Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies

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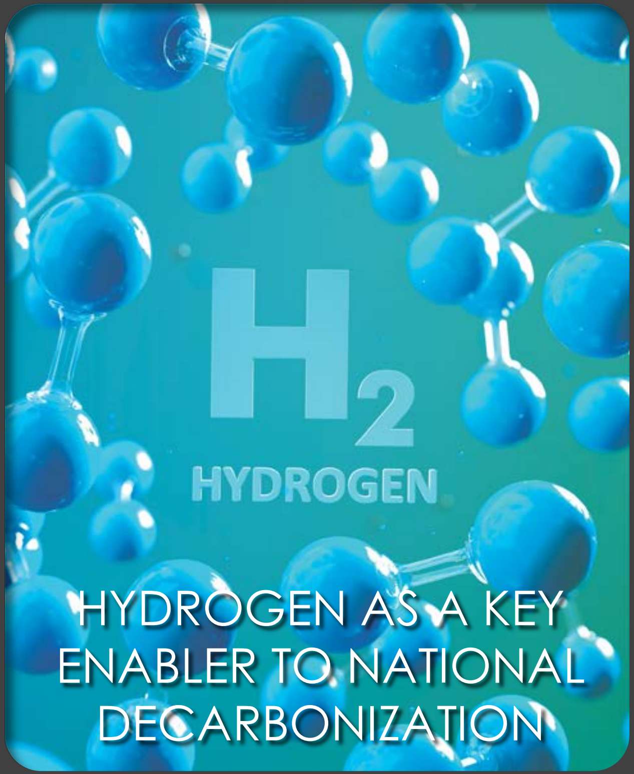
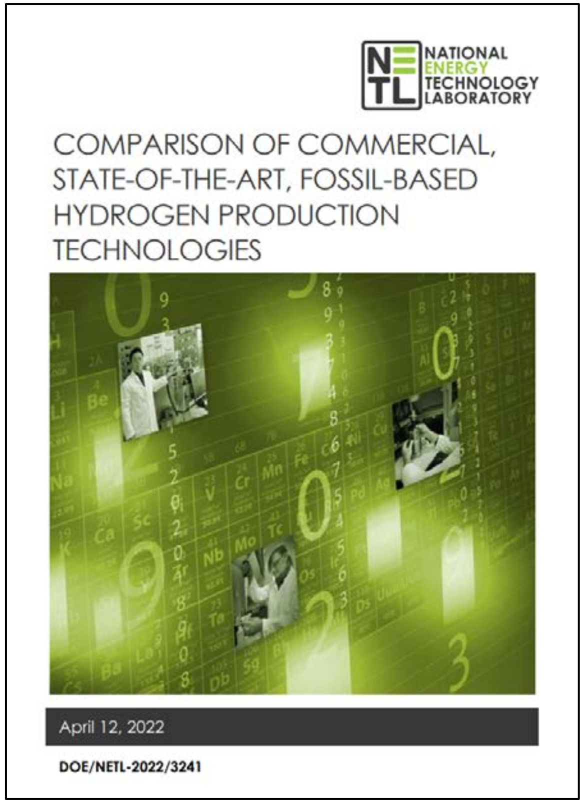


Recent H_2 Production Study Publication

NATIONAL ENERGY TECHNOLOGY LABORATORY

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]


NATIONAL ENERGY TECHNOLOGY LABORATORY

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

April 12, 2022

DOE/NETL-2022/3241

<u>Today's Topics:</u>

- **Study Deep Dive**
  - **Summary – justification, objectives, highlights, and approach**
  - **Detailed Overview – literature review, design basis, results, analysis, future work**
- **Questions**

[1]Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies, DOE/NETL-2022/3241, April 12, 2022 https://www.osti.gov/biblio/1862910

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

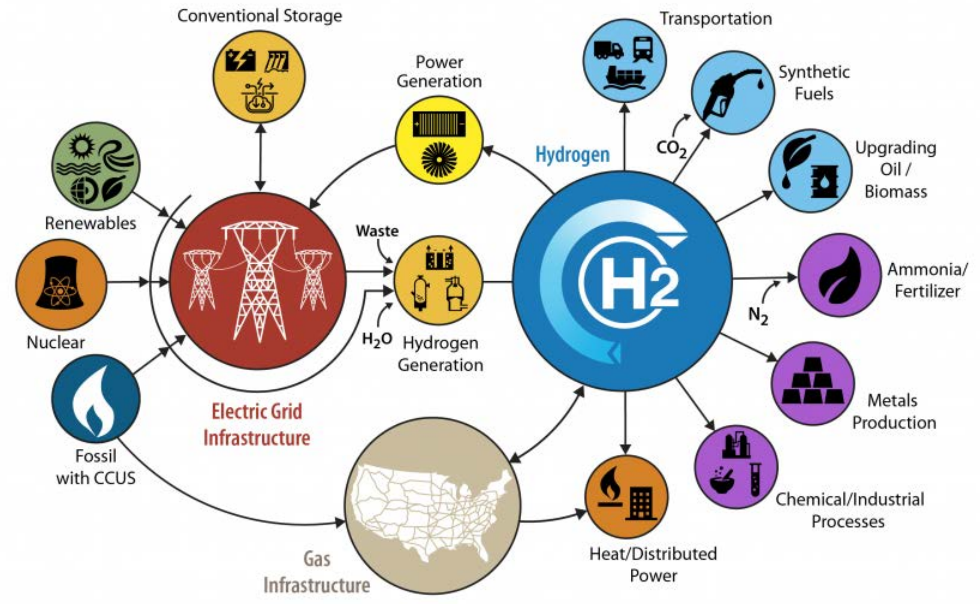
Study Summary

Justification

- This TEA analysis 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 natural gas (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



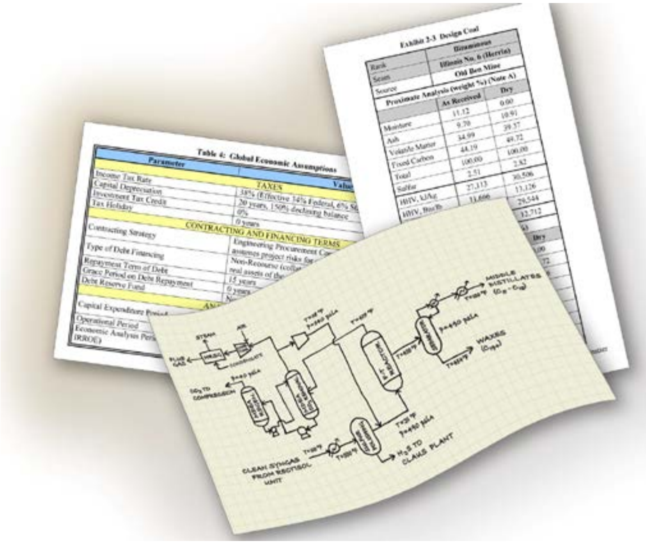
Source: DOE

[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

Approach

- **Literature Review**
  - Characterization of the global, high-purity H_2 production industry
  - Review of commercially operating, fossil-based H_2 production plants with and without CCS
  - Review of commercially available CO_2 separation technologies for H_2 applications
  - Investigation into H_2 from alternative feedstocks (e.g., biomass, municipal solid waste (MSW))
- **Design Basis**
  - Development of study case definitions, performance, and economic assumptions
- **Performance Modeling**
  - Development of Aspen Plus® models (6 cases total)
- **Economic Modeling**
  - Development of new capital and operation and maintenance (O&M) costs for major process areas
  - Cost scaling performed according to NETL QGESS methodology[1]
  - LCOH developed for each study case
- **Results Reporting**
  - NETL report publication



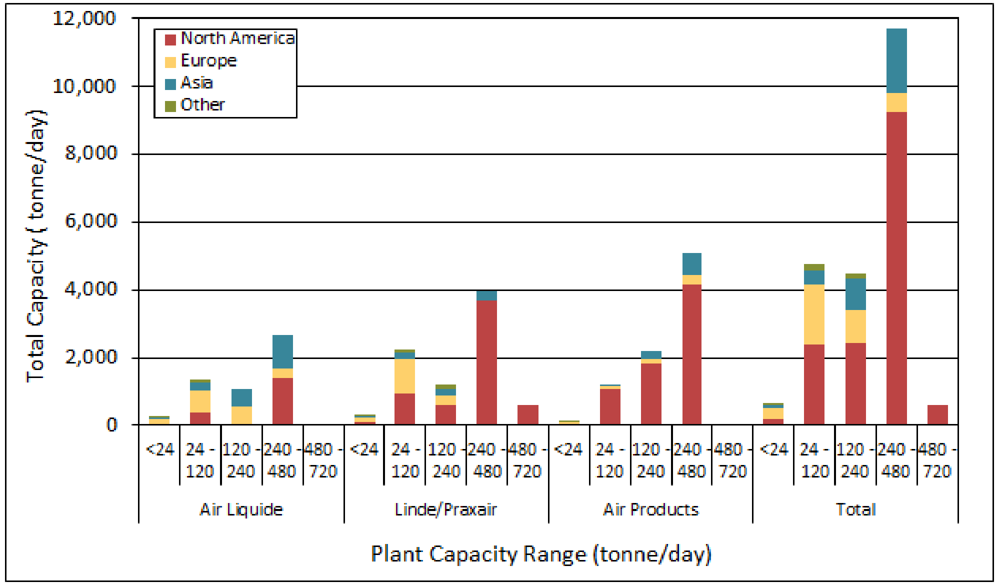
Source: NETL

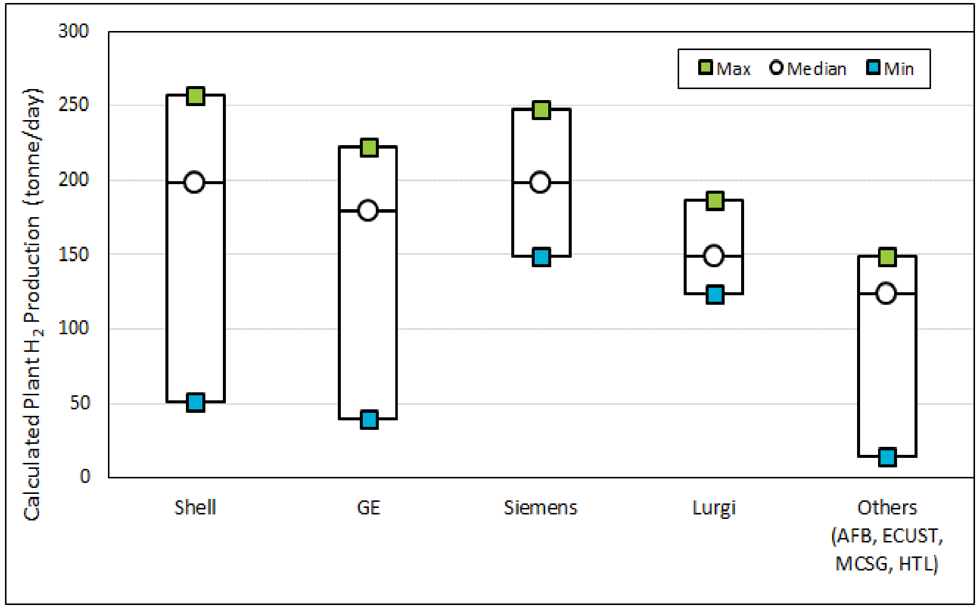
[1] "Quality Guidelines for Energy System Studies (QGESS): Capital Cost Scaling Methodology," NETL, 2019

Literature Review

Primary Findings

- **High-purity H_2 from NG[1]**
  - Merchant production facilities are spread globally and mostly support refinery and ammonia applications
  - Facility sizes typically 24 - 480 tonne/day H_2





- **High-purity H_2 from coal[2]**
  - Coal gasification predominantly in China for ammonia
  - Estimated to have a median H_2 production rate between 120 and 250 tonne/day
  - Engineering studies have been completed for such facilities up to 680 tonne/day H_2 production

[1]PNNL, Hydrogen Production, https://h2tools.org/hyarc/hydrogen-production
[2]NETL, China Gasification Database, https://netl.doe.gov/research/coal/energy-systems/gasification/gasification-plant-databases/china-gasification-database

Literature Review

Primary Findings (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 likely produces H_2 as a precursor to ammonia (Showa Denko), but could not be verified
  - 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

Literature Review

Primary Findings (cont'd.)

- **H_2/CO_2 Separation Technologies**
  - Carbon capture utilization & storage (CCUS) is operating commercially at just a few H_2 facilities (e.g., Air Products Port Arthur SMR, Air Liquide Port Jérôme SMR)
    - Overall capture rates are <90 percent since the SMR furnace flue gas is not treated
    - Vacuum swing adsorption and CRYOCAP™ H_2 technologies are used to separate CO_2 from the syngas stream
  - Multiple announced projects incorporate CCUS in vendor ATR flowsheets to achieve 90+ percent overall capture rate
    - Commercial CO_2 separation technologies are being proposed (e.g., amine solvents, Rectisol)
  - Pressure Swing Adsorption (PSA) is the predominant H_2 purification technology

Design Basis

Case Selection

Case[A]	Plant Type	Feedstock(s)	Reformer Type	Gasifier Type	CO_2 Capture (%)	H_2 Purification	H_2 Production Capacity
1	Reforming	NG	SMR	-	0	PSA	200 MMSCFD 483 tonne/day
2					96.2		
3			ATR		94.5		274 MMSCFD 660 tonne/day
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 tonne/day

[A] Reforming and gasification plants are assumed to operate at 90 and 80 percent capacity factor, respectively, 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.

Design Basis

Feedstock Characteristics

NG[1]		
Component		**Volume Percentage**
Methane	CH_4	93.1
Ethane	C_2H_6	3.2
Propane	C_3H_8	0.7
n-Butane	C_4H_{10}	0.4
Carbon Dioxide	CO_2	1.0
Nitrogen	N_2	1.6
Methanethiol[A]	CH_4S	$5.75x10^{-6}$
	Total	**100.0**
Heating Value		
	LHV	**HHV**
kJ/kg (Btu/lb)	47,201 (20,293)	52,295 (22,483)
MJ/scm (Btu/scf)	34.52 (927)	38.25 (1,027)

[A]The sulfur content of NG is primarily composed of added Mercaptan (methanethiol [CH_4S]) with trace levels of hydrogen sulfide (H_2S)
Note: Fuel composition is normalized, and heating values are calculated using Aspen

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

Design Basis

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**

Design Basis

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 NG 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	Acid gas removal (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

Design Basis

Feedstock Costs

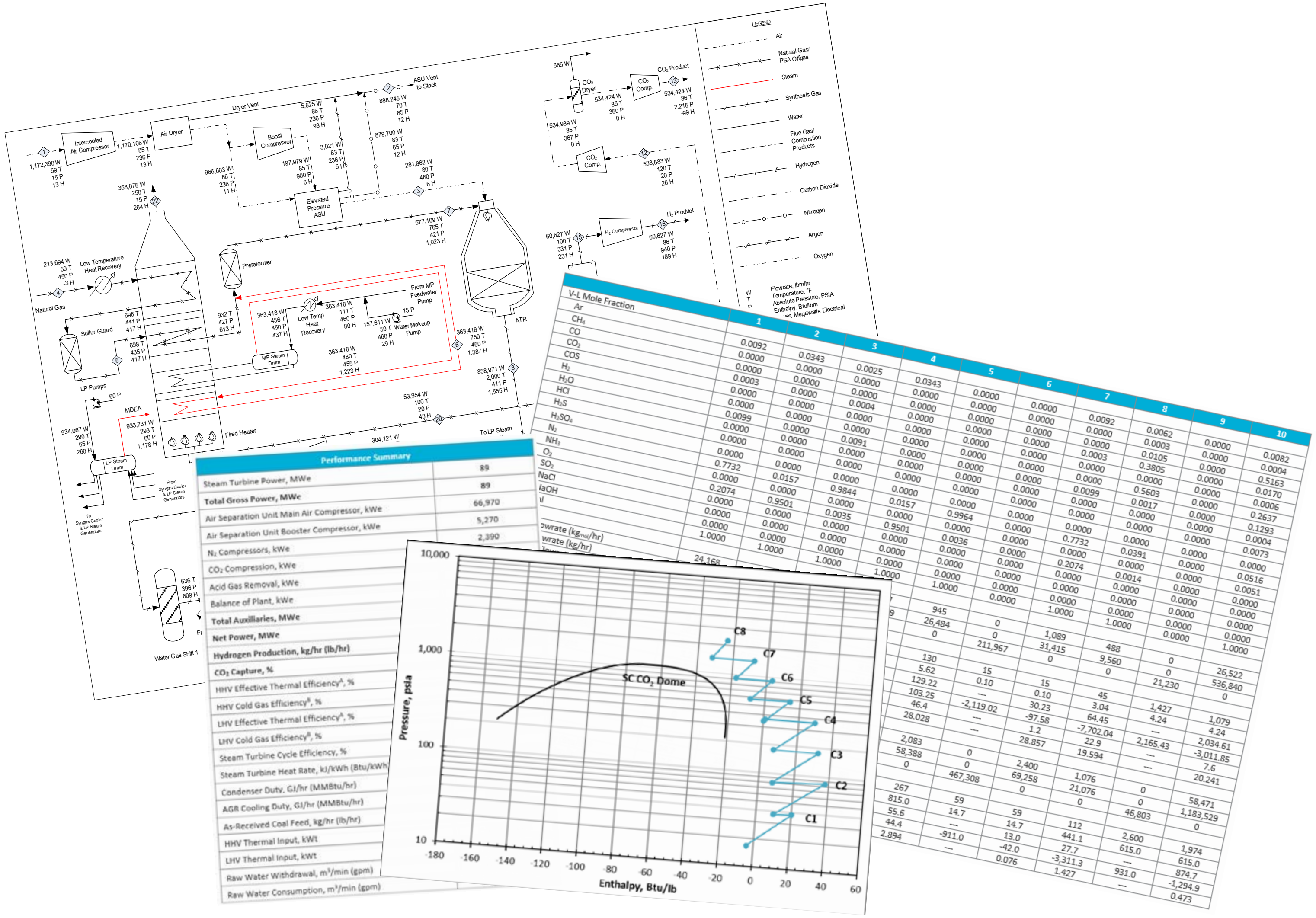
- **Delivered coal and NG costs are consistent with current NETL QGESS methodology[1]**
  - Delivered Illinois No. 6 – $2.22/MMBtu
  - Delivered NG – $4.42/MMBtu
- **Delivered biomass cost was calculated using an existing NETL cost model**
  - Delivered biomass - $5.43/MMBtu
- **Assumed grid power price of $71.7/MWh[2]**

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

[2] 2019 average Midcontinent Independent System Operator (MISO) market price for industrial customers as reported in "Annual Electric Power Industry Report," Form EIA-861

Results

Performance Modeling



- **Aspen Plus® was used to develop:**
  - Material and energy balances
  - Stream tables
  - Gate-to-gate air emissions
  - Performance estimates
  - Equipment lists
- **Plant material and energy quantities were used for LCA modeling**

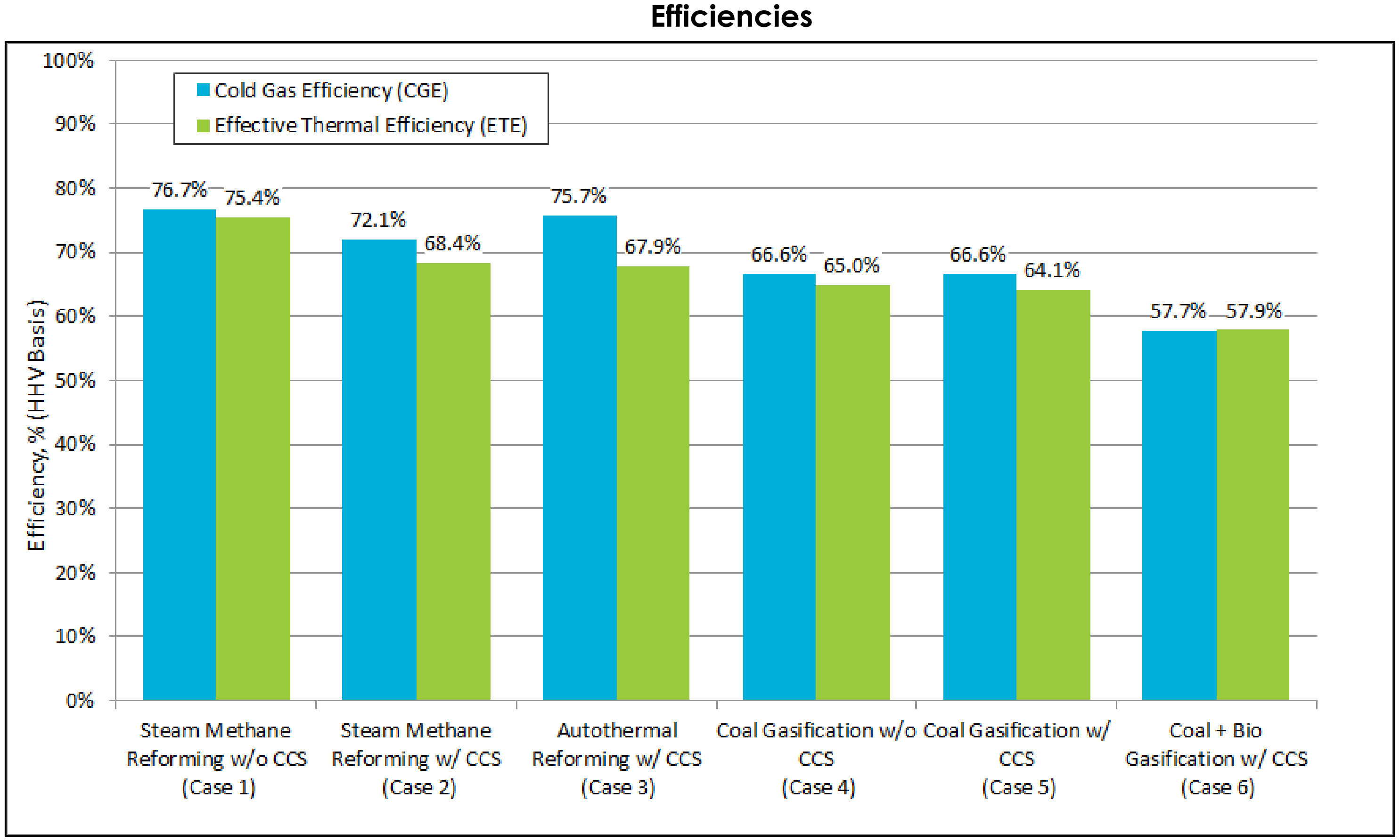
Results

Variability and Uncertainty

- **Plant performance, cost, and environmental results reflect only the process configurations studied**
  - Alternative process configurations (i.e., internal power generation, CO_2 capture approach) will produce different results
  - Capital cost estimates carry uncertainty ranges of -15%/+25% (reforming) and -25%/+50% (gasification)
- **Life cycle green house gas emissions**
  - NG –variability throughout the life cycle and across the regional sources of NG
  - Coal – mostly from variability in reported coal mine methane emissions
  - Southern yellow pine – variability in yield and fertilization rates
  - Electricity – variability in reported emissions
- **LCA Impact Assessment method**
  - Default values use Intergovernmental Panel on Climate Change (IPCC) AR5 GWPs 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 GWPs are provided in the report

Results

Plant and Environmental Performance



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

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

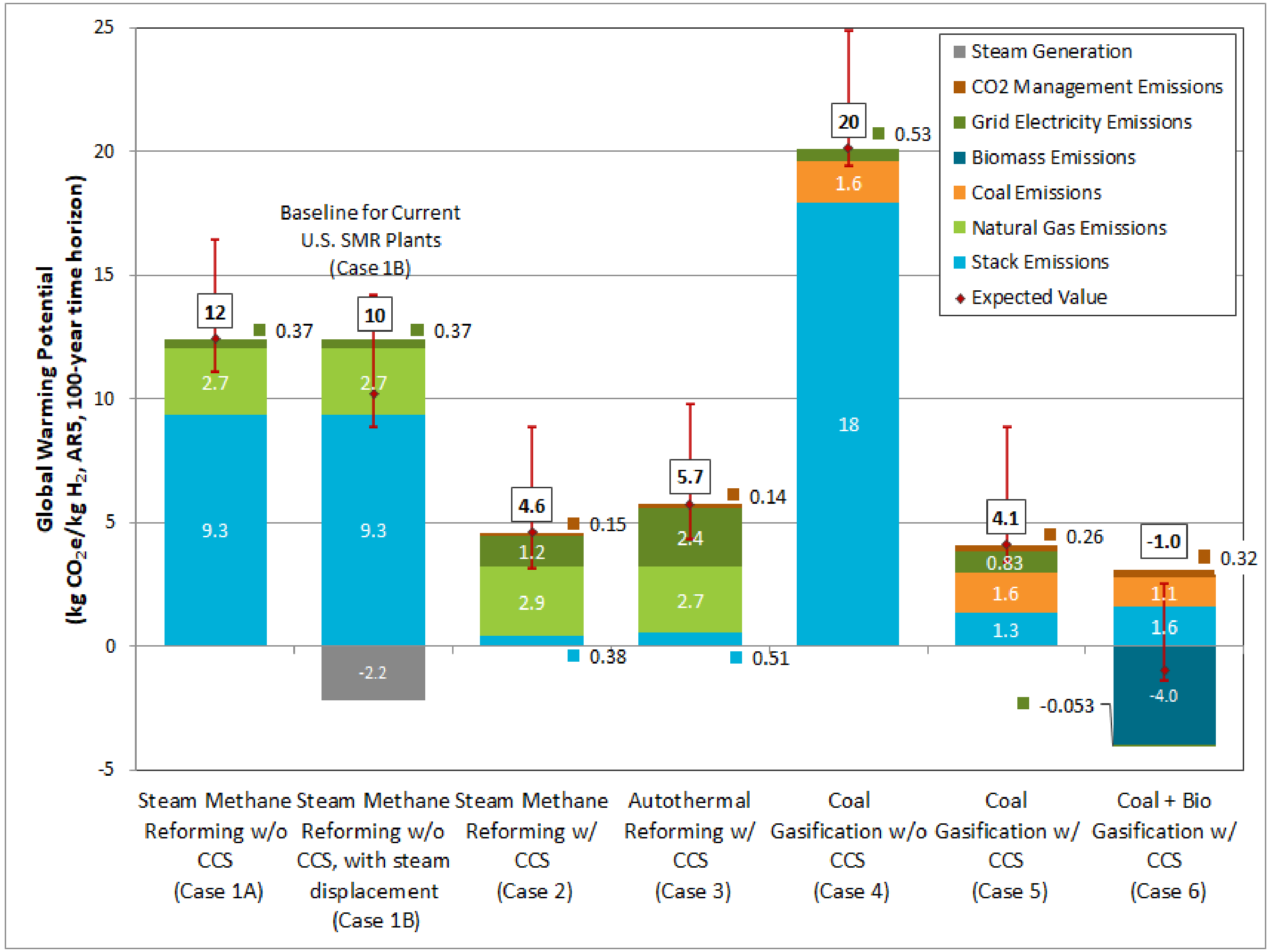
- **SMR w/o CCS achieves the highest plant efficiency (both CGE and ETE). ATR w/ CCS achieves the highest CGE among cases w/ CCS**
- **Efficiency (both CGE and ETE) is reduced by the addition of CCS in the SMR cases. ETE, not CGE, is impacted by the addition of CCS in gasification cases**
- **Coal/biomass 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.)

- **Co-gasification of 43.5 percent torrefied, woody biomass enables 0 kg CO_2e/kg H_2 of GHG emissions across the life cycle**
- **Coal gasification w/ CCS has the lowest GHG emissions over the plant life cycle of all 100% fossil feedstock cases (4.1 kg CO_2e/kg H_2)**
- **SMR w/ CCS is the next lowest, emitting at a rate 12 percent higher than coal gasification w/ CCS**
- **For SMR and ATR w/ CCS, the NG supply chain and grid electricity imports are the dominant sources of LCA GHG emissions**

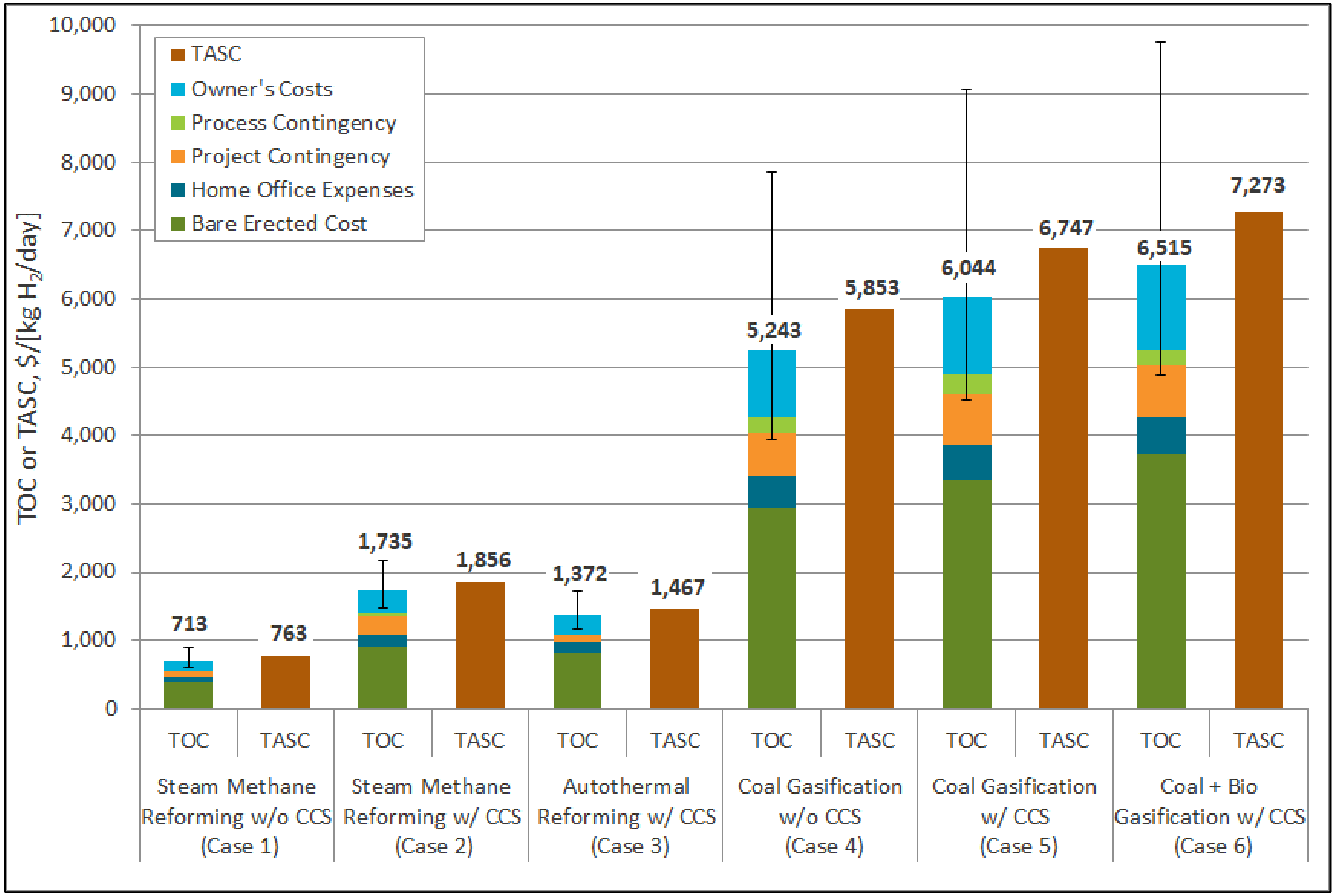
Global Warming Potentials (GWP)



Results

Economic

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



- **SMR w/o CCS achieves the lowest TOC (\$713/[kg H_2/day]) of all cases and reforming cases. SMR w/ CCS has the highest TOC (\$1,735/[kg H_2/day]) of reforming cases**
- **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**

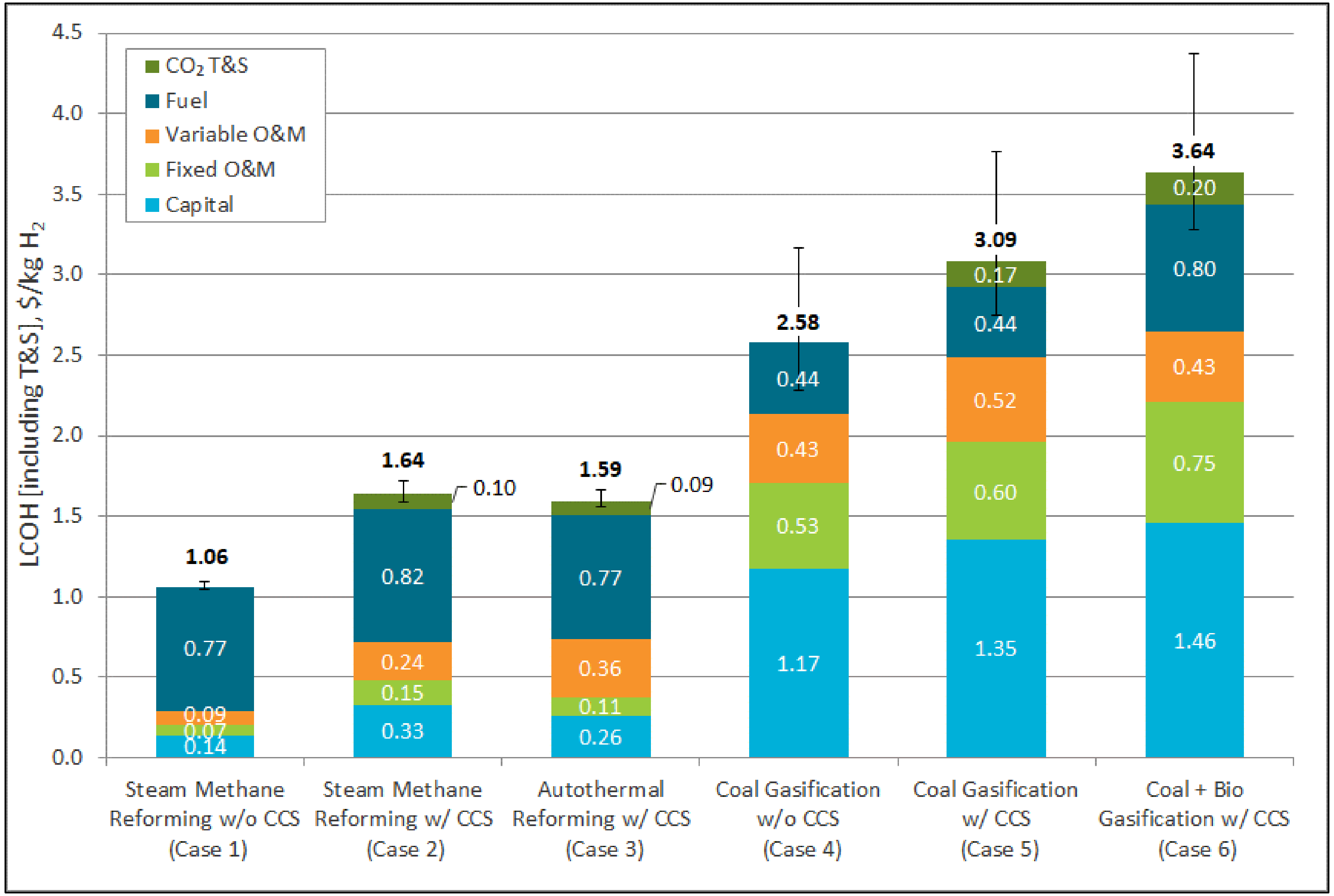
[1]TOC error bars depict uncertainty ranges of -15%/+25% (AACE Class 4) and -25%/+50% (AACE Class 5) for reforming and gasification cases, respectively

Results

Economic (cont'd.)

- **SMR w/o CCS achieves the lowest LCOH (\$1.06/kg H_2) of all cases. SMR w/ CCS has the highest LCOH (\$1.64/kg H_2) of all reforming cases**
- **Coal/biomass co-gasification w/ CCS has the highest LCOH (\$3.64/kg H_2) of all cases and gasification cases. The coal gasification w/o CCS achieves the lowest LCOH (\$2.58/kg H_2) of all gasification cases**
- **Excludes the following**
  - CO_2 Tax credits (e.g., 45Q) and penalties
  - Byproduct sale revenues (e.g., steam, argon)

LCOH (2018\$)[1,2]

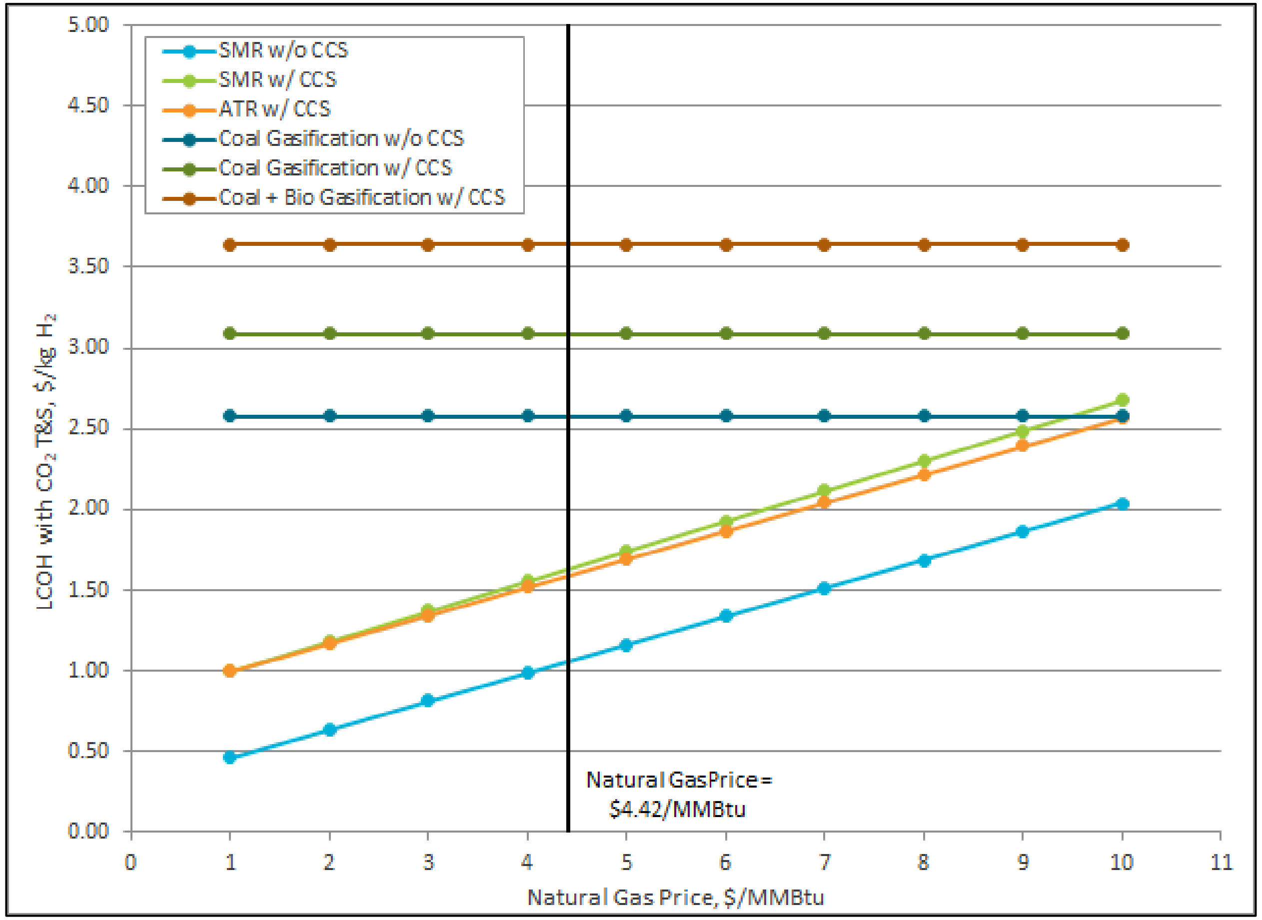


[1]LCOH error bars depict TOC uncertainty ranges of -15%/+25% (AACE Class 4) and -25%/+50% (AACE Class 5) for reforming and gasification cases, respectively

[2]Costs can vary widely depending on natural gas price and electricity cost, as shown on subsequent slides

Sensitivity Analyses

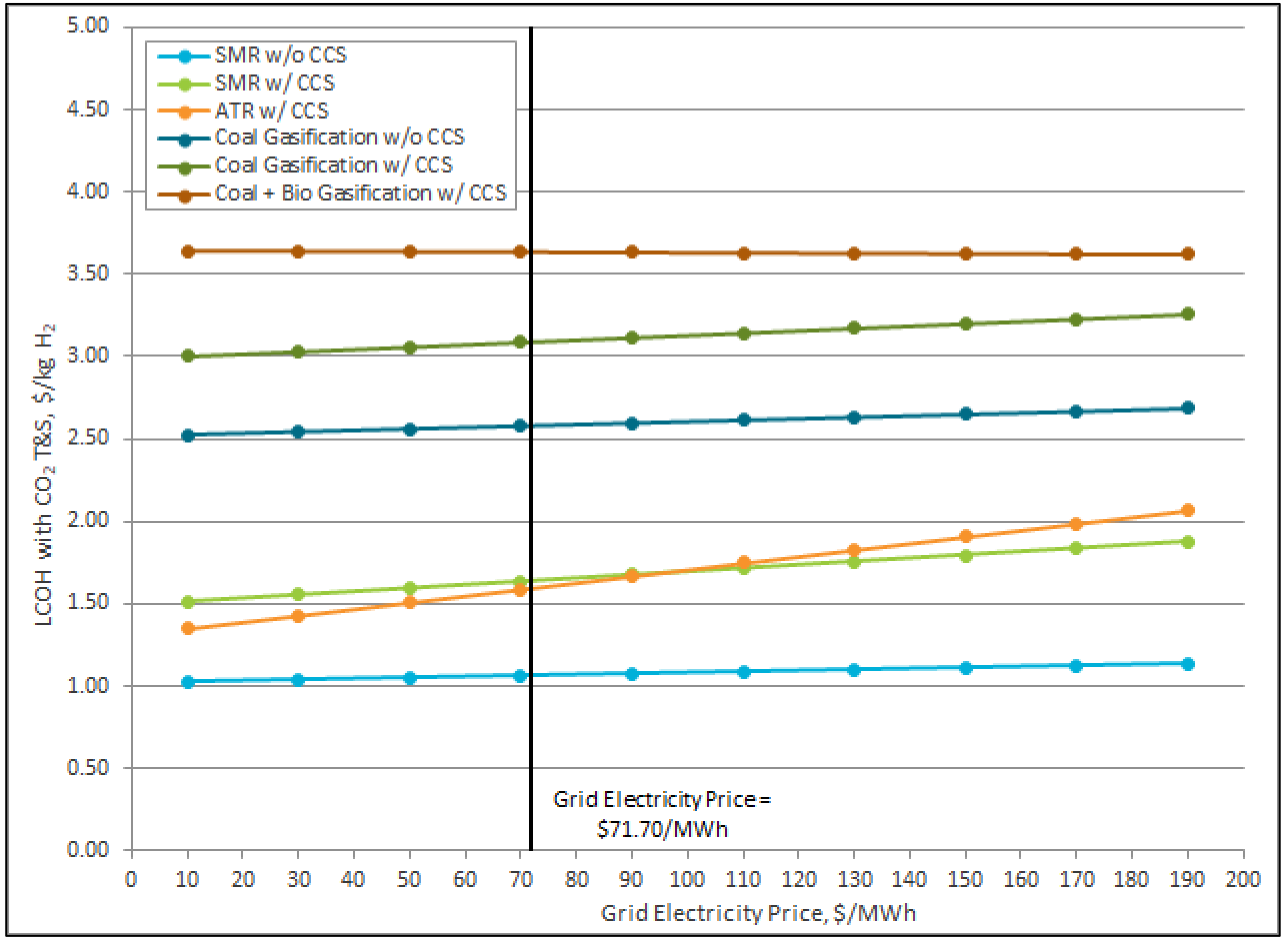
NG Price



- **The difference in LCOH between the SMR and ATR plants w/ CCS (Case 2 and Case 3) diminishes as the NG price is reduced**
- **At a NG price of $1/MMBtu, the reforming plants w/ CCS (Case 2 and Case 3) reaches $1/kg H_2**
- **At an NG price above $9/MMBtu, the SMR plant w/ CCS (Case 2) becomes on-par with the coal gasification plant w/o CCS (Case 4)**

Sensitivity Analyses

Power Price



- The LCOH has a relatively low sensitivity to variations in the grid electricity price
- The cases with larger net power demands are more sensitive to the cost of grid electricity, such as Case 3 and Case 5
- At a price of grid electricity above $100/MWh, the ATR plant w/ CCS (Case 3) becomes more expensive than the SMR plant w/ CCS (Case 2)

Additional Analysis

H_2 Pressure Credit

- In the H2A models, a pumping power credit is applied for H_2 product pressures above 300 psig[1]
- This is calculated by estimating the cost of a hypothetical H_2 compressor that compresses from 300 psig to the final H_2 pressure by using the estimated power and compressor capital cost. This number, in the unit of \$/kg H_2, is then subtracted from the LCOH
- The same methodology was followed to calculate a pressure credit to be applied to the LCOH for cases 1–6. The results show that the LCOH is reduced by about \$0.04/kg H_2 in all cases

H_2 Pressure Credit						
Case	1	2	3	4	5	6
LCOH (\$/kg H_2) (including T&S)	1.06	1.64	1.59	2.58	3.09	3.64
Pressure Credit (\$/kg H_2)	-0.042	-0.043	-0.041	-0.039	-0.036	-0.046
Adjusted LCOH (\$/kg H_2)	1.02	1.59	1.55	2.54	3.05	3.59

Note: LCA results at a H_2 product pressure of 300 psig are not considered

[1] DOE Hydrogen and Fuel Cells Program Record 19009: Hydrogen Production Cost from PEM Electrolysis - 2019 (energy.gov)

Future Work

Examples

Renewable Natural Gas (RNG) Blending

- Blending RNG with pipeline NG may reduce the LCA GHG profile depending on the GWP of the RNG considered

Low Carbon Auxiliary Power

- Grid emissions are a significant contributor to the LCA GHG profile of reforming plants w/ CCS. Options for utilizing low-carbon electricity can be evaluated (e.g., aux. power from H_2, fossil power w/ CCS, renewables)

Advanced Reforming Concepts

- Investigate the relative merits/demerits of membrane-assisted sorption-enhanced, and gas switching reforming

NG Pyrolysis

- Develop thermal and catalytic pyrolysis TEAs to assess merits/demerits of relative to conventional reforming technologies

Final Thoughts

Study Utilization

- **Given the recent interest in the production, transport, storage, and utilization of clean hydrogen, the study is expected to have utilization beyond the original objectives, including:**
  - Updates to GREET®[1]
  - Updates to H2A production models[2]
  - Development of a NEMS hydrogen market module[3]
  - Hydrogen Shot pathway screening analysis reference

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[1] https://greet.es.anl.gov/
[2] https://www.nrel.gov/hydrogen/h2a-production-models.html
[3] https://www.energy.gov/fecm/component-design-report-representing-hydrogen-national-energy-modeling-system?utm_medium=email&utm_source=govdelivery

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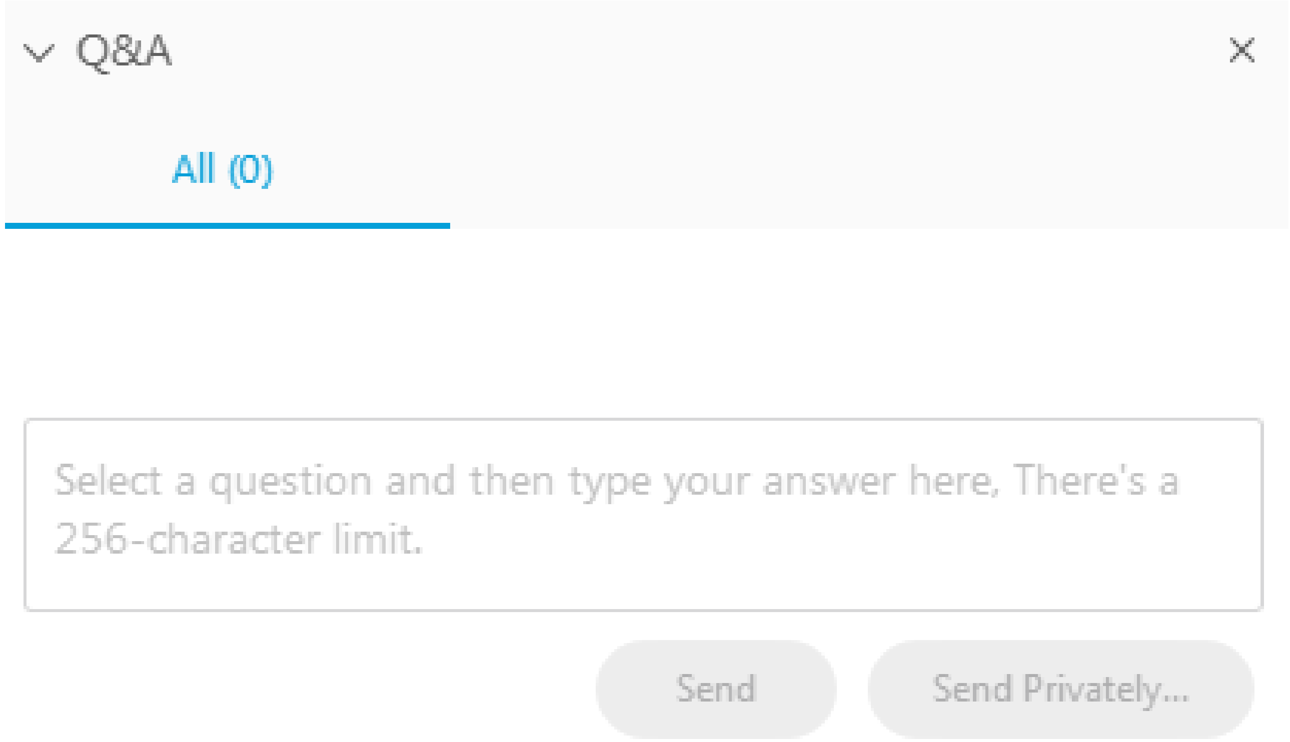
INCREASE YOUR H2IQ

The #H2IQ Hour Q&A

Please type your questions into the **Q&A Box**



INCREASE YOUR H_2IQ

The #H2IQ Hour

Thank you for your participation!

Learn more:

energy.gov/fuelcells
hydrogen.energy.gov

Supplemental Slides

NETL H_2 Production TEA Examples

- **Baseline Coal Gasification and NG SMR:**
  - "Assessment of Hydrogen Production with CO_2 Capture; Volume 1," November 14, 2011
  - "Capital and Operating Cost of Hydrogen Production from Coal Gasification," April, 2003
- **Advanced H_2 Separation Technologies:**
  - "Assessment of Hydrogen Production with CO_2 Capture; Volume 2-4," November 14, 2011
  - "Hydrogen Production Facilities Plant Performance and Cost Comparisons," March 2002
  - "Production of High Purity Hydrogen from Domestic Coal: Assessing the Techno-Economic Impact of Emerging Technologies," August 30, 2010
- **Fuel Cell Technology:**
  - "Solid Oxide Cell Manufacturing Cost Tool," January 14, 2022 and User Manual

Design Basis

Life Cycle Emissions

- **Overall data is representative of 2016-2017**
- **NG**
  - 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

NETL H_2 Production TEA Examples (cont'd.)

- **Fuel Cell Technology:**
  - "Solid Oxide Cell Manufacturing Cost Tool," January 14, 2022 and User Manual

H2A Case Study Contributions

- **NETL TEAs currently provide the basis for the HFTO H2A production case studies:**
  - Current, Centralized Coal with CO_2 Capture & Sequestration
  - Current and Future, Centralized NG without CO_2 Capture & Sequestration
  - Current and Future, Centralized NG with CO_2 Capture & Sequestration