**Project Goal:** Assess opportunities, costs, and lifecycle emissions benefit for blending hydrogen into natural gas pipelines

**Vision**

*Develop tools to quantify the economic and environmental impacts of blending hydrogen into the U.S. natural gas pipeline system*

**What**

- Model the economic impact and lifecycle emissions associated with blending hydrogen into the U.S. natural gas pipeline system
- Evaluate user-defined scenarios to blend hydrogen to achieve X% composition into a pipeline network

**How**

- Leverage DOE/lab tools (ProFAST, HDSAM, GREET®, H2A) to estimate value proposition of blending
- **Design and analyze scenarios** to evaluate the hydrogen blending’s application across different sections of the U.S. natural gas transmission pipeline system

**Why**

- Quantify the value proposition of hydrogen blending to accelerate early-market hydrogen technology adoption and achieve short-term emissions reduction
- Provide natural gas pipeline operators a pathway to enable decarbonization while leveraging existing infrastructure assets
**Overview:** Pipeline Blending CRADA

## Timeline and Budget

<table>
<thead>
<tr>
<th>Start: October 2021</th>
<th>End: September 2023</th>
</tr>
</thead>
<tbody>
<tr>
<td>55% complete (NREL’s TEA tasks)*</td>
<td>*As of March 31st, 2023</td>
</tr>
</tbody>
</table>

Overall CRADA project budget: $15 MM
- DOE Share: $11 MM
- Cost Share: $4 MM

NREL’s total project budget: $1.7 MM
- DOE funds spent*: $282k
- Industry cost share funds spent*: $500k

ANL’s total project budget: $1.6 MM
- DOE funds spent*: $1.1MM

**as of ~March 31st, 2023**

## Barriers

- Inconsistent Data, Assumption and Guidelines
- Insufficient Suite of Models and Tools

## Partners

**National Labs (Role)**
- National Renewable Energy Laboratory - Mark Chung, PI (Techno-economic Analysis)
- Argonne National Laboratory – Amgad Elgowainy, PI (Lifecycle Analysis)
- Sandia National Laboratories – Chris San Marchi, PI (Metals Compatibility)
- Pacific Northwest National Laboratory – Kevin Simmons, PI (Polymer Compatibility)

**Industry Partners (alphabetical)**
- Air Liquide
- Chevron
- DNV
- Enbridge
- EPRI
- ExxonMobil
- GTI
- Hawaii Gas
- Hydril
- National Grid
- NJNG
- ONEGAS
- PRCI
- SMUD
- Southern Company
- Stony Brook University
- SWRI
The U.S. possesses an extensive natural gas (NG) network consisting of 2.44 million miles of pipe. Leveraging this existing infrastructure for hydrogen blending advances DOE goals by:

- Offering a pathway *with incremental steps* towards cost-effective pure hydrogen transportation
- Promoting *early-market access* for hydrogen technology adoption
- Enabling *short-term carbon emissions reductions* (with low-carbon H₂) with the potential for long-term emissions reductions for hard-to-decarbonize sectors
- Potentially providing *lower cost H₂* transport than new-built H₂ pipes or truck delivery
- Facilitating a *smooth transition* for natural gas workforce into clean energy jobs
- Utilize existing infrastructure right-of-way to *avoid environmental and social impacts* of developing new energy infrastructure

**Potential Impact:** Utilizing existing natural gas infrastructure might enable low-cost H₂ transport and facilitate private sector uptake.
Approach (1/3): NREL developed a Pipeline Preparation Cost Tool (PPCT) that provides case-by-case analysis capabilities

- The PPCT is a Python tool that answers the following:
  - What modifications to the pipeline network are necessary to enable blending up to $X\%$ of hydrogen in pipeline gas?
  - What incremental capital investment and operating expense are required to upgrade the natural gas pipeline network for $X\%$ of hydrogen in pipeline gas?
- This model targets application at the initial project assessment stage for transmission pipelines
- Intent is to provide the user with an understanding of the most promising opportunities before proceeding with more detailed pipeline inspections based on “probable” economic outcome

*ProFAST is a pythonic version of H2FAST
Approach (2/3): Pipeline Blending CRADA Lifecycle Assessment

Objectives

- Identify the GHG emissions associated with each stage across the full supply chain of H₂/NG blend, e.g., NG recovery and transport, hydrogen production and injection, the compression and transmission and final application of H₂/NG blend.
**Approach (3/3): Pipeline Blending CRADA Analysis Milestones**

<table>
<thead>
<tr>
<th>Due Date</th>
<th>Lab</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 2022</td>
<td>ANL</td>
<td>Evaluation of cost, energy use and emissions of capturing, purifying and transportation of CO(_2): from various sources</td>
<td>Complete</td>
</tr>
<tr>
<td>June 2022</td>
<td>NREL</td>
<td>Status memorandum on the key components of the natural gas supply-chain to be prioritized</td>
<td>Complete</td>
</tr>
<tr>
<td>September 2022</td>
<td>NREL</td>
<td>Status memorandum and presentation to DOE and industry parties summarizing the status of Pipeline Blending TEA progress</td>
<td>Complete</td>
</tr>
<tr>
<td>September 2022</td>
<td>ANL</td>
<td>Evaluation of energy and emissions of delivering NG/H(_2): blends from injection point to end use applications</td>
<td>Complete</td>
</tr>
<tr>
<td>September 2022</td>
<td>ANL</td>
<td>Model of CH(_4): synthesis process</td>
<td>Complete</td>
</tr>
<tr>
<td>December 2022</td>
<td>ANL</td>
<td>Integrating life cycle assessment with techno-economic analysis of synthetic NG production</td>
<td>Complete</td>
</tr>
<tr>
<td>December 2022</td>
<td>NREL</td>
<td>Draft journal article of initial techno-economic pipeline preparation tool and case study results</td>
<td>Complete</td>
</tr>
<tr>
<td>March 2023</td>
<td>ANL</td>
<td>Evaluation of emissions of NG/H(_2): combustion at various end use applications</td>
<td>Complete</td>
</tr>
<tr>
<td>March 2023</td>
<td>ANL</td>
<td>Life cycle assessment of synthetic NG production</td>
<td>Complete</td>
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<tr>
<td>March 2023</td>
<td>NREL</td>
<td>Draft journal article on the economic assessment of alternative pathways for natural gas decarbonization</td>
<td>Complete</td>
</tr>
<tr>
<td>June 2023</td>
<td>ANL</td>
<td>Life cycle assessment of various NG/H(_2): blending pathways</td>
<td>In progress</td>
</tr>
<tr>
<td>June 2023</td>
<td>NREL</td>
<td>Draft journal article on quantifying the valuation of hydrogen blending to early-adoption end users</td>
<td>In progress</td>
</tr>
<tr>
<td>September 2023</td>
<td>ANL</td>
<td>Final technical report draft for DOE and public webinar</td>
<td>In progress</td>
</tr>
<tr>
<td>September 2023</td>
<td>NREL</td>
<td>Open-source techno-economic pipeline preparation model provided on NREL’s website with supporting documentation (NREL Report). Public webinar completed after publication</td>
<td>In progress</td>
</tr>
</tbody>
</table>
1. Given network data (pipe topology, length, diameter, schedule) and desired hydrogen fraction, model the existing pipeline network to identify necessary operating pressures and flowrates to meet demand.

2. Identify independent pipe segments:
   - Separated by compression stations or pressure reduction stations for line-packing
   - Separated by changes in pipe diameter for in-line inspection
   - May have multiple pipes within one segment with different age, grade, elevation, etc.
   - Can have an offtake mid-segment if it does not result in change in diameter

3. Choose an ASME B31.12 design option and calculate maximum allowable operating pressure (MAOP) for existing network for desired hydrogen blend.
Accomplishments and Progress (2/11): The PPCT pipeline modification module offers 3 methods to bring pipeline to specification for blending

Method 1 - Direct Pipeline Replacement:
- Directly replace existing pipes that cannot meet targeted operating pressure
- Identify pipes that violate ASME B31.12 requirements for a chosen design option
- Replace those pipes with new pipes (presumably use the design option that allows the highest design factor to be applied for new pipes)
- Modify or replace compressors necessary to meet required operating pressure
- Replace valves and meters as necessary to handle hydrogen
- This method requires removing existing pipe, but we assume no new right-of-way costs

Direct Pipeline Replacement
Accomplishments and Progress (3/11): The PPCT pipeline modification module offers 3 methods to bring pipeline to specification for blending

Both methods shown here require reducing design pressure to that allowed by chosen ASME B31.12 design option but take different approaches to increase pipeline capacity

Method 2 – Parallel Looping
- Build parallel loops to accommodate higher volumetric flowrates
  - Calculate loop length for different diameters
  - Select least-cost feasible loop diameter and schedule to meet demand
- Method incurs additional right of way costs

Method 3 – Additional Compressors
- Add compressor stations to increase volumetric flowrates
- Calculate number and placement of additional compressor stations
- Method incurs new compressor station capital and right-of-way costs

Both methods also require modifying or replacing compressors necessary to meet required operating pressure, and replacing valves and meters as necessary to handle hydrogen
Accomplishments and Progress (4/11): Alliance Pipeline serves as a preliminary PPCT case study demonstration

- Alliance Pipeline is a well-documented, large-scale pipeline representative of future potential blending scenarios

- Case study covers 327 mi segment of U.S. pipeline; simulated to transport 1,544,000 MMBTU/d of gas to end users (enough to heat 924,000 homes a day*)

- Demonstrated each modification method to assess costs to achieve 50% vol H₂ for a 2030 cost scenario – Assumed revised design factor of 0.4 – worst case scenario based on ASME B31.12

Network design modification results for each method applied for blending to 20% by vol. hydrogen

<table>
<thead>
<tr>
<th>Applied PPCT Modification Method</th>
<th>ASME B31.12 Design Pressure</th>
<th>Required length of added new pipe</th>
<th>Compressor stations (CS) added</th>
<th>Required increase in CS rated power</th>
<th>Transported gas used as fuel</th>
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<tbody>
<tr>
<td>Direct pipe replacement</td>
<td>1740 psig</td>
<td>327 miles</td>
<td>-</td>
<td>101%</td>
<td>0.81%</td>
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<tr>
<td>Parallel looping</td>
<td>678 psig</td>
<td>314 miles</td>
<td>-</td>
<td>107%</td>
<td>0.83%</td>
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<tr>
<td>Additional Compressors</td>
<td>678 psig</td>
<td>-</td>
<td>16</td>
<td>1620%</td>
<td>6.51%</td>
</tr>
</tbody>
</table>

*Assuming 1,037 Btu/cf gas heat content and 588 cf/yr average residential natural gas consumption
Accomplishments and Progress (5/11): Levelized cost of transport (LCOT) is estimated for blends up to 50% vol. $H_2$ in Alliance Pipeline case study w/o IRA incentives

- Levelized cost of transport for each pipeline modification method applied to case study from 1% to 50% vol. $H_2$ in pipeline gas
- Delivered energy cost for each pipeline modification method applied to case study from 1% to 50% vol. $H_2$ in pipeline gas

- Direct replacement and parallel looping modifications are favored for this case study
  - Direct replacement involves higher pipe costs than parallel looping
  - Compressor capex and fuel costs are greater for parallel looping relative to direct replacement for blends ≤ 20%
  - Additional compressors method has no new pipe costs but very high compressor capex and fuel costs

- LCOT is a small portion of delivered cost of energy
- Delivered energy cost increases with increasing $H_2$ blending (at $3.44 - $3.58 per kg $H_2$ projected for 2030 w/out incentives)

Capital and operating costs associated with pipeline modification to accommodate hydrogen have a small impact on the delivered cost of energy
Accomplishments and Progress (6/11): Impact of H₂ blending ratio on gas properties and pipeline performance

**Gas compression energy**
- H₂ has lower volumetric energy density than NG. H₂ blending increases Z and decreases LHV and density.
- Compression power = f (Z, CR, density⁻¹, throughput)

**Constant volumetric flow rate**
- H₂ blending → lower gas density → lower pressure drop → lower CR
- Compression power is reduced with lower CR and lower throughput
- 100% H₂ leads to 70% drop in gas energy content

**Constant energy throughput**
- Constant energy throughput requires an increase of gas flow rate
- Compression energy increases, due to increase in Z, density⁻¹, CR
- Max x_H₂ limited by max pipe velocity and compression speed

Graphs showing:
- % Variation of gas property (H₂ mole fraction)
- % Variation from pure NG (H₂ mole fraction)
- % Variation from pure NG (H₂ mole fraction)

Graphs include:
- Pressure drop
- Compression power
- Mass flow rate
- Volumetric flow rate
- Energy throughput
- Compression power
- Pressure drop

H₂ moles fraction: 0, 0.1, 0.2, 0.3
Accomplishments and Progress (7/11):
Transmission and life cycle GHG emissions

**Transmission emissions (compression + leakage*)**

- Gas leakage (joints, valves, compressors, etc.) estimated as:
  \[ R_{\text{mix}} \approx R_{\text{CH}_4} \cdot \sqrt{\frac{\rho_{\text{CH}_4}}{\rho_{\text{mix}}}} \]
- Leakage rate increases with H\textsubscript{2} blending ratio
- For constant energy throughput, the sharp increase of GHG emissions partially offset the benefit of zero carbon from H\textsubscript{2}.

**Life cycle GHG emissions (H\textsubscript{2} from LTE with nuclear power)**

- For a constant energy scenario, the life cycle emissions are slightly lower (-6%) at x\textsubscript{H\textsubscript{2}}=30% due to lower upstream and lower combustion emissions of blend
- T&D emissions increased with the H\textsubscript{2} content due to higher compression energy demand partially offsetting the benefit of zero carbon from H\textsubscript{2}.

\*GWP of H\textsubscript{2} = 0
Accomplishments and Progress (8/11):
Modeling of alternative SNG production

- **SNG plant was scaled for a commercial capacity (20 MT/hr), validated in Europe.**
- **The plant consumes 1.6 GW electricity, generates 1020 MMBtu-HHV/hr SNG, 3% of national average NG pipeline throughput, with energy efficiency of 77% (without steam byproduct) and 91% (with steam byproduct)**
Accomplishments and Progress (9/11):
TEA of alternative SNG production

- DAC = Direct air capture
- LT = Low temperature
- HT = High temperature
- PTC = Production tax credit
- ITC = Investment tax credit

The H₂ production and storage cost is based on NREL estimate that considers potential tax credits.
The SNG product cost with PTC credit could be comparable to Fossil NG and RNG cost depending on H₂ storage method and CO₂ source.
Accomplishments and Progress (10/11): LCA of alternative SNG production

- DAC = Direct air capture
- LT = Low temperature
- HT = High temperature

- NREL analysis assumes wind power for H₂ production and storage
- SNG can potentially reduced GHG by 56-93% GHG compared to Fossil NG
Accomplishments and Progress (11/11):
Response to Previous Year Reviewers’ Comments

• This project has not received comments at the previous AMR
**Collaboration and Coordination**

- **U.S. DOE National Laboratories**
  - NREL: Project Lead, Techno-economic analysis (TEA)
  - ANL: Life cycle assessment (LCA) and emissions analysis; LCA/TEA of Synthetic Natural Gas (SNG) production
  - PNNL: Polymeric material testing and analysis
  - SNL: Metallic material testing and analysis; supporting polymeric material testing

- **Industry stakeholders**
  - Guide and inform research to yield insights to better inform industry-wide solutions
  - Provide insight or guidance on how NREL-developed economic tools can be most useful
Remaining Challenges and Barriers

- Availability of data to develop representative pipeline case studies are protected as critical energy infrastructure information
  - Develop simplified case studies limited to infrastructure data public disclosures
  - Obtain feedback from industry stakeholders on case study representation
- Current lack of guidance around pipeline retrofits for H₂ service; ASME B31.12 is primarily developed for new pipelines
  - Use SNL and industry stakeholder guidance to explore potential scenarios that involve existing pipeline assessment with higher design factors than recommended by ASME B31.12 but also, additional risk control measures (increased inspection, etc.)
  - Incorporating lessons-learned domestically and internationally
- The availability of test emission data on NG/H₂ production, usage and transportation with various blending ratios is the main challenge. Various estimation or calculation is used to fill data gap.
Proposed Future Work

• **Planned tasks for FY23**
  – Improve PPCT model design assessment and modification methods and economic assumptions
  – Publish PPCT as open source, accompanied by journal paper summarizing it and presenting preliminary results
  – Identify early hydrogen blending adopter opportunities in the US; assess end use energy cost and emissions impacts in a representative case study
  – Evaluation of life cycle NO\textsubscript{x} emissions at different end-use applications
  – Quantify life cycle GHG emissions associated with pipeline upgrade/modifications

• **Planned work beyond FY23**
  – Extending PPCT model capabilities and user accessibility
  – Provide technical support for partners and interested users planning to use the current version of the PPCT
  – Power grid capacity expansion modeling with consideration of hydrogen production for natural gas blending
  – Investigating impact of GWP of hydrogen to life cycle emissions of hydrogen blending
  – Developing engineering models of direct air capture to evaluate associated costs and emissions

*Any proposed future work is subject to change based on funding levels*
• NREL developed a Pipeline Preparation Cost Tool (PPCT) that provides case-by-case analysis capabilities to assess cost of blending hydrogen into natural gas transmission pipelines
• The PPCT consists of a pipeline design assessment and a modification module which
  – Models and segments transmission pipelines and calculates segment design pressures using ASME B31.12
  – Offers three unique pipeline modification approaches to upgrade pipeline as to meet ASME B31.12 specifications for hydrogen blending
• PPCT demonstration on a representative case study highlights pipeline design modifications and the marginal contribution of pipeline modification cost to delivered cost of energy

• The life cycle GHG emissions of the NG/H₂ blends decrease with the increasing hydrogen blending ratio, driven by the reduced combustion emissions due to reduced carbon content in the gas.
• The reduction of combustion emission is partially offset by the increase of emissions associated with the transmission of the blend when delivering the same energy throughput.
• Synthetic natural gas has a production cost of $40-70/MMBtu-HHV without credit. However, stacking various tax credits can reduce the production cost to $3-20/MMBtu-HHV by using industrial CO₂ sources.
Thank You
Technical Backup and Additional Information
Technology Transfer Activities

• **Pipeline Upgrade Cost Model** is being developed and will be released as open-source (target September 2023)

• **ProFAST** is a closed-source pythonic version to **H2FAST**. It is currently being developed and may be publicly available (target TBD). Access to **H2FAST** is provided in the following link: (https://www.nrel.gov/hydrogen/h2fast.html)
Publications and Presentations

Publications


Presentations


Accomplishments and Progress (Backup): Detailed pipeline design modifications estimated for direct replacement and parallel looping methods in Alliance Pipeline case study

### Case study pipeline design after applying direct replacement method for blending hydrogen to 20 vol.%

<table>
<thead>
<tr>
<th>Segment ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline diameter (NPS)</td>
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<td>36</td>
<td>36</td>
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<tr>
<td>Schedule</td>
<td>S 40</td>
<td>S 40</td>
<td>S 40</td>
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<tr>
<td>Grade</td>
<td>X60</td>
<td>X60</td>
<td>X60</td>
</tr>
<tr>
<td>Length (mi)</td>
<td>115</td>
<td>118</td>
<td>94</td>
</tr>
<tr>
<td>ASME B31.12 design pressure (psig)</td>
<td>1740</td>
<td>1740</td>
<td>1740</td>
</tr>
</tbody>
</table>

### Case study pipeline design after applying parallel looping method for blending hydrogen to 20 vol.%

<table>
<thead>
<tr>
<th>Segment ID</th>
<th>1</th>
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</thead>
<tbody>
<tr>
<td>Loop diameter (NPS)</td>
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<td>Loop Schedule</td>
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<tr>
<td>Loop Length (mi)</td>
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<td>116</td>
<td>83</td>
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<tr>
<td>Percent of Segment looped (%)</td>
<td>98.2</td>
<td>98.4</td>
<td>88.1</td>
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<td>ASME B31.12 design pressure (psig)</td>
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</table>

### Case study compressor station design and operating conditions after applying direct replacement method for blending hydrogen to 20 vol.% hydrogen

<table>
<thead>
<tr>
<th>Compressor station ID</th>
<th>Mile post</th>
<th>Fuel consumption (MMBTU/hr)</th>
<th>Operating shaft power (hp)</th>
<th>Compressor station rated capacity (hp)</th>
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<tbody>
<tr>
<td>CS 1</td>
<td>115</td>
<td>259.5</td>
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<td>CS 2</td>
<td>233</td>
<td>264.0</td>
<td>37,044</td>
<td>37,133</td>
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</table>

### Case study compressor station design and operating conditions after applying parallel looping method for blending hydrogen to 20 vol.% hydrogen

<table>
<thead>
<tr>
<th>Compressor station ID</th>
<th>Mile post</th>
<th>Fuel consumption (MMBTU/hr)</th>
<th>Operating shaft power (hp)</th>
<th>Compressor station rated capacity (hp)</th>
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<tbody>
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<td>270.5</td>
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<td>CS 2</td>
<td>233</td>
<td>269.0</td>
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### Accomplishments and Progress (Backup): Detailed pipeline design modifications estimated for additional compressor method in Alliance Pipeline case study

Case study compressor station design and operating conditions after applying additional compressors method for blending hydrogen to 20 vol.% hydrogen

<table>
<thead>
<tr>
<th>Compressor station ID</th>
<th>Type</th>
<th>Mile post</th>
<th>Fuel consumption (MMBTU/hr)</th>
<th>Operating shaft power (hp)</th>
<th>Compressor station rated capacity (hp)</th>
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</thead>
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<tr>
<td>CS 1a</td>
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<td>CS 1b</td>
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<td>36,615</td>
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<td>CS 1c</td>
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<td>166.2</td>
<td>23,314</td>
<td>23,314</td>
</tr>
</tbody>
</table>
Accomplishments and Progress (Backup): Assumptions used to develop hydrogen costs in Alliance Pipeline case study

Locational data and wind capital and operating costs (in 2020$) for 2030 used in case study

<table>
<thead>
<tr>
<th>Wind Power Plant Data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Turbine Overnight CAPEX</td>
<td>$956/kW</td>
</tr>
<tr>
<td>Storage Fixed OpEx</td>
<td>$38.95/kW-yr</td>
</tr>
<tr>
<td>Approximate Location</td>
<td>43.66466268, -94.05460598</td>
</tr>
<tr>
<td>Capacity Factor</td>
<td>34.3%</td>
</tr>
</tbody>
</table>

Hydrogen Facility Equipment Capital and Operating Cost References

<table>
<thead>
<tr>
<th>Equipment Costs</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage Compressor</td>
<td>[1]</td>
</tr>
<tr>
<td>Lined Rock Cavern CAPEX</td>
<td>[2]</td>
</tr>
<tr>
<td>Pipeline Compressor</td>
<td>[1]</td>
</tr>
<tr>
<td>H₂ Pipeline</td>
<td>[3]</td>
</tr>
</tbody>
</table>

PEM electrolyser capital and operating costs (in 2020$) for 2030 used in case study

<table>
<thead>
<tr>
<th>PEM Electrolyser Data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overnight CAPEX</td>
<td>$592/kW</td>
</tr>
<tr>
<td>Fixed OpEx (Percent of overnight CAPEX)</td>
<td>3.55%</td>
</tr>
<tr>
<td>Variable OpEx (excluding refurbishment)</td>
<td>$1.3/MWh</td>
</tr>
<tr>
<td>Time between refurbishment</td>
<td>80,000 hr</td>
</tr>
<tr>
<td>Refurbishment Cost (Percent of direct CAPEX)</td>
<td>15%</td>
</tr>
<tr>
<td>Efficiency (on a HHV Basis)</td>
<td>71%</td>
</tr>
</tbody>
</table>

Inflation Reduction Act Incentive used in case study for H₂ costing

<table>
<thead>
<tr>
<th>Covered Equipment</th>
<th>Applicable IRA Incentive</th>
<th>Assumed Incentive Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Power Plant</td>
<td>45Y (Wind PTC)</td>
<td>$0.026/kWh</td>
</tr>
<tr>
<td>PEM Electrolyser</td>
<td>45V (H₂ PTC)</td>
<td>$3/kg H₂</td>
</tr>
<tr>
<td>Lined Rock Cavern Storage and Storage Compressors</td>
<td>45E (ITC)</td>
<td>30% of Overnight CAPEX</td>
</tr>
</tbody>
</table>

References:

Accomplishments and Progress (Backup): Location-specific hydrogen costs are used in Alliance Pipeline case study

<table>
<thead>
<tr>
<th>Cost Scenario</th>
<th>Blend Target (vol. % H₂ in Pipeline Gas)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1%</td>
</tr>
<tr>
<td>2030, No IRA Incentives</td>
<td>3.58</td>
</tr>
<tr>
<td>2030, IRA Incentives</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Accomplishments and Progress (Backup): Levelized cost of transport (LCOT) is estimated for blends up to 50% vol. H₂ in Alliance Pipeline case study w/ IRA incentives

Levelized cost of transport for each pipeline modification method applied to case study from 1% to 50% vol. H₂ in pipeline gas

- IRA incentives reduces LCOT case for each method applied to this case study due to reduced compressor fuel costs
  - Direct replacement and additional compressor entail increasing compressor fuel costs with increasing blending
  - Parallel looping results compressor fuel costs reducing with increasing blending
- Additional compressors method results in more comparable levelized cost of transport relative to other two methods

Delivered energy cost for each pipeline modification method applied to case study from 1% to 50% vol. H₂ in pipeline gas

- LCOT and H₂ injection cost are a small portion of delivered cost of energy
- Delivered energy cost decreases with increasing H₂ blending (at -$0.06 to $0.05 per kg H₂ projected for 2030 w/ incentives) displacing natural gas