Energy & Environmental Research Center (EERC)

MEETING SYNGAS QUALITY REQUIREMENTS/FEEDING CHALLENGES

Gasification Technology Status and Pathways for Net-Zero Carbon Economy Workshop
November 30, 2022
Virtual

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Energy & Environmental Research Center (EERC)

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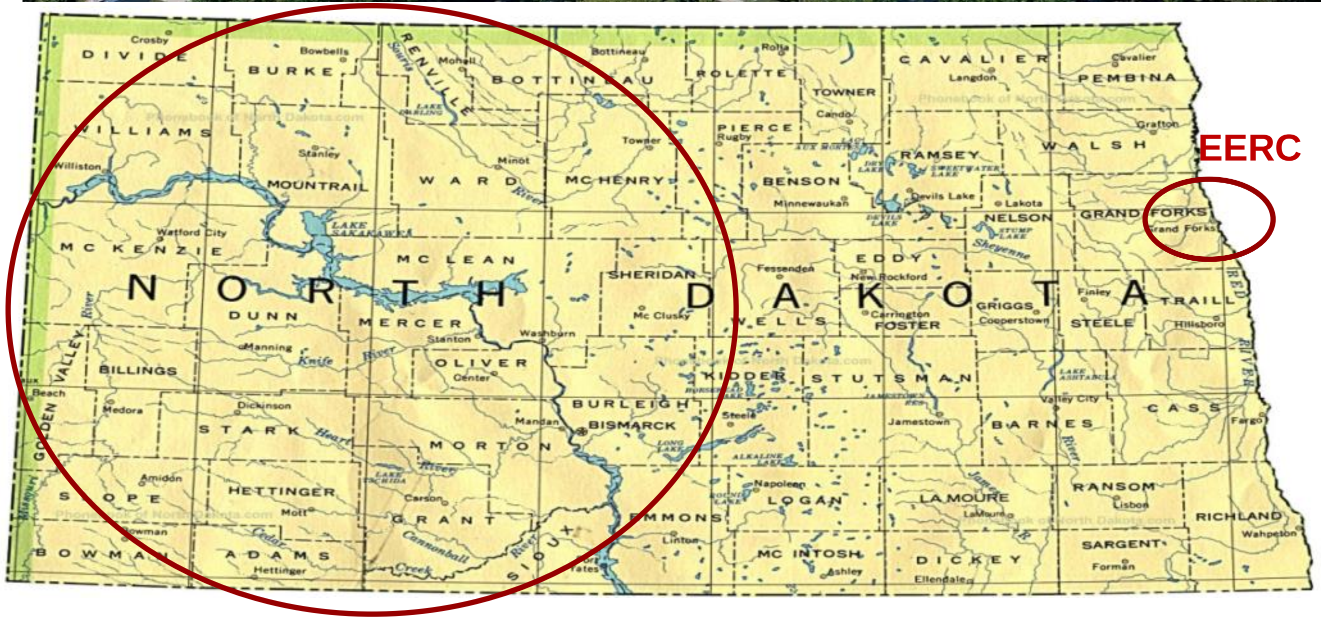
ENERGY & ENVIRONMENTAL RESEARCH CENTER (EERC)

- Nonprofit branch of the University of North Dakota focused on energy and environmental solutions.
- More than 254,000 square feet of state-of-the-art laboratory, demonstration, and office space.

Gasification Testing



Oil and Gas Activity, Ideal Carbon Storage Geology

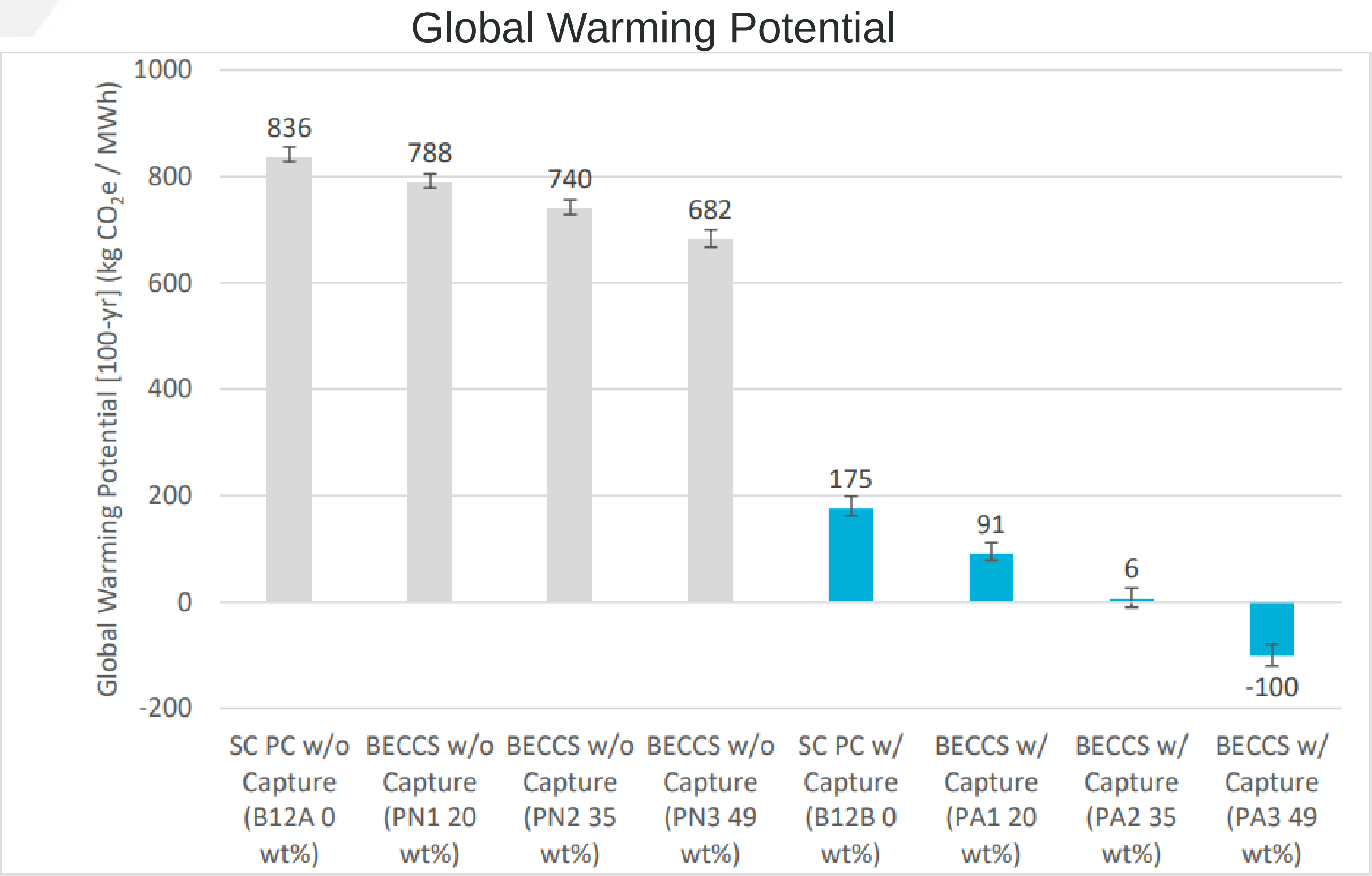
BIOENERGY WITH CARBON CAPTURE AND STORAGE (BECCS)

- Goal: Develop technology that results in power generation or hydrogen production with a net-carbon-negative footprint by using coal and biomass blends or 100% biomass with carbon capture.

NET-CARBON-NEGATIVE TECHNOLOGIES

- Negative-carbon emission technologies are key to future generation of hydrogen, electricity, or chemicals.
- Coal and biomass-generated syngas, combined with carbon capture, could result in net-negative carbon dioxide (CO_2) emissions.
- Inclusion of biomass can add to the complexity of a process and create challenges:
  - Fuel preparation and feeding
  - Slagging/agglomeration
  - Syngas cleanup
  - Impacts to carbon capture

IMPACT OF BIOMASS BLENDS ON GHG



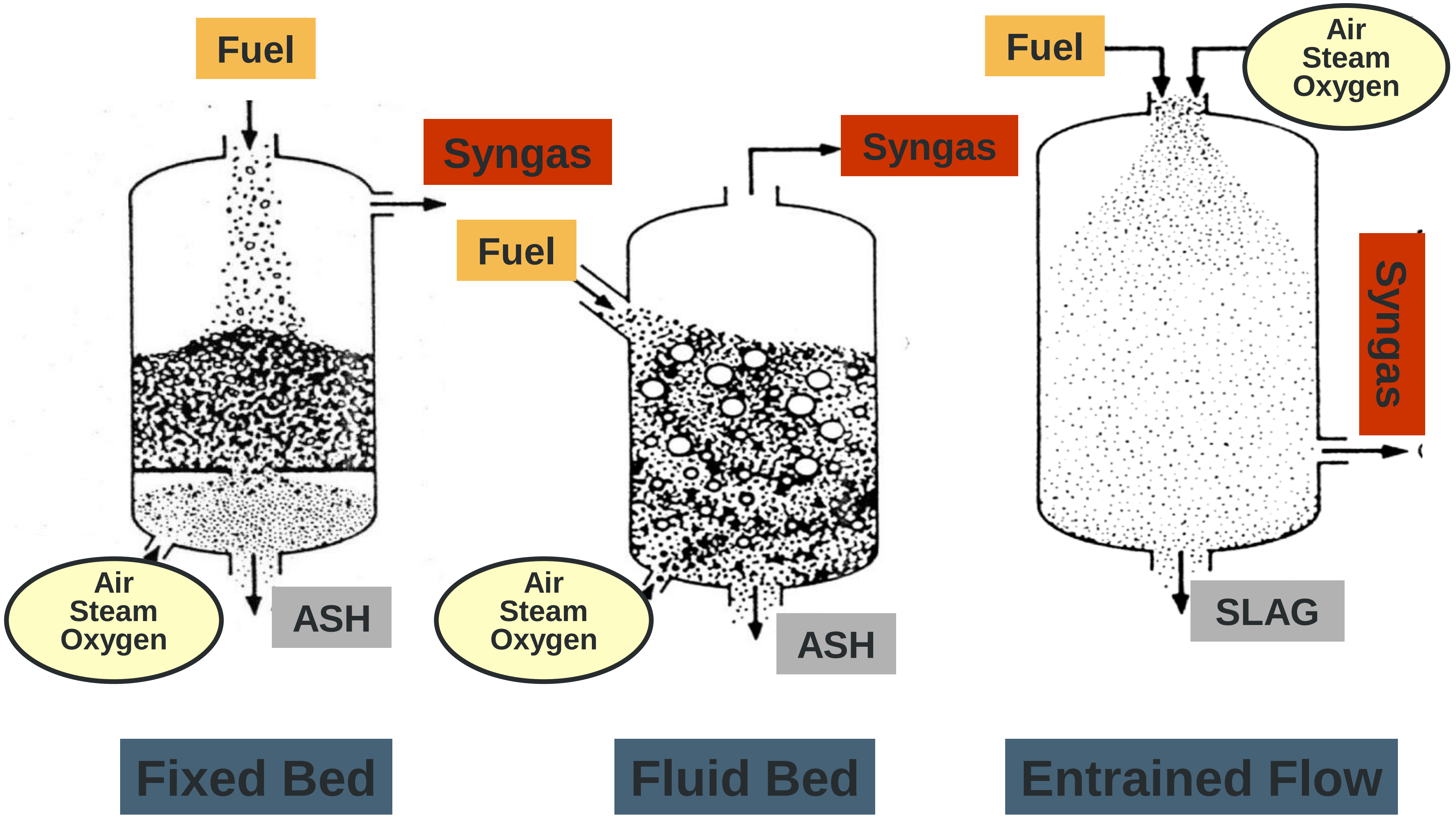
Note: blue bars indicate the presence of 90% CCS

- Data developed using bituminous coal and hybrid poplar as the feedstocks.
- Net-negative greenhouse gases (GHGs) at more than 35.9% biomass with 90% carbon capture.

- Source: Buchheit et al. Technoeconomic and Life Cycle Analysis of Bio-Energy with Carbon Capture and Storage (BECCS) Baseline; DOE National Energy Technology Laboratory; July 16, 2021.

FUEL FEED CHALLENGES

GENERAL CLASSIFICATION OF GASIFIERS

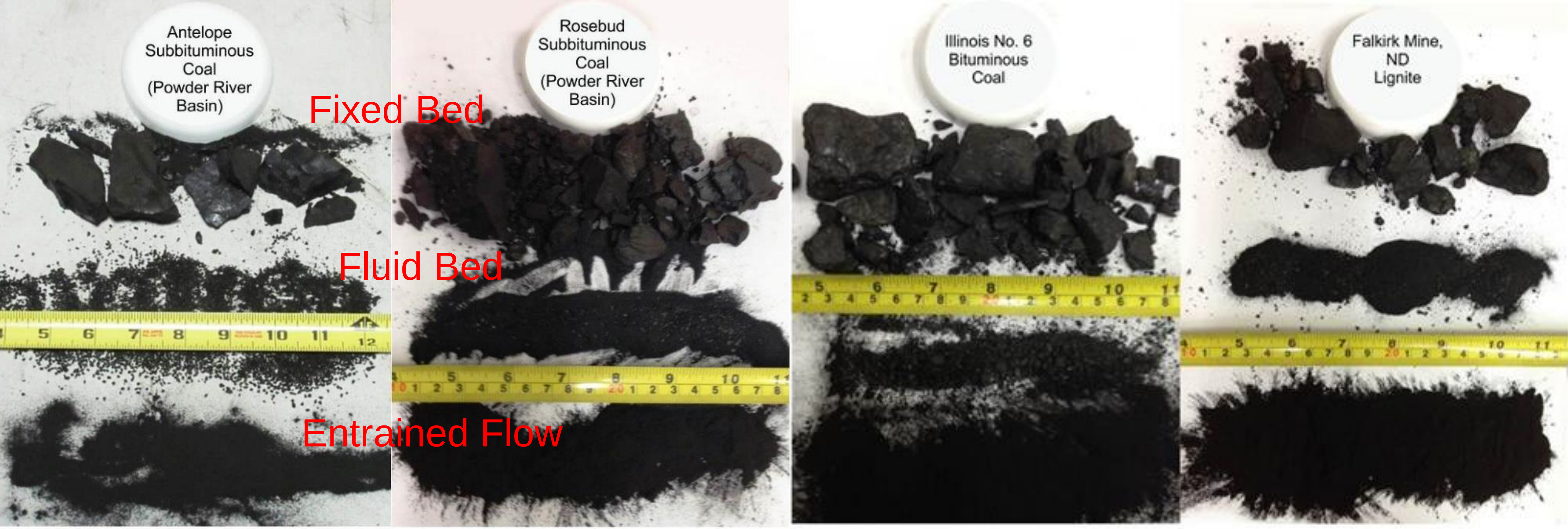


GENERAL GASIFIER TYPES AND THEIR DESIGN CONFIGURATIONS

Flow Regime	Moving or Fixed Bed	Fluidized Bed	Entrained Flow
Combustion Analogy	Grate-fired combustors	Fluidized-bed combustors (FBCs)	Pulverized coal combustors
Fuel Type	Solids	Solids	Solids or liquids
Fuel Size	5–50 mm	0.5–5 mm	<500 µm
Solids Residence Time	15–30 min	5–50 s	1–10 s
Oxidant	Air- or O_2-blown	Air- or O_2-blown	Almost always O_2-blown
Gas Outlet T, °C	752°–932°F (400°–500°C)	1292°–1652°F (700°–900°C)	1652°–2552°F (900°–1400°C)
Ash Handling	Slagging and nonslagging	Nonslagging	Slagging
Examples	Lurgi dry ash and British Gas/Lurgi (BGL) slagging	GTI U-Gas, HT Winkler, and Kellogg Rust Westinghouse (KRW)	Shell, GE, Siemens SFG, ConocoPhillips, Lurgi MPG, and Uhde Prenflo
Comments	Gas and solid flows countercurrent in moving beds	Preferred for high-ash feedstocks	Unsuitable for fuels that are difficult to atomize or pulverize

Modified after Ondrey, G. Chemical Engineering, Feb 2007.

CLASSIC FUEL PREPARATOIN WITH COAL



BIOMASS CHARACTERISTICS

- **Advantages**
  - Generally good reactivity
  - Some are low ash
  - Can be low to negative cost
  - Typically low sulfur content
  - GHG-neutral

- **Disadvantages**
  - Low energy density
  - Typically high in moisture
  - Highly distributed resource
  - Varying physical and chemical composition
  - Seasonal or cyclic resource
  - Can be challenging to grind

WOODY BIOMASS

Raw

Torrefied

As Received

EERC MH45307.CDR

EERC MH45306.CDR

Hammer-Milled and Sized

FUEL PREP – WOOD PELLETS

Wood pellets were ground in a hammer mill once with an 1/8” screen and then reprocessed through a 3/32” screen.

SWITCHGRASS AND CORN STOVER

Switchgrass

Corn Stover

As Received

Hammer-Milled and Screened

RAW FEEDSTOCK

- Feedstocks are very nonhomogeneous in nature.
- Can cause difficulties with handling and fuel preparation.

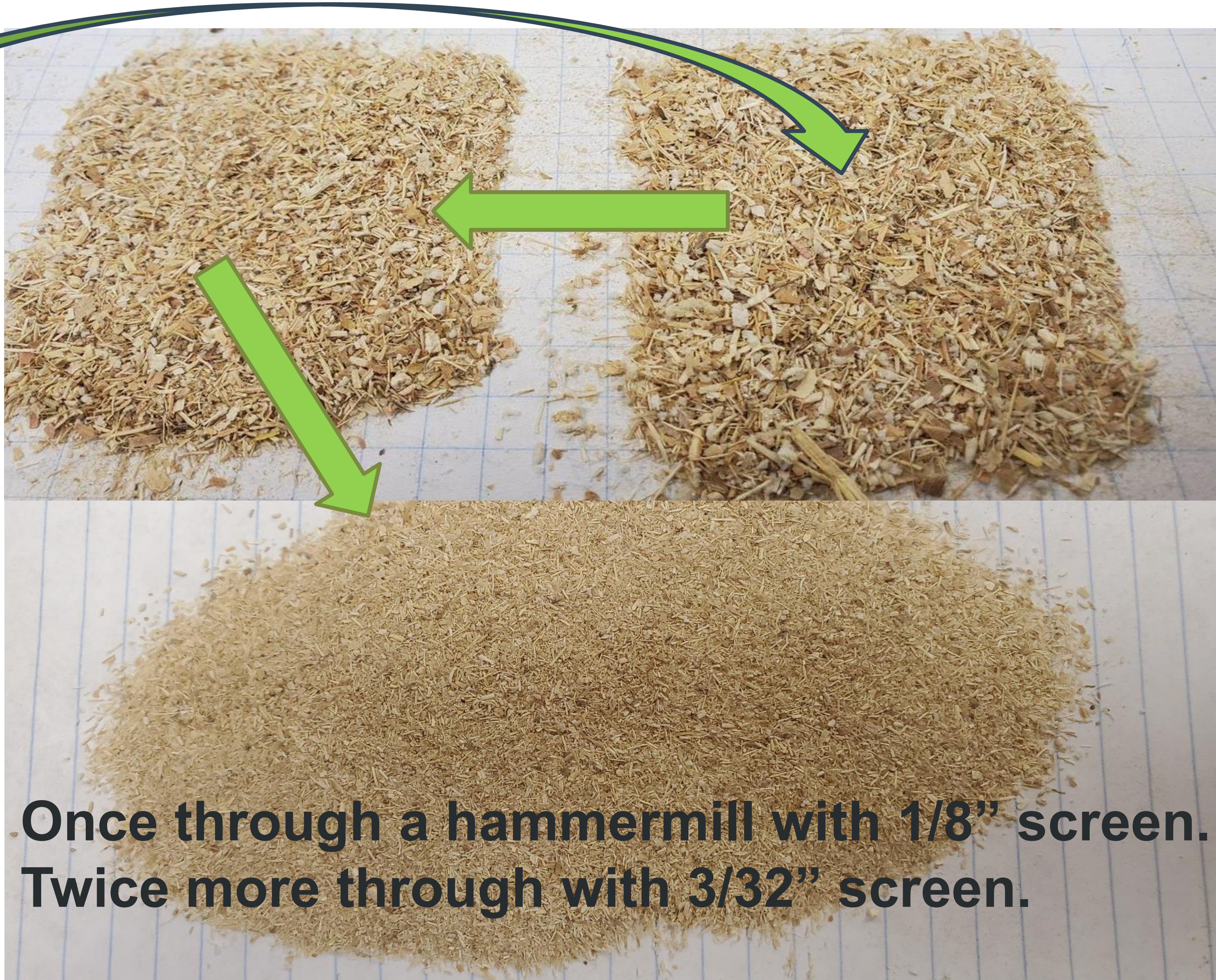
EERC MH47713.CDR

SWITCHGRASS AND CORN STOVER

- A finer screen was used for the switchgrass and corn stover to eliminate long strands, which can clog the fuel feed systems.

FUEL PREP – CORN STOVER

Past Example



Once through a hammermill with 1/8" screen.
Twice more through with 3/32" screen.

MOISTURE CONCERNS

MOISTURE (CONT.)

MOISTURE (CONT.)

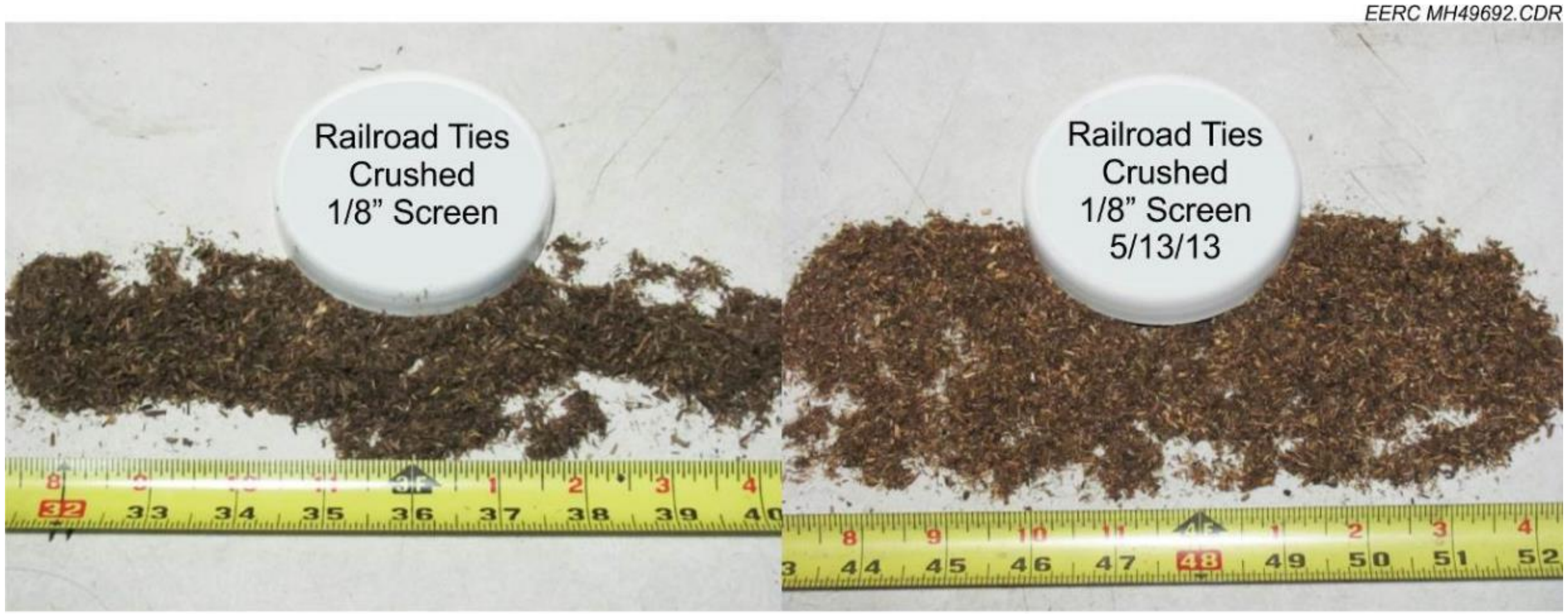
CORN STOVER ASH

Buildup of ash in the EERC's pilot-scale combustor after 36 hours of operation.

BLENDING VS. COGRINDING

- We generally blend instead of cogrinding at the EERC because of research needs and the need for confidence in blend ratios.
- Cogrinding of coal and biomass is an option at commercial facilities and can reduce energy needs and improve grinding results.

RAILROAD TIES



(a) (b)

AQUATIC BIOMASS

SELECTED RESULTS, ASH-FORMING CONSTITUENTS

Falkirk Lignite–9.3% Ash

Component	wt%
SiO_2	43.63
Al_2O_3	14.05
Fe_2O_3	5.37
TiO_2	0.58
P_2O_5	0.15
CaO	15.77
MgO	4.61
Na_2O	3.39
K_2O	1.67
SO_3	9.88
SrO	0.35
BaO	0.50
MnO	0.05

PRB Antelope Coal–5.6% Ash

Component	Norm., wt%
SiO_2	37.90
Al_2O_3	18.91
Fe_2O_3	5.97
TiO_2	1.20
P_2O_5	0.63
CaO	18.49
MgO	3.43
Na_2O	1.20
K_2O	0.73
SO_3	10.81
SrO	0.24
BaO	0.44
MnO	0.05

Southern Pine–0.5% Ash

Component	wt%
SiO_2	7.53
Al_2O_3	3.13
Fe_2O_3	1.03
TiO_2	0.08
P_2O_5	7.91
CaO	31.86
MgO	10.80
Na_2O	5.18
K_2O	25.05
SO_3	7.43

Corn Stover–6.1% Ash

Component	Norm., wt%
SiO_2	65.73
Al_2O_3	2.89
Fe_2O_3	1.19
TiO_2	0.13
P_2O_5	1.64
CaO	5.97
MgO	4.97
Na_2O	0.75
K_2O	15.85
SO_3	0.68
SrO	0.02
BaO	0.03
MnO	0.15

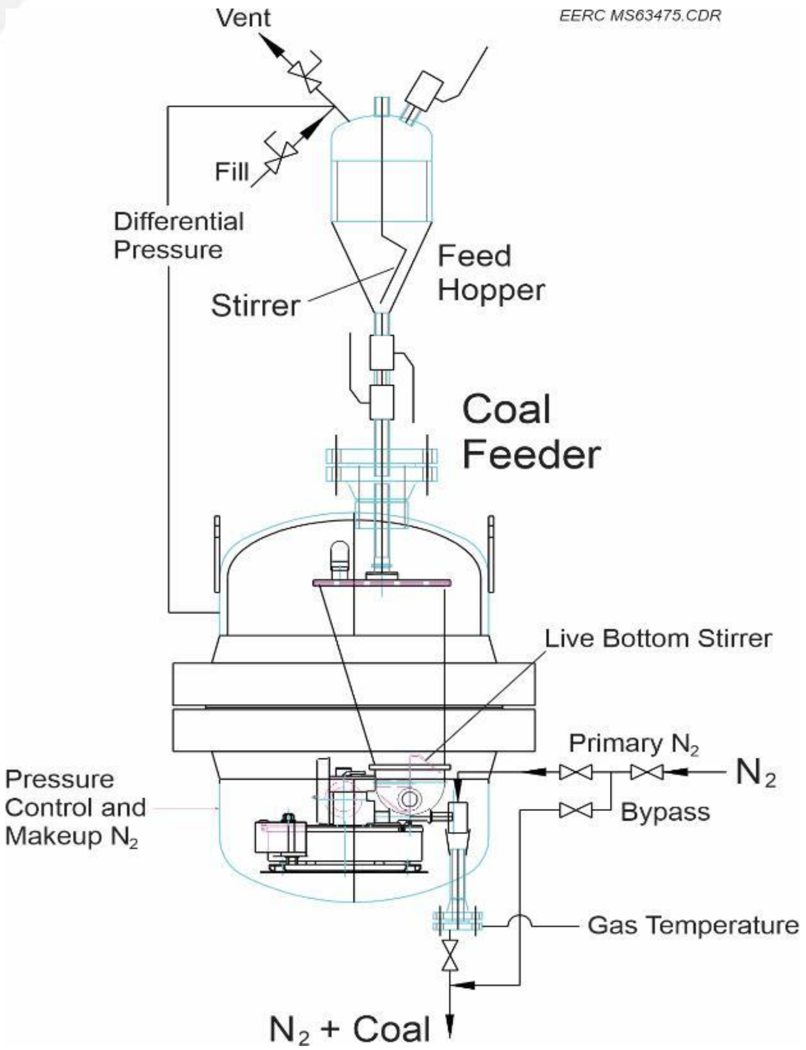
BIOMASS FEED CHALLENGES/EERC EXPERIENCE

- Most biomass/waste generally is very low bulk density; resulting in much larger volumetric flow rates than coal (up to 4 to 5 times higher): requires much larger feeding vessels and chutes.
- Biomass very difficult to pulverize for entrained-flow gasifiers (EFG).
- Biomass/waste needs to be dried to less than 10% for an EFG.
- Cofiring pulverized biomass in EFG possible to about 25–30 wt%.
- Biomass torrefaction results in most biomass feedstocks processing and handling like coal.
- 100% biomass feeding to EFG only feasible with torrefied biomass.
- No tar formation issues with EFG systems because of high operating temperature.

BIOMASS FEED CHALLENGES/EERC EXPERIENCE (CONT'D)

- Fluid-bed gasifiers (FBG) and moving fixed-bed gasifiers (MFBG) can utilize much-larger-particle-size biomass/waste, reducing feedstock processing costs.
- More fibrous nature of biomass makes feeding issues such as rat-holing and bridging across cones and chutes more problematic.
- Densification through pelletizing can reduce high volumetric flow and handling issues, but pellets must be small enough to pass through chutes and augers and still be fluidizable for FBGs.
- Biomass feedstock to FBG should probably be dried to less than 20%, while MFBG can be more tolerant of higher moisture levels.
- Avoiding feeder designs with cones and the use of live bottom-feeding vessels with very high angles of repose are generally recommended.
- Smooth bore piping and transitions with diameter changes are recommended to avoid impact and biomass retention points.
- Higher tar formation with biomass in FBG and MFBG systems.

EERC EXAMPLES OF BENCH-SCALE BIOMASS/WASTE FEEDER

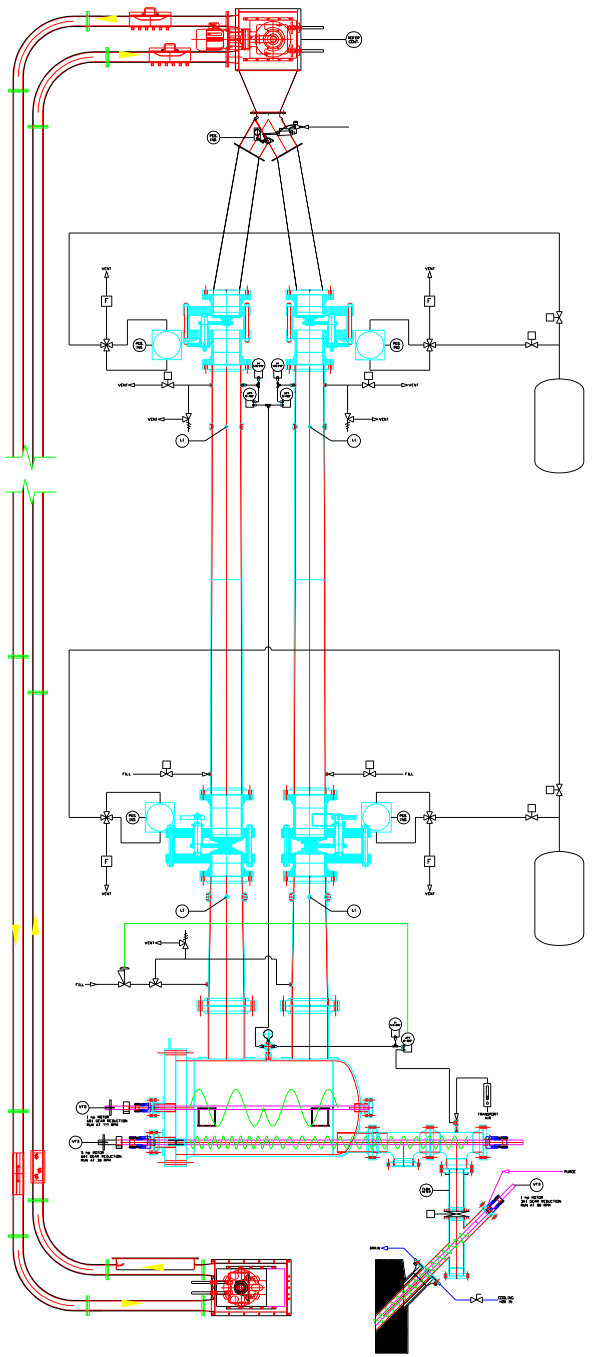


EERC FEEDER DESCRIPTION AND RESULTS

- Commercial K-Tron feeder with dual screw feed auger.
- Smooth bore hopper and feed piping.
- Live bottom stirrer.
- Cone on bottom of lock hopper was unavoidable because of space constraints and has been problematic at times, but use of internal stirrer has allowed utilization of biomass feedstocks.
- Successfully fed 100% torrefied biomass to EFG; cofeed wood, corn stover, switchgrass, railroad ties, algae, aquatic nuisance weeds, torrefied RDF.
- Successfully fed 100% wood and torrefied wood, C&D waste, MSW, dried distillers grain (DDG), olive pits, dried biosolids to FBG; cofeed wood, corn stover, DDG, olive pits, lignin, beet pulp, and beet tailings.

PILOT-SCALE BIOMASS FEEDER

- Diverging cone lock hoppers with no cones.
- Smooth bore piping with no constrictions.
- Dual live bottom stirrers to keep feed auger full.
- Options for pneumatic or auger conveyance into FBG.
- Double lock hopper with high cycle rates to feed low-density biomass.
- Utilization of drag chain conveyer to move biomass from first floor to 7th floor of structure.
- Successfully fed 100% wood, corn stover, switchgrass; cofed wood, corn stover, switchgrass, torrefied wood, railroad ties, algae, aquatic nuisance weeds.



MEETING SYNGAS QUALITY REQUIREMENTS

EERC GASIFICATION TESTING – THREE GASIFIERS

- **Produce syngas with low level of trace contaminants to meet SOFC operation.**

All Gasifiers

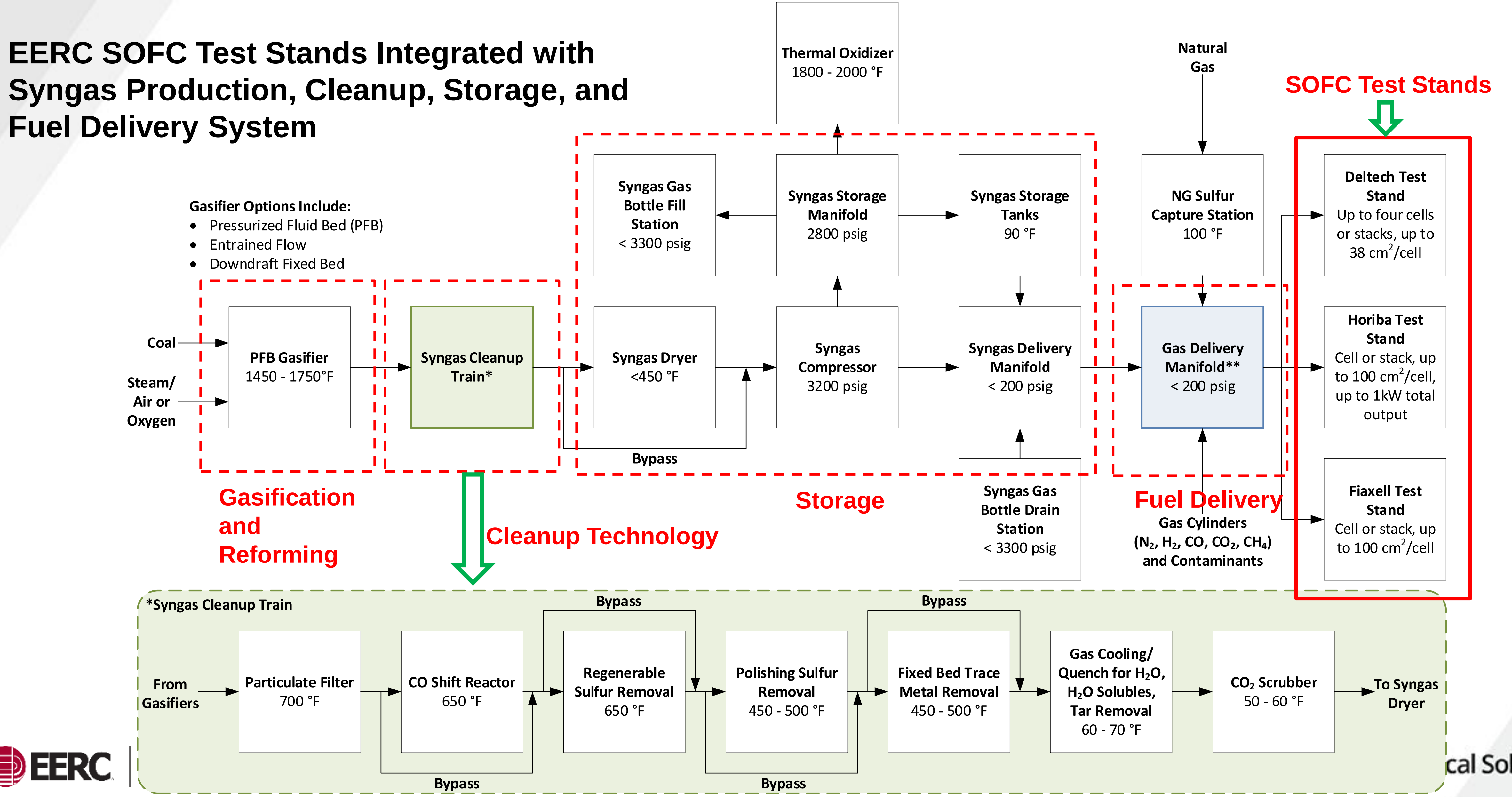
- Wide range of feedstocks: coal, biomass, other solid or liquid feedstocks
- Bench-scale warm-gas cleanup train
- Gas-sweetening absorption system
  - Additional gas cleanup and acid gas removal
- Produce up to 120 scfh of syngas
- Syngas storage and delivery system
- Wide range of H_2/CO ratio
- Low contaminant level

Pressurized Fluidized-Bed Gasification (PFB)

Downdraft Fixed-Bed Gasification (DFB)

Entrained-Flow Gasification (EFG)

FUEL PRODUCTION AND CLEANUP TECHNOLOGY – FLOWCHART



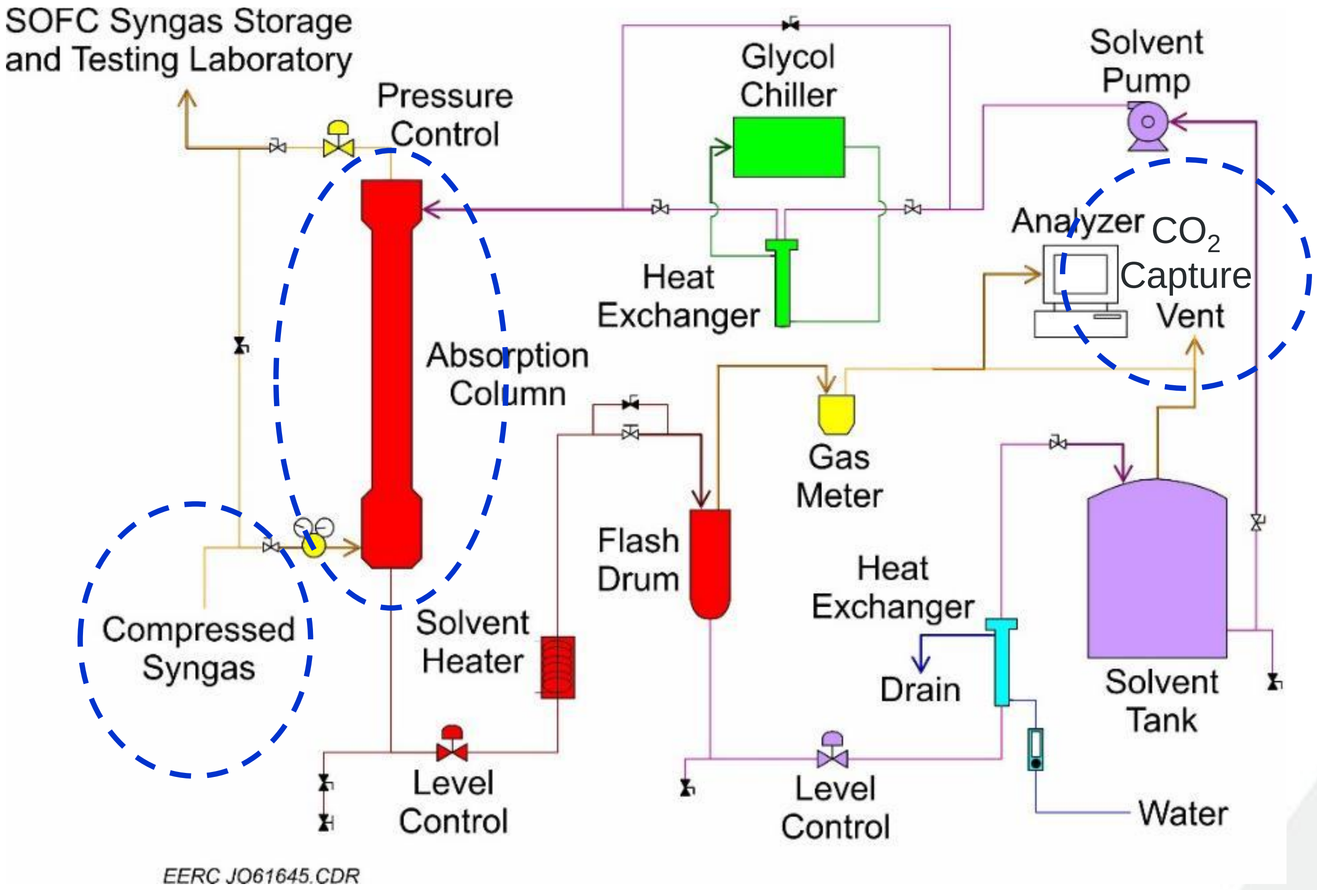
EERC | ...cal Solutions.

CARBON CAPTURE

- **Produce syngas to operate SOFC system with low CO_2 footprint**

- 12-day PFB gasification run to generate and store coal-derived syngas
  - Produced approximately **17,000 scf/2000 psi** syngas
  - Stored syngas to be utilized for SOFC operation and testing

Syngas Gas Component	Mole Percent
Hydrogen	59.5
Carbon Dioxide	0.9
Ethane	0.0
Argon	0.4
Nitrogen	32.5
Methane	5.2
Carbon Monoxide	1.7



CO_2 Capture System

COAL-DERIVED SYNGAS QUALITY PRODUCED AT THE EERC

- EERC syngas production and cleanup system capable of producing ultraclean syngas.
  - Tailored syngas quality possible.
- Can be used as fuel to directly feed to SOFC stacks/systems for long-term operation.
  - Completed 1000-hr durability test with lower degradation rate.

EERC

Syngas Gas Contaminant	Concentration
Antimony (Sb)	<1 ppbv
Cadmium (Cd)	<0.5 ppbv
Arsine (AsH_3)	<5 ppbv
Hydrogen Sulfide (H_2S)	<5 ppbv
Phosphine (PH_3)	<0.5 ppbv
Selenium (Se)	<0.5 ppbv
Hydrochloric Acid (HCl)	<100 ppbv
Silicon (Si)	<1 ppbv
Zinc (Zn)	2.5 ppbv
Benzene (C_6H_6)	<15 ppmv
Xylene (C_8H_{10})	<10 ppmv

Industrial Gasifier with Rectisol

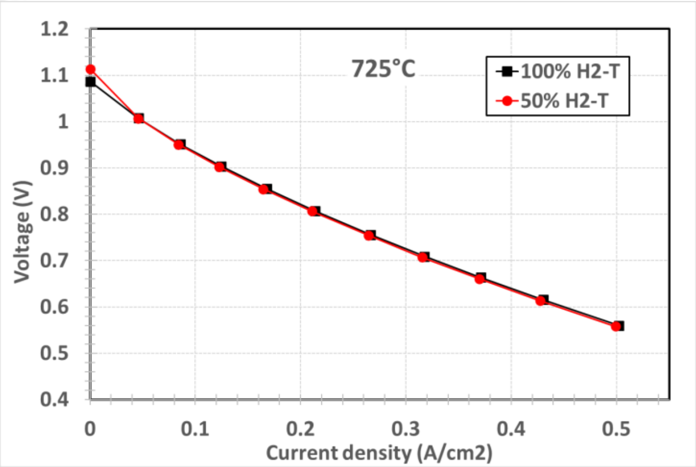
Syngas Gas Contaminant	Concentration[1]
Antimony (Sb)	25 ppbv
Cadmium (Cd)	N/A
Arsine (AsH_3)	150–580 ppbv
Hydrogen Sulfide (H_2S)	~500 ppbv
Phosphine (PH_3)	1900 ppbv
Selenium (Se)	150 ppbv
Hydrochloric Acid (HCl)	<1000 ppbv
Zinc (Zn)	9000 ppbv
Chromium (Cr)	25 ppbv
Mercury (Hg)	25 ppbv

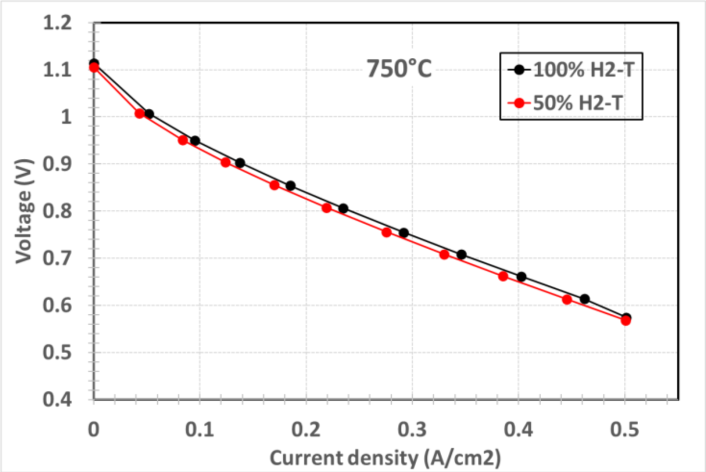
1) Eastman Chemical Company's system at Kingsport.

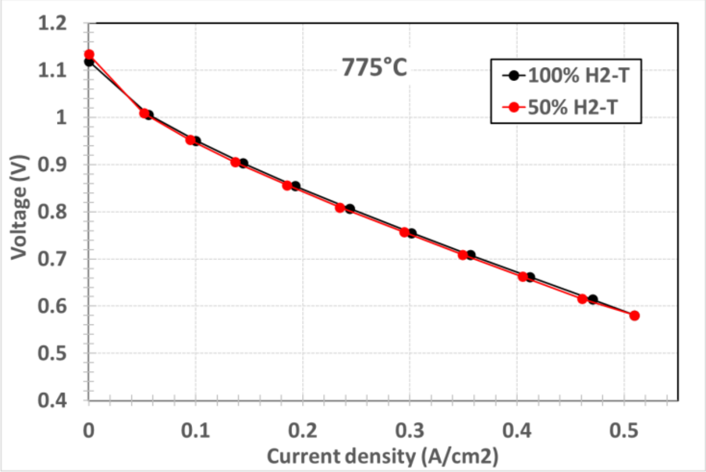
SOFC PERFORMANCE VS. TEMPERATURE AND FUEL COMPOSITIONS

Commercially available SOFC cells show comparable performance in syngas gas and H_2 fuel.

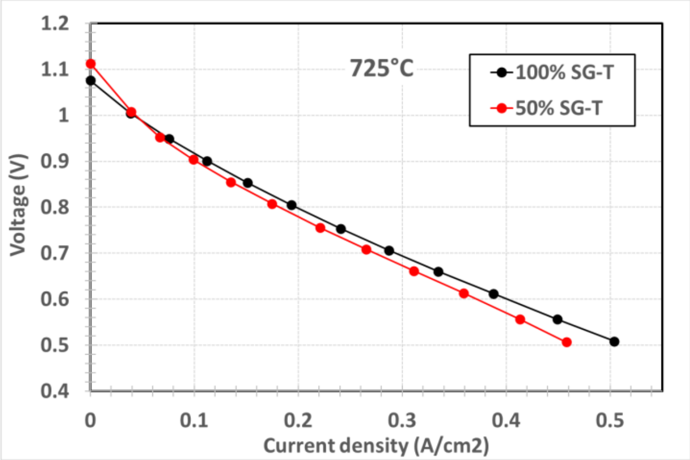
SPS Cell

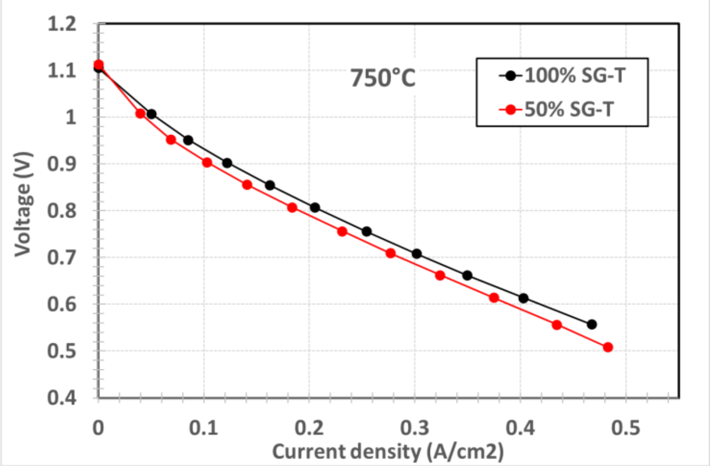


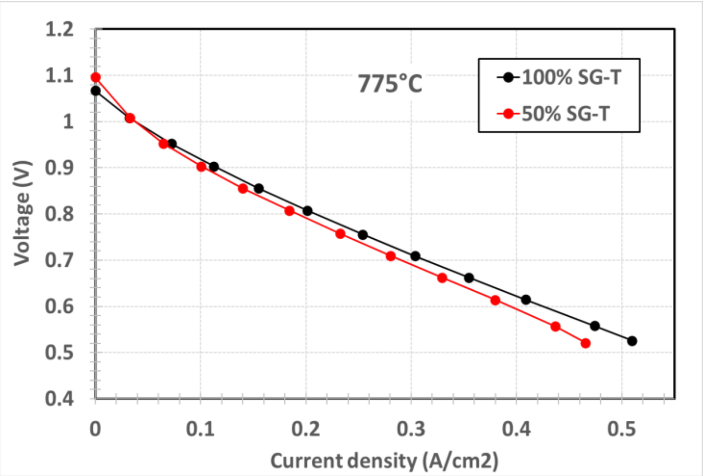




H_2 fuel





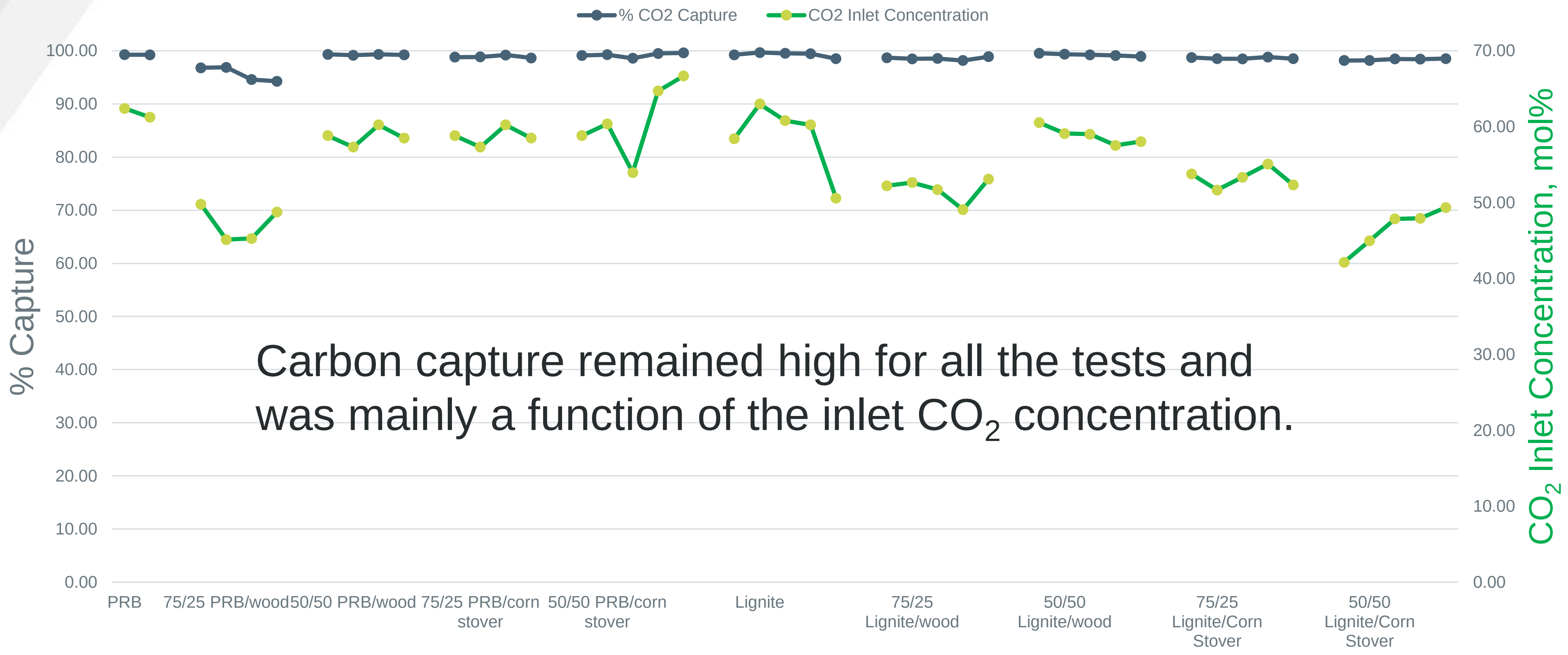


Coal-Derived Syngas

BECCS PILOT-SCALE GASIFICATION TESTING

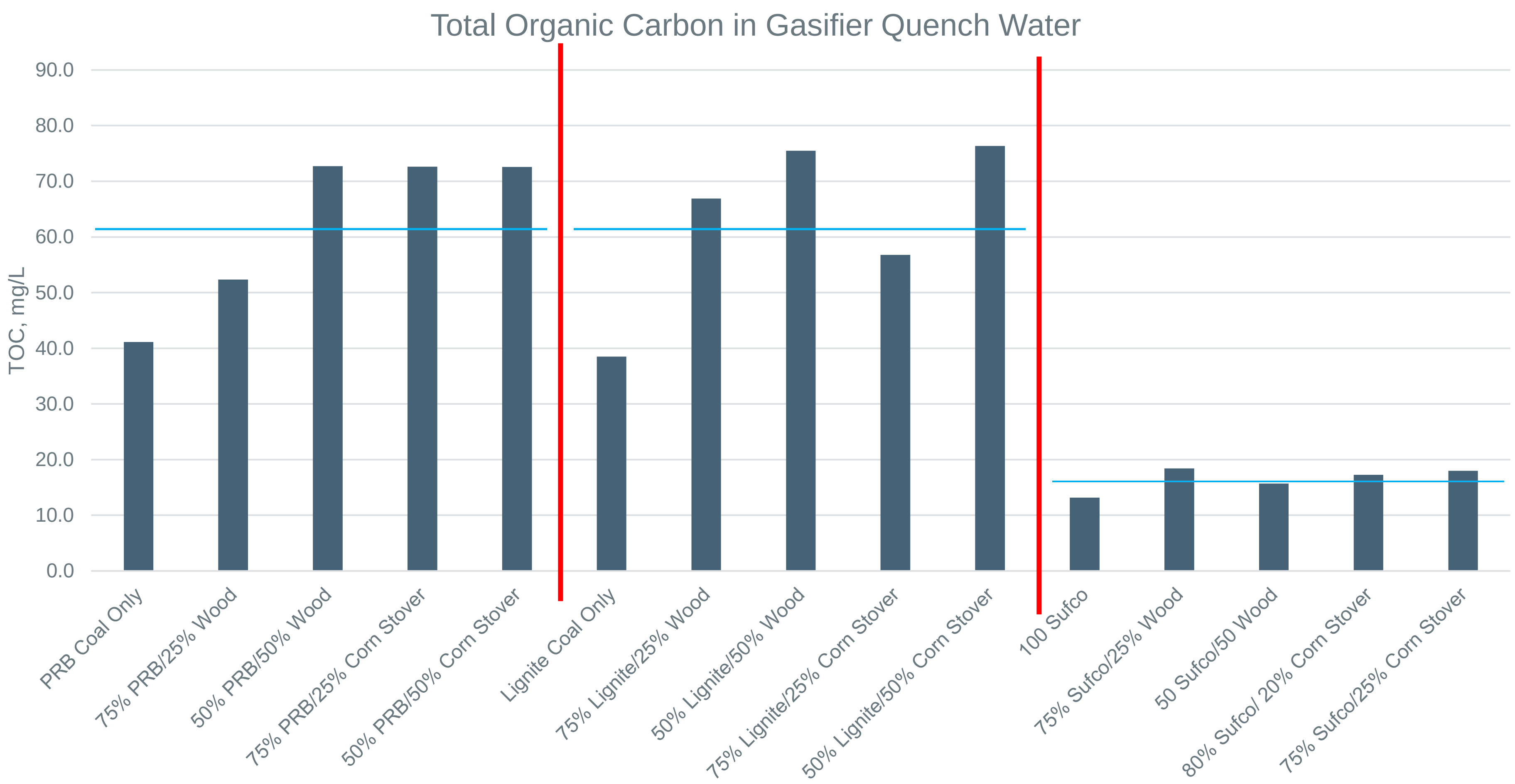
Run/ Weeks	Coal Type	Biomass Type	Biomass Blend	Testing Duration, days	Actual/ Planned Completion Date	Run Time on Solvent, h
1A	Subbituminous	None	0%	2.5	10/23/20	47
2	Subbituminous	Wood	25%	5	10/30/20	72
3	Subbituminous	Wood	50%	5	11/20/20	84
4	Subbituminous	Corn stover	25%	5	12/04/20	74
5	Subbituminous	Corn stover	50%	5	12/11/20	78
6	Lignite	None	0%	5	12/18/20	98
7	Lignite	Wood	25%	5	1/08/21	103
8	Lignite	Wood	50%	5	01/15/21	104
9	Lignite	Corn stover	25%	5	01/29/21	104
10	Lignite	Corn stover	50%–40%	5	02/05/21	17/45 (62 tot.)
1B	Subbituminous	None	0%	2.5	02/19/21	55 (102 tot.)
11	Bituminous (Sufco)	None	0%	5	03/05/21	35
12	Bituminous (CAPP)	Wood	25%	5	02/26/21	60
13	Bituminous (Sufco)	Wood	50%	5	03/19/21	98
14	Bituminous (Sufco)	Corn stover	25%	5	03/26/21	42
15	Bituminous (Sufco)	Corn stover	20%	5	04/09/21	96
16	Bituminous (Sufco)	Wood	25%	5	4/16/21	101
			Total	75		1311

CAPTURE AND CO_2 INLET CONCENTRATION



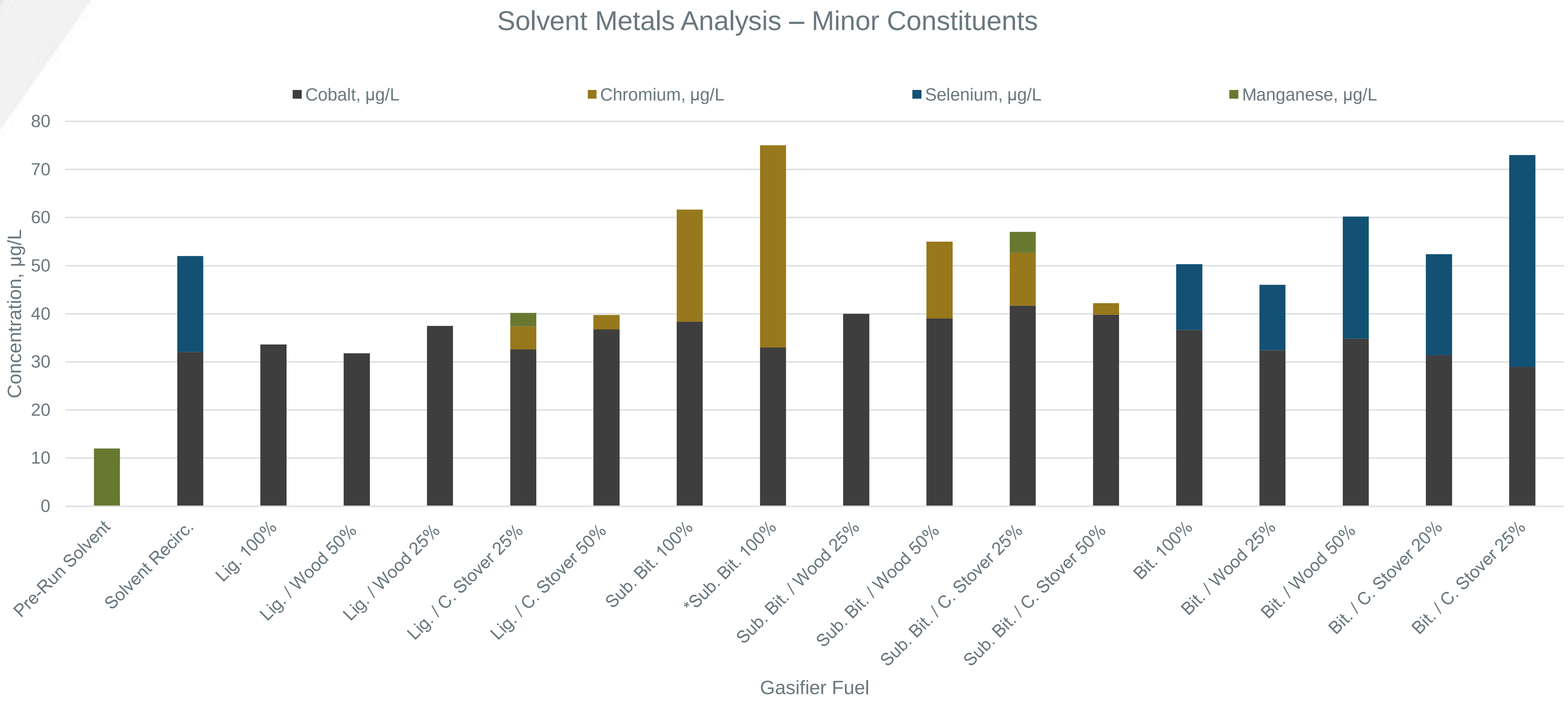
Carbon capture remained high for all the tests and was mainly a function of the inlet CO_2 concentration.

ORGANIC CARBON CONDENSED IN QUENCH WATER

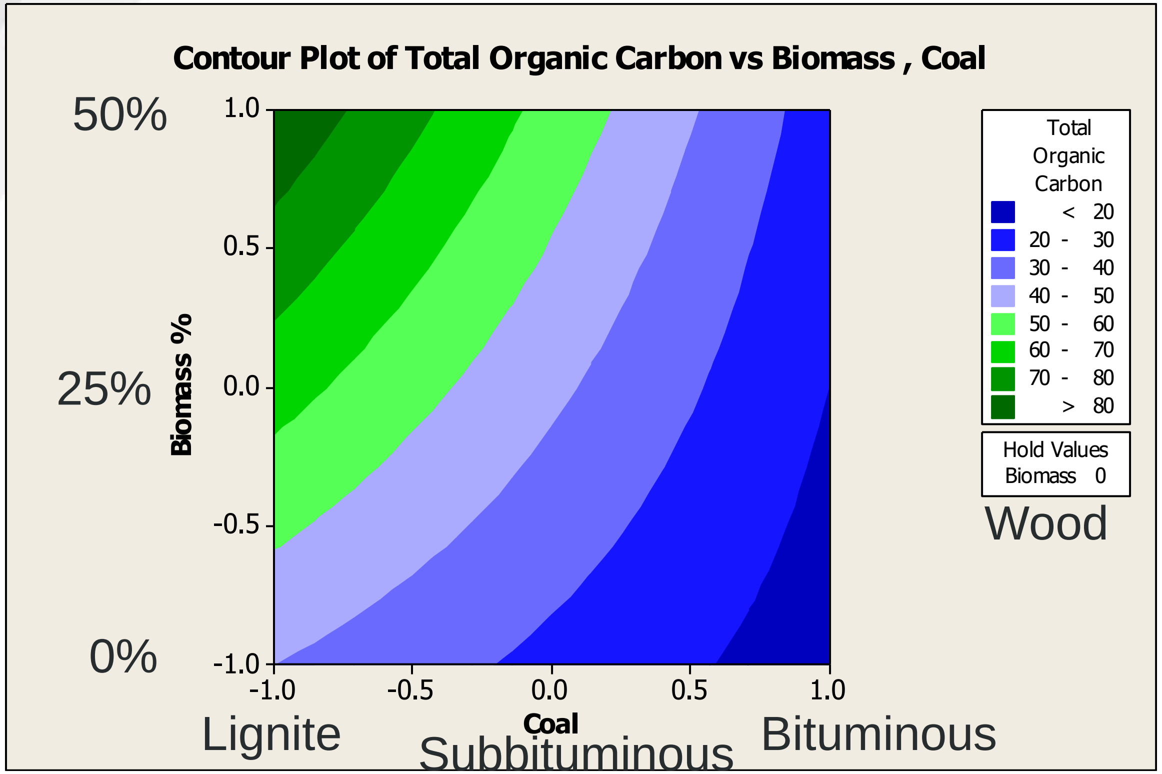


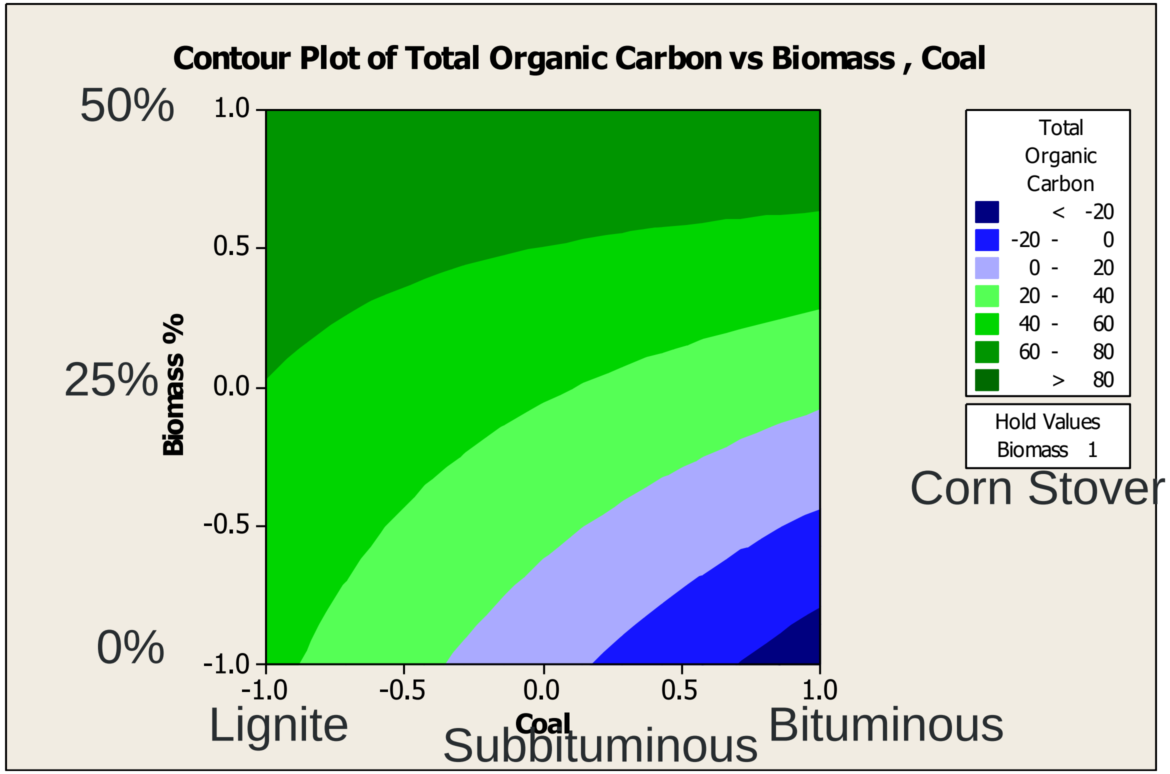
Correlation between the addition of biomass and increased organic production.

SOLVENT ANALYSIS – ELEMENTAL



CONTOUR PLOTS FROM STATISTICAL ANALYSIS





- Data show that organic levels are highest with lignite coal and high biomass blends.
- Coal type becomes irrelevant when high levels of corn stover are used, indicating a significant interaction.

SUMMARY

- Biomass gasification with carbon capture provides a significant opportunity for production of hydrogen, chemicals, or power with a net-carbon-negative footprint.
- The research conducted at the EERC highlights the challenges that must be overcome, but no significant technical showstoppers have been identified.
- Fixed-bed and fluid-bed gasifiers require less up-front fuel preparation but will result in higher levels of tar production than EFGs and therefore will require more back-end processing steps.
- Carbon capture solvents and SOFCs are able to handle the trace amounts of impurities that may make it through the primary cleaning step.
  - Longer-term data are needed.
  - Cost/benefit trade-offs.

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THANK YOU

Critical Challenges. Practical Solutions.

APPENDIX

EERC POSTCOMBUSTION TEST MATRIX

Run/ Weeks	Coal Type	Biomass Type	Biomass Blend	Testing Duration, days	Completion Date	Run Time on Solvent (h)
1	Subbituminous	None	0%	5	5/7/21	88
2	Subbituminous	Wood	17.5%	5	6/18/21	92
3	Subbituminous	Wood	35%	5	7/02/21	94
4	Subbituminous	Corn Stover	17.5%	5	5/14/21	91
5	Subbituminous	Corn Stover	35%	5	6/11/21	79
6	Lignite	None	0%	5	7/16/21	74
7	Lignite	Wood	17.5%	5	8/20/21	81
8	Lignite	Wood	35%	5	9/03/21	93
9	Lignite	Corn Stover	17.5%	5	7/23/21	77
10	Lignite	Corn Stover	35%	5	8/13/21	81
11	Bituminous (CAPP)	None	0%	5	9/17/21	81
12	Bituminous (CAPP)	Wood	17.5%	5	10/15/21	93
13	Bituminous (CAPP)	Wood	35%	5	10/29/21	95
14	Bituminous (CAPP)	Corn Stover	17.5%	5	9/24/21	95
15	Bituminous (CAPP)	Corn Stover	35%	5	10/08/21	94
16	None	Corn Stover	100%	~15	03/03/22	229
			Total	90		1537

Lignite – Falkirk Mine, ND   Subbituminous – Antelope (Rochelle Mine), WY
Bituminous – Central Appalachian Basin (CAPP), provided by Blackhawk Coal Sales

PLANNED SAMPLING ACTIVITIES

- Mercury concentrations at inlet/outlet of FGD
- EPA Method 5 downstream of FGD
- Aerosol particle-size distribution at inlet to direct contact cooler (DCC) and outlet of water wash
- FTIR measurements at ESP outlet, DCC inlet, absorber inlet/outlet, water wash outlet, and stripper outlet

Solvent Analysis

- Aluminum
- Arsenic
- Calcium
- Chromium
- Cobalt
- Copper
- Iron
- Magnesium
- Manganese
- Mercury
- Nickel
- Potassium
- Selenium
- Silicon
- Sodium
- Vanadium
- Zinc
- Acetate
- Bromide
- Chloride
- Formate
- Fluoride
- Nitrate
- Nitrite
- Oxalate
- Sulfate
- Thiosulfate
- pH

WOOD PELLETS

- The wood pellets were obtained for postcombustion testing from Thunderbolt Biomass, Inc., Allendale, South Carolina. The company website is https://thunderboltbiomass.com.

- The material is manufactured from several species of southern yellow pine (SYP) within 150 miles of Allendale, South Carolina. The forest industry in the area operates year-round, and all sources are commercial forest tracts prorated for this purpose.

- The SYP is purchased green (50% moisture content) or dry (approximately 10% moisture content) as sawmill residuals from local sawmills and some remanufacturing operations. The material is 100% virgin preconsumer SYP. Any green material is dried to about 10% moisture content in a dryer. Dry/dried material is sized to about 3–5 mm using a hammermill and then pressed through a pellet die. Pellets are about 6 mm in diameter and 10–24 mm in length. The pellets are cooled and then packaged for shipment. The process uses up to 0.05% starch addition for a binder and as a die lubricant.

- Thunderbolt Biomass produced about 4000 tons of pellets in 2020. The demand appears to be stable, and it is anticipated that production will increase throughout 2021.

AERSOLS – CONCENTRATIONS ACROSS THE CAPTURE SYSTEM