Techno-economic and Lifecycle Greenhouse Gas Assessments of H_2 Production from Coal, Coal/Biomass, and Biomass

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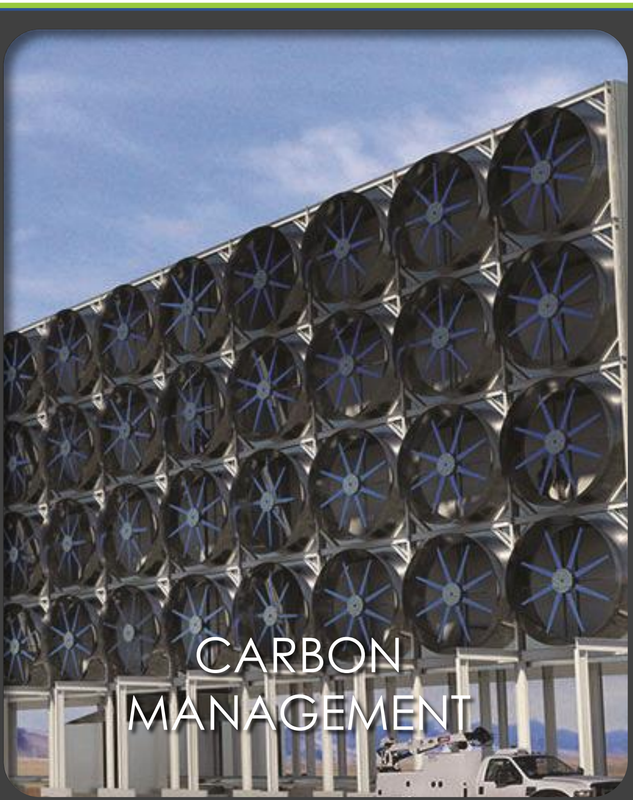
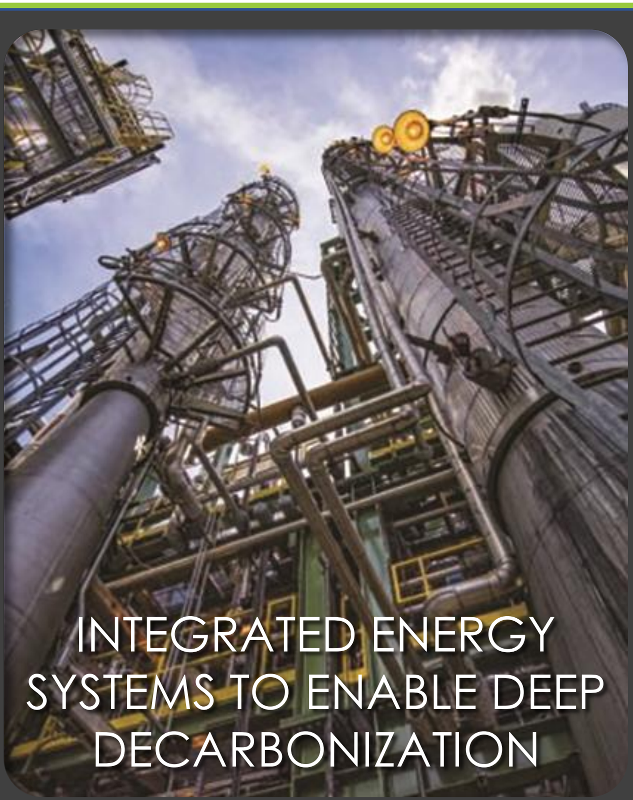
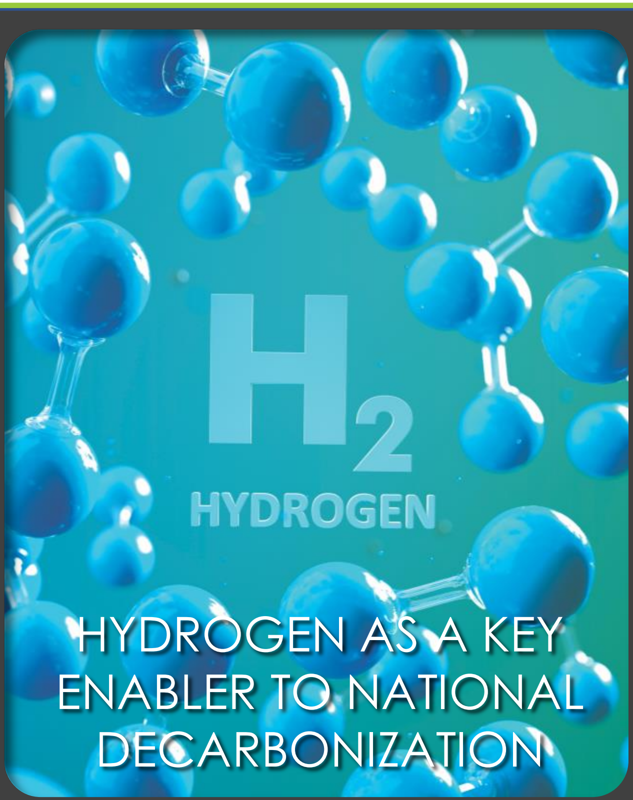

CARBON MANAGEMENT


INTEGRATED ENERGY SYSTEMS TO ENABLE DEEP DECARBONIZATION



HYDROGEN AS A KEY ENABLER TO NATIONAL DECARBONIZATION

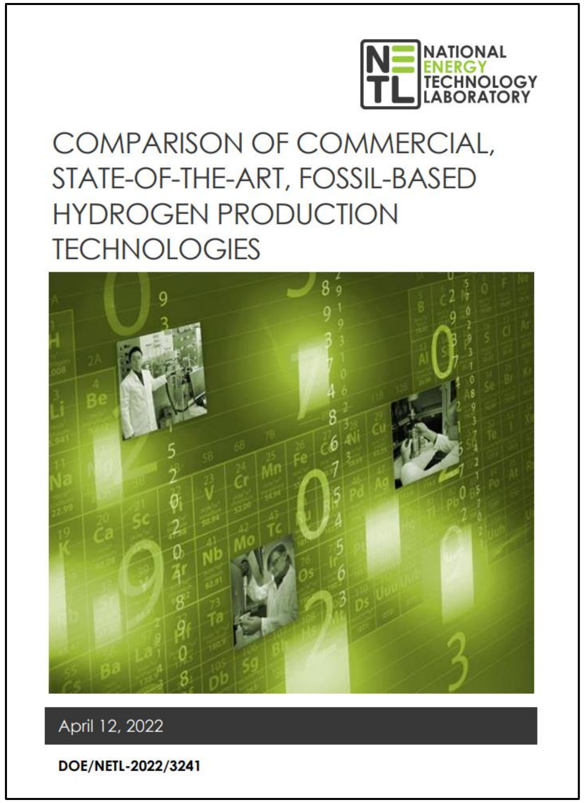

LIFE CYCLE ANALYSIS

Gasification Technology Status and Pathways for Net-Zero Carbon Economy Workshop

November 30, 2022

Recent H_2 Production Study Publication

NETL has published a combined techno-economic (TEA) and life cycle analysis (LCA) of commercial, state-of-the-art fossil-based H_2 production technologies[1,2]



COMPARISON OF COMMERCIAL, STATE-OF-THE-ART, FOSSIL-BASED HYDROGEN PRODUCTION TECHNOLOGIES

April 12, 2022

DOE/NETL-2022/3241

Today's Topics:

- Motivation
- Summary - justification, objectives, & primary TEA/LCA findings
- Key Assumptions & Results
- Current Work

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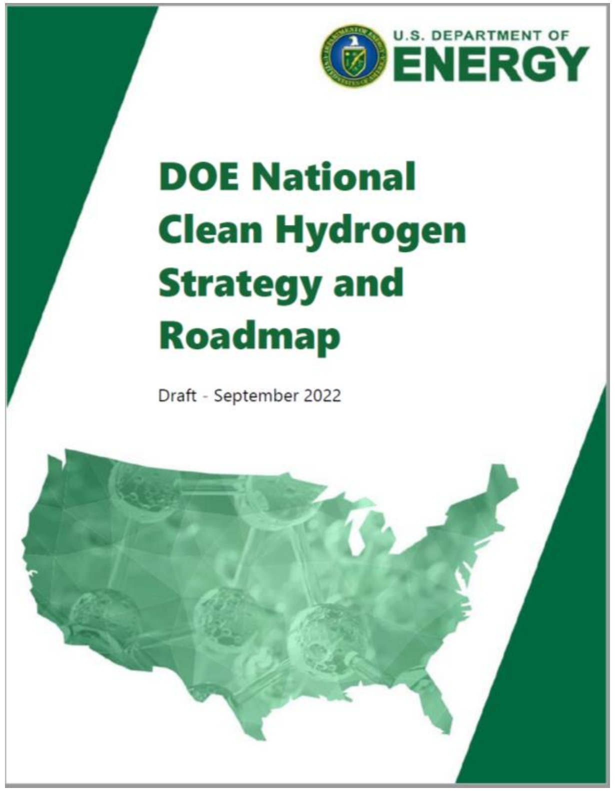
[1] Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies, DOE/NETL-2022/3241, April 12, 2022 https://netl.doe.gov/energy-analysis/details?id=ed4825aa-8f04-4df7-abef-60e564f636c9

[2] Funding provided by the DOE Office of Fossil Energy and Carbon Management (FECM)

Study Motivation



U.S. DEPARTMENT OF ENERGY

DOE National Clean Hydrogen Strategy and Roadmap

Draft - September 2022

1 Dollar 1 Kilogram 1 Decade

https://www.energy.gov/eere/fuelcells/hydrogen-shot

- **June 2021 - DOE launched the first Energy Earthshot to reduce the cost of clean hydrogen production to $1 per 1 kilogram in 1 decade (“1, 1, 1”)**
- **November 2021 - Infrastructure Investment and Jobs Act (IIJA) passed**
- **April 2022 – NETL releases contemporary H_2 production study**
- **August 2022 - Inflation Reduction Act (IRA) passed**
- **September 2022 – DOE releases the draft initial Clean Hydrogen Production Standard (CHPS)**
- **September 2022 – DOE releases the draft National Clean Hydrogen Strategy and Roadmap**
- **September 2022 – DOE releases the Regional Clean Hydrogen Hubs Funding Opportunity Announcement (DE-FOA-0002779)**

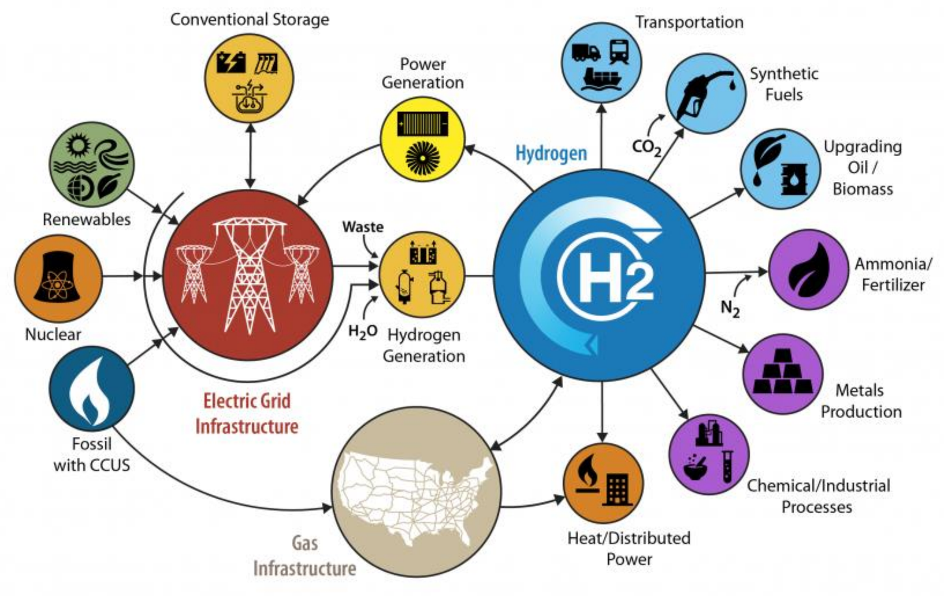
Study Summary

Justification

- This TEA/LCA of fossil-to-H_2 production routes using current, commercial technologies provides a basis for DOE FECM R&D program planning to reduce the levelized cost of hydrogen (LCOH) and greenhouse gas (GHG) footprint of future fossil-to-H_2 plants

Objectives

- Develop a reference study of H_2 production technologies using current, commercial technologies[1] with emphasis on coal gasification, co-gasification of coal with an alternative feedstock, and NG technologies using the LCOH (2018 $/kg) as the figure of merit
- Identify areas of R&D to further improve the performance and cost of fossil fuel-based H_2 production, including follow-on analyses



Source: DOE

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[1] Commercial technologies are considered process systems that do not face fundamental R&D challenges within the plant flowsheets considered and at the scales studied

Study Summary

Case Selection

Case[A]	Plant Type	Feedstock(s)	Reformer Type	Gasifier Type	CO_2 Capture (%)	H_2 Purification	H_2 Production Capacity
1	Reforming	Natural Gas	SMR	-	0	PSA	200 MMSCFD 483,000 kg/day 44,400 lb/hr
2					96.2		
3			ATR		94.5		274 MMSCFD 660,000 kg/day 60,600 lb/hr
4	Gasification	Illinois No. 6 Coal	-	Shell[B]	0		
5					92.5		
6		Illinois No. 6 Coal/Torrefied Woody Biomass			92.6		55 MMSCFD 133,000 kg/day 12,200 lb/hr

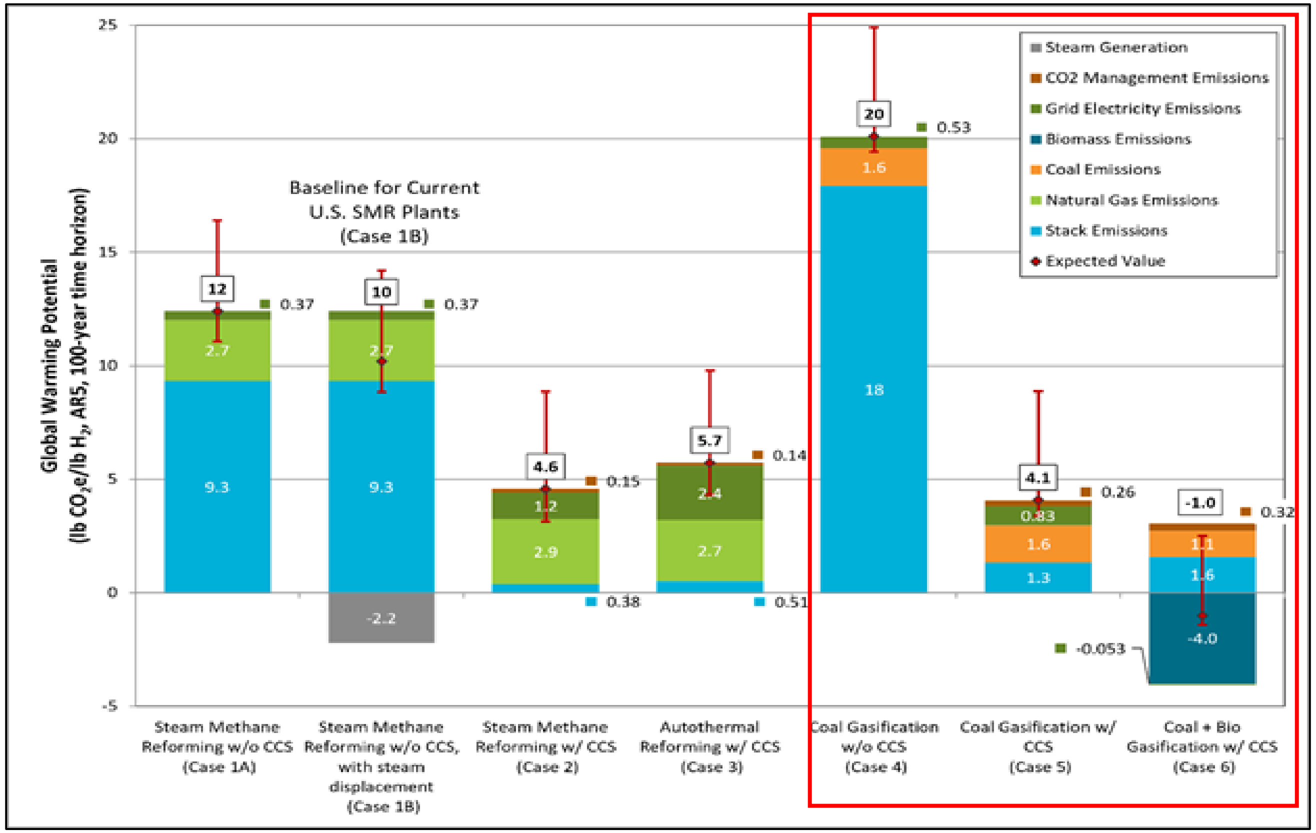
[A] Gasification plants are assumed to operate at 80 percent capacity factor and are located at a generic plant site in the midwestern United States.

[B] The Shell gasifier has been used in multiple prior NETL studies. As of May 2018, Air Products has acquired the coal gasification technology licensing business from Shell. To be consistent with prior NETL studies and avoid confusion, the gasifier is labeled the "Shell" gasifier.

Study Summary

Primary Results - LCA GHG Emissions (Cradle-to-Gate)

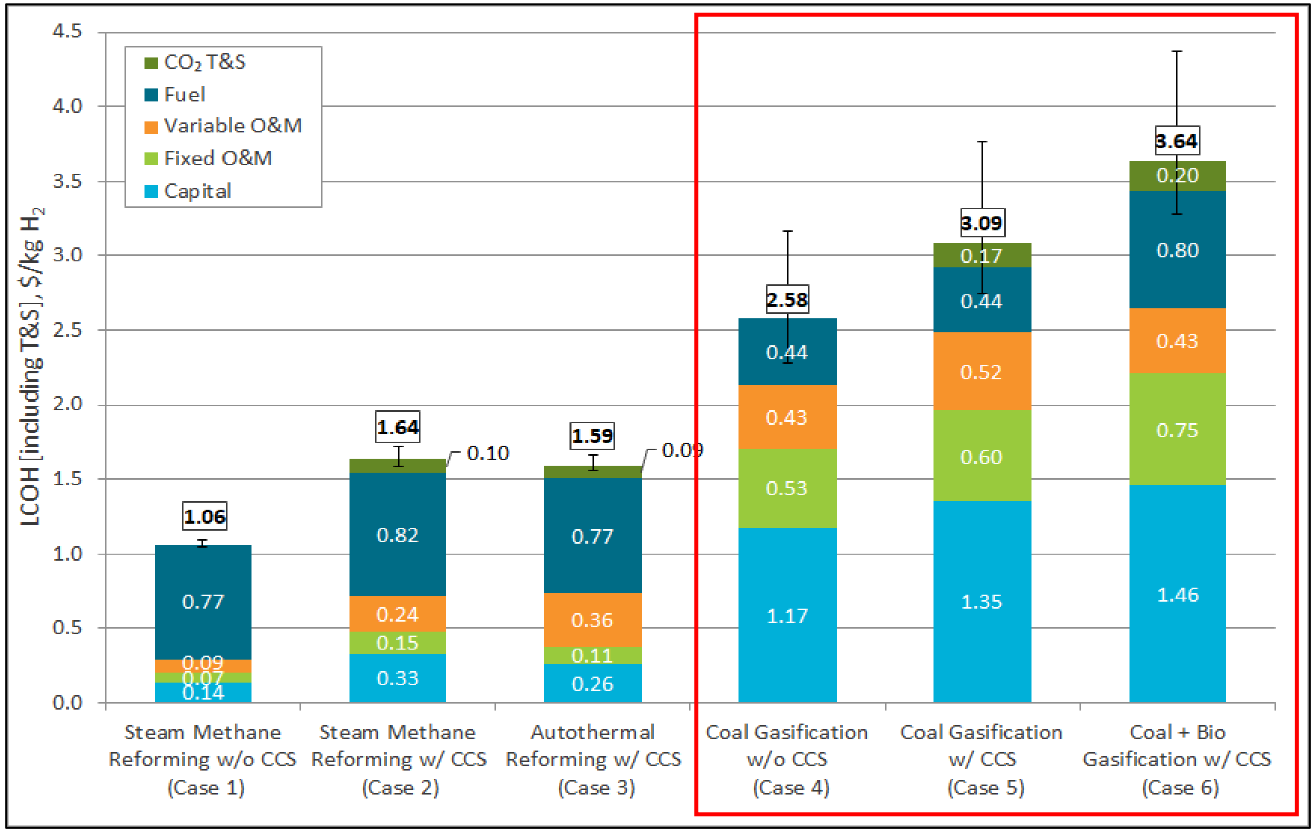
- Co-gasification of 43.5 percent torrefied, woody biomass enables -1.0 lb CO_2e/lb H_2 of GHG emissions across the lifecycle
- Coal gasification w/ CCS has the lowest GHG emissions over the plant life-cycle of all 100% fossil feedstock cases (4.1 lb CO_2e/lb H_2)



Study Summary

Primary Results - LCOH

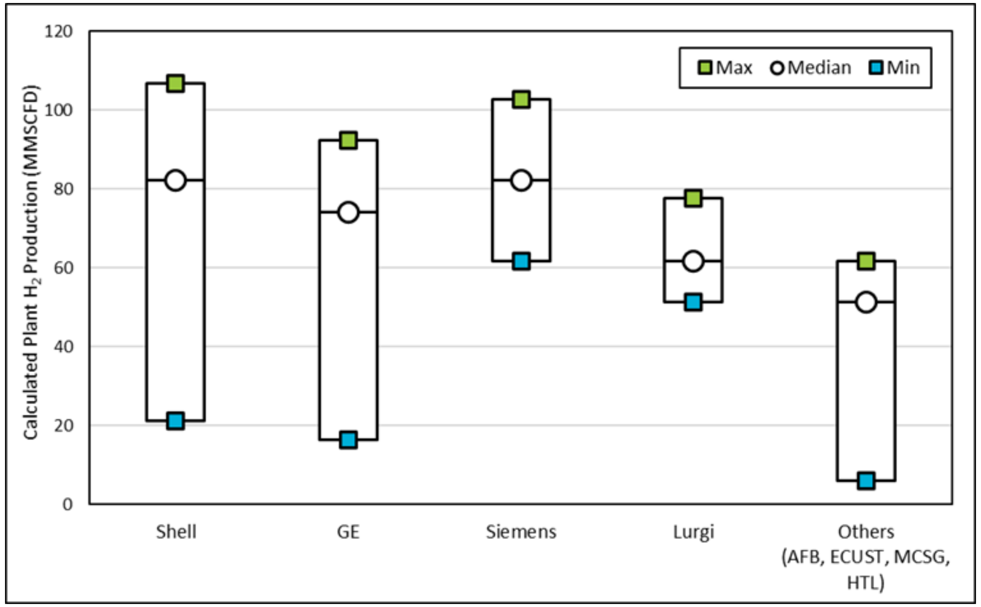
- Coal/biomass co-gasification w/ CCS has the highest LCOH (\$3.64/kg H_2) of all cases. Primary cost drivers are:
  - Greater biomass feedstock cost
  - Smaller plant capacity
- Coal gasification w/o CCS achieves the lowest LCOH (\$2.58/kg H_2) of all gasification cases



[1] LCOH error bars depict TOC uncertainty ranges of -15%/+25% (AACE Class 4) and -25%/+50% (AACE Class 5) for reforming and gasification cases, respectively

Study Summary

Primary Findings - Literature Review



- **High-purity H_2 from coal[1]**
  - Coal gasification predominantly in China for ammonia
  - Estimated to have a median H_2 production rate between 50 and 100 MMSCFD
  - Engineering studies have been completed for such facilities up to 282 MMSCFD H_2 production

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[1] NETL, China Gasification Database, https://netl.doe.gov/research/coal/energy-systems/gasification/gasification-plant-databases/china-gasification-database

Literature Review

Primary Findings - Literature Review (cont'd.)

- **H_2 from alternative feedstocks (e.g., biomass, MSW)**
  - No currently operating commercial alternative feedstock gasification facilities producing high-purity H_2 as an end product
    - A few are planned or on hold
    - One produces H_2 as a precursor to ammonia (Showa Denko)
  - Buggenum IGCC (coal/biomass co-gasification - decommissioned) and Eastman Kingsport (coal/waste plastics) are the only examples of commercially operating facilities to co-gasify coal with an alternative feedstock
    - Neither produces H_2 as an end-product

Key Assumptions

Solid Feedstock Characteristics

Rank	**Bituminous[1]**	
Seam	**Illinois No. 6**	
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, kJ/kg (Btu/lb)	26,151 (11,252)	29,444 (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

Torrefied Woody Biomass		
	As Received	**Dry**
Ultimate Analysis (weight %)		
Moisture	5.72	0.00
Carbon	59.89	63.52
Hydrogen	5.11	5.42
Nitrogen	0.41	0.44
Chlorine	0.00	0.00
Sulfur	0.00	0.00
Ash	0.51	0.54
Oxygen	28.36	30.08
Total	**100.00**	**100.00**
Heating Value		
HHV (Btu/lb)	9,749	10,340
LHV (Btu/lb)	9,203	9,825

[1] Quality Guidelines for Energy System Studies: Specification for Selected Feedstocks (Technical Report) | OSTI.GOV

Key Assumptions

H_2 Product Specifications

Characteristics	Concentration
Hydrogen Purity (vol%)	99.90
Max. CO_2 (ppm)	A
Max. CO (ppm)	A
Max. H_2S (ppb)	10
Max. H_2O (ppm)	A
Max. O_2 (ppm)	A

[A] The maximum total concentration of all oxygen containing species is 10ppm

- **The hydrogen product meets the purity specification shown, which results in a product suitable for several potential applications**
- **Contaminant levels are for ammonia-grade H_2 to avoid catalyst poisoning**
- **Additionally, the specification results in a product exceeding specifications for the following ISO 14687:2019 gaseous H_2 grades:**
  - Grade A – combustion applications
    - Internal combustion engines, residential/commercial heating appliances
  - Grade B – industrial power and heat applications
    - Excluding PEM fuel cells
- **H_2 product is compressed to 6.4 MPa (925 psig) for pipeline injection**

Key Assumptions

Facility Air Emissions

- **The primary air emission sources for the cases are:**
  - SMR furnace
  - ATR fired heater
  - Auxiliary boiler – gasification cases
- **Plants are in an attainment area, thus the inclusion of Best Available Control Technologies will be required per New Source Review**
- **The tables below include the control technologies and achievable limits**

BACT Environmental Design Basis for Natural Gas Cases

Pollutant	Environmental Design Basis	
	Control Technology	**Limit**
Sulfur Oxides	Zinc oxide guard bed	Negligible
Nitrogen Oxides	Low NOx Burners	2.5 ppmv (dry) @ 15% O_2
Particulate Matter	N/A	Negligible
Mercury	N/A	Negligible

BACT Environmental Design Basis for Coal Cases

Pollutant	Environmental Design Basis	
	Control Technology	**Limit**
Sulfur Oxides	AGR + Claus Plant or equivalent performing system	99+% or ≤ 0.050 lb/10^6 Btu
Nitrogen Oxides	Low NOx Burners	15 ppmv (dry) @ 15% O_2
Particulate Matter	Cyclone/Barrier Filter/Wet Scrubber/AGR Absorber	0.015 lb/10^6 Btu
Mercury	Activated Carbon Bed or equivalent performing system	95% removal

Key Assumptions

Life Cycle Emissions

- **Overall data is representative of 2016-2017**
- **Natural gas**
  - Model and methods documentation - *"Life Cycle Analysis of Natural Gas Extraction and Power Generation," NETL, April 19, 2019*
  - Emissions and production data - *"Industry Partnerships & Their Role In Reducing Natural Gas Supply Chain Greenhouse Gas Emissions – Phase 2," NETL, February 12, 2021*
- **Electricity emissions**: Assembled from publicly reported emissions and power generation datasets for 2016[1]
- **Coal**:
  - Model and methods documentation - *"Life Cycle Analysis: Supercritical Pulverized Coal (SCPC) Power Plant," NETL, April 13, 2018*
  - Coal mine methane emissions are from 2016 EPA GHGRP data
- **Torrefied southern yellow pine**:
  - Model and methods documentation - *"Comprehensive Analysis of Coal and Biomass Conversion to Jet Fuel: Oxygen Blown, Transport Reactor Integrated Gasifier (TRIG) and Fischer-Tropsch (F-T) Catalyst Configurations," NETL, September 8, 2015*
  - Background data (e.g., electricity and fuel) from 2016
- **Saline aquifer storage**
  - Model and methods documentation - *"Life Cycle Analysis: Supercritical Pulverized Coal (SCPC) Power Plant," NETL, April 13, 2018*

[1] Federal Commons

Key Assumptions

Solid Feedstock Costs

- **Delivered coal and NG costs are consistent with current NETL QGESS methodology[1]**
  - Delivered Illinois No. 6 – \$2.22/MMBtu
  - Delivered NG - \$4.42/MMBtu
- **A site-delivered cost of torrefied Southern yellow pine was calculated using an existing NETL cost model that considers centralized production of the design feedstock and distribution to the H_2 plant**
- **The modeled cost was levelized to be consistent with current NETL QGESS methodology**
  - Delivered biomass - \$5.43/MMBtu

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[1] Quality Guidelines for Energy System Studies: Fuel Prices for Selected Feedstocks in NETL Studies (Program Document) | OSTI.GOV

Key Assumptions

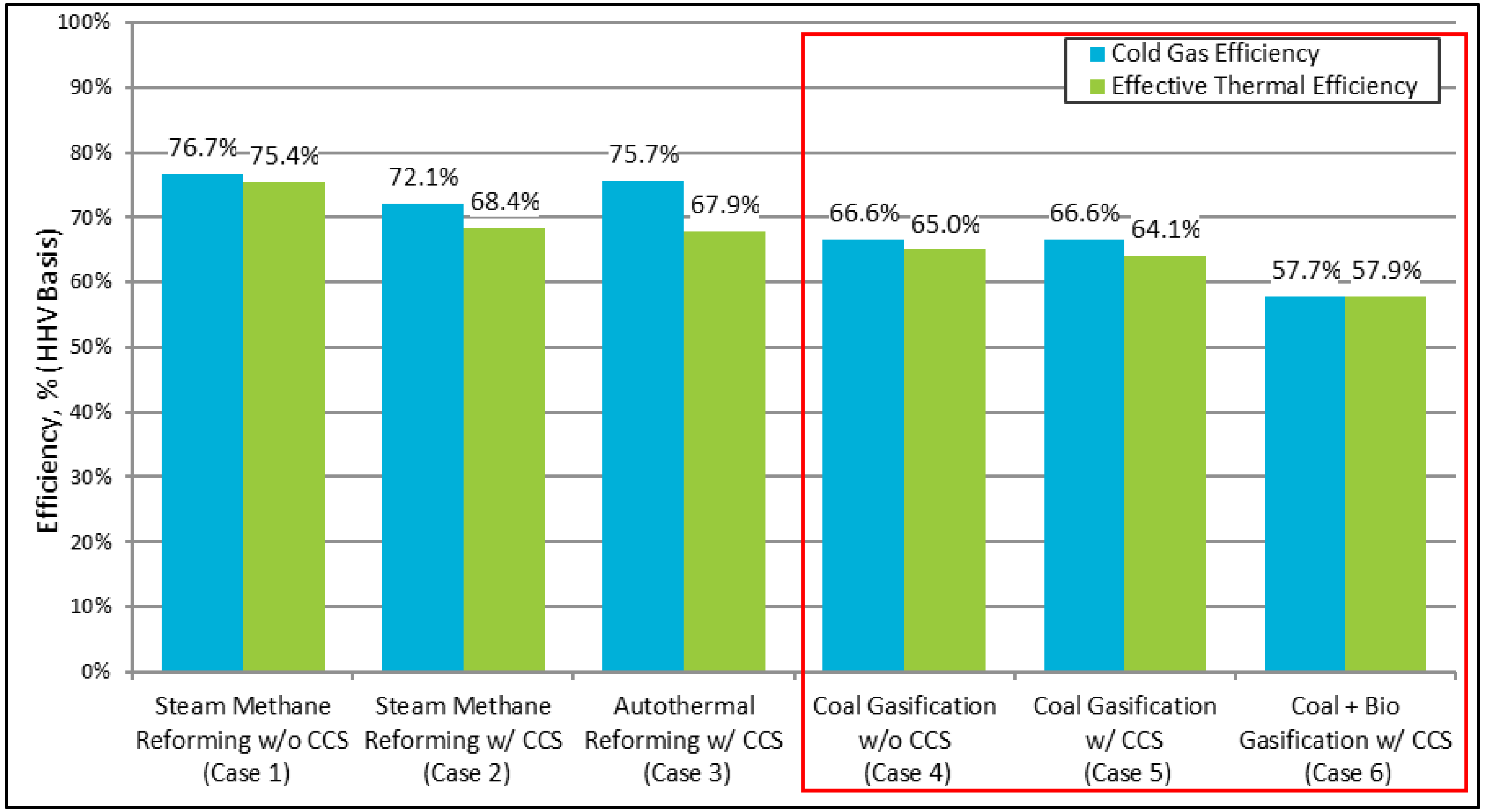
Byproduct Revenues, Tax Credits, Emission Penalties

- No revenues generated from the sale of air gases (e.g., N_2, Ar), steam, or pipelined CO_2
- Export power is sold to the grid at $71.7/MWh
- No CO_2 emissions penalty
- No tax credits for CCS (e.g., 45Q) or clean H_2 production (e.g., 45V) are included
- Sensitivity analyses quantify the economic impact from several of these factors

Results

Plant and Environmental Performance

Efficiencies



[A] Effective Thermal Efficiency (ETE) = (Hydrogen Heating Value + Net Power) / Fuel Heating Value

[B] Cold Gas Efficiency (CGE) = Hydrogen Heating Value / Fuel Heating Value

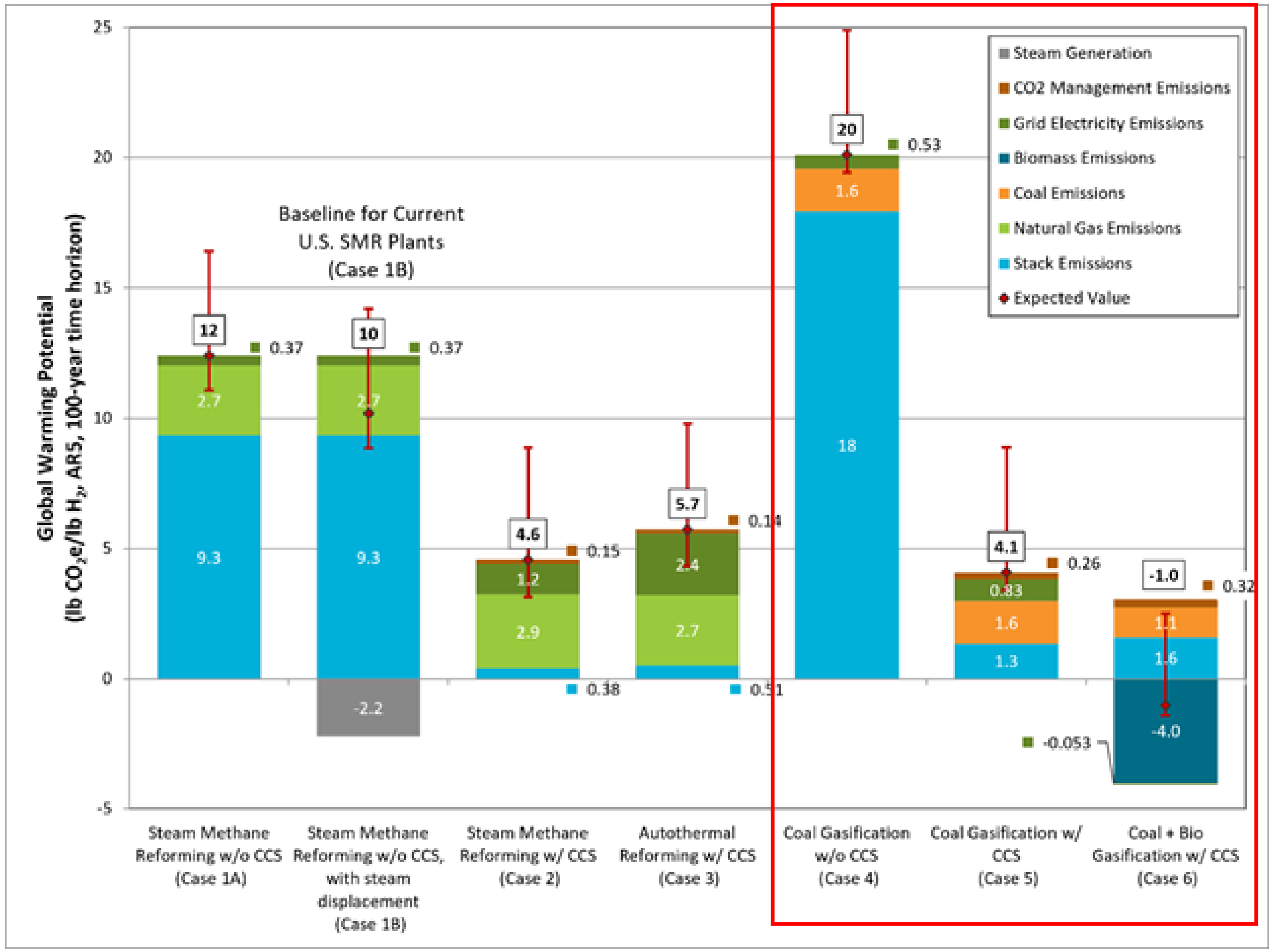
- **Coal/biomass co-gasification w/ CCS has the lowest plant efficiency (CGE and ETE). A lower PSA H_2 recovery (75% vs. 85%) is used to avoid grid power import**

Results

Plant and Environmental Performance (cont'd.)

- **Variability and uncertainty**
  - Natural gas –variability throughout the life cycle and across the regional sources of natural gas
  - Coal – mostly from variability in reported coal mine methane emissions
  - Southern yellow pine – variability in yield and fertilization rates
  - Electricity – variability in reported emissions
- **Impact Assessment method**
  - Default values use IPCC AR5 global warming potentials with climate carbon feedback.
  - 100-year time horizon
  - Key here is the value of 36 kg CO_2-equivalents per kg of fossil methane.
  - Results based on other vintages of global warming potentials are provided in the report

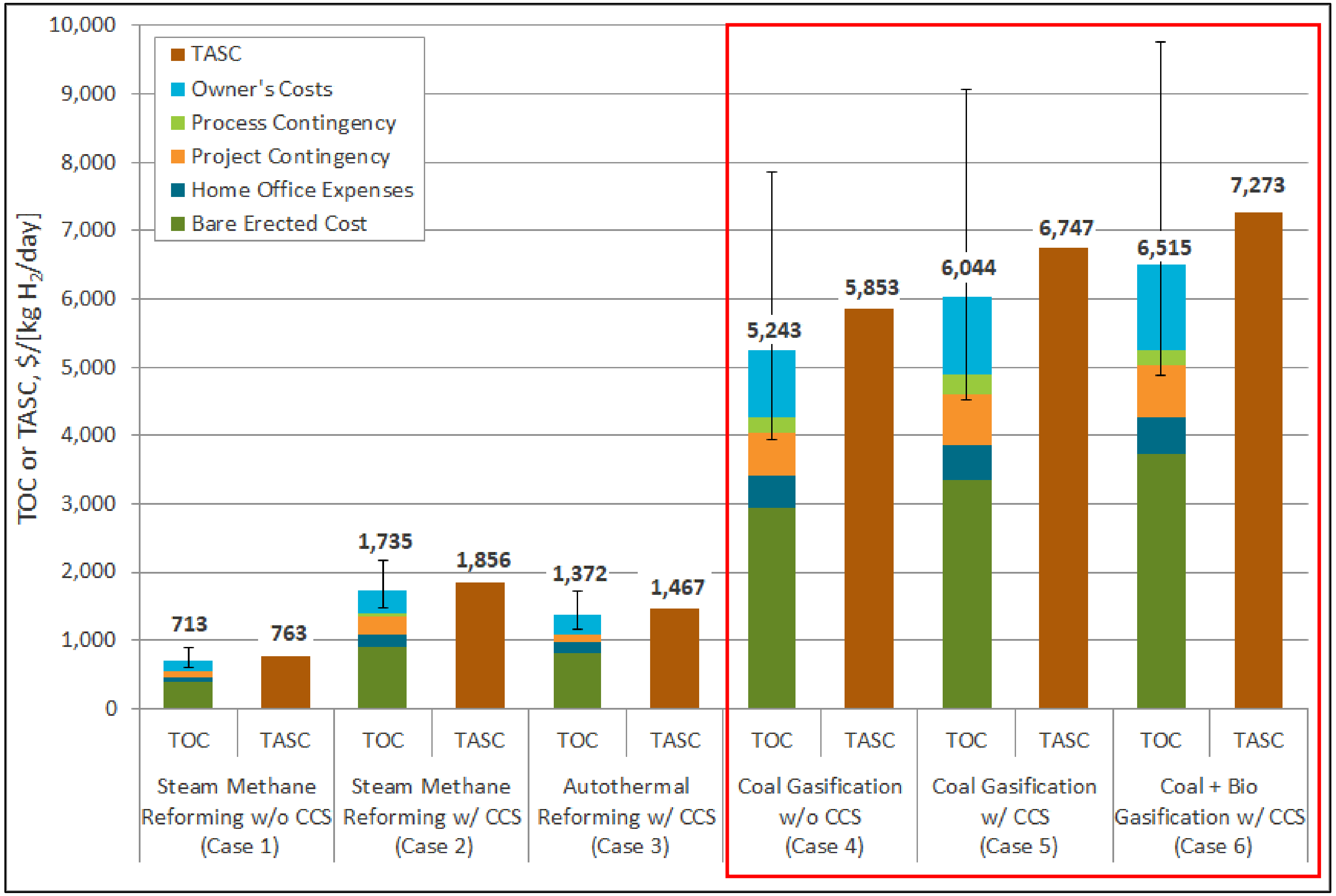
Global Warming Potentials



Results

Economic

Total Overnight Cost (TOC) and Total As-Spend Cost (TASC)[1]

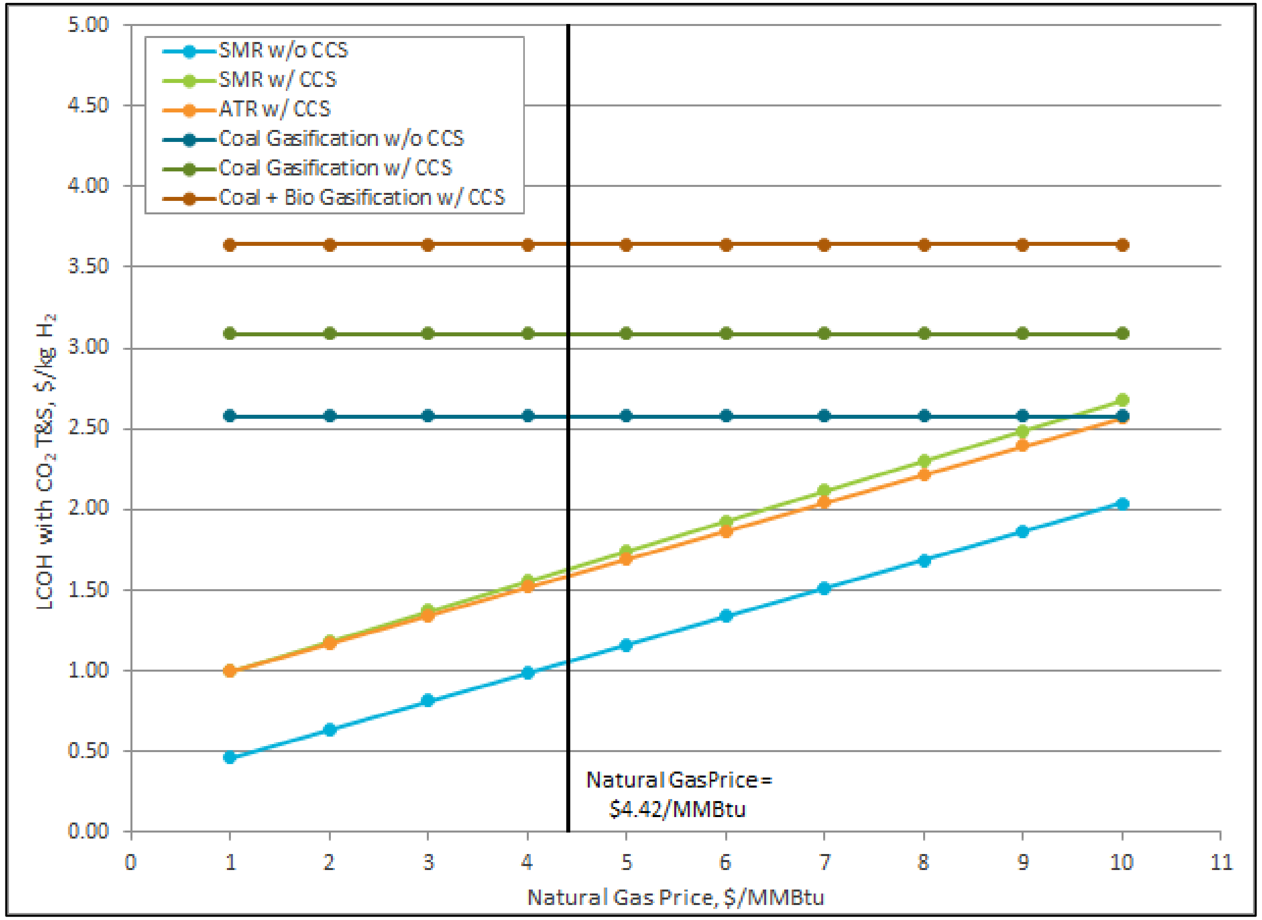


- **The coal/biomass co-gasification w/ CCS has the highest TOC ($6,515/[kg H_2/day]) of all cases and gasification cases.**
- **The coal gasification w/o CCS achieves the lowest TOC ($5,243/[kg H_2/day]) of gasification cases**

[1] TOC error bars depict uncertainty ranges of -15%/+25% (AACE Class 4) and -25%/+50% (AACE Class 5) for reforming and gasification cases, respectively

Results

NG Price Sensitivity



- **At an NG price above $9/MMBtu, the SMR plant w/ CCS becomes on-par with the coal gasification plant w/o CCS**
- **Coal w/ CCS becomes competitive with NG w/ CCS above $11/MMBtu**

Current Work

Net-Zero H_2 from Alternative Feedstock Gasification

- Gasification-to-H_2 approaches are generally more costly than natural gas approaches
- However, 2035 net-zero GHG power sector and 2050 economy-wide Administration goals, and consideration of other socioeconomic benefits (e.g., energy justice), creates additional value propositions for gasification technologies; particularly, by using carbon neutral and waste feedstocks
- To address the cost challenge, NETL is developing analyses that will:
  - Characterize cost and performance of current, state-of-the art gasification pathways using various alternative, carbonaceous feedstocks (e.g., biomass, MSW, and waste plastics) capable of achieving net-zero GHG H_2 production
  - Characterize current market conditions for the utilization of such feedstocks as well as competing alternatives
  - Formulate strategies for reducing the levelized cost of net-zero H_2 through technology R&D (e.g., advanced CO_2 capture)

Acknowledgements

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