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

Eric Lewis, P.E.
National Energy Technology Laboratory (NETL)
NETL has published a combined techno-economic (TEA) and life cycle analysis (LCA) of commercial, state-of-the-art fossil-based H₂ production technologies¹,²

Today’s Topics:

- **NETL**
  - Mission and vision
  - H₂ analysis competencies
  - Coordination with the DOE Hydrogen Program & Administration priorities

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

- Questions
MISSION

Driving innovation and delivering solutions for an environmentally sustainable and prosperous energy future:

- Ensuring affordable, abundant and reliable energy that drives a robust economy and national security, while
- Developing technologies to manage carbon across the full life cycle, and
- Enabling environmental sustainability for all Americans.

VISION

To be the nation’s premier energy technology laboratory, delivering integrated solutions to enable transformation to a sustainable energy future.
Coordination with DOE Hydrogen Program
## NETL Core Competencies

### Effective Resource Development • Efficient Energy Conversion • Environmental Sustainability

<table>
<thead>
<tr>
<th>Computational Science &amp; Engineering</th>
<th>Materials Engineering &amp; Manufacturing</th>
<th>Geological &amp; Environmental Systems</th>
<th>Energy Conversion Engineering</th>
<th>Strategic Systems Analysis &amp; Engineering</th>
<th>Program Execution &amp; Integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Analytics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine Learning</td>
<td></td>
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</tr>
</tbody>
</table>
Energy Process Analysis
- Plant-level modeling, performance assessment
- Cost estimation for plant-level systems
- General plant-level technology evaluation and support

Energy Systems Analysis
Resource Availability and Cost Modeling
- CO₂ storage (saline and EOR)
- Fossil fuel extraction
- Rare earth elements
- General subsurface technology evaluation and support

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

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

Life Cycle Analysis (LCA)

Advanced Technology Design & Cost Estimation

Travis Shultz

Luciane Cunha, Ph.D.
Analysis Across the Hydrogen Value Chain

**Hydrogen Production**
- Excess Electricity: Wind/Solar, Nuclear
- Electrolysis
- Gasification
- Chemical Looping
- Reforming
- Pyrolysis
- Natural Gas
- Coal, Biomass, Waste Plastics
- Excess Electricity: Fossil w/CCS

**Green Hydrogen**
- Hydrogen Transport & Storage
- Export
- Ammonia & Other Hydrogen Carriers
- H₂, Road, Rail, & Marine Transport
- H₂, Pipelines
  - Hydrogen Storage
  - H₂ Separation
  - H₂ Blending in Natural Gas Pipelines

**Blue Hydrogen**
- H₂ Storage
- NG/H₂, Storage

**H₂**
- Storage
- Solid Carbon Co-Products

**Outside NETL Research & Development**
- Transportation Sector
- Industrial Use: Refining, Synthetic Fuels
- Electric Power Production
- Heating

**Within NETL Research & Development**
Analysis Across the Hydrogen Value Chain

- Levelized Cost of Hydrogen Production Comparison
- Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies
- NG Infrastructure
- CO₂ Infrastructure
- Advanced Hydrogen Production Analyses - SOECs, Adv. Gasification, Microwave Technologies, Methane Pyrolysis
- Hydrogen Energy Earthshot Pathway Scenario Analysis
- Hydrogen R&D Opportunities (H2OP) Team (Evaluates likely cradle-to-grave hydrogen pathways for further analysis)
- Integrated Energy Systems for Hydrogen and Power Co-production (IDAES and DISPATCHES)
- Appalachian Hydrogen Infrastructure Study - H2/NG Pipelines - H2/NG Storage - Economic Impact
- Gap Analysis of Sensors for Hydrogen Production or Utilization
- HyBlend LCA Analyses
- Hydrogen Subsurface Storage FWP
- Hydrogen Turbine and SOFC Technoeconomic Analyses
- Hydrogen Upscaling of CO₂ Scoping Study
- Syngas and Hydrogen Conversion to Industrial Chemicals
- Near-Future Capability: Integrated Hydrogen Value Chain Optimization for Hydrogen Hub Deployments or state/national hydrogen planning
Administration Priorities

2030 – 50-52 percent reduction in economy-wide new greenhouse gas pollution from 2005 levels

2035 – Carbon pollution-free electricity sector
- Address environmental justice and job creation

2050 – Zero-carbon economy

Hydrogen is essential to meet ambitious GHG and zero-carbon economy goals

Advanced hydrogen technology development: job creation in multiple sectors
Hydrogen Highlights

• Covers $9.5B for clean hydrogen:
  • $8B for at least four regional clean hydrogen hubs
  • $1B for electrolysis research, development and demonstration
  • $500M for clean hydrogen technology manufacturing and recycling R&D

• Aligns with Hydrogen Shot priorities by directing work to reduce the cost of clean hydrogen to $1 per kilogram by 2030

• Requires developing a clean hydrogen standard
  • Standard will define clean hydrogen to have a carbon intensity of $\leq 2$ kg CO$_2$e/kg H$_2$ produced
  • The definition may be lowered in out years

• Requires developing a National Hydrogen Strategy and Roadmap
  • Currently under development
Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies

Study Deep Dive
Study Background

• The DOE Office of Fossil Energy and Carbon Management (FECM) - previously Fossil Energy (FE) - Hydrogen Strategy was released in July 2020

• In July 2020 DOE FECM also issued a Request for Information (RFI) seeking input from stakeholders about hydrogen technology opportunities and R&D needs to advance fossil-based hydrogen technologies

• In August 2020 NETL initiated a techno-economic analysis to update out-of-date benchmarks for thermal conversion-based clean hydrogen production
Study Summary

Justification

• This technoeconomic analysis of fossil-to-H₂ production routes using current, commercial technologies provides a basis for DOE FE R&D program planning to reduce the levelized cost of hydrogen (LCOH) and greenhouse gas (GHG) footprint of future fossil-to-H₂ plants

Objectives

• Develop a reference study of H₂ production technologies using current, commercial technologies¹ 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 H₂ production, including follow-on analyses

Highlights

• Lowest LCOH of cases examined w/ CCS is ATR – $1.59/kg H₂
• Lowest nominal LCA GHG profile of fossil-only cases examined w/ CCS is coal gasification – 4.1 lb CO₂e/lb H₂
• Co-gasifying 43.5 wt.% biomass with coal enables net-zero GHG H₂ production
• NG supply chain and grid electricity are significant contributors to LCA GHG emissions of reforming plants w/ CCS

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

Source: DOE
Study Summary

Results

• SMR w/o CCS achieves the lowest LCOH ($1.06/kg H₂) of all cases. SMR w/ CCS has the highest LCOH ($1.64/kg H₂) of all reforming cases.

• Coal/biomass co-gasification w/ CCS has the highest LCOH ($3.64/kg H₂) of all cases and gasification cases. The coal gasification w/o CCS achieves the lowest LCOH ($2.58/kg H₂) of all gasification cases.
Study Summary

Results

• Co-gasification of 43.5 percent torrefied, woody biomass enables -1.0 lb CO$_2$e/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$_2$e/lb H$_2$)

• SMR w/ CCS is the next lowest, emitting at a rate 28 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
Study Summary

Approach

- **Literature Review**
  - Characterization of the global, high-purity H₂ production industry
  - Review of commercially operating, fossil-based H₂ production plants with and without CCS
  - Review of commercially available CO₂ separation technologies for H₂ applications
  - Investigation into H₂ from alternative feedstocks (e.g., biomass, 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 O&M costs for major process areas
  - Cost scaling performed according to NETL QGESS methodology¹
  - LCOH developed for each study case
- **Results Reporting**
  - NETL report publication
  - Joint NETL/EERE journal article

¹ “Quality Guidelines for Energy System Studies (QGESS): Capital Cost Scaling Methodology,” NETL, 2019
Primary Findings

- **High-purity H₂ from natural gas**¹
  - Merchant production facilities are spread globally and mostly support refinery and ammonia applications
  - Facility sizes typically 10 - 200 MMSCFD H₂

- **High-purity H₂ from coal**²
  - Coal gasification predominantly in China for ammonia
  - Estimated to have a median H₂ production rate between 50 and 100 MMSCFD
  - Engineering studies have been completed for such facilities up to 282 MMSCFD H₂ production

¹PNNL, Hydrogen Production, [https://h2tools.org/hyarc/hydrogen-production](https://h2tools.org/hyarc/hydrogen-production)
H₂ from alternative feedstocks (e.g., biomass, MSW)

- No currently operating commercial alternative feedstock gasification facilities producing high-purity H₂ as an end product
  - A few are planned or on hold
  - One likely produces H₂ 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 H₂ as an end-product
Primary Findings (cont’d.)

• H₂/CO₂ Separation Technologies
  ◦ Carbon capture utilization & storage (CCUS) is operating commercially at just a few H₂ 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™ H₂ technologies are used to separate CO₂ from the syngas stream
  ◦ Multiple announced projects incorporate CCUS in vendor ATR flowsheets to achieve 90+ percent overall capture rate
    — Commercial CO₂ separation technologies are being proposed (e.g., amine solvents, Rectisol)
  ◦ Pressure Swing Adsorption (PSA) is the predominant H₂ purification technology
### Case Selection

<table>
<thead>
<tr>
<th>Case</th>
<th>Plant Type</th>
<th>Feedstock(s)</th>
<th>Reformer Type</th>
<th>Gasifier Type</th>
<th>CO₂ Capture (%)</th>
<th>H₂ Purification</th>
<th>H₂ Production Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reforming</td>
<td>Natural Gas</td>
<td>SMR</td>
<td>-</td>
<td>0</td>
<td></td>
<td>200 MMSCFD 483,000 kg/day 44,400 lb/hr</td>
</tr>
<tr>
<td>2</td>
<td>Reforming</td>
<td>Natural Gas</td>
<td>SMR</td>
<td>-</td>
<td>0</td>
<td>PSA</td>
<td>274 MMSCFD 660,000 kg/day 60,600 lb/hr</td>
</tr>
<tr>
<td>3</td>
<td>Gasification</td>
<td>Illinois No. 6 Coal</td>
<td>ATR</td>
<td>-</td>
<td>0</td>
<td>94.5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Gasification</td>
<td>Illinois No. 6 Coal</td>
<td>-</td>
<td>Shell^B</td>
<td>0</td>
<td></td>
<td>55 MMSCFD 133,000 kg/day 12,200 lb/hr</td>
</tr>
<tr>
<td>5</td>
<td>Gasification</td>
<td>Illinois No. 6 Coal/Torrefied Woody Biomass</td>
<td>-</td>
<td>Shell^B</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Gasification</td>
<td>Illinois No. 6 Coal/Torrefied Woody Biomass</td>
<td>-</td>
<td>Shell^B</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

^ 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

## Site Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Greenfield, Midwestern U.S.</td>
</tr>
<tr>
<td>Topography</td>
<td>Level</td>
</tr>
<tr>
<td>Size (Gasification), acres</td>
<td>300</td>
</tr>
<tr>
<td>Size (SMR/ATR), acres</td>
<td>100</td>
</tr>
<tr>
<td>Transportation</td>
<td>Rail or Highway</td>
</tr>
<tr>
<td>Slag Disposal</td>
<td>Off-Site</td>
</tr>
<tr>
<td>Water</td>
<td>50% Municipal and 50% Ground Water</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation, m (ft)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Barometric Pressure, MPa (psia)</td>
<td>0.101 (14.696)</td>
</tr>
<tr>
<td>Average Ambient Dry Bulb Temperature, °C (°F)</td>
<td>15 (59)</td>
</tr>
<tr>
<td>Average Ambient Wet Bulb Temperature, °C (°F)</td>
<td>10.8 (51.5)</td>
</tr>
<tr>
<td>Design Ambient Relative Humidity, %</td>
<td>60</td>
</tr>
<tr>
<td>Cooling Water Temperature, °C (°F)</td>
<td>15.6 (60)</td>
</tr>
</tbody>
</table>

Air composition based on published psychrometric data, mass %

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>75.055</td>
</tr>
<tr>
<td>O₂</td>
<td>22.998</td>
</tr>
<tr>
<td>Ar</td>
<td>1.280</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.616</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.050</td>
</tr>
</tbody>
</table>

Total: 100.00%

*The cooling water temperature is the cooling tower cooling water exit temperature. This is set to 4.8°C (8.5°F) above ambient wet bulb conditions in ISO cases.*

---

Design Basis

Feedstock Characteristics

<table>
<thead>
<tr>
<th>Natural Gas¹</th>
<th>Component</th>
<th>Volume Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>93.1</td>
</tr>
<tr>
<td>Ethane</td>
<td>C₂H₆</td>
<td>3.2</td>
</tr>
<tr>
<td>Propane</td>
<td>C₃H₈</td>
<td>0.7</td>
</tr>
<tr>
<td>n-Butane</td>
<td>C₄H₁₀</td>
<td>0.4</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>CO₂</td>
<td>1.0</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N₂</td>
<td>1.6</td>
</tr>
<tr>
<td>Methanethiol¹</td>
<td>CH₄S</td>
<td>5.75x10⁻⁶</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>100.0</td>
</tr>
</tbody>
</table>

Heating Value

<table>
<thead>
<tr>
<th>Component</th>
<th>LHV (kJ/kg (Btu/lb))</th>
<th>HHV (kJ/kg (Btu/lb))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>47.201 (20.293)</td>
<td>52.295 (22.483)</td>
</tr>
<tr>
<td>Ethane</td>
<td>34.52 (927)</td>
<td>38.25 (1,027)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Heating Value (kJ/kg (Btu/lb))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>47.201</td>
</tr>
<tr>
<td>Ethane</td>
<td>34.52</td>
</tr>
<tr>
<td>Total</td>
<td>81.72</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Heating Value (MJ/scm (Btu/scf))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>34.52 (927)</td>
</tr>
<tr>
<td>Ethane</td>
<td>38.25 (1,027)</td>
</tr>
<tr>
<td>Total</td>
<td>72.77</td>
</tr>
</tbody>
</table>

¹The sulfur content of natural gas is primarily composed of added Mercaptan [methanethiol [CH₄S]] with trace levels of hydrogen sulfide [H₂S]

Note: Fuel composition is normalized, and heating values are calculated using Aspen

<table>
<thead>
<tr>
<th>Bituminous¹</th>
<th>Rank</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seam</td>
<td>Illinois No. 6</td>
<td>-</td>
</tr>
</tbody>
</table>

Proximate Analysis (weight %)¹

<table>
<thead>
<tr>
<th>Component</th>
<th>As Received</th>
<th>Dry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>11.12</td>
<td>0.00</td>
</tr>
<tr>
<td>Ash</td>
<td>9.70</td>
<td>10.91</td>
</tr>
<tr>
<td>Volatile Matter</td>
<td>34.99</td>
<td>39.37</td>
</tr>
<tr>
<td>Fixed Carbon</td>
<td>44.19</td>
<td>49.72</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>Sulfur</td>
<td>2.51</td>
<td>2.82</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>HHV (kJ/kg (Btu/lb))</th>
<th>LHV (kJ/kg (Btu/lb))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>27.113 (11.666)</td>
<td>30.506 (13.126)</td>
</tr>
<tr>
<td>Ethane</td>
<td>26.151 (11.252)</td>
<td>29.444 (12.712)</td>
</tr>
<tr>
<td>Total</td>
<td>53.264 (22.918)</td>
<td>59.949 (25.878)</td>
</tr>
</tbody>
</table>

Ultimate Analysis (weight %)

<table>
<thead>
<tr>
<th>Component</th>
<th>As Received</th>
<th>Dry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>11.12</td>
<td>0.00</td>
</tr>
<tr>
<td>Carbon</td>
<td>63.75</td>
<td>71.72</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>4.50</td>
<td>5.06</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.25</td>
<td>1.41</td>
</tr>
<tr>
<td>Chlorine</td>
<td>0.15</td>
<td>0.17</td>
</tr>
<tr>
<td>Sulfur</td>
<td>2.51</td>
<td>2.82</td>
</tr>
<tr>
<td>Ash</td>
<td>9.70</td>
<td>10.91</td>
</tr>
<tr>
<td>Oxygen²</td>
<td>7.02</td>
<td>7.91</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>

¹The proximate analysis assumes sulfur as volatile matter
²By difference

<table>
<thead>
<tr>
<th>Torrefied Woody Biomass</th>
<th>As Received</th>
<th>Dry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Analysis (weight %)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>5.72</td>
<td>0.00</td>
</tr>
<tr>
<td>Carbon</td>
<td>59.89</td>
<td>63.52</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>5.11</td>
<td>5.42</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.41</td>
<td>0.44</td>
</tr>
<tr>
<td>Chlorine</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Ash</td>
<td>0.51</td>
<td>0.54</td>
</tr>
<tr>
<td>Oxygen</td>
<td>28.36</td>
<td>30.08</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Heating Value (Btu/lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>9.749</td>
</tr>
<tr>
<td>Ethane</td>
<td>9.203</td>
</tr>
<tr>
<td>Total</td>
<td>18.952</td>
</tr>
</tbody>
</table>
# Design Basis

## H₂ Product Specifications

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Purity (vol%)</td>
<td>99.90</td>
</tr>
<tr>
<td>Max. CO₂ (ppm)</td>
<td>A</td>
</tr>
<tr>
<td>Max. CO (ppm)</td>
<td>A</td>
</tr>
<tr>
<td>Max. H₂S (ppb)</td>
<td>10</td>
</tr>
<tr>
<td>Max. H₂O (ppm)</td>
<td>A</td>
</tr>
<tr>
<td>Max. O₂ (ppm)</td>
<td>A</td>
</tr>
</tbody>
</table>

*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 H₂ to avoid catalyst poisoning.
- Additionally, the specification results in a product exceeding specifications for the following ISO 14687:2019 gaseous H₂ grades:
  - Grade A – combustion applications
    - Internal combustion engines, residential/commercial heating appliances
  - Grade B – industrial power and heat applications
    - Excluding PEM fuel cells
- H₂ product is compressed to 6.4 MPa (925 psig) for pipeline injection.
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

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Environmental Design Basis</th>
<th>Control Technology</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur Oxides</td>
<td></td>
<td>AGR + Claus Plant or equivalent performing system</td>
<td>99+% or ≤ 0.050 lb/10^6 Btu</td>
</tr>
<tr>
<td>Nitrogen Oxides</td>
<td>Low NOx Burners</td>
<td></td>
<td>15 ppmv (dry) @ 15% O₂</td>
</tr>
<tr>
<td>Particulate Matter</td>
<td>Cyclone/Barrier Filter/Wet Scrubber/AGR Absorber</td>
<td></td>
<td>0.015 lb/10^6 Btu</td>
</tr>
<tr>
<td>Mercury</td>
<td>Activated Carbon Bed or equivalent performing system</td>
<td></td>
<td>95% removal</td>
</tr>
</tbody>
</table>

BACT Environmental Design Basis for Natural Gas Cases

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Environmental Design Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur Oxides</td>
<td>Zinc oxide guard bed</td>
</tr>
<tr>
<td>Nitrogen Oxides</td>
<td>Low NOx Burners</td>
</tr>
<tr>
<td>Particulate Matter</td>
<td>N/A</td>
</tr>
<tr>
<td>Mercury</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Negligible
Design Basis

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

- **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**
  - 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
Design Basis

Water Emissions

• No current Effluent Limitation Guidelines (ELG) industry categories are applicable to the cases in this study.

• However, the gasification cases include zero liquid discharge equipment due to the similarity of the cases to IGCC plants, which fall under the ELGs.

• All other process effluent for the cases is assumed to be treated in an onsite treatment facility to meet EPA standards for suspended solids, oil and grease, pH, and miscellaneous metals.
  ◦ Condensate from post-combustion capture units are retained as internal recycle.
Design Basis

Capacity Factor

• A 90 percent capacity factor is assumed representative of commercial SMR/ATR facilities
  ◦ It was assumed no spare reformers are required to achieve this capacity factor

• An 80 percent capacity factor is assumed for the gasification facilities
  ◦ It was assumed no spare gasifiers are required to achieve this capacity factor
  ◦ Tradeoff analysis indicated achieving 90 percent would require an additional gasifier outweighing the benefit
Design Basis

Feedstock Costs

• Delivered coal and natural gas 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
Design Basis

Electricity Costs

• A grid power price of $71.7/MWh is assumed based on the 2019 average Midcontinent Independent System Operator (MISO) market price for industrial customers as reported in “Annual Electric Power Industry Report,” Form EIA-861
  ◦ Reforming cases do not generate power and purchase entirely from the grid
  ◦ Gasification cases generate power; only the coal + biomass co-gasification case exports power to the grid (<1 MW)
Design Basis

Byproduct Revenues, Tax Credits, Emission Penalties

• No revenues generated from the sale of air gases (e.g., N₂, Ar), steam, or pipelined CO₂
• Export power is sold to the grid at $71.7/MWh
• No CO₂ emissions penalty
• No tax credits for CCUS (e.g., 45Q) are included
• Sensitivity analyses quantify the economic impact from several of these factors
Levelized Cost of Hydrogen

- The levelized cost of hydrogen is the figure of merit for each of the six cases
  - LCOH is reported in $/kg, expressed in real, 2018 dollars to maintain consistency with the current QGESS cost estimating methodology [8]

- Capital financing structure is shown below with reforming and gasification cases having 3- and 5-year expenditure periods, respectively

<table>
<thead>
<tr>
<th>CapExp Period</th>
<th>D/E</th>
<th>IRROE/ Econ. Life</th>
<th>Debt Rate / Term</th>
<th>FCR</th>
<th>TASC/ TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-yr</td>
<td>38/62</td>
<td>3.10%/30 yrs</td>
<td>5.15%/30 yrs</td>
<td>0.0586</td>
<td>1.070</td>
</tr>
<tr>
<td>5-yr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.116</td>
</tr>
</tbody>
</table>
• 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

Plant and Environmental Performance

- 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 H₂ recovery (75% vs. 85%) is used to avoid grid power import

**Efficiencies**

![Efficiencies Chart]

- **Cold Gas Efficiency (CGE)** = Hydrogen Heating Value / Fuel Heating Value
- **Effective Thermal Efficiency (ETE)** = (Hydrogen Heating Value + Net Power) / Fuel Heating Value

\[ \text{Effective Thermal Efficiency (ETE)} = \frac{(\text{Hydrogen Heating Value} + \text{Net Power})}{\text{Fuel Heating Value}} \]

\[ \text{Cold Gas Efficiency (CGE)} = \frac{\text{Hydrogen Heating Value}}{\text{Fuel Heating Value}} \]
Results

Plant and Environmental Performance (cont’d.)

• Co-gasification of 43.5 percent torrefied, woody biomass enables 0 lb CO₂e/lb H₂ 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 CO₂e/lb H₂)

• 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
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 appendix
Economic

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

- SMR w/o CCS achieves the lowest TOC ($713/[kg H2/day]) of all cases and reforming cases. SMR w/ CCS has the highest TOC ($1,735/[kg H2/day]) of reforming cases.
- The coal/biomass co-gasification w/ CCS has the highest TOC ($6,515/[kg H2/day]) of all cases and gasification cases. The coal gasification w/o CCS achieves the lowest TOC ($5,243/[kg H2/day]) of gasification cases.

¹TOC 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 H₂) of all cases. SMR w/ CCS has the highest LCOH ($1.64/kg H₂) of all reforming cases.
- Coal/biomass co-gasification w/ CCS has the highest LCOH ($3.64/kg H₂) of all cases and gasification cases. The coal gasification w/o CCS achieves the lowest LCOH ($2.58/kg H₂) 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.
Sensitivity Analyses

Natural Gas 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 H₂.
- 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

H₂ Pressure Credit

• In the H2A models, a pumping power credit is applied for H₂ product pressures above 300 psig

• This is calculated by estimating the cost of a hypothetical H₂ compressor that compresses from 300 psig to the final H₂ pressure by using the estimated power and compressor capital cost. This number, in the unit of $/kg H₂, 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 H₂ in all cases

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCOH ($/kg H₂) (including T&amp;S)</td>
<td>1.06</td>
<td>1.64</td>
<td>1.59</td>
<td>2.58</td>
<td>3.09</td>
<td>3.64</td>
</tr>
<tr>
<td>Pressure Credit ($/kg H₂)</td>
<td>-0.042</td>
<td>-0.043</td>
<td>-0.041</td>
<td>-0.039</td>
<td>-0.036</td>
<td>-0.046</td>
</tr>
<tr>
<td>Adjusted LCOH ($/kg H₂)</td>
<td>1.02</td>
<td>1.59</td>
<td>1.55</td>
<td>2.54</td>
<td>3.05</td>
<td>3.59</td>
</tr>
</tbody>
</table>

Note: LCA results at a H₂ product pressure of 300 psig are not considered
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/ capture. Options for utilizing low-carbon electricity can be evaluated (e.g., aux. power from H₂, fossil power w/ capture, 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 DOE modeling tools
  • IIJA Roadmap development reference
  • Hydrogen Shot pathway screening analysis reference
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Supplemental Slides
NETL H₂ Production TEA Examples

• **Baseline Coal Gasification and NG SMR:**
  • “Assessment of Hydrogen Production with CO₂ Capture; Volume 1,” November 14, 2011
  • “Capital and Operating Cost of Hydrogen Production from Coal Gasification,” April, 2003

• **Advanced H₂ Separation Technologies:**
  • “Assessment of Hydrogen Production with CO₂ Capture; Volume 2-4,” November 14, 2011
  • “Production of High Purity Hydrogen from Domestic Coal: Assessing the Techno-Economic Impact of Emerging Technologies,” August 30, 2010

• **Fuel Cell Technology:**
NETL H₂ Production TEA Examples (cont'd.)

- **Fuel Cell Technology:**
H2A Case Study Contributions

- NETL TEAs currently provide the basis for the HFTO H2A production case studies:
  - Current, Centralized Coal with CO₂ Capture & Sequestration
  - Current and Future, Centralized NG without CO₂ Capture & Sequestration
  - Current and Future, Centralized NG with CO₂ Capture & Sequestration