HyBlend: Pipeline CRADA Cost and Emissions Analysis

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Project ID: IN034

DOE Hydrogen Program
2023 Annual Merit Review
and Peer Evaluation
Meeting

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

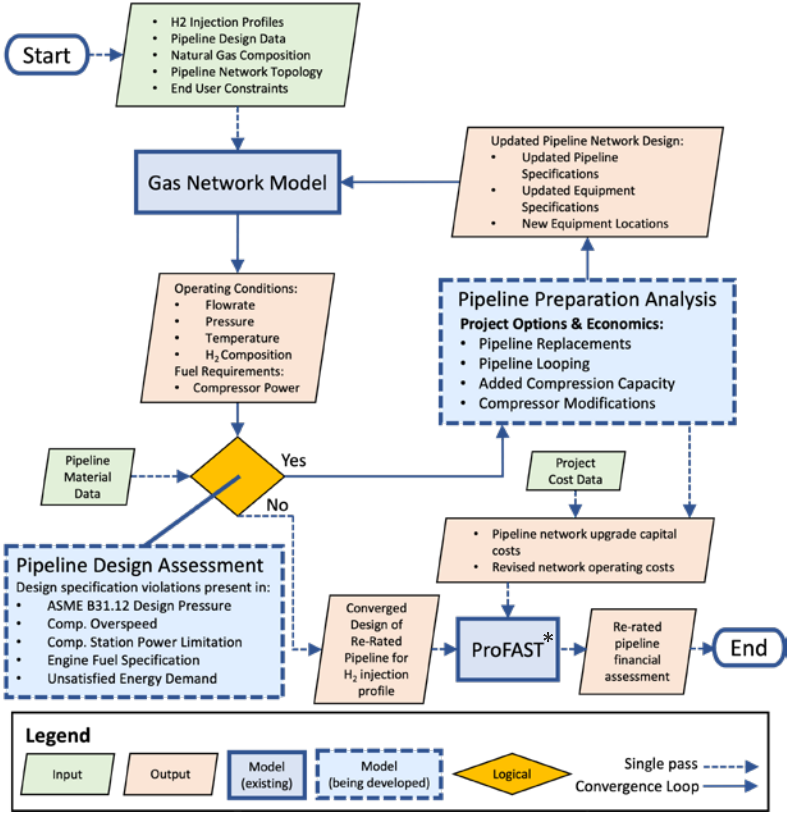
Timeline and Budget	Barriers
Start: October 2021 End: September 2023 55% complete (NREL's TEA tasks)* *As of March 31st, 2023 Overall CRADA project budget: $15 MM • DOE Share: $11 MM • Cost Share: $4 MM NREL's total project budget: $1.7 MM • DOE funds spent*: $282k • Industry cost share funds spent*: $500k ANL's total project budget: $1.6 MM • DOE funds spent*: $1.1MM **as of ~March 31st, 2023	• 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 and SWRI

Potential Impact: Utilizing existing natural gas infrastructure might enable low-cost H_2 transport and facilitate private sector uptake

- 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 H_2) with the potential for long-term emissions reductions for hard-to-decarbonize sectors
  - Potentially providing *lower cost H_2* transport than new-built H_2 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

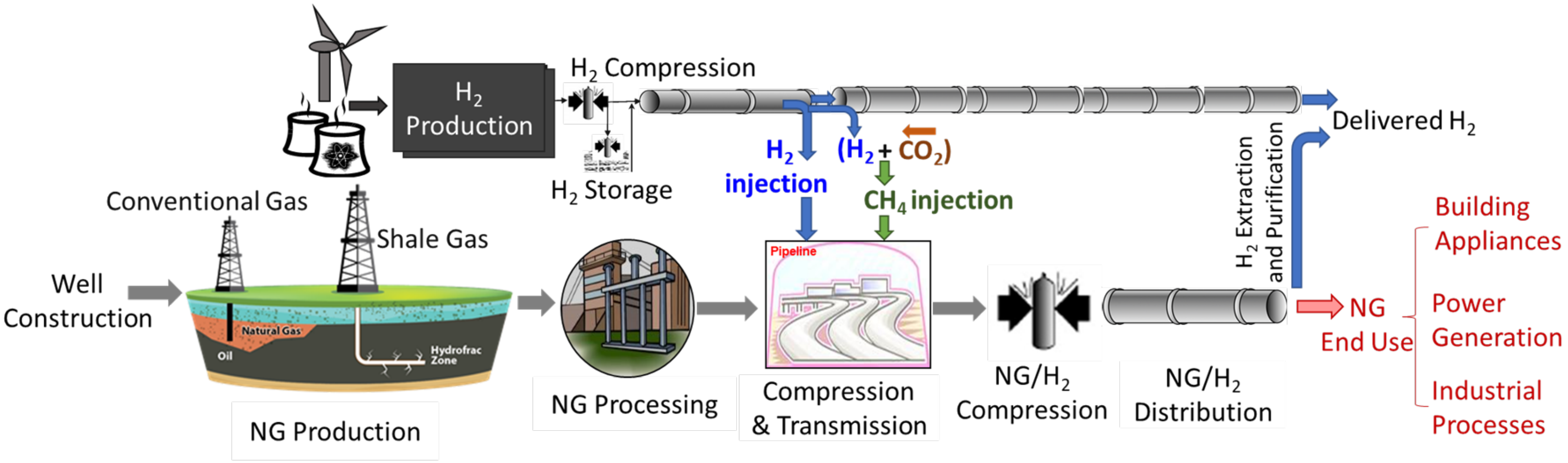
Approach (1/3): NREL developed a Pipeline Preparation Cost Tool (PPCT) that provides case-by-case analysis capabilities

- 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 <u>most promising opportunities</u> 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 H_2/NG blend, e.g., NG recovery and transport, hydrogen production and injection, the compression and transmission and final application of H_2/NG blend.

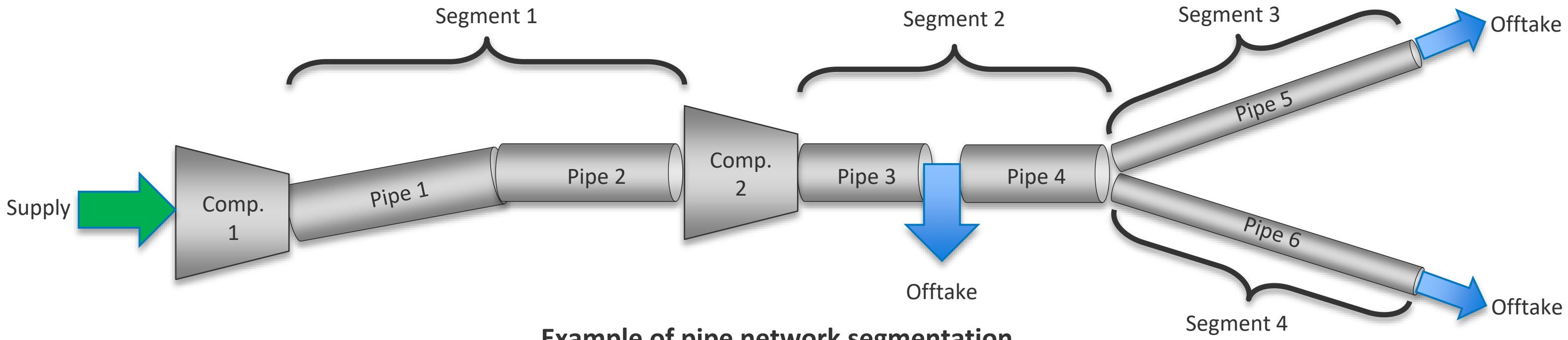
Approach (3/3): Pipeline Blending CRADA Analysis Milestones

Due Date	Lab	Description	Status
June 2022	ANL	Evaluation of cost, energy use and emissions of capturing, purifying and transportation of CO_2 from various sources	Complete
June 2022	NREL	Status memorandum on the key components of the natural gas supply-chain to be prioritized	Complete
September 2022	NREL	Status memorandum and presentation to DOE and industry parties summarizing the status of Pipeline Blending TEA progress	Complete
September 2022	ANL	Evaluation of energy and emissions of delivering NG/H_2 blends from injection point to end use applications	Complete
September 2022	ANL	Model of CH_4 synthesis process	Complete
December 2022	ANL	Integrating life cycle assessment with techno-economic analysis of synthetic NG production	Complete
December 2022	NREL	Draft journal article of initial techno-economic pipeline preparation tool and case study results	Complete
March 2023	ANL	Evaluation of emissions of NG/H2 combustion at various end use applications	Complete
March 2023	ANL	Life cycle assessment of synthetic NG production	Complete
March 2023	NREL	Draft journal article on the economic assessment of alternative pathways for natural gas decarbonization	Complete
June 2023	ANL	Life cycle assessment of various NG/H2 blending pathways	In progress
June 2023	NREL	Draft journal article on quantifying the valuation of hydrogen blending to early-adoption end users	In progress
September 2023	ANL	Final technical report draft for DOE and public webinar	In progress
September 2023	NREL	Open-source techno-economic pipeline preparation model provided on NREL's website with supporting documentation (NREL Report). Public webinar completed after publication	In progress

Accomplishments and Progress (1/11): The PPCT design assessment module identifies independent pipe segments and calculates design pressures

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



Example of pipe network segmentation.

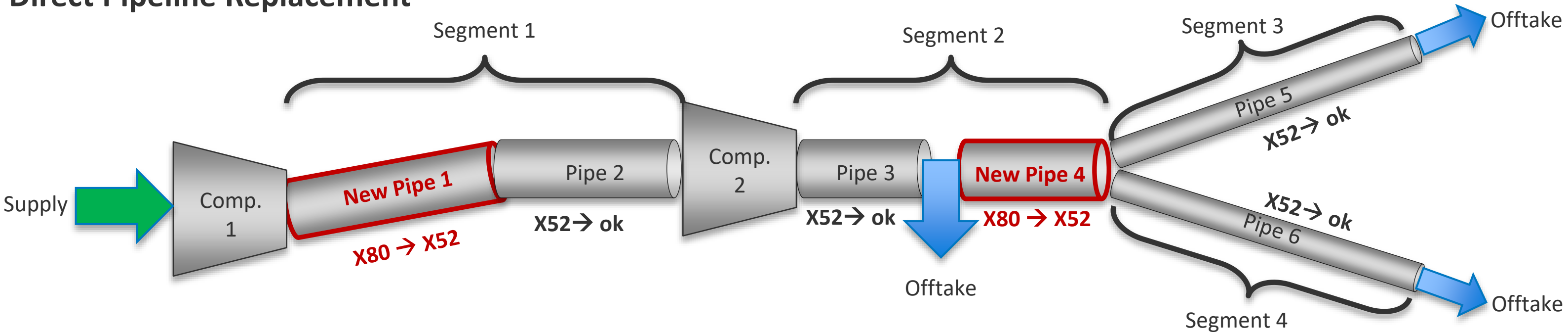
3. Choose an ASME B31.12 design option and calculate maximum allowable operating pressure (MAOP) for existing network for desired hydrogen blend

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



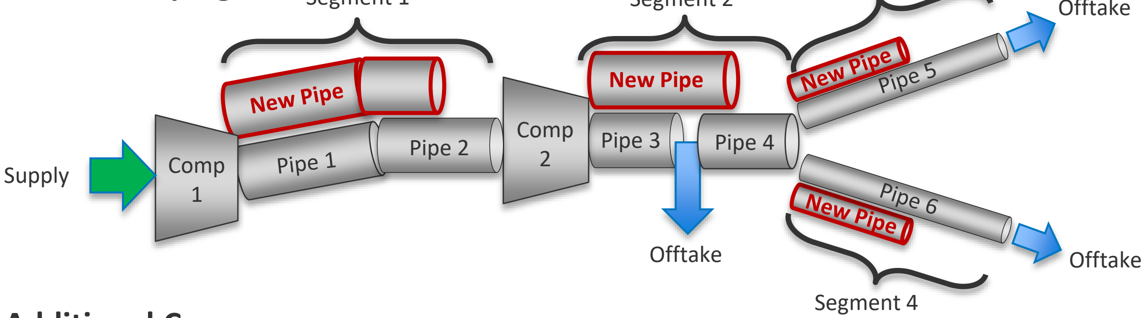
Accomplishments and Progress (3/11): The PPCT pipeline modification module offers 3 methods to bring pipeline to specification for blending

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

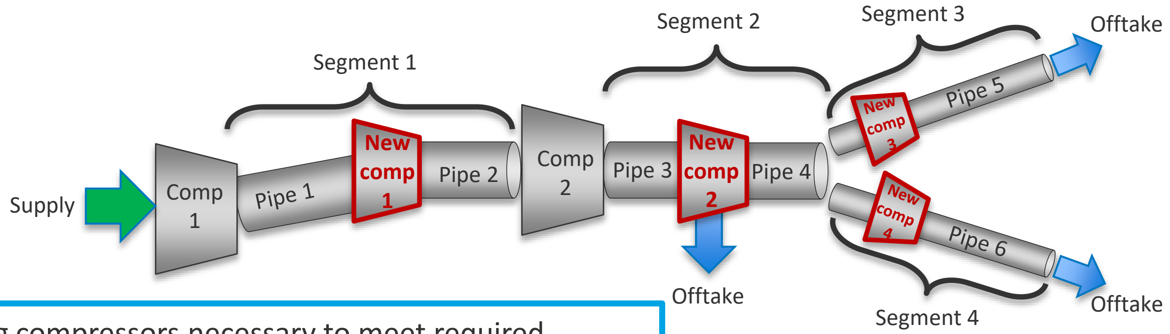
Method 2 – Parallel Looping
- Build parallel loops to accommodate higher volumetric flowrates
  - Calculate loop length for different diameters
  - Select least-cost feasible loop diameter and schedule to meet demand
- Method incurs additional right of way costs

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

Parallel Looping



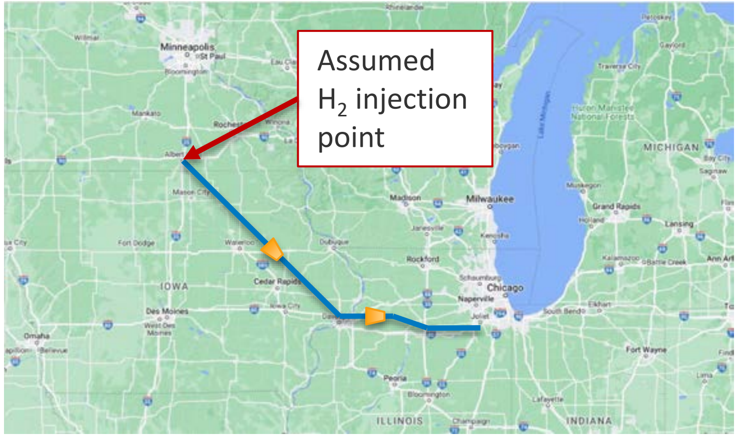
Additional Compressors



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 H_2 for a 2030 cost scenario
  - Assumed revised design factor of 0.4 – worst case scenario based on ASME B31.12



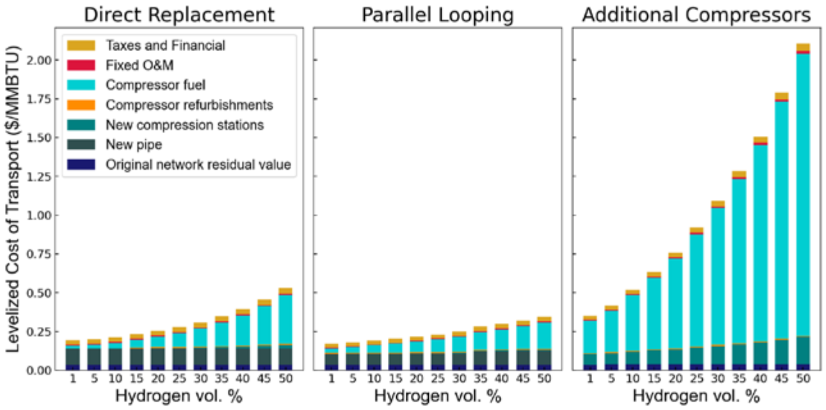
Segments of Alliance Pipeline (▬) and compressor stations (▶) represented in case study

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

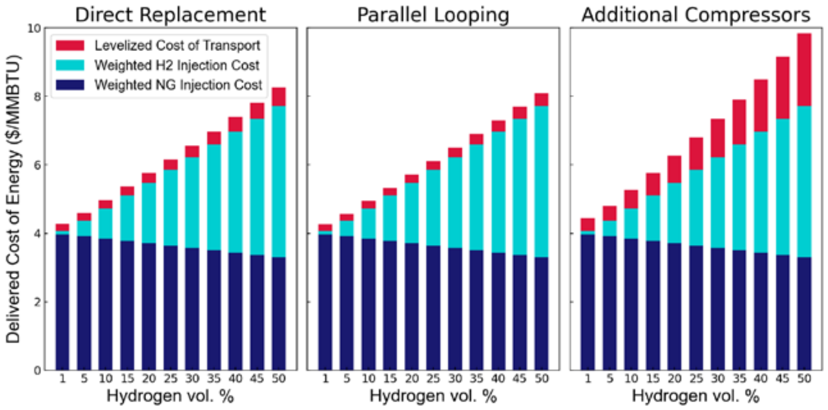
Applied PPCT Modification Method	ASME B31.12 Design Pressure	Required length of added new pipe	Compressor stations (CS) added	Required increase in CS rated power	Transported gas used as fuel
Direct pipe replacement	1740 psig	327 miles	-	101%	0.81%
Parallel looping	678 psig	314 miles	-	107%	0.83%
Additional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

*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

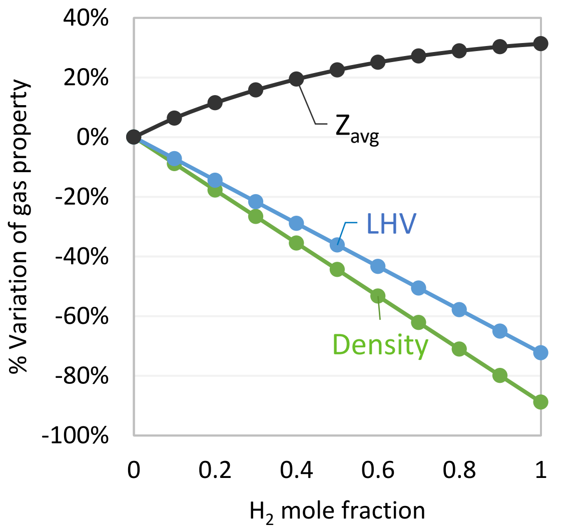
- LCOT is a small portion of delivered cost of energy
- Delivered energy cost increases with increasing H_2 blending (at **\$3.44 - \$3.58 per kg H_2** projected for 2030 w/out incentives)

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 H_2 blending ratio on gas properties and pipeline performance

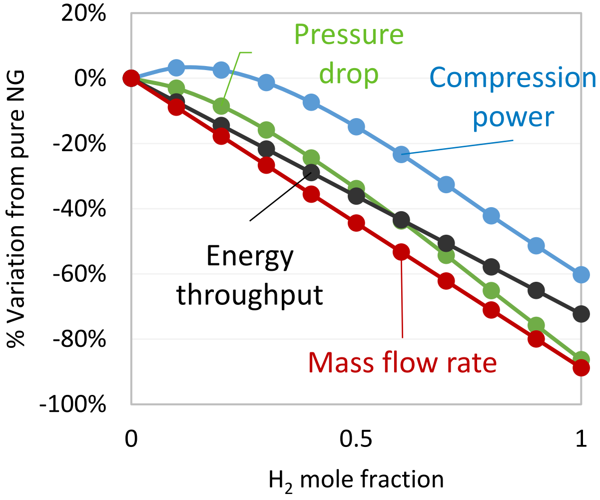
Gas compression energy

- H_2 has lower volumetric energy density than NG. H_2 blending increases Z and decreases LHV and density.
- Compression power = *f* (*Z*,*CR*, density^{-1}, throughput)



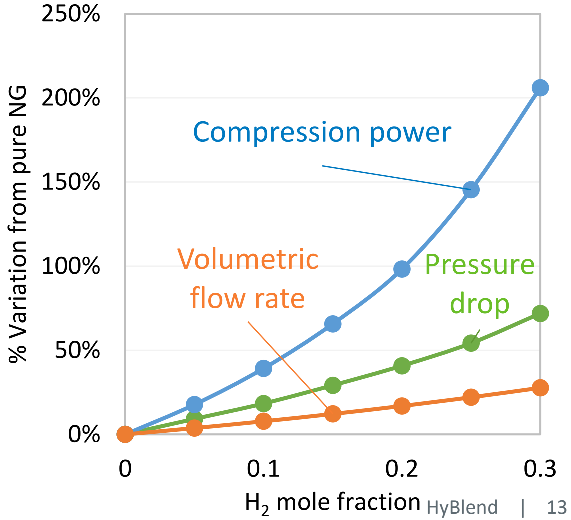
Constant volumetric flow rate

- H_2 blending→ lower gas density → lower pressure drop→ lower CR
- Compression power is reduced with lower CR and lower throughput
- 100% H_2 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



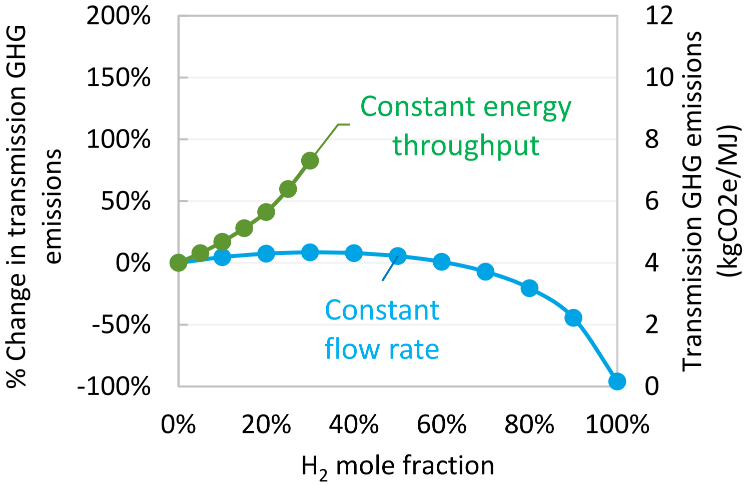
Accomplishments and Progress (7/11): Transmission and life cycle GHG emissions

Transmission emissions (compression + leakage)*

- Gas leakage (joints, valves, compressors, etc.) estimated as:

$$R_{mix} \approx R_{CH4} \cdot \sqrt{\rho_{CH4}/\rho_{mix}}$$

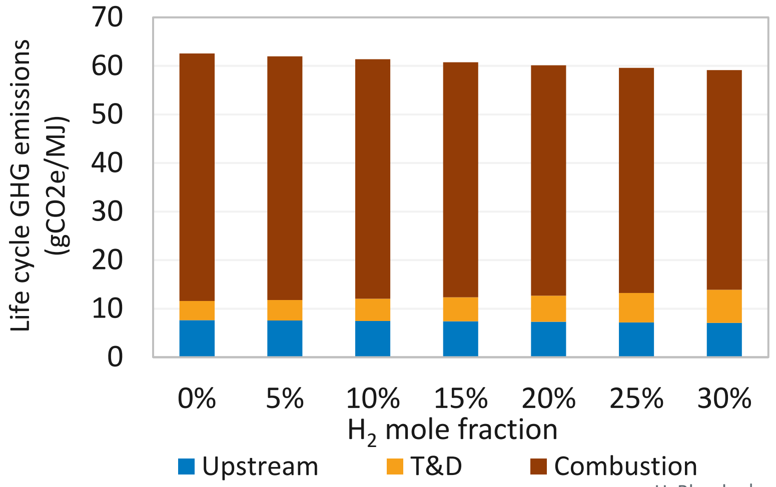
- Leakage rate increases with H_2 blending ratio
- For constant energy throughput, the sharp increase of GHG emissions partially offset the benefit of zero carbon from H_2.



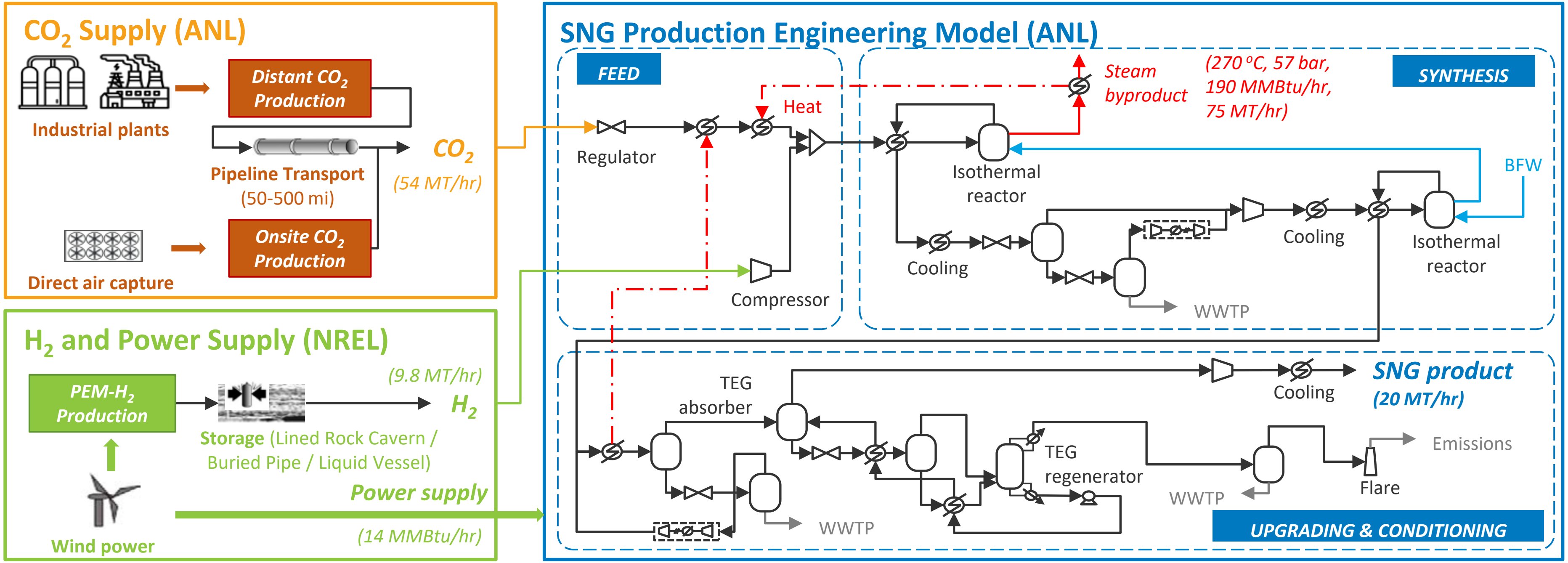
*GWP of H_2 = 0

Life cycle GHG emissions (H_2 from LTE with nuclear power)

- For a **constant energy scenario**, the life cycle emissions are slightly lower (-6%) at x_{H2}=30% due to lower upstream and lower combustion emissions of blend
- T&D emissions increased with the H_2 content due to higher compression energy demand partially offsetting the benefit of zero carbon from H_2.



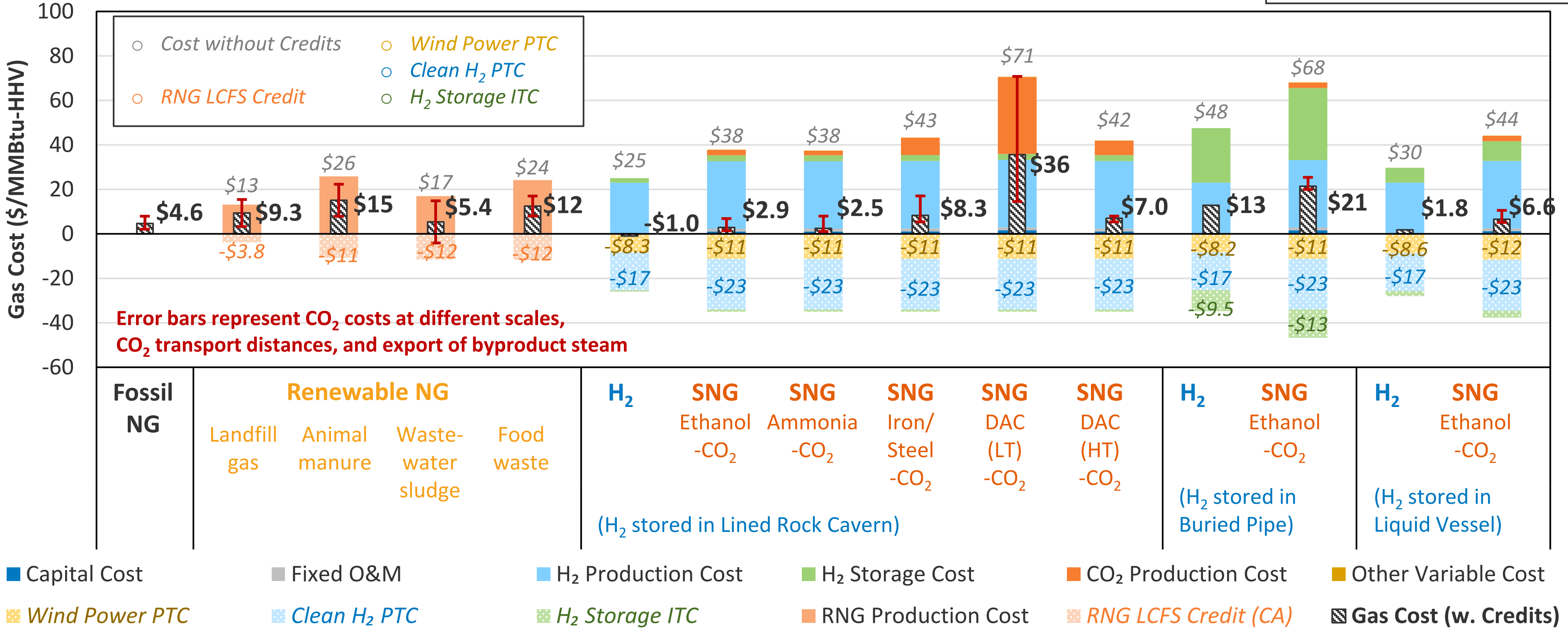
Accomplishments and Progress (8/11):
Modeling of alternative SNG production



- *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

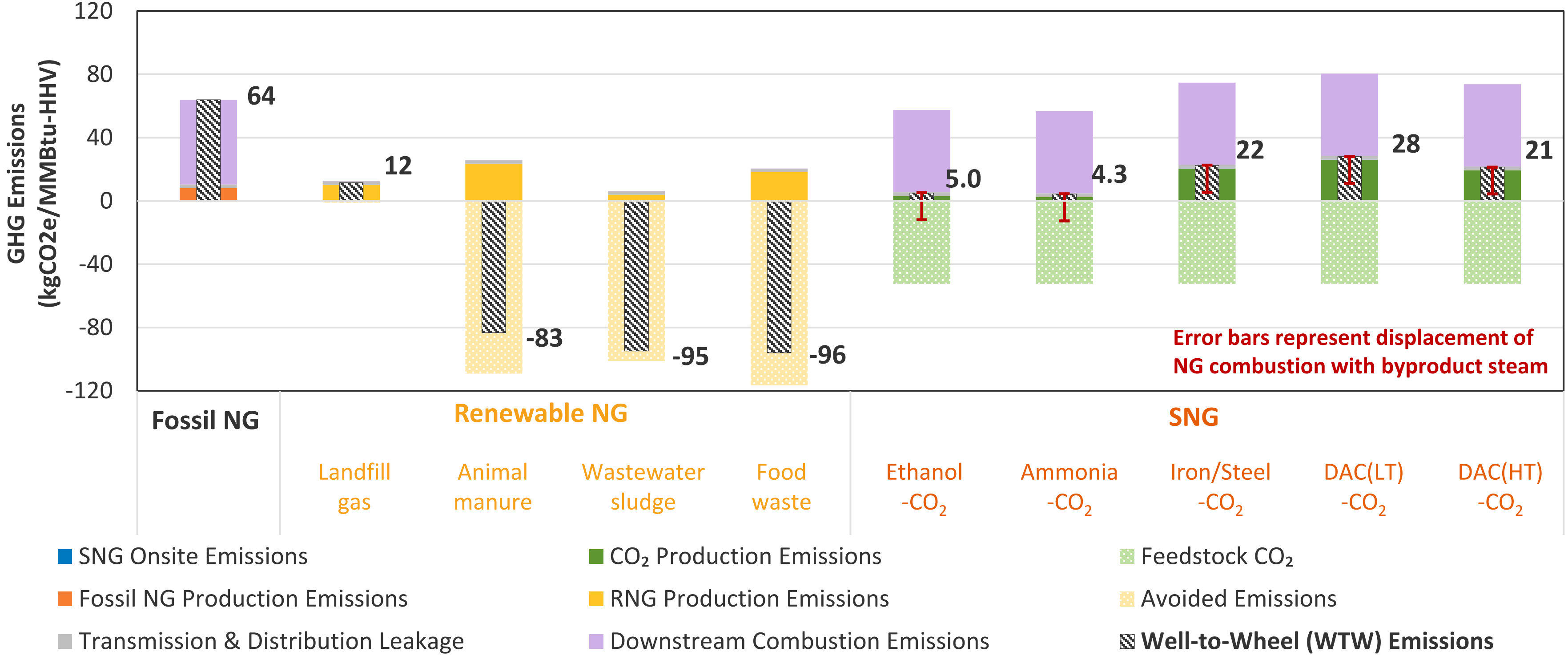
- DAC = Direct air capture
- LT = Low temperature
- HT = High temperature
- PTC = Production tax credit
- ITC = Investment tax credit



- *The H_2 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 **H_2 storage method** and **CO_2 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 H_2 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 H_2 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/H_2 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_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

Summary

- 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/H_2 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 the 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 CO_2 sources

Thank You

NREL/PR-5400-85939

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HyBlend
U.S. DEPARTMENT OF ENERGY

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

- Kevin Topolski, Evan P. Reznicek, Burcin Cakir Erdener, Omar Jose Guerra Fernandez, Bri-Mathias Hodge, Chris W. San Marchi, Joseph A. Ronevich, Lisa Fring, Kevin Simmons, and Mark Chung. "Hydrogen blending into natural gas pipeline infrastructure: review of the state of technology." National Renewable Energy Laboratory, Golden, CO. NREL/TP-5400-81704. 2022.

Presentations

- Evan Reznicek, Kevin Topolski, and Mark Chung. "Pipeline Blending CRADA – A HyBlend Project." Federation of Indian Petroleum Industry webinar on Gas-H_2 Blending. April 8th, 2022.
- Mark Chung, Amgad Elgowainy, Kevin Topolski, Evan Reznicek and Pingping Sun. "HyBlend: Pipeline CRADA Cost and Emissions Analysis . U.S. Department of Energy Hydrogen Program Annual Merit Review and Peer Evaluation Meeting. June 8th, 2022.
- Kevin Topolski, Evan Reznicek, Jamie Kee and Mark Chung. "Techno-Economic Analysis of Blending Hydrogen into Natural Gas Transmission Networks." Fuel Cell and Hydrogen Energy Seminar. February 9th, 2023.

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.%

Segment ID	1	2	3
Pipeline diameter (NPS)	36	36	36
Schedule	S 40	S 40	S 40
Grade	X60	X60	X60
Length (mi)	115	118	94
ASME B31.12 design pressure (psig)	1740	1740	1740

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

Segment ID	1	2	3
Loop diameter (NPS)	44	44	36
Loop Schedule	S Std	S Std	S 10
Loop Grade	X56	X56	X56
Loop Length (mi)	113	116	83
Percent of Segment Looped (%)	98.2	98.4	88.1
ASME B31.12 design pressure (psig)	678	678	678

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

Compressor station ID	Mile post	Fuel consumption (MMBTU/hr)	Operating shaft power (hp)	Compressor station rated capacity (hp)
CS 1	115	259.5	36,403	36,491
CS 2	233	264.0	37,044	37,133

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

Compressor station ID	Mile post	Fuel consumption (MMBTU/hr)	Operating shaft power (hp)	Compressor station rated capacity (hp)
CS 1	115	270.5	37,950	37,950
CS 2	233	269.0	37,745	37,745

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

Compressor station ID	Type	Mile post	Fuel consumption (MMBTU/hr)	Operating shaft power (hp)	Compressor station rated capacity (hp)
CS 1a	New	17.2	261.0	30,681	36,623
CS 1b	New	34.5	261.0	31,056	36,615
CS 1c	New	51.8	261.0	36,623	36,615
CS 1d	New	69.2	261.0	36,615	36,620
CS 1e	New	86.5	261.0	36,615	36,615
CS 1f	New	103.8	211.4	36,620	29,661
CS 1	Original	115	218.7	36,615	30,681
CS 2a	New	132.4	264.2	29,661	37,073
CS 2b	New	149.9	264.2	37,073	37,073
CS 2c	New	167.4	264.3	37,073	37,077
CS 2d	New	184.8	264.3	37,077	37,078
CS 2e	New	202.3	264.3	37,078	37,078
CS 2f	New	219.7	232.3	37,078	32,594
CS 2	Original	232.5	221.3	32,594	31,056
CS 3a	New	250.1	267.6	37,552	37,552
CS 3b	New	267.7	267.6	37,547	37,547
CS 3c	New	285.3	267.6	37,547	37,547
CS 3d	New	302.8	166.2	23,314	23,314

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

Wind Power Plant Data	Value
Wind Turbine Overnight CAPEX	$956/kW
Storage Fixed OpEx	$38.95/kW-yr
Approximate Location	43.66466268, -94.05460598
Capacity Factor	34.3%

Hydrogen Facility Equipment Capital and Operating Cost References

Equipment Costs	Ref.
Storage Compressor	[1]
Lined Rock Cavern CAPEX	[2]
Pipeline Compressor	[1]
H_2 Pipeline	[3]

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

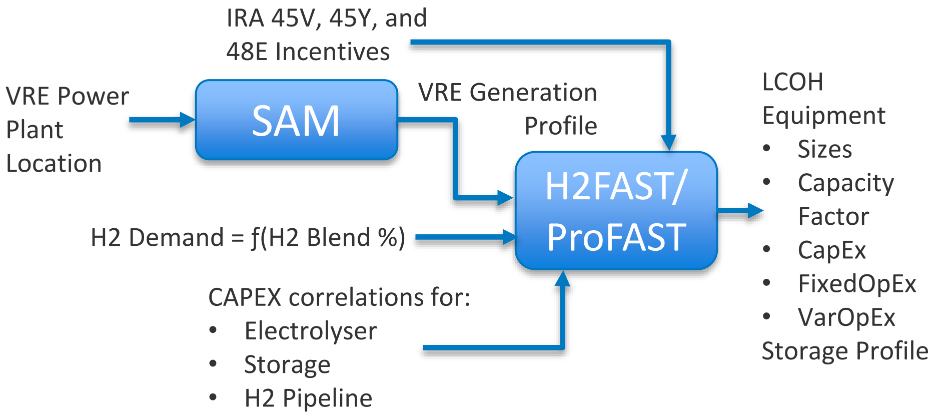
PEM Electrolyser Data	Value
Overnight CAPEX	$592/kW
Fixed OpEx (Percent of overnight CAPEX)	3.55%
Variable OpEx (excluding refurbishment)	$1.3/MWh
Time between refurbishment	80,000 hr
Refurbishment Cost (Percent of direct CAPEX)	15%
Efficiency (on a HHV Basis)	71%

Inflation Reduction Act Incentive used in case study for H_2 costing

Covered Equipment	Applicable IRA Incentive	Assumed Incentive Value
Wind Power Plant	45Y (Wind PTC)	$0.026/kWh
PEM Electrolyser	45V (H_2 PTC)	$3/kg H_2
Lined Rock Cavern Storage and Storage Compressors	45E (ITC)	30% of Overnight CAPEX

[1] Elgowainy, A., Reddi, K., Mintz, M., & Brown, D. (2015). H2A Delivery Scenario Analysis Model Version 3.0*(Hdsam 3.0) User's Manual. *Prepared for US Department of Energy Fuel Cell Technology Office*.
[2] Papadias, D. D., & Ahluwalia, R. K. (2021). Bulk storage of hydrogen. *International Journal of Hydrogen Energy*, *46*(70), 34527-34541.
[3] Brown, D., Reddi, K., & Elgowainy, A. (2022). The development of natural gas and hydrogen pipeline capital cost estimating equations. *International Journal of Hydrogen Energy*, *47*(79), 33813-33826.

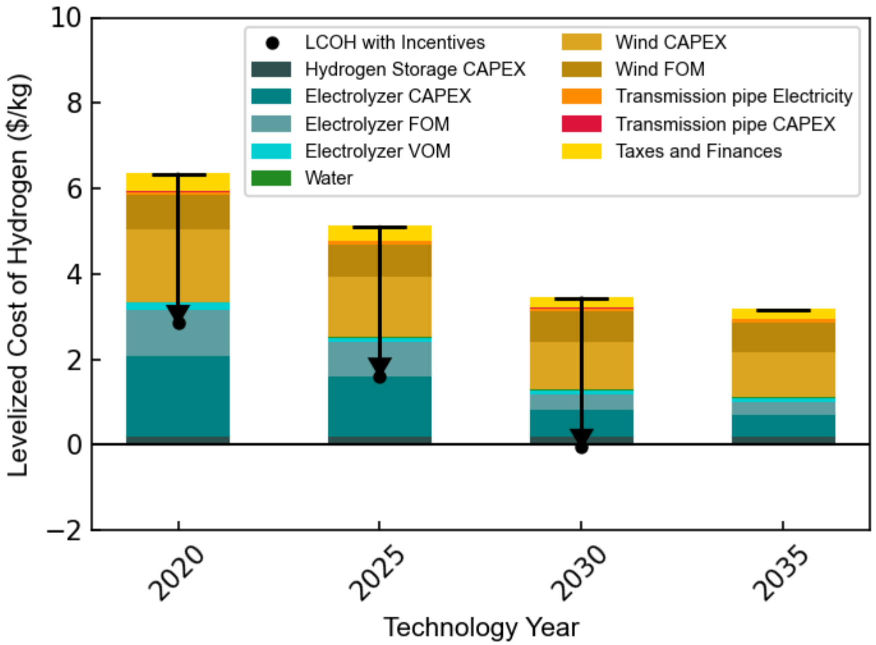
Accomplishments and Progress (Backup): Location-specific hydrogen costs are used in Alliance Pipeline case study



H_2 production, storage, and transport cost framework

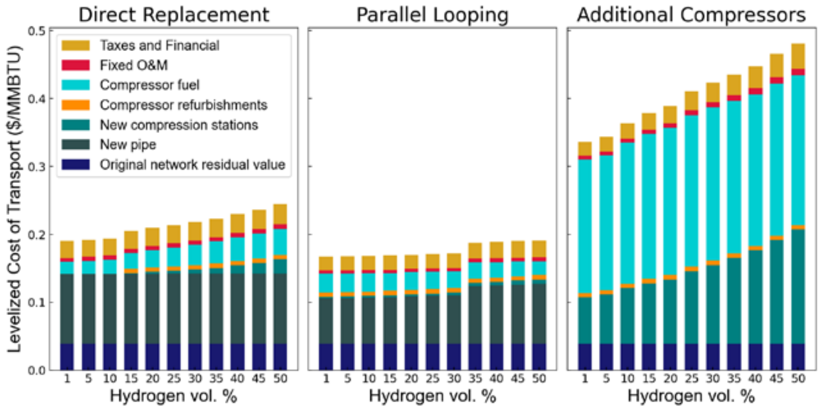
H_2 cost ($/kg) at pipeline injection point in PPCT case study

Cost Scenario	Blend Target (vol. % H_2 in Pipeline Gas)					
	1%	5%	10%	15%	20%	25%
2030, No IRA Incentives	3.58	3.45	3.44	3.44	3.44	3.44
2030, IRA Incentives	0.05	-0.05	-0.05	-0.05	-0.06	-0.06

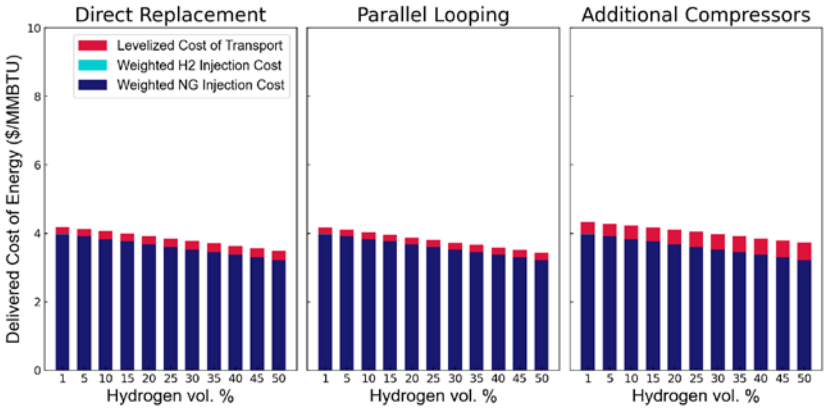


Levelized Cost of Hydrogen (LCOH) breakdown over time (with and without IRA incentives) for the 20% vol. H_2 in pipeline gas blending scenario

Accomplishments and Progress (Backup): Levelized cost of transport (LCOT) is estimated for blends up to 50% vol. H_2 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. 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

- 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

- LCOT and H_2 injection cost are a small portion of delivered cost of energy
- Delivered energy cost decreases with increasing H_2 blending (at -$0.06 to $0.05 per kg H_2 projected for 2030 w/ incentives) displacing natural gas