Plant and Process Level Carbon Capture Techno-Economic Analysis at NETL

Timothy Fout

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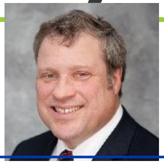
U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

Systems Engineering & Analysis

Associate Director, Acting
Peter C. Balash, Ph.D.



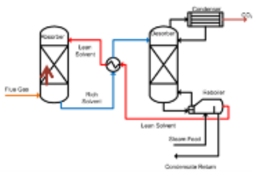
Senior Fellow
David Miller, Ph.D.

NATIONAL ENERGY TECHNOLOGY LABORATORY

Energy Process Analysis

Energy Process Design, Analysis, and Cost Estimation

- Plant-level modeling, performance assessment
- Cost estimation for plant-level systems
- General plant-level technology evaluation and support



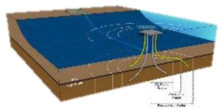
Advanced Technology Design & Cost Estimation

Travis Shultz

Energy Systems Analysis

Resource Availability and Cost Modeling

- CO_2 storage (saline and EOR)
- Fossil fuel extraction
- Rare earth elements
- General subsurface technology evaluation and support



Life Cycle Analysis (LCA)

Luciane Cunha, Ph.D.

Process Systems Engineering Research

- Process synthesis, design, optimization, intensification
- Steady state and dynamic process model development
- Uncertainty quantification
- Advanced process control

CCSI Carbon Capture Simulation Initiative

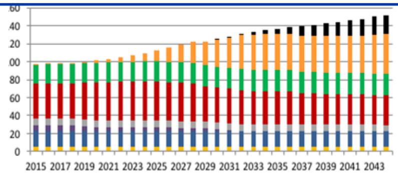
$CCSI^2$ Carbon Capture Simulation for Industry Impact

Anthony Burgard, Ph.D.

IDAES Institute for the Design of Advanced Energy Systems

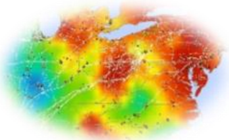
Balash, Acting

Energy Markets Analysis



Energy Economy Modeling and Impact Assessment

- Enhanced fossil energy representation
- Multi-model scenario/policy analysis
- Grid, infrastructure, energy-water



- Economic impact assessment
- General regulatory, market and financial expertise

Overview

- **BECCS Study (includes LCA)**
  - Design Basis Review
  - Performance Results
  - Economic Results
- **Ongoing Updates**
- **Questions**

BECCS Key Research Questions:

1. Can co-firing biomass with coal reduce greenhouse gas (GHG) emissions on a life cycle basis?
2. Will adding biomass to coal-fired power plants increase or decrease the cost of electricity?
3. What is the optimal combination of coal and biomass to achieve low-carbon electricity and low costs?

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Site Characteristics

- **Site characteristics and ambient conditions are consistent with Revision 4 of the Bituminous Baseline Study**

Site Characteristics

Parameter	Value
Location	Greenfield, Midwestern U.S.
Topography	Level
Size (pulverized coal), acres	300
Size (natural gas combined cycle), acres	100
Transportation	Rail or Highway
Ash Disposal	Off-Site
Water	50% Municipal and 50% Ground Water

Site Ambient Conditions

Parameter	Value
Elevation, m (ft)	0 (0)
Barometric Pressure, MPa (psia)	0.101 (14.696)
Average Ambient Dry Bulb Temperature, °C (°F)	15 (59)
Average Ambient Wet Bulb Temperature, °C (°F)	10.8 (51.5)
Design Ambient Relative Humidity, %	60
Cooling Water Temperature, °C (°F)[A]	15.6 (60)
Air composition based on published psychrometric data, mass %	
N_2	75.055
O_2	22.998
Ar	1.280
H_2O	0.616
CO_2	0.050
Total	100.00

[A] The cooling water temperature is the cooling tower cooling water exit temperature; this is set to 8.5°F above ambient wet bulb conditions in International Organization for Standardization (ISO) cases

- Quality Guidelines for Energy Systems Studies: Process Modeling Design Parameters, June 2019, NETL-PUB 22478
https://netl.doe.gov/projects/files/QualityGuidelinesforEnergySystemStudiesProcessModelingDesignParameters_062819.pdf

Fuel Characteristics

- **The coal analysis is consistent with the Bituminous Baseline Rev4 analysis**
- **Biomass characteristics consistent with prior NETL report**

Hybrid Poplar[1]		
Ultimate Analysis (weight %)		
	As Received	**Dry**
Moisture	50.00	0.00
Carbon	26.18	52.36
Hydrogen	2.80	5.60
Nitrogen	0.19	0.37
Chlorine	0.00	0.00
Sulfur	0.02	0.03
Ash	0.74	1.48
Oxygen[B]	20.08	40.16
Total	100.0	100.00
HHV, kJ/kg (Btu/lb)	9,813 (4,219)	19,627 (8,438)
LHV, kJ/kg (Btu/lb)	9,232 (3,969)	18,464 (7,938)

	Volume 1 Rev 4	
Rank	**Bituminous**	
Seam	**Illinois No. 6[2]**	
Source	-	
Proximate Analysis (weight %)[A]		
	As Received	**Dry**
Moisture	11.12	0.00
Ash	9.70	10.91
Volatile Matter	34.99	39.37
Fixed Carbon	44.19	49.72
Total	100.00	100.00
Sulfur	2.51	2.82
HHV, kJ/kg (Btu/lb)	27,113 (11,666)	30,506 (13,126)
LHV, Btu/lb (Btu/lb)	26,151 (11,252)	29,544 (12,712)
Ultimate Analysis (weight %)		
	As Received	**Dry**
Moisture	11.12	0.00
Carbon	63.75	71.72
Hydrogen	4.50	5.06
Nitrogen	1.25	1.41
Chlorine	0.15	0.17
Sulfur	2.51	2.82
Ash	9.70	10.91
Oxygen[B]	7.02	7.91
Total	100.00	100.00

[A] The proximate analysis assumes sulfur as volatile matter
[B] By difference

1. Greenhouse Gas Reductions in the Power Industry Using Domestic Coal and Biomass – Volume 2: PC Plants, February 2012, DOE-NETL-2012/1547
https://netl.doe.gov/projects/files/GreenhouseGasReductionsinthePowerIndustryUsingDomesticCoalandBiomassVolume2PCPlants_020113.pdf
2. Quality Guidelines for Energy Systems Studies: Specification for Selected Feedstocks, January 2019, NETL-PUB 22460
https://netl.doe.gov/projects/files/QGESS%20Feed%20Specs%20-%20Final.pdf

MATS and NSPS Limits

- **The utility Mercury and Air Toxics Standards (MATS) and New Source Performance Standards (NSPS) limits for pulverized coal (PC) plants considered in the Bituminous Baseline Rev4 is adhered to**

MATS and NSPS Emission Limits for PM, HCl, SO_2, NOx, and Hg	
Pollutant[A]	PC (lb/MWh-gross)
SO_2	1.00
NOx	0.70
PM (Filterable)	0.09
Hg	$3x10^{-6}$
HCl	0.010

[A] CO emissions were not considered, or reported, in BBR Rev 4

Biomass Pre-Processing

- The current and prior studies assume that cut and sized hybrid poplar logs are received at the plant site by truck
- The logs are then pre-processed to improve the energy density, handling characteristics, and combustion efficiency of the hybrid poplar, as depicted below

Receiving/ Unloading/ Handling → Chipping/ Grinding → Drying → Pelletizing → Storage

Receiving/ Unloading/ Handling
- Cut/sized logs
- Field dried to 50 wt. % H_2O
- 48,000 lb truck capacity

Chipping/ Grinding
- Size reduction (<5 mm) to facilitate drying and pelletizing steps

Drying
- WTA drying process
- Dry to 10 wt.% H_2O

Pelletizing
- Improved physical properties for downstream storage and handling (e.g., pulverization, boiler injection)

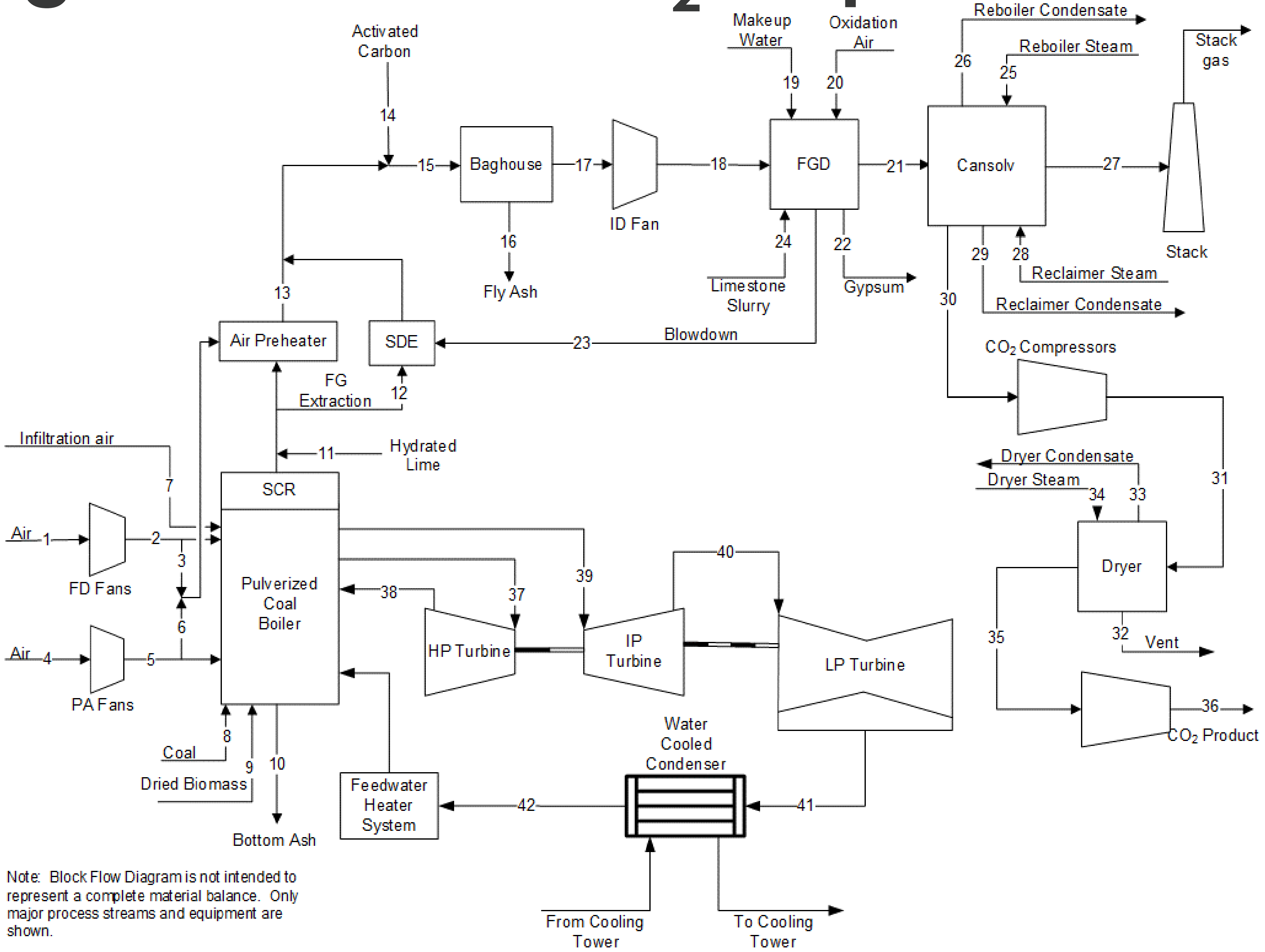
Storage
- 72 hours of short term storage

Design Assumptions

- Biomass is available in the quantity, type, frequency, and at the cost assumed in the study
- Biomass co-firing does not effect performance/cost of the carbon capture system
- Product CO_2 must meet requirements of NETL QGESS on CO_2 product purity[1]
- Facility Capacity Factor = Availability = 85% for all cases
- Capital Cost Uncertainty Range -15%/+30% (AACE Class 4)[2]
- Use mature plant costing methodology[2]
    - Initial plants will likely have higher costs when incorporating CCS and co-firing

1. Quality Guidelines for Energy Systems Studies: CO_2 Impurity Design Parameters, January 2019, NETL-PUB 22529 https://netl.doe.gov/projects/files/QGESSCO2ImpurityDesignParameters_010119.pdf
2. Quality Guidelines for Energy Systems Studies: Capital Cost Scaling Methodology: Revision 4 Report, October 2019, NETL-PUB 22697 https://netl.doe.gov/projects/files/QualityGuidelinesforEnergySystemStudiesCapitalCostScalingMethodologyRevision4Report_110719.pdf

Plant Configuration with CO_2 Capture



Note: Block Flow Diagram is not intended to represent a complete material balance. Only major process streams and equipment are shown.

Case Matrix

- **The following case matrix was considered part of this study update**

Case	Biomass Type	Plant Type	% Biomass in Feed	CO_2 Capture %	Capture Strategy
PN1	Hybrid Poplar	Greenfield Supercritical	20	0	N/A
PN2			35		
PN3			49		
PA1			20	90	Amine (Cansolv)
PA2			35		
PA3			49		

  - 20 wt%
    - Lower end of co-firing
    - Represents the majority of currently in practice co-firing rates
    - Boiler efficiency impacts not statistically significant
  - 35 wt%
    - Mid-range of feasible co-firing
    - Close to the potential net-zero greenhouse gas emissions point (with capture)
    - If the desired result is for a net-zero LCA, this co-fire rate could be changed
  - 49 wt%
    - Current potential maximum rate of co-firing based on logistical supply constraints
    - Maintains coal with biomass co-firing idea
  - Case nomenclature: P – poplar, N – non-capture, A – amine, numericals – case designation

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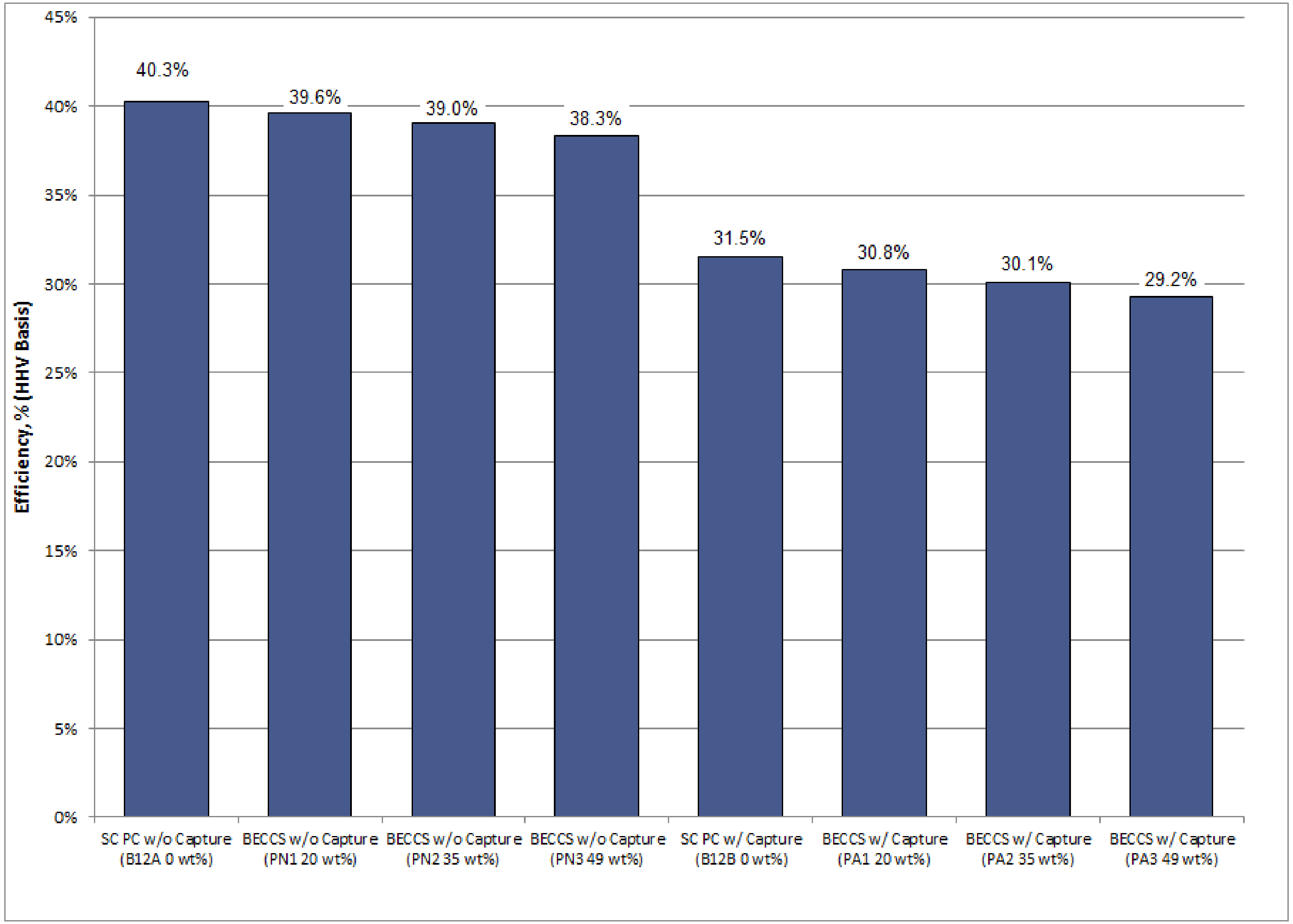
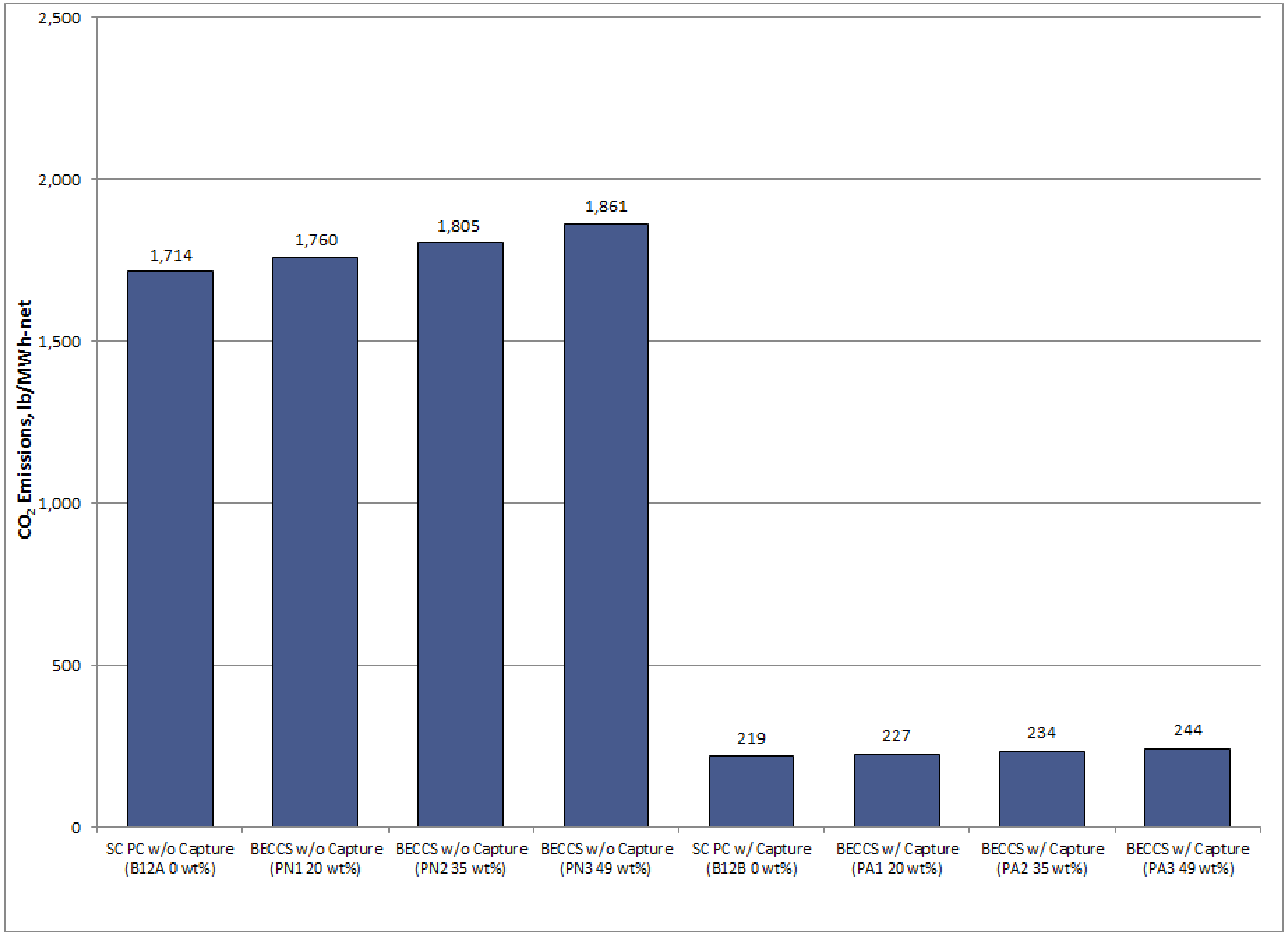
Net Plant Efficiency

- **Plant efficiency is reduced as co-firing percentages increase primarily due to two factors:**
  - Hybrid poplar has a lower heating value compared to coal leading to a higher overall fuel consumption rate and lower efficiency
  - Increased auxiliary loads due to pelletization and drying biomass from 50 wt% down to 10 wt% moisture



Gross Plant CO_2 Emissions

- Carbon dioxide emissions within the plant boundary increase as co-fire rates increase again due in part to lower biomass fuel heating value and increased auxiliary load requirements
- This does not include the carbon dioxide captured during the biomass growth cycle



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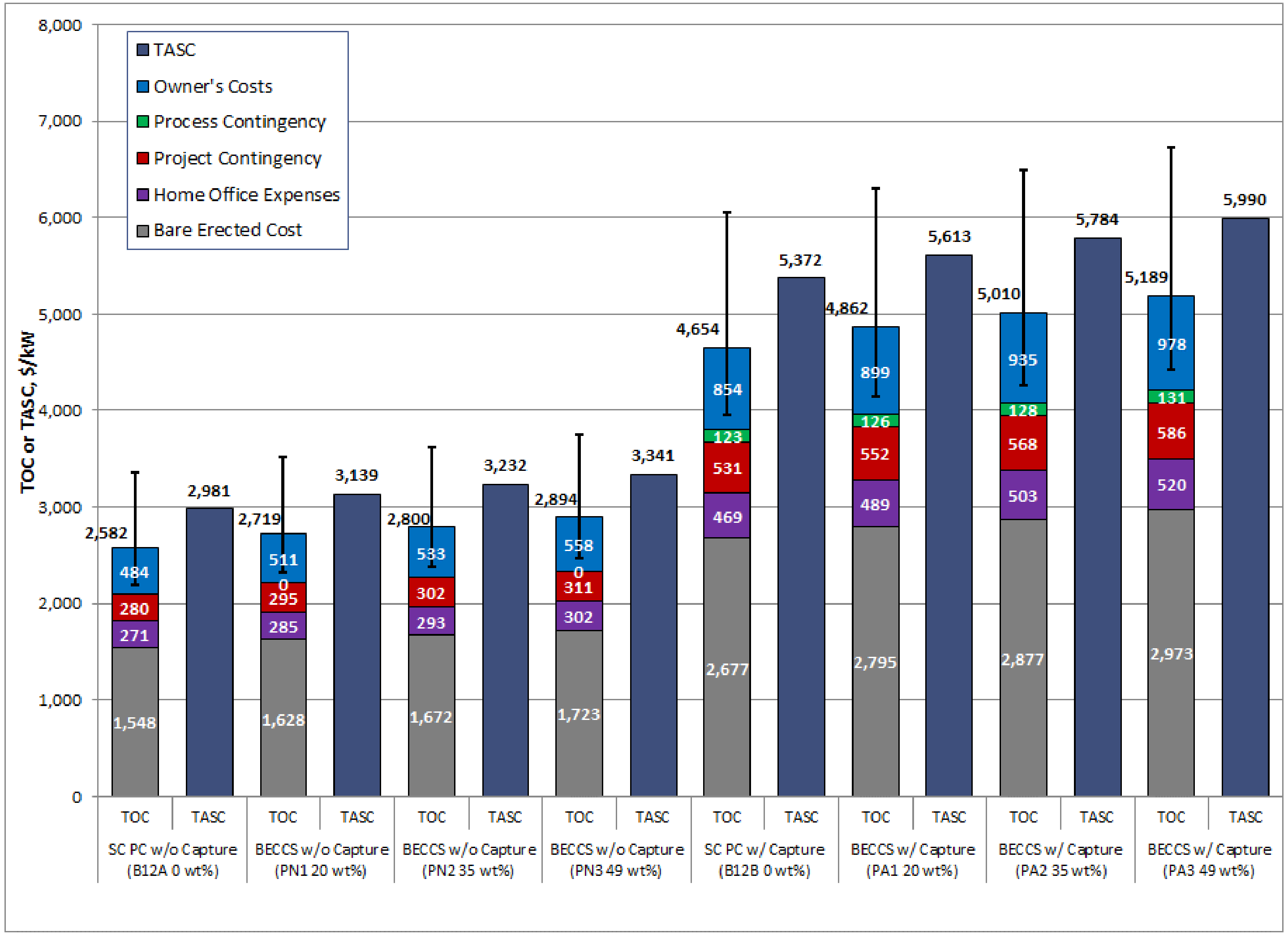
Total Overnight Cost/Total As Spent Cost (TOC/TASC)

- **Total costs impacted as overall plant efficiency decreases with the co-fire rate increase**

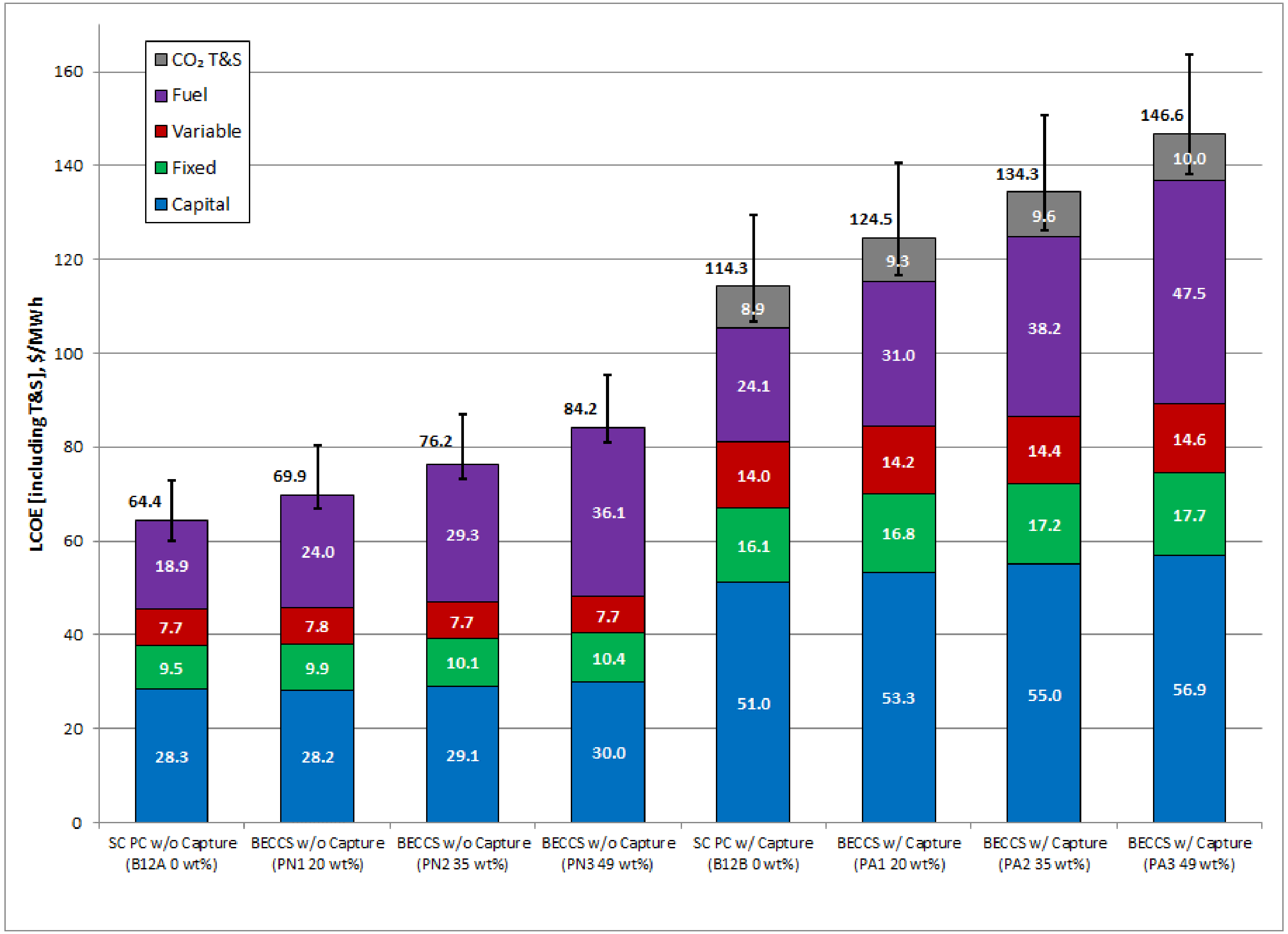
wt% Biomass	% Increase TOC	
-	w/o Capture	w/ Capture
20	5.3%	4.5%
35	8.4%	7.7%
49	12.1%	11.5%



Levelized Cost of Electricity (LCOE)

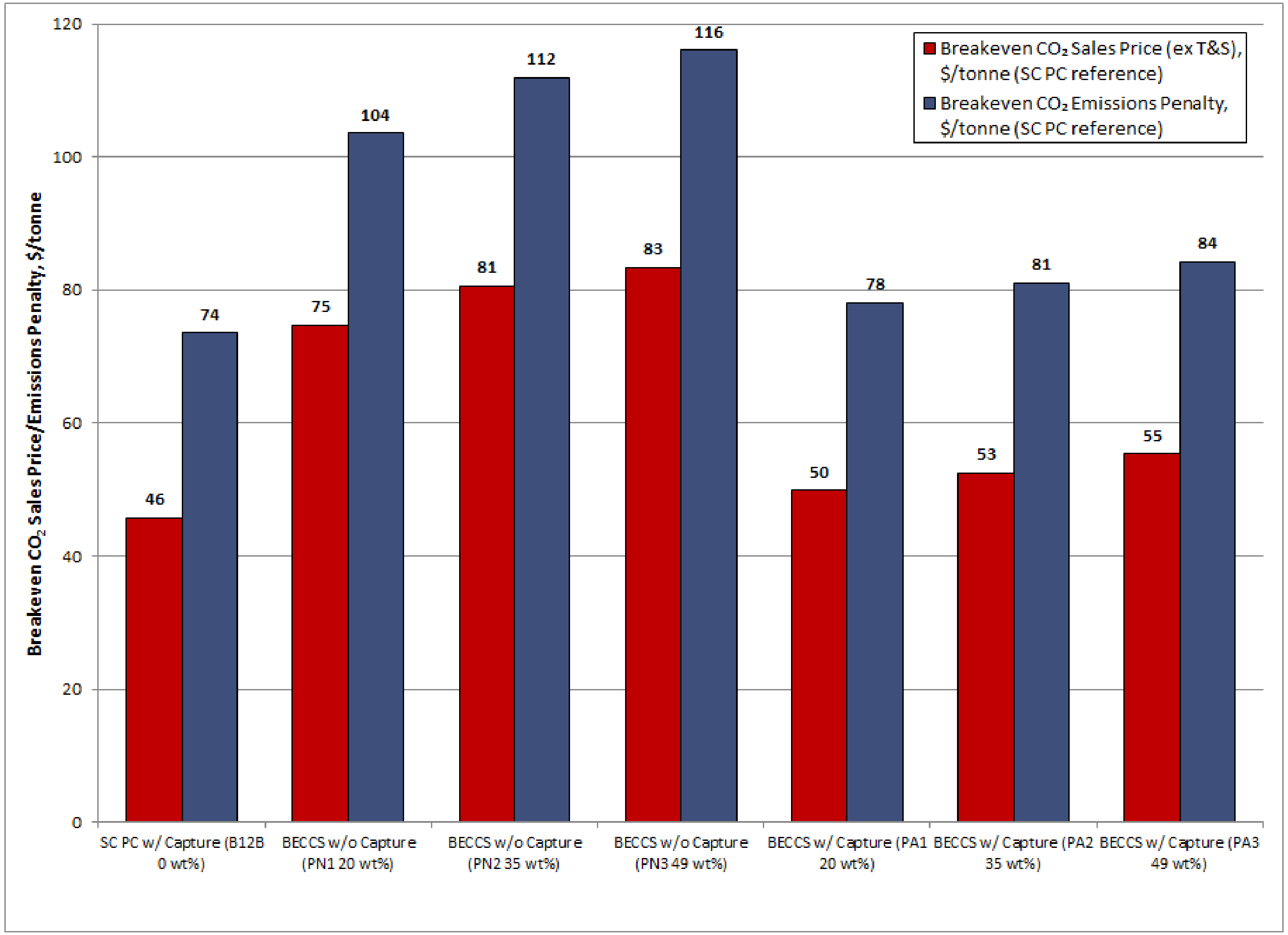
- Levelized cost of electricity increases dominated by increased biomass fuel costs

wt% Biomass	% Increase LCOE	
-	w/o Capture	w/ Capture
20	8.5%	9.0%
35	18.4%	17.5%
49	30.7%	28.3%



Breakeven CO_2 Sales Price/Penalty

- High biomass costs drive the breakeven sales price/penalty above that of Case B12B
- Including the Cansolv unit with cofiring reduces the marginal increases
- Cases presented do not consider lifecycle emissions



BECCS TEA Conclusions

- **PC with CCS, 0% biomass, offers lowest breakeven CO_2 cost option**
- **High cost of carbon emissions or desire for carbon negative systems makes co-firing with biomass plus CCS attractive**
- **Carbon-neutral or –negative coal-fired electricity can be achieved by adding both biomass and CCS to PC systems**
  - Neutrality occurs near 35% Biomass with 90% CCS

Life Cycle GHG Emissions per MWh, busbar

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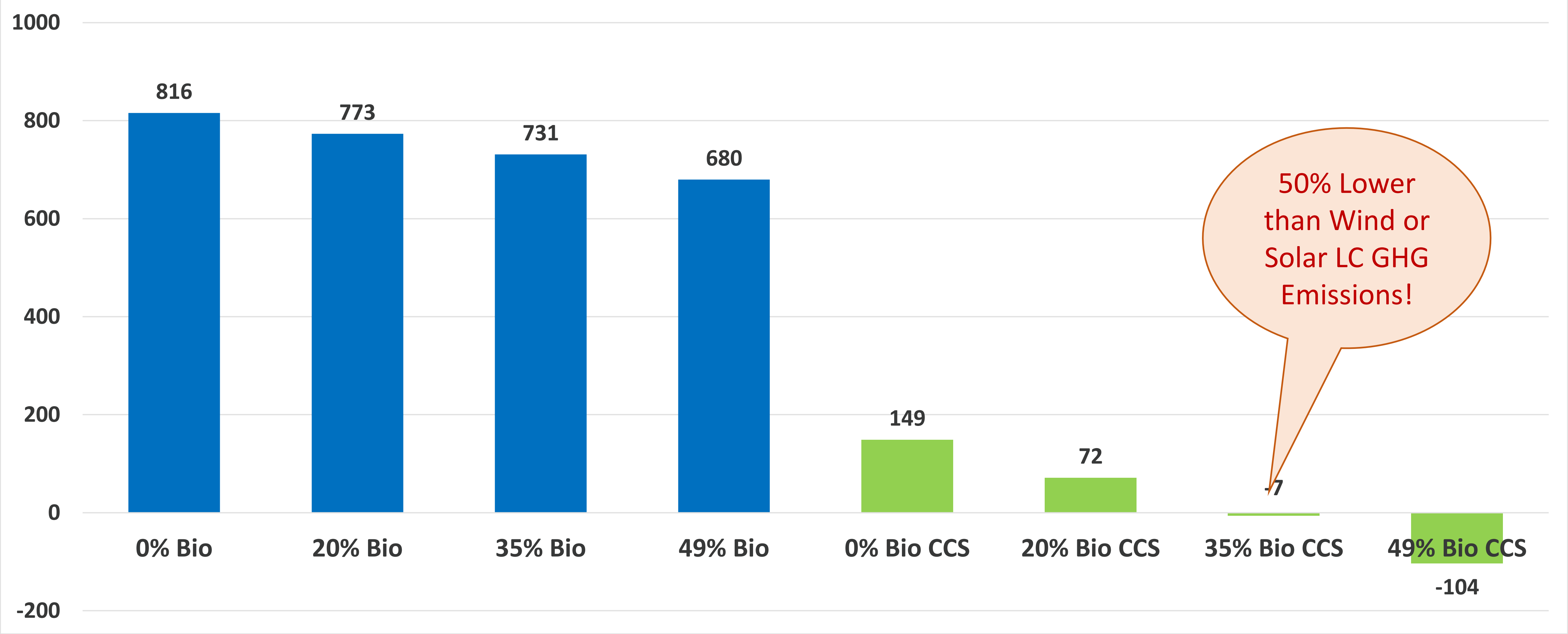
Global Warming Potential [100-yr] (kg CO_2e/MWh)



Higher Biomass rates = larger land use requirements, can be reduced through application of higher capture rates (i.e. 95% capture with amines or CFB with oxy-combustion, etc.)

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NGCC with EGR

Updating Exhaust Gas Recycle Reports

- **NETL has examined the use of EGR to increase the CO_2 concentration in NGCC flue gas to enable lower cost post-combustion capture of CO_2**
  - Current and Future Technologies for NGCC Power Plants, 2013 DOE/NETL-341-061013
  - Carbon Capture Approaches for NGCC Systems, Revision 2, 2010 DOE/NETL-2011-1470
- **Developing baseline cases for NGCC with EGR and CCS**
  - Focusing on parallel cases with B31B – F Class turbine
  - Evaluating interim results w.r.t recent EPRI report[1]
- **Will develop an H-Class EGR with CCS case as well**

[1]Booras, G. "Natural Gas Combined Cycle Power Plants with Post-Combustion CCS", EPRI Technical Update Report # 3002016289, August 2020

NGCC Retrofit Study

Updating NGCC Retrofit Report

- **Will update NGCC retrofit report[1] and Carbon Capture Retrofit Database (CCRD)[2]**
  - Align with financial assumptions and performance updates of Rev 4 of Fossil Energy Baseline
  - Calculate costs and performance based on retrofit design
    - Retrofit difficulty factors applied to capital cost
    - Derate energy cost accounted
  - Will include F and H class cases
  - Sensitivities
  - Serves as basis for scaling factors used in CCRD for NGCC
- **Also will be examining greater than 90% capture for NGCC (separate report)**
- **Update to PC retrofit report[3] and CCRD[4] to follow**

1. Cost and Performance of Retrofitting NGCC Units for Carbon Capture, November 2013, DOE/NETL-2018/1896 https://netl.doe.gov/projects/files/CostPerformanceRetrofittingNGCCforCarbonCapture_040119.pdf
2. NGCC CCRD, April 2019 https://netl.doe.gov/energy-analysis/details?id=086796fb-e0d9-4d1d-831f-c2e986a7072e
3. Eliminating the Derate of Carbon Capture Retrofits, September 2011, DOE/NETL-401/091211 https://netl.doe.gov/projects/files/EliminatingtheDerateofCarbonCaptureRetrofits_091211.pdf
4. PC CCRD, April 2019 https://netl.doe.gov/energy-analysis/details?id=69db8281-593f-4b2e-ac68-061b17574fb8

Industrial CO_2 Capture Report[1] Update

- **Cases model capture and compression of a CO_2 source from Industry type**
  - Do not model the Industrial Facility
  - Capture/Compression not integrated with Industrial Facility
- **Updating report to reflect Fossil Baseline Rev 4 assumptions**
  - Updated Financial Assumptions
  - Updated Equipment Quotes
    - Alignment of CO_2 Capture Systems used
- **Utilized as a basis for Industrial Capture goals**
- **Reference for Carbon Capture Retrofit Database**
  - Will update CCRD[2] as well

1. Cost of Capturing CO2 from Industrial Sources, January 2014, DOE/NETL 2013/1602 https://netl.doe.gov/projects/files/CostofCapturingCO2fromIndustrialSources_011014.pdf
2. Industrial Sources CCRD, April 2019 https://netl.doe.gov/energy-analysis/details?id=6692ea96-fcfa-4ba9-be2c-23647d08a65c

Industrial Source CO_2 Capture (2014)

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Industrial Process	Reference Plant Capacity	CO_2 Source Stream	CO_2 to Product Ratio (tonne CO_2/tonne Product)	Source Stream CO_2 Concentration (mol%)	Source Stream CO_2 Partial Pressure (psia)	CO_2 Available for Capture (M tonnes CO_2/year)		Breakeven Cost of Capturing CO_2 ($/tonne CO_2)
						Reference Plant	**All U.S. sources**	
High Purity Sources								
Ethanol	*50 M gal/year*	Distillation gas	0.96	100	18.4	0.14	40	30
Ammonia	*907,000 tonnes/year*	Stripping vent	1.9	99	22.8	0.458	6	27
Natural Gas Processing	*500 MMscf/d*	CO_2 vent	N/A[1]	99	23.3	0.649	27	18
Ethylene Oxide	*364,500 tonnes/year*	AGR product stream	0.33	100	43.5	0.122	1	25
Coal-to-Liquids (CTL)	*50,000 bbl/d*	AGR product stream	N/A[2]	100	265	8.74	-	9
Gas-to-Liquids (GTL)	*50,000 bbl/d*	AGR product stream	N/A[2]	100	265	1.86	-	9
Low Purity Sources								
Refinery Hydrogen	*59,000 tonnes/year*	PSA tail gas	10.5	44.5	8.9	0.274	68	118
Iron/Steel	*2.54 M tonnes/year*	Plant Total COG PPS COG/BFG[3]	2.2	N/A 23.2 26.4	N/A 3.4 3.9	3.9 2.75 1.16	49	99 99 101
Cement *SCR/FGD Sensitivity*	*992,500 tonnes/year*	Kiln Off-gas	1.2	22.4	3.3	1.14	80	100 *127*
Coal-fired power plants	*550 MW*	*Flue Gas*	*NA*	*13.5*	*2.0*	*4.13*	*2,545[4]*	*77[5,6]*

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Questions?