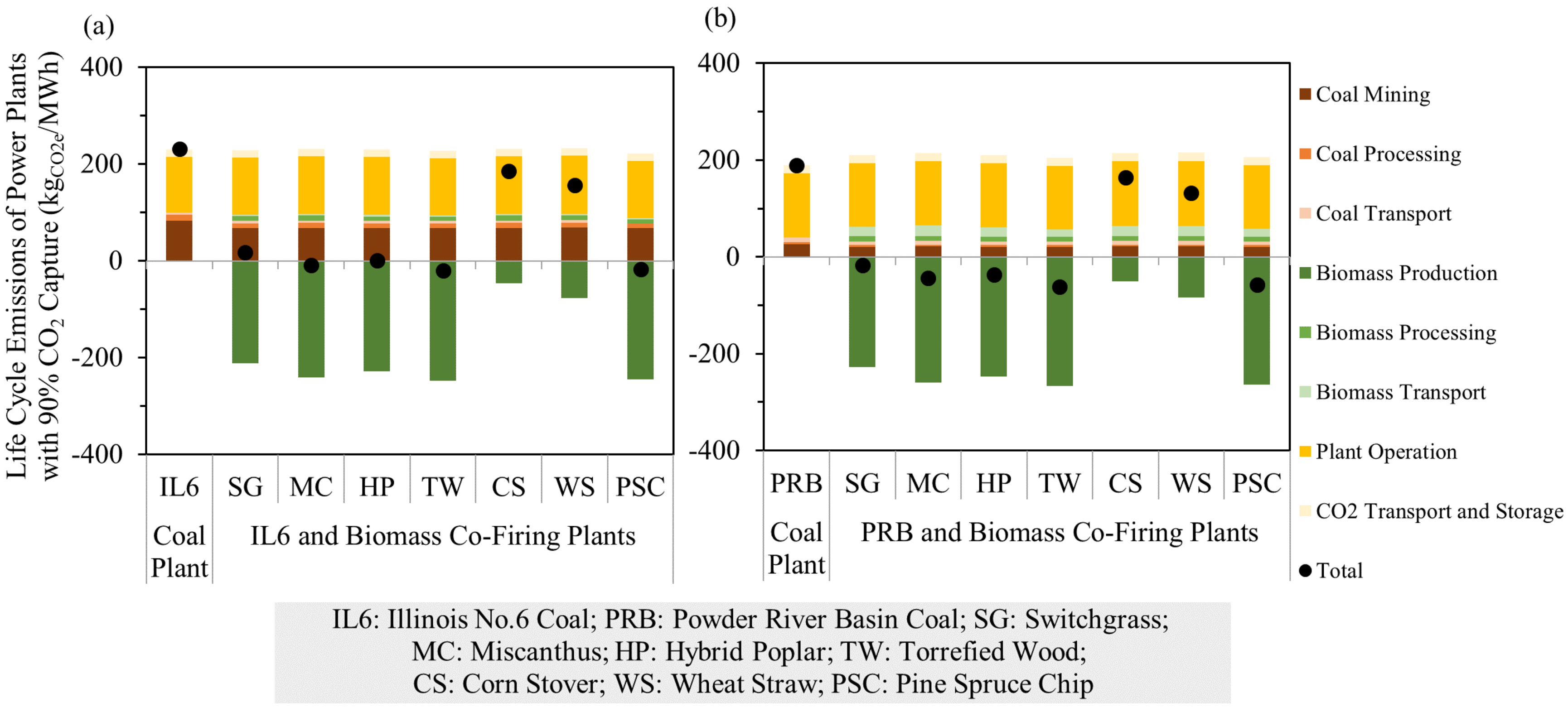
Life Cycle Emissions of 20% Co-Firing Power Plants without CO_2 Capture



IL6: Illinois No.6 Coal; PRB: Powder River Basin Coal; SG: Switchgrass;
MC: Miscanthus; HP: Hybrid Poplar; TW: Torrefied Wood;
CS: Corn Stover; WS: Wheat Straw; PSC: Pine Spruce Chip

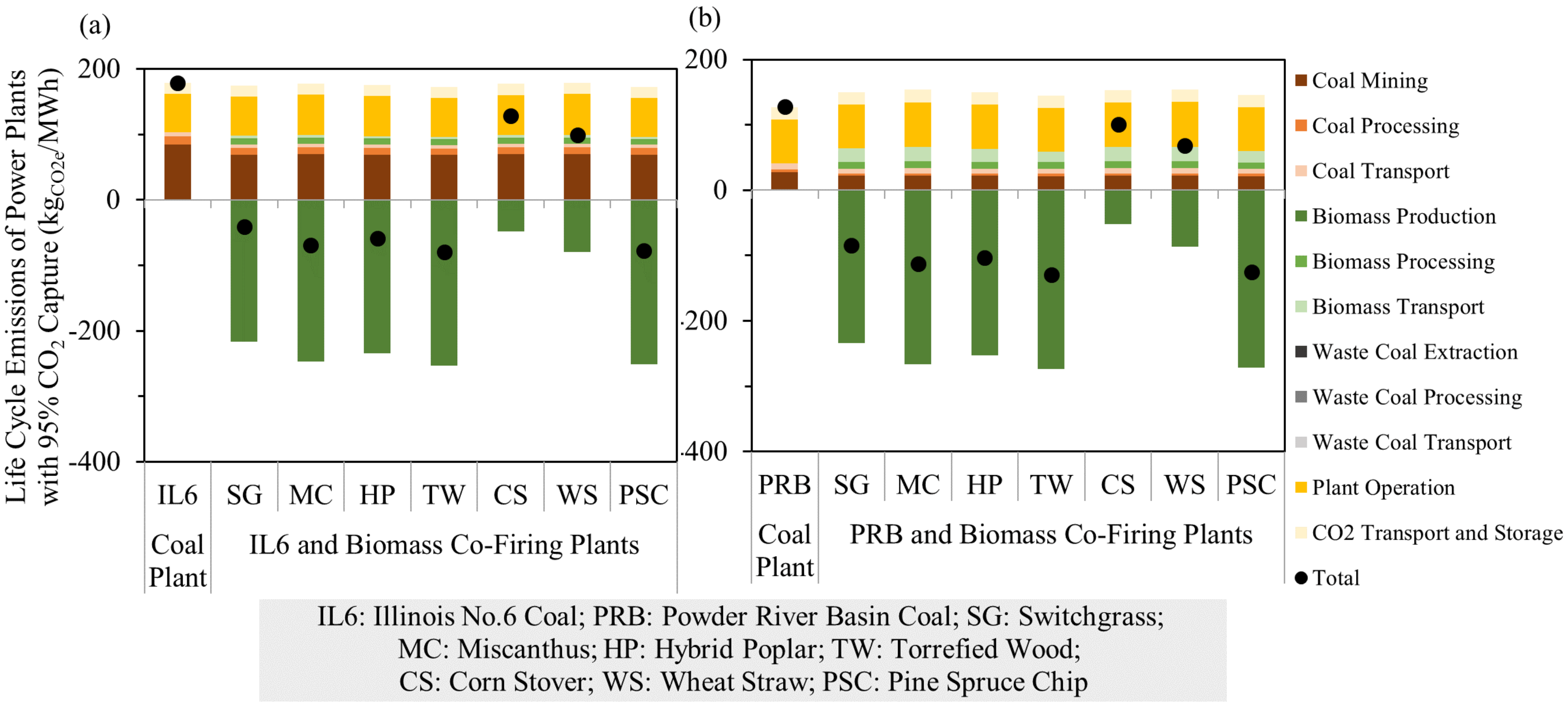
- GHG emissions from power plant operations dominate the total life cycle emissions.
- The life cycle GHG emissions of IL6 coal-fired plants and PRB coal-fired plants are similar, with IL6 coal-fired plant having slightly less emissions.
- Without CCS, it is difficult to achieve net-zero emissions on a life cycle basis.

Life Cycle Emissions of 20% Co-Firing Power Plants with 90% CO_2 Capture



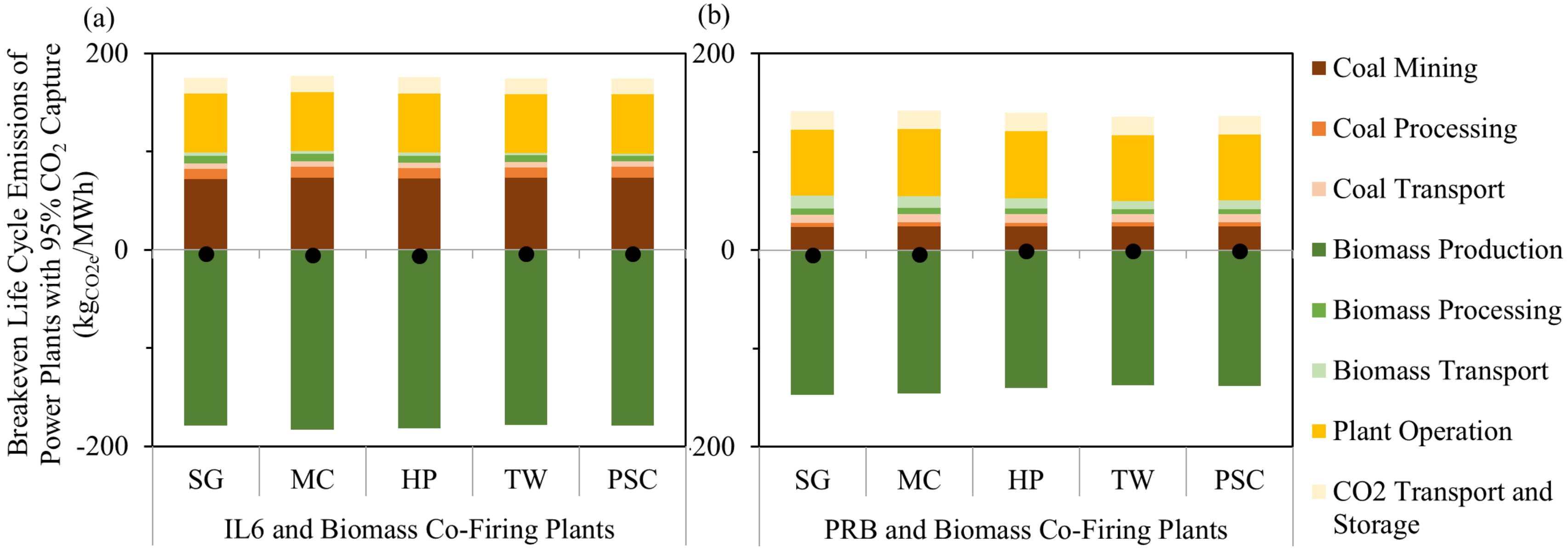
- Deploying CCS for 90% CO_2 capture reduces the life cycle GHG emissions of co-firing power plants by 95% on average, compared to the cases without CCS.
- Net-zero life cycle GHG emissions can be achieved if coal is co-fired with miscanthus, torrefied wood, or pine spruce chip at power plants with 90% CO_2 capture.

Life Cycle Emissions of 20% Co-Firing Power Plants with 95% CO_2 Capture



- Deploying CCS for 95% CO_2 capture decreases the life cycle GHG emissions of co-firing power plants by 102% on average, compared to the cases without CCS.
- Net-zero life cycle GHG emissions can be reached if coal is co-fired with switchgrass, miscanthus, hybrid poplar, torrefied wood, or pine spruce chip at power plants with 95% CO_2 capture.

Co-Firing Level for Net-Zero Life Cycle Emissions at Power Plants with 95% CO_2 Capture



IL6: Illinois No.6 Coal; PRB: Powder River Basin Coal; SG: Switchgrass;
MC: Miscanthus; HP: Hybrid Poplar; TW: Torrefied Wood;
PSC: Pine Spruce Chip

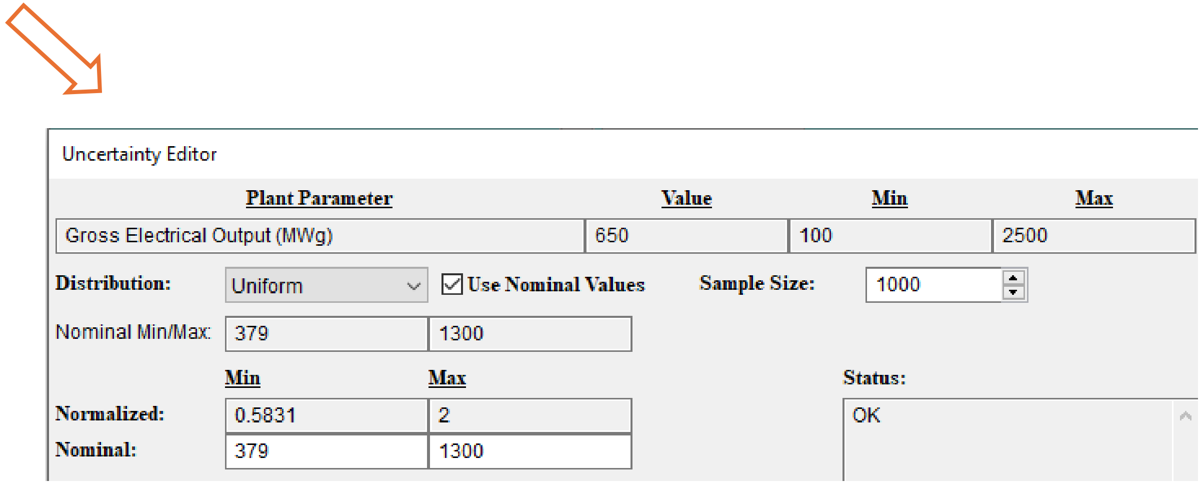
- With the deployment of deep CCS, net-zero life cycle GHG emissions can be attained with biomass co-firing levels ranging from 10% to 17% on an energy basis.

Probabilistic Analysis of Life Cycle GHG Emissions

Life Cycle GHG Emissions Analysis: Uncertainty Engine

- The IECM's uncertainty engine is embedded into the LCA module, which enables probabilistic estimates of life cycle emissions.

Title	Unc	Value	Calc
Gross Electrical Output (MWg)	?	650	☑
Unit Type		Supercritical	
Steam Cycle Heat Rate, HHV (kJ/kWh)	?	9396	☑
Boiler Firing Type		Tangential	
Boiler Efficiency (%)	?	86.34	☑
Excess Air For Furnace (% stoich.)	?	20	☑
Leakage Air at Preheater (% stoich.)		10	☑
Gas Temperature Exiting Economizer (°C)		371.1	
Gas Temperature Exiting Air Preheater (°C)		148.9	
Percent Water in Bottom Ash Sluice (%)		0	☑
Hydrated Lime for SO_3 Removal (kg/kmol SO_3)		1059	



Major Uncertain Parameters and Probability Distribution Functions: Coal Supply

Parameter	Base Case Value	Probability Distribution Function	Source(s) of Uncertainty Range
Illinois No. 6 Coal Mining (kg_{CO2e}/kg_{coal})	0.169	Triangular(0.100, 0.169, 0.742)	Skone et al (2018), NETL LCI (2020)
Illinois No. 6 Coal Processing (kg_{CO2e}/kg_{coal})	0.025	Triangular(0.019, 0.025, 0.029)	Cunanan et al. (2021), DOE (2003), DOE (1996), NETL (2013), DOE (2007)
Powder River Basin Coal Mining (kg_{CO2e}/kg_{coal})	0.035	Uniform(0.0133, 0.0429)	Skone et al (2016), NETL LCI (2020)
Powder River Basin Coal Processing (kg_{CO2e}/kg_{coal})	0.0055	Triangular(0.0037, 0.0055, 0.0072)	Cunanan et al. (2021), DOE (2003), DOE (1996), NETL (2013), DOE (2007)

Major Uncertain Parameters and Probability Distribution Functions: Biomass Supply

Parameter	Base Case Value	Probability Distribution Function	Source(s) of Uncertainty Range
Torrefied Wood's Carbon (wt%)	55.38	Uniform(54.7, 57.30)	Bridgeman et al. (2008), Ibrahim, et al. (2013)
Torrefied Wood's HHV* (kJ/kg)	21835	Uniform(21396, 23072)	
Torrefied Wood's Wet-Basis Yield (kg/ha/yr)	12075	Uniform(4282, 15760)	Kuzovkina et al (2018)
Corn Stover's Carbon (wt%)	41.24	Triangular(35.57, 41.24, 45.21)	ECN (2022), Shah et al (2012)
Corn Stover's HHV* (kJ/kg)	16230	Triangular(13642, 16230, 18626)	
Corn Grain's Carbon (wt%)	38.25	Triangular(23.65, 38.25, 47.26)	Folkedahl (2009), NETL (2010), Yao et al (2016)
Corn Grain's HHV* (kJ/kg)	16212	Triangular(9691,16212,18150)	
Corn Stover's Wet-Basis Yield (kg/ha/yr)	2473	Uniform(2019, 2909)	USDA (2024), NETL (2010)
Corn Grain's Harvest Index (fraction)	0.57	Triangular(0.35, 0.57, 0.79)	Pennington (2013), NETL (2010)
Corn Stover's Collection Efficiency (fraction)	0.35	Triangular(0.25, 0.35, 0.95)	Scarlat, et al. (2010), NETL (2010), Prewitt, et al (2007)
Pine Spruce Chip's Carbon (wt%)	47.91	Triangular(25.70, 47.91, 48.82)	ECN (2022)
Pine Spruce Chip's HHV* (kJ/kg)	19305	Triangular(9330, 19305, 19350)	
Pine Spruce Chip's Wet-Basis Yield (kg/ha/yr)	61537	Uniform(7605, 105648)	Eker, et al (2017), Bergman, et al (2022), ECN (2022)

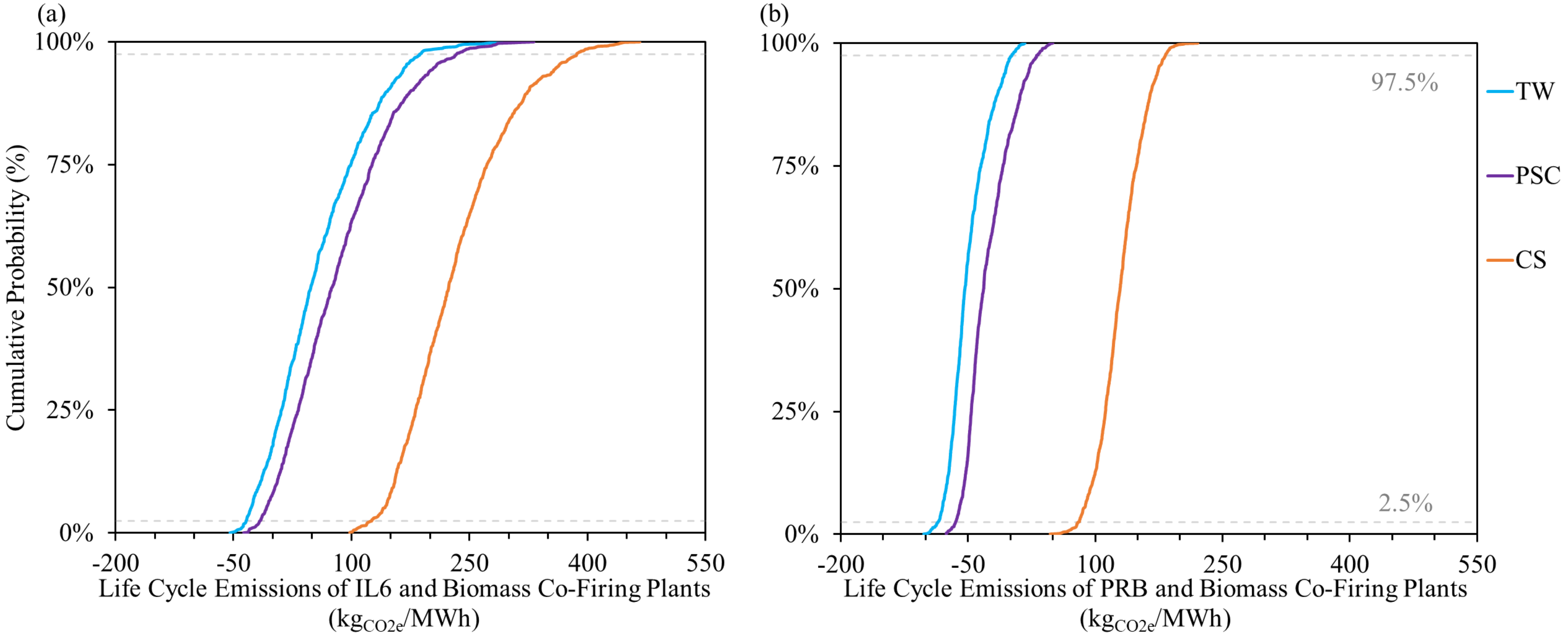
*HHV stands for Higher Heating Value;
The Switchgrass, Miscanthus, Hybrid poplar, and Wheat straw's uncertain parameters and its probability distribution functions are provided in the Appendix.

Major Uncertain Parameters and Probability Distribution Functions: Plant Operation

Parameter	Base Case Value	Probability Distribution Function	Source(s) of Uncertainty Range
Base Plant Operation			
Gross Capacity (MW_g)	650	Uniform(379, 1300)	EIA860 (2022)
Boiler Efficiency (%)	88*	Uniform(81, 92)	DOE (2002), Vakkilainen (2017)
90% CO_2 Capture: Steam Cycle Heat Rate (kJ/MWh)	9392*	Uniform(8393,10180)	IECM (2021)
95% CO_2 Capture: Steam Cycle Heat Rate (kJ/MWh)	9525*	Uniform(8507, 10350)	IECM (2021)
Excess Air to Furnace (% stoich)	20	Uniform(15, 25)	Rubin et al (1994)
CO_2 Capture Technology			
90% CO_2 Capture: Regeneration Heat Requirement (kJ/kg CO_2)	3517	Triangular(2645, 3517, 4408)	Ou et al (2016)
95% CO_2 Capture: Regeneration Heat Requirement (kJ/kg CO_2)	3570	Triangular(2685, 3570, 4475)	Ou et al (2016), IECM (2019)
Heat-to-Electricity Efficiency (%)	18.7	Triangular(14, 18.7, 22)	Ou et al (2016)

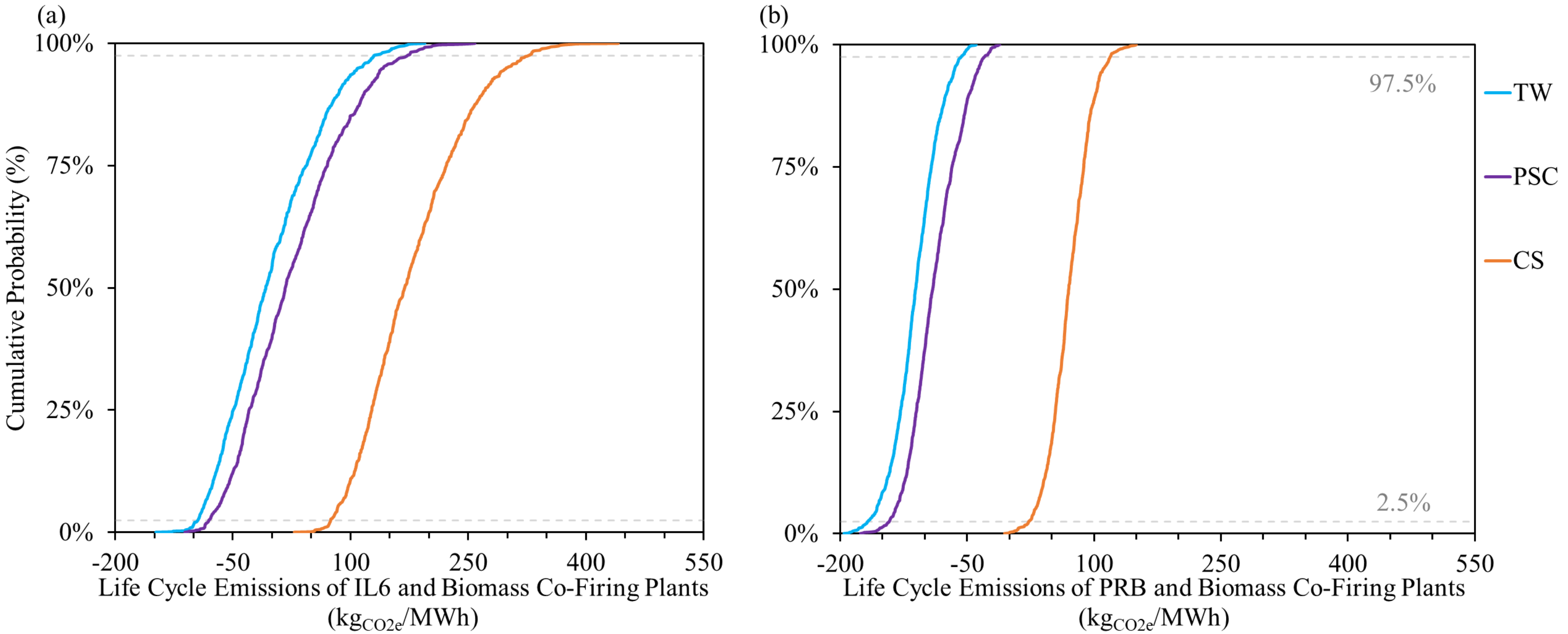
*The value represents the Il6-fired cases.

Probability Distribution of Life Cycle Emissions of 20% Co-firing Plants with 90% CO_2 Capture



- The life cycle GHG emissions distribution for IL6 co-firing plants has a broader range than that of PRB plants, due to the larger uncertainty of coal mine methane emission during underground mining.
- Co-firing with torrefied wood shows promise in reducing life cycle GHG emissions of coal-fired power plants.
- Deploying CCS for 90% CO_2 capture, the 95-percentile life cycle GHG emissions distribution of the coal power plant fired with 20% torrefied wood ranges from –34 to 186 kg_{CO2e}/MWh for IL6 as primary fuel and from –85 to 1 kg_{CO2e}/MWh for PRB as primary fuel.

Probability Distribution of Life Cycle Emissions of 20% Co-firing Plants with 95% CO_2 Capture



- Deployment of CCS for 95% CO_2 capture in the coal power plant fired with 20% torrefied wood, the 95-percentile life cycle GHG emissions distribution ranges from –94 to 125 kg_{CO2e}/MWh for IL6 as primary fuel and from –167 to -61 kg_{CO2e}/MWh for PRB as primary fuel.

Conclusions

- Underground mining has a larger environmental impact than surface mining, majorly due to the larger coal mine methane emission from ventilation.
- It is hard for biomass co-firing without CCS to achieve net-zero life cycle emissions.
- Fuel supply and plant operation are the major stages influencing the life cycle emissions.
- Deployment of 90% or 95% CCS significantly decreases the life cycle emissions.
- The breakeven co-firing level to net-zero GHG emissions varies by plant performance and fuel properties.
- The integration of deep CCS (95% CO_2 capture rate) with biomass co-firing can achieve net-zero emissions on a life cycle basis.

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