HyBlend: Pipeline CRADA Cost and Emissions Analysis

PIs: Mark Chung (NREL) and Amgad Elgowainy (ANL)
Presenters: Kevin Topolski (NREL) and Amgad Elgowainy (ANL)
National Renewable Energy Laboratory (NREL)
Argonne National Laboratory (ANL)

WBS 8.6.2.1
May 7th, 2024
Project ID: IN034

DOE Hydrogen Program
2024 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

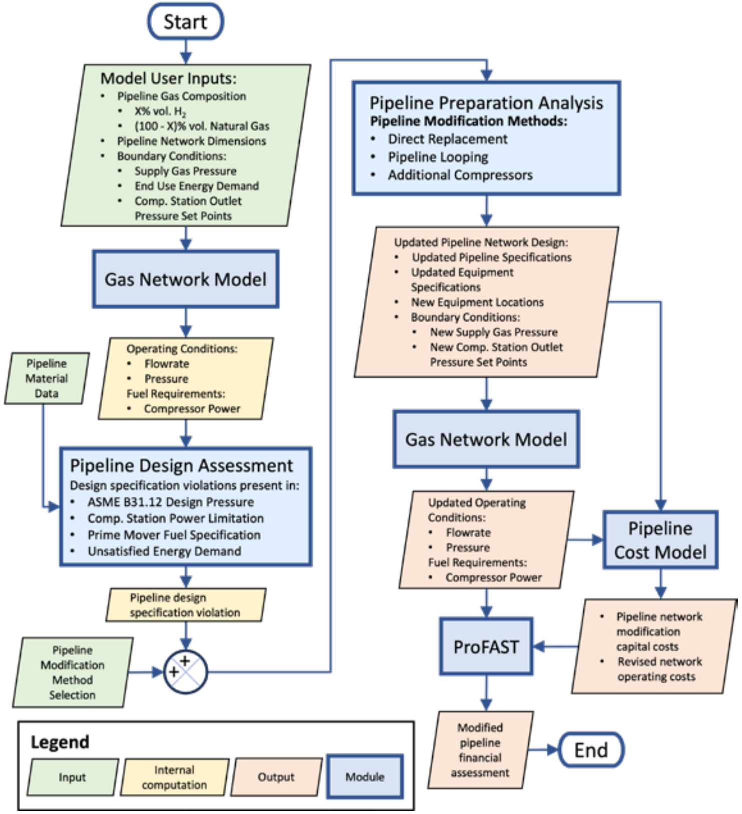
Timeline and Budget	Barriers
Start: October 2021 End: September 2024* Overall CRADA project budget: $15 MM (Analysis project budget: $3.4MM) • DOE Share: $11 MM • Cost Share: $4 MM NREL's total project budget: $1.8 MM • DOE funds spent**: $0.6 MM • Industry cost share funds spent**: $1.0 MM ANL's total project budget: $1.6 MM • DOE funds spent**: $1.5MM * 1-yr no-cost time extension executed **as of ~March 1st, 2024	• 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 Energy, Hawaii Gas, Hydril, National Grid, NJNG, ONEGAS, Operation Technology Development NFP, PRCI, SMUD, Southern Company, Stony Brook University, SWRI and Utilization Technology Development NFP

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

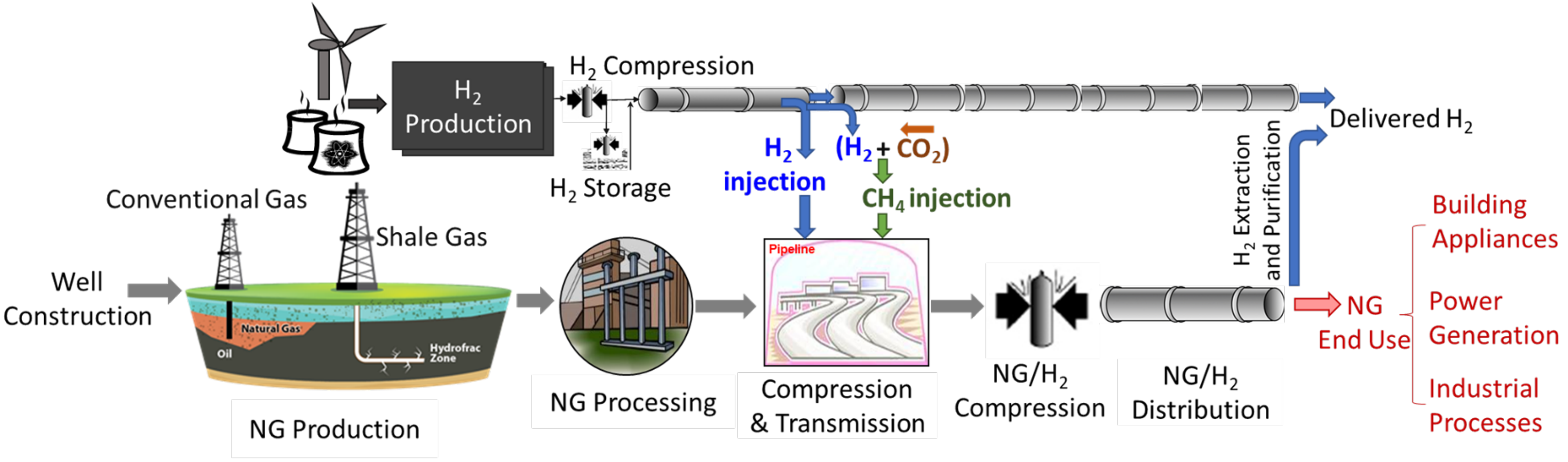
Approach (1/3): NREL developed the Blending Pipeline Analysis Tool for Hydrogen (BlendPATH) that provides case-by-case analysis capabilities

- BlendPATH is a Python tool that allows users to answer the following for blending hydrogen to *X%* in pipeline gas while meeting energy demand:
  - What modifications to a natural gas transmission pipeline network are required?
  - What are the incremental capital investment and operating expense associated with network modifications?
- This tool 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



Blending Pipeline Analysis Tool for Hydrogen framework.

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
- Evaluate cost and life cycle GHG emissions of alternative synthetic natural gas production

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

Due Date	Lab	Description	Status
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	In progress
June 2023	ANL	Life cycle assessment of various NG/H2 blending pathways	Complete
June 2023	NREL	Technical summary on the valuation of hydrogen blending to early-adoption end users	Complete
September 2023	ANL	Final technical report draft for DOE and public webinar	Complete
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	Complete

Accomplishments and Progress (1/11): BlendPATH enables three user-specified ASME B31.12 design options to assess and update design pressures of pipeline segments planned for transporting blends

- The industry standard for hydrogen piping and pipelines, ASME B31.12, limits pipeline segment design pressures such that the segment hoop stress is limited to a fraction of the segment's material specific minimum yield strength (SMYS) equal to a design factor (see Table below)
- Each design option requires varying extents of material characterization for existing pipeline qualification
  - Both design options A and B require destructive testing of sampled pipeline material to qualify pipelines.
  - If the pipeline material cannot be qualified to design options A and B requirements, ASME B31.12 permits limiting hoop stress to 40% (or 0.4 design factor) of pipeline material's SMYS. We refer to this option as "no fracture control"

ASME B31.12 design factor per design option and location class

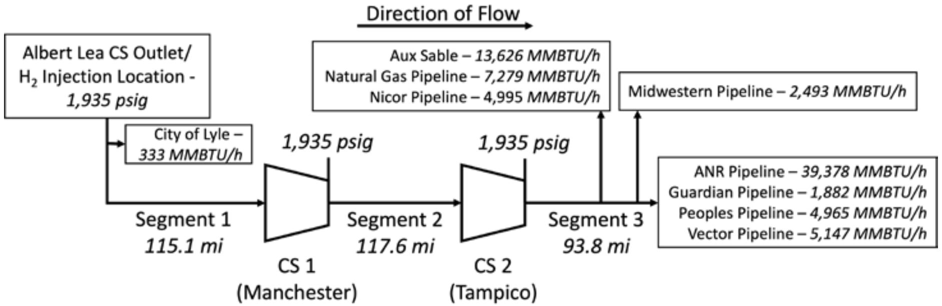
Location Class	ASME B31.12 Design Option		
	No Fracture Control	Option A*	Option B
Location Class 1, Division 2	0.40	0.50	0.72
Location Class 2	0.40	0.50	0.60
Location Class 3	0.40	0.50	0.50
Location Class 4	0.40	0.40	0.40

*Option A also entails a material performance factor in addition the design factor when setting pipeline design pressure

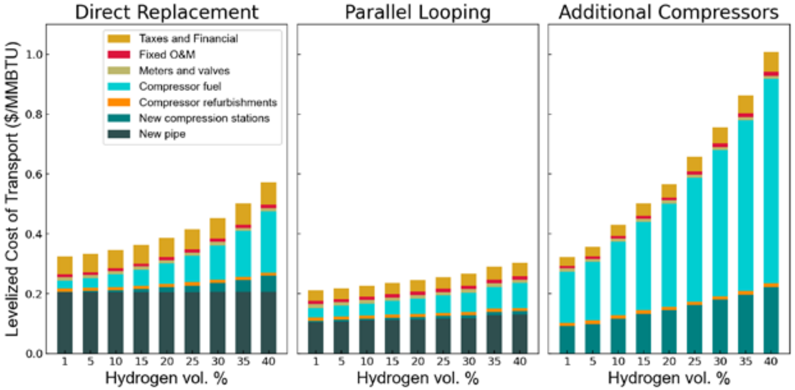
- **BlendPATH identifies which segments' operating pressures exceed (and therefore violate) their updated ASME B31.12 design pressures and earmarks these segments for modification**

Accomplishments and Progress (2/11): Alliance Pipeline case study analysis now includes sensitivity on applied ASME B31.12 design option

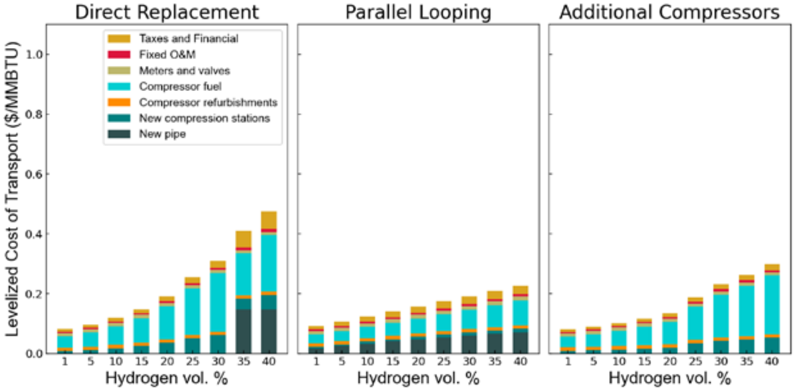
- Alliance Pipeline is a 36” diameter, 99.5% capacity factor pipeline operating with hoop stress of 80% of pipeline material specific minimum yield strength
- **”No Fracture Control” design option application establishes baseline modified network design and economics that pipeline operators could achieve**
- **Design option B can enable reduced network modification and transport cost+; this option requires fracture control qualification on existing pipeline**



Segments of Alliance Pipeline and compressor stations represented in case study with end user energy demands



Levelized cost of transport for each pipeline modification method applied with no fracture control from 1% to 40% vol. H_2 in pipeline gas

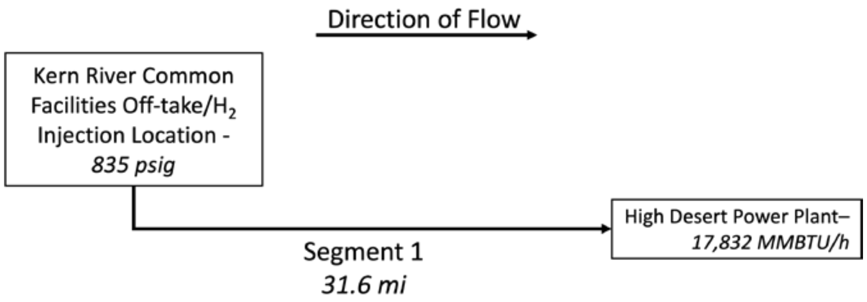


Levelized cost of transport for each pipeline modification method applied with Design Option B+ from 1% to 40% vol. H_2 in pipeline gas

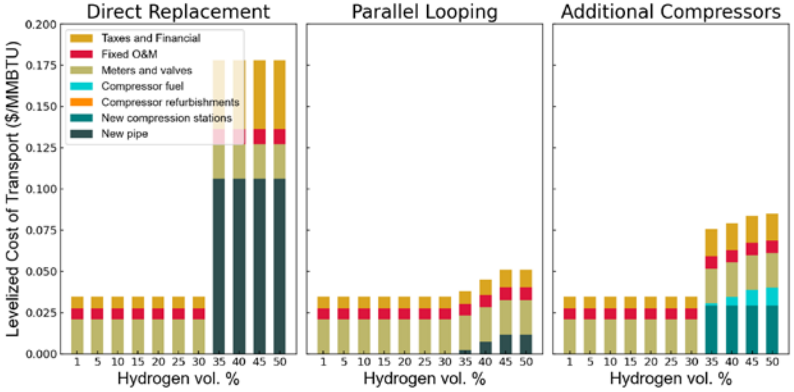
+Results presented here are meant illustrate how ASME B31.12 design options can affect the modified design and economics for a given pipeline network rather than to suggest that the pipeline can or should qualify for design option B

Accomplishments and Progress (3/11): The High Desert Lateral case study provides an alternative perspective for blending into smaller-diameter, lower-capacity factor pipelines

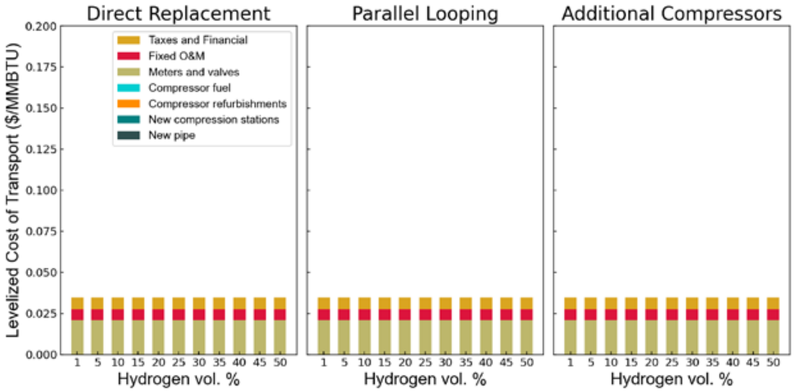
- The High Desert Lateral is 24” diameter, 26% capacity factor pipeline operating with hoop stress of 42% of pipeline material specific minimum yield strength
- Sole offtake is an 830 MW natural gas combined cycle power plant; power plant modification is not in scope
- **The High Desert Lateral may not require significant pipeline modification if Design Option B^{+} is applied or if no fracture control is applied and blending ≤ 30% vol. H_2, given loose pipeline hydraulic constraints**



High Desert Lateral pipeline represented in case study with end user energy demands



Levelized cost of transport for each pipeline modification method applied with no fracture control from 1% to 50% vol. H_2 in pipeline gas

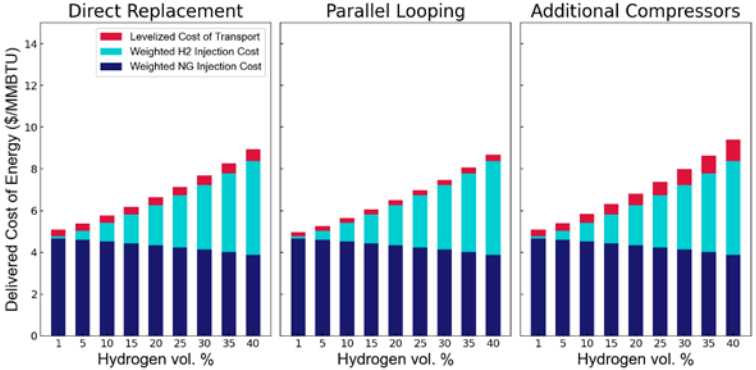


Levelized cost of transport for each pipeline modification method applied with Design Option B^{+} from 1% to 50% vol. H_2 in pipeline gas

$^{+}$Results presented here are meant illustrate how ASME B31.12 design options can affect the modified design and economics for a given pipeline network rather than to suggest that the pipeline can or should qualify for design option B

Accomplishments and Progress (4/11): Alliance pipeline and High Desert Lateral case studies suggests blended gas transport costs to be small relative to gas production costs

Alliance Pipeline - No Fracture Control

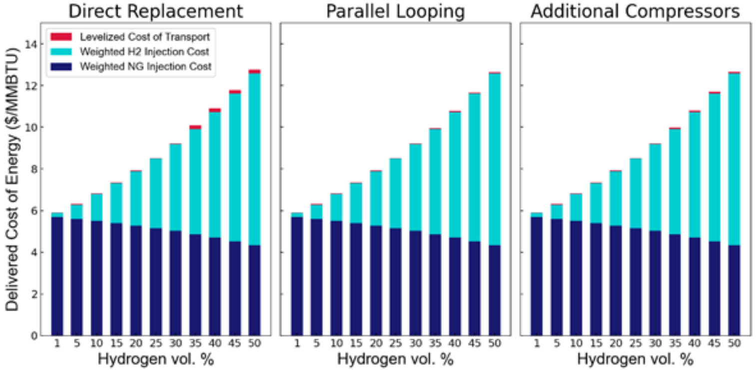


Delivered cost of energy for each pipeline modification method applied to the Alliance pipeline case study with no fracture control from 1% to 40% vol. H_2 in pipeline gas

The Alliance Pipeline case study involves the following assumptions for a 2030 blending scenario:

- Natural gas cost at **$4.69/MMBTU**
- Hydrogen injection costs at **$3.49-$3.76 per kg H_2** assuming local availability for the following:
  - Land-based wind-hydrogen production in Southern Minnesota
  - Lined rock cavern hydrogen storage
  - 77 mi hydrogen pipeline

High Desert Lateral - No Fracture Control



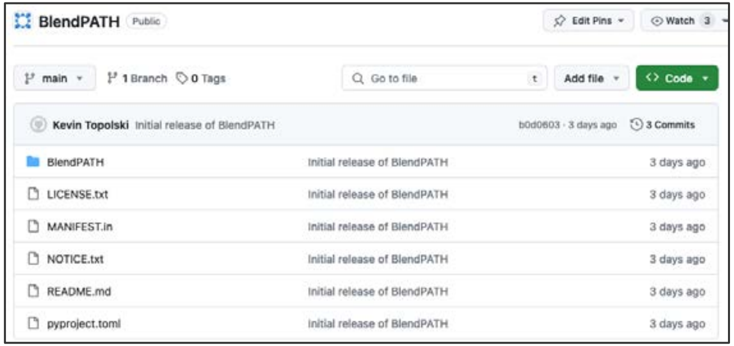
Delivered cost of energy for each pipeline modification method applied to the High Desert Lateral case study with no fracture control from 1% to 50% vol. H_2 in pipeline gas

The High Desert Lateral case study involves the following assumptions for a 2030 blending scenario:

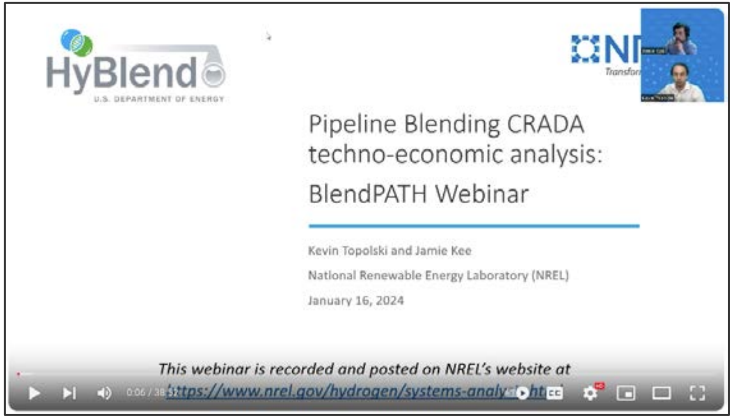
- Natural gas cost at **$5.70/MMBTU**
- Hydrogen injection costs at **$4.62-$8.49 per kg H_2** assuming local availability for the following:
  - Solar PV-hydrogen production in Southern California
  - Salt cavern hydrogen storage
  - 45 mi hydrogen pipeline

Accomplishments and Progress (5/11): BlendPATH is released as an open-source Python package on github.com/NREL

- BlendPATH is now available via this link: https://github.com/NREL/BlendPATH
  - The released version of BlendPATH requires a commercial simulator, SAInt, to run
  - Future releases of BlendPATH will be made available on GitHub
- NREL also hosted a webinar detailing the BlendPATH model and use in a demonstration
- Both webinar recording and presentation are now available via: https://www.nrel.gov/hydrogen/systems-analysis.html



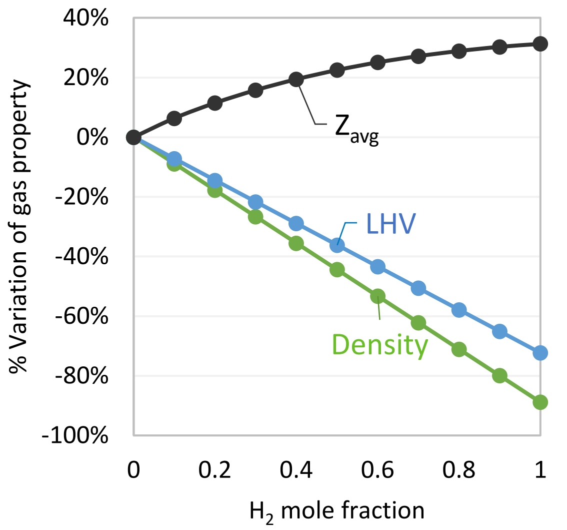
BlendPATH GitHub Repository

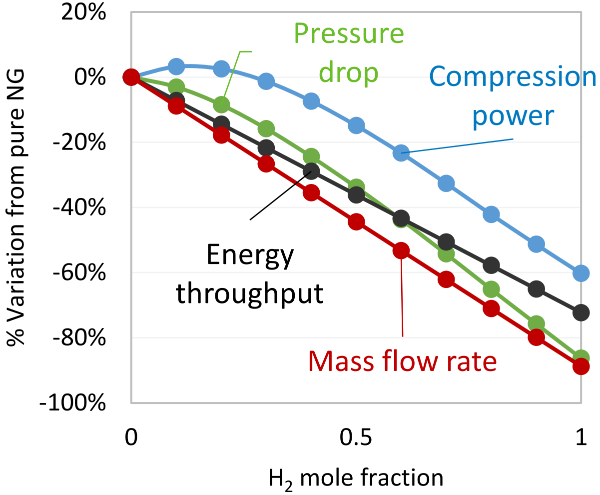


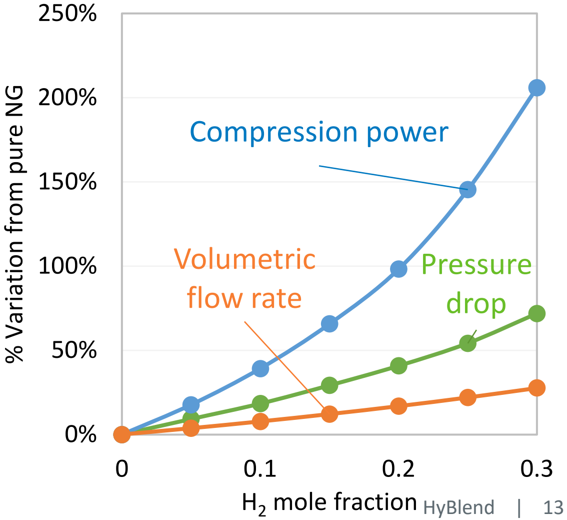
BlendPATH webinar as posted on YouTube

Accomplishments and Progress (6/11): Impact of H_2 blending ratio on gas properties and Alliance pipeline performance — No modification to existing infrastructure

Gas compression energy	***Constant volumetric flow rate***	***Constant energy throughput***
• 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)	• 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 requires an increase of gas flow rate • Compression energy increases, due to increase in Z, density^{-1}, CR while maintaining pipeline MAOP • Max x_{H2} limited by max pipe velocity and compression speed







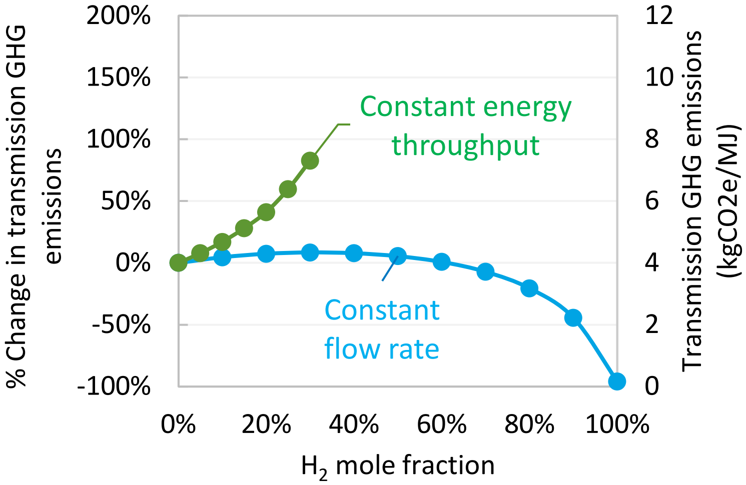
Accomplishments and Progress (7/11): Transmission and life cycle GHG emissions for Alliance pipeline — No modification to existing infrastructure

Transmission emissions (compression + leakage)*

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

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

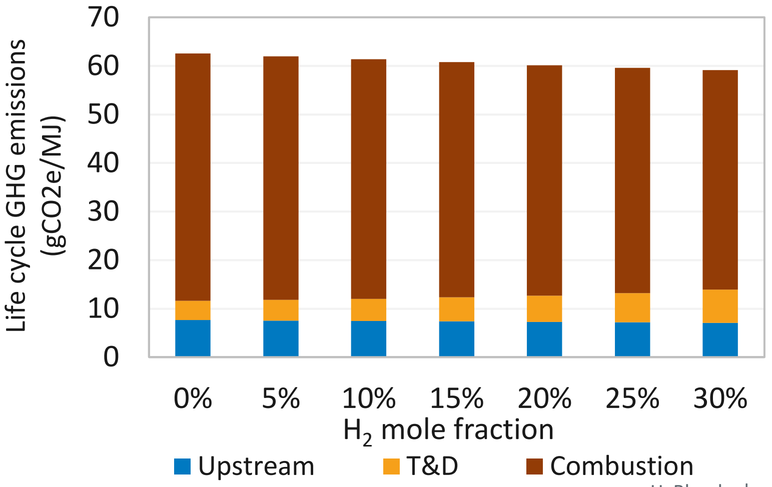
- Leakage rate increases with H_2 blending ratio
- For constant energy throughput, the sharp increase of GHG emissions at gas-driven compression station partially offset the benefit of zero carbon from H_2.



*GWP of H_2 = 0

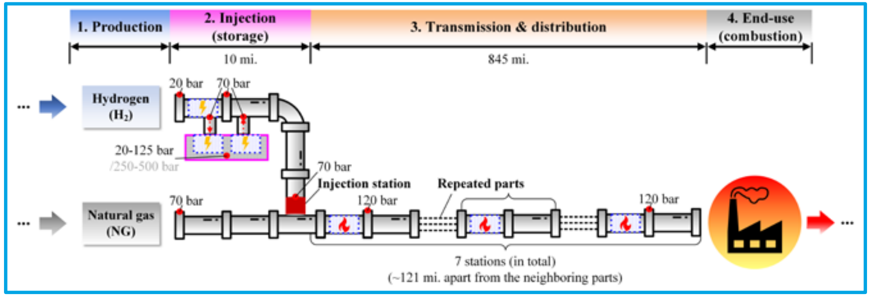
Life cycle GHG emissions (H_2 from LTE with nuclear power)

- 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 when maintaining MAOP with gas-driven compressors, partially offsetting the benefit of zero carbon from H_2.

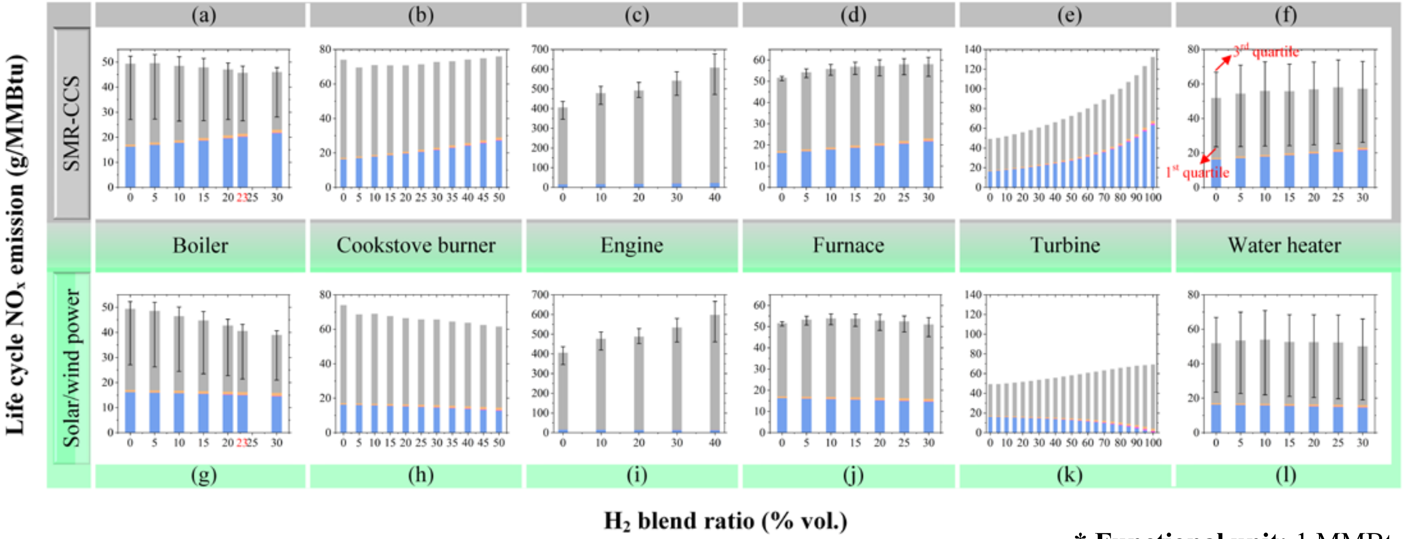


Accomplishments and Progress (8/11):

Life cycle NO_x emissions (various scenarios)

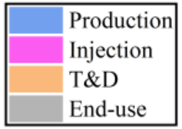


- The impact of H_2 blending on **life cycle** NO_x emissions **varies**
- Emissions may **not** be significantly increased by the H_2 addition
- Majorities of NO_x emissions are from the **production** and **end-use** stages
- **Cleaner** pathways would facilitate the reduction of NO_x emissions



Selected scenarios (for plots):

- **H_2 production:** ☑SMR-CCS, ☑solar/wind power, ☐nuclear power
- **Electricity source:** ☑U.S. grid mix, ☐nuclear
- **Gas delivery:** ☑Constant volumetric flow rate, ☐Constant energy throughput
- **End-use application:** ☑Boiler, ☑cookstove burner, ☑engine, ☑furnace, ☑turbine, ☑water heater



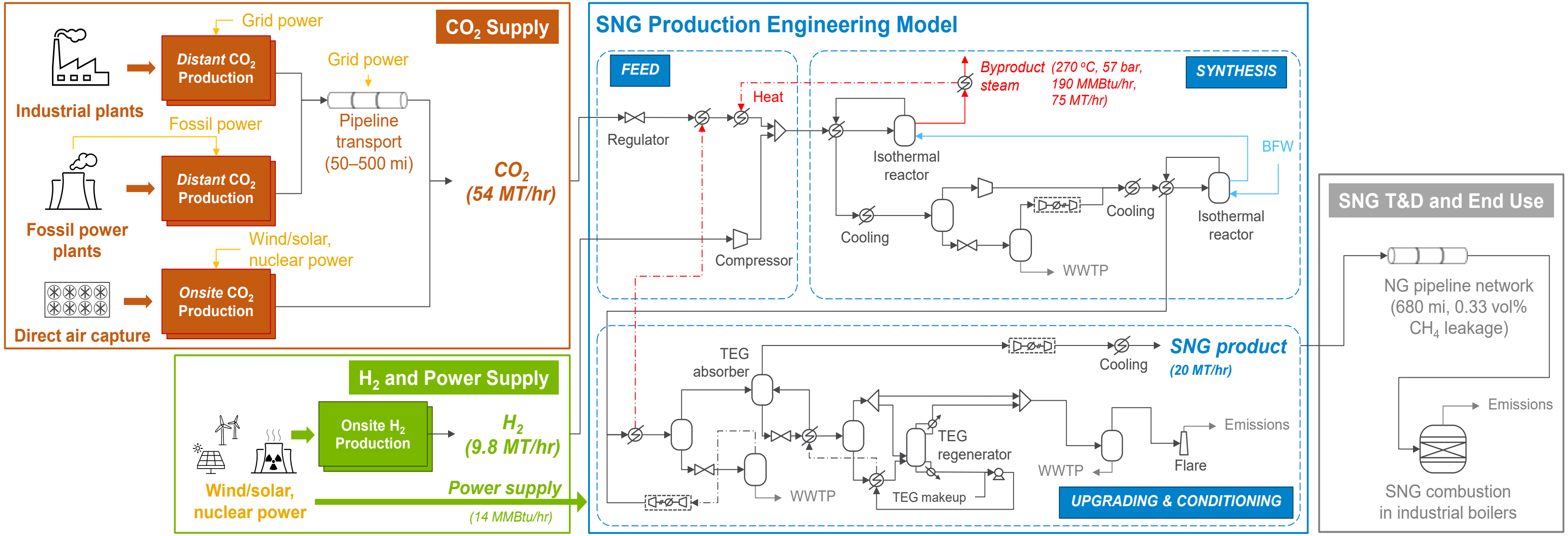
* **Functional unit:** 1 MMBtu energy delivered

Accomplishments and Progress (9/11):
Modeling of alternative SNG production

❑ Alternative pathway can maintain energy delivery without retrofitting infrastructures (pipelines, compression stations, end-use applications)

Process modeling of SNG production

- SNG plant was scaled for a commercial capacity (20 MT/hr), validated in Europe.
- The plant generates 1,020 MMBtu-HHV/hr SNG, 3% of national average NG pipeline throughput, with energy efficiency of 77% (without steam byproduct) and 91% (with steam byproduct)

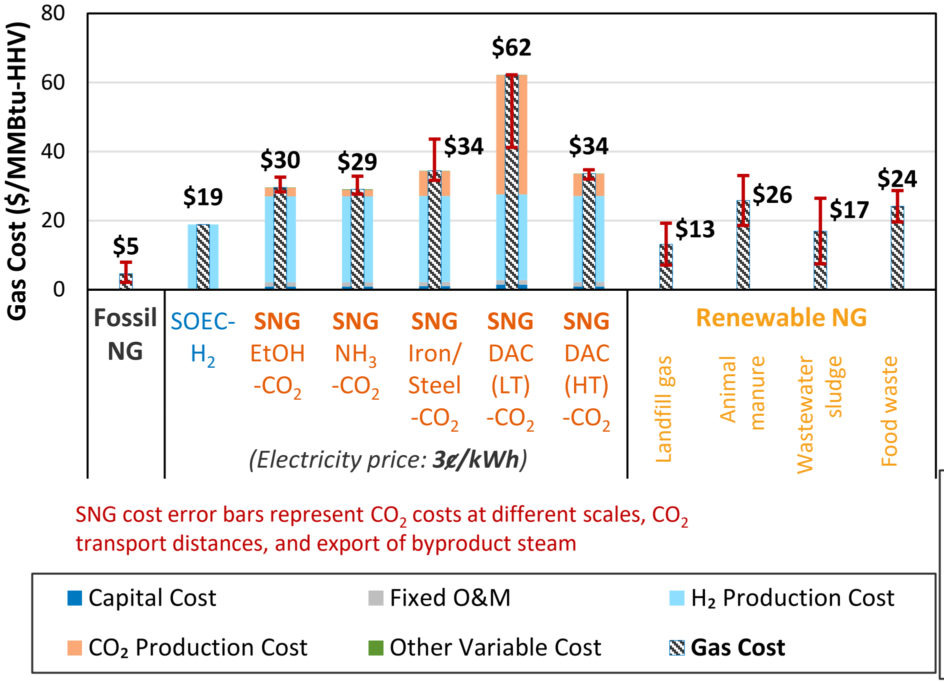


Accomplishments and Progress (10/11): TEA and LCA of alternative SNG production

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

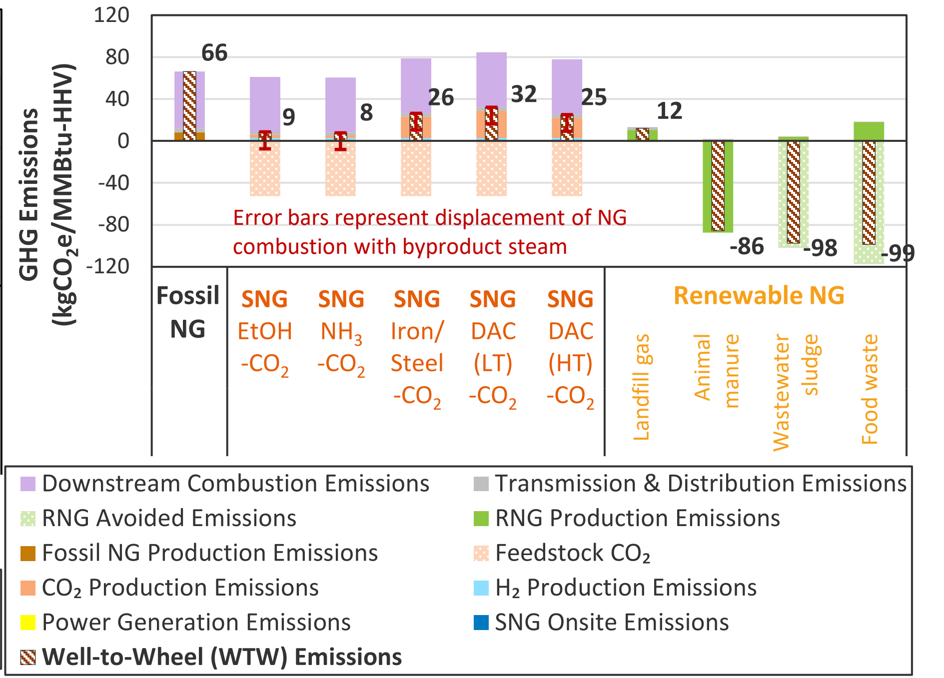
Techno-economic analysis of SNG production

- ***The SNG product cost without tax credits** is higher than **Fossil NG** and **RNG** cost*
- *Tax credits (e.g., 45V) can potentially lower SNG cost*



Life cycle analysis of SNG production

- ***SNG can potentially reduced life cycle GHG emissions by 52-88% compared to Fossil NG***



Accomplishments and Progress (11/11): Response to Previous Year Reviewers' Comments

- *FY23 Reviewer Comment:* The proposed next steps should emphasize model use and validation using existing projects and/or planned projects by industrial partners.
  - **Agreed. We have prioritized analysis on sections of the U.S. natural gas transmission pipeline system that either have planned blending projects or are in areas with geographic and market conditions where hydrogen blending may be favorable. Opportunities for model validation against existing projects are limited as current transmission pipeline hydrogen blending projects in the contiguous U.S. remain in planning stages. Model validation is a focus in our future work as these projects are commissioning.**
- *FY23 Reviewer Comment:* It is not clear how the synthetic natural gas (SNG) evaluation fits into the project, as it does not appear to be included in the originally stated goals, nor is it clear how it factors into the blending cost modeling
  - **Synthetic natural gas (SNG) is investigated as an alternative low-carbon energy transportation pathway for an economic and emissions impacts comparison with hydrogen blending. For sections within the U.S. natural gas transmission pipeline system where is challenging to blending, SNG production and injection could serve as an alternative. It also relaxes the constraints by various end use applications on hydrogen offtake amount in the blending scenario.**
- *FY23 Reviewer Comment:* This project is strongly advised to embrace the changes seen/expected in the power mix associated with the grid power. Presumably in the not-too-distant future, part to all of this grid will be zero-emission. Inclusion of this change in power mix will directly affect the compressor performance with respect to GHG emissions.
  - **Agreed. Grid power generation is going through rapid decarbonization, which will impact various supply chain activities, especially hydrogen production via electrolysis and hydrogen compression for storage and delivery. The power generation mix has minor impact on natural gas supply chain which is mainly driven by methane emissions and natural gas use for most activities, including pipeline compression.**

Collaboration and Coordination

- **U.S. DOE National Laboratories**
  - CRADA analysis tasks are coordinated and performed by National Renewable Energy and Argonne National Labs
  - These tasks leverages Sandia and Pacific Northwest National Labs’ materials expertise to inform analysis on natural gas transmission pipeline structural integrity and leakage
- **Industry stakeholders**
  - BlendPATH assessment and modification methods are based industry partner interaction and guidance
  - Analysis methods, assumptions and results are reviewed by industrial partners within CRADA quarterly progress updates
- **Knowledge sharing and information dissemination**
  - 2023 Fuel Cell and Hydrogen Energy Association Seminar
  - PHMSA’s 2023 Pipeline Safety Research & Development Forum
  - Hydrogen and Fuel Cell Technology Office October 2023 H2IQ Hour Webinar

Remaining Challenges and Barriers

Data procurement to develop representative pipeline case studies for demonstrating analysis remains a challenge

- **Techno-economic Analysis:**
  - Most natural gas transmission pipeline infrastructure data are protected and designated as critical energy infrastructure information (CEII)
  - Cost data on equipment modification (e.g., compressor re-wheeling, meter station modification) are not as well documented as that for pipelines and compression stations
- **Life-cycle Assessment:**
  - The availability of test emission data on NG/H_2 production, usage and transportation with various blending ratios is the main challenge. Calculation is used to fill data gap

Proposed Future Work

- **Techno-economic Analysis:**
  - Develop a non-commercial hydraulic pipeline alternative within BlendPATH
  - Extend BlendPATH model capability to assess blending up to pure hydrogen service
  - Expand BlendPATH capabilities to accommodate more complex gas pipeline networks
  - Update BlendPATH to reflect imminent changes to ASME B31.8/12
- **Lifecycle Assessment:**
  - Investigating impact of GWP of hydrogen to life cycle emissions of hydrogen blending
  - Quantify life cycle GHG emissions associated with pipeline upgrade/modifications
  - Inclusion of embodied emissions for blended gas supply chain (pipeline construction, electrolyzer, power generation)
- **If interested in future work, HyBlend is seeking partners for a Phase II effort. Contact HyBlend_CRADA@nrel.gov or visit [HyBlend partner overview] for more details**

Any proposed future work is subject to change based on funding levels

Summary

- HyBlend™ Pipeline Blending CRADA is a multi-lab, stakeholder-driven project
  - Goal of Analysis R&D: provide the community with **tools and analysis to use existing infrastructure for blending hydrogen to achieve cost-efficient decarbonization**
- **Techno-economic analysis:**
  - *BlendPATH:* released as an open-source Python module for public use, future works involve
    - Providing a non-commercial hydraulic simulator to improve accessibility of tool to a larger user base
    - Extending analysis capability for pure hydrogen service
  - *Pipeline Conversion Cost Analysis:* expanded pipeline case study analyses to consider
    - Examples of blending hydrogen into natural gas transmission main and lateral pipelines
    - Applied ASME B32.12 design options (i.e., no fracture control, A and B)
- **Lifecycle Assessment:**
  - 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 tax credits. Stacking various tax credits can potentially reduce the production cost

Join the team!

HyBlend partner overview

<HyBlend_CRADA@nrel.gov>

Thank You

Kevin Topolski <kevin.topolski@nrel.gov>

Amgad Elgowainy <aelgowainy@anl.gov>

NREL/PR-5400-89198

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Hydrogen and Fuel Cell Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

HyBlend

U.S. DEPARTMENT OF ENERGY

Technical Backup and Additional Information

Technology Transfer Activities

- ***Blending Pipeline Analysis Tool for Hydrogen (BlendPATH)*** is an open-source NREL model and is available with the following link: (https://github.com/NREL/BlendPATH)

- ***ProFAST*** is a closed-source pythonic version to ***H2FAST*** and is publicly available for use. Access to ***ProFAST*** is provided in the following link: (https://github.com/NREL/ProFAST/)

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.
- Jamie Kee, Evan Reznicek, Kevin Topolski, and Mark Chung. "Blending Pipeline Analysis Tool for Hydrogen (BlendPATH) Documentation and User Manual." National Renewable Energy Laboratory, Golden, CO. NREL/TP-5400-XXXXX. 2024.
- Evan Reznicek, Kevin Topolski, Jamie Kee, Omar Guerra and Mark Chung. "A techno-economic model to assess feasibility and cost of repurposing natural gas transmission pipeline networks to accommodate hydrogen." Manuscript submitted for review. 2024.
- Kyuha Lee, Pingping Sun, Amgad Elgowainy, Kwang Hoon Baek, and Pallavi Bobba, "Techno-economic and life cycle analysis of synthetic natural gas production from low-carbon H_2 and point-source or atmospheric CO_2." Journal of CO2 Utilization, 2024. (under review)
- Vincenzo Cappello, Pingping Sun, Amgad Elgowainy. "Blending low-carbon hydrogen with natural gas: impact on energy and life cycle emissions in natural gas pipelines". Manuscript submitted for review. 2024.

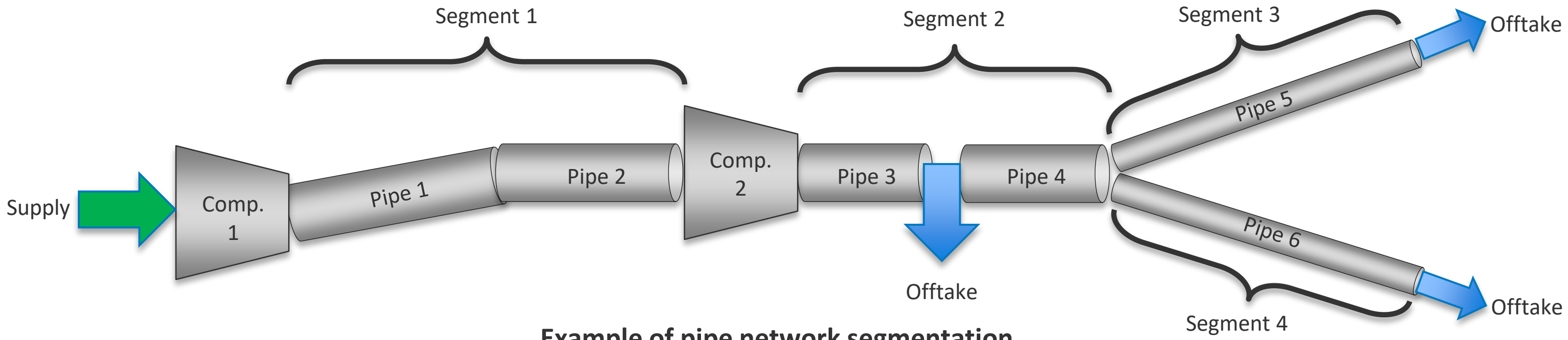
Presentations

- 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 Blending 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.
- Mark Chung, Amgad Elgowainy, Kevin Topolski, and Pingping Sun. "HyBlend: Pipeline Blending CRADA Cost and Emissions Analysis." U.S. Department of Energy Hydrogen Program Annual Merit Review and Peer Evaluation Meeting. June 6th, 2023.
- Todd Deutsch, Chris San Marchi, Kevin Simmons, Kevin Topolski, and Amgad Elgowainy. "Pipeline Blending CRADA – A HyBlend™ Project Overview." Hydrogen and Fuel Cell Technology Office H2IQ Hour Webinar. October 26th, 2023.
- Kevin Topolski, and Jamie Kee. "Pipeline Blending CRADA Technoeconomic Analysis: BlendPATH Webinar." National Renewable Energy Laboratory Webinar. January 16th, 2024.

Approach (Backup): The BlendPATH 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.

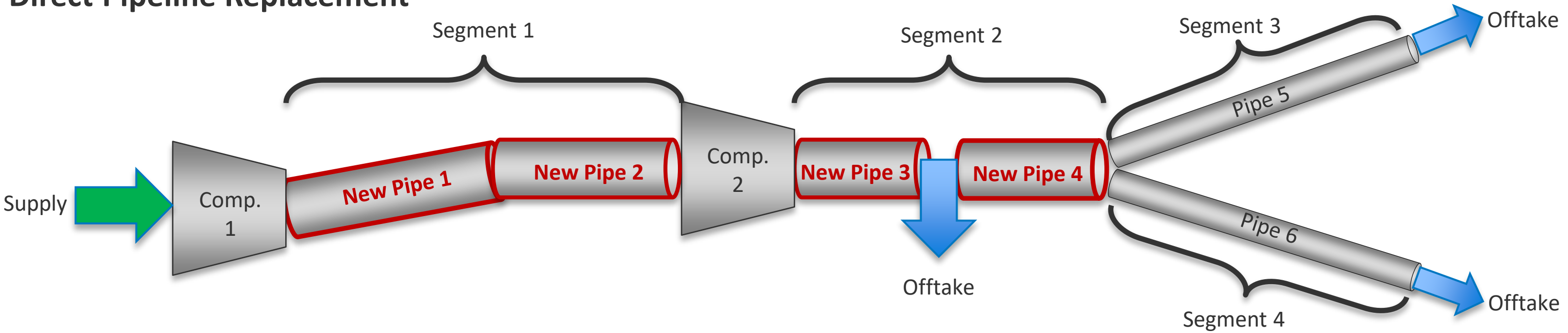
3. Choose an ASME B31.12 design option and calculate maximum allowable operating pressure (MAOP) for existing network for desired hydrogen blend

Approach (Backup): The BlendPATH pipeline modification module offers three 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



Approach (Backup): The BlendPATH pipeline modification module offers three 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

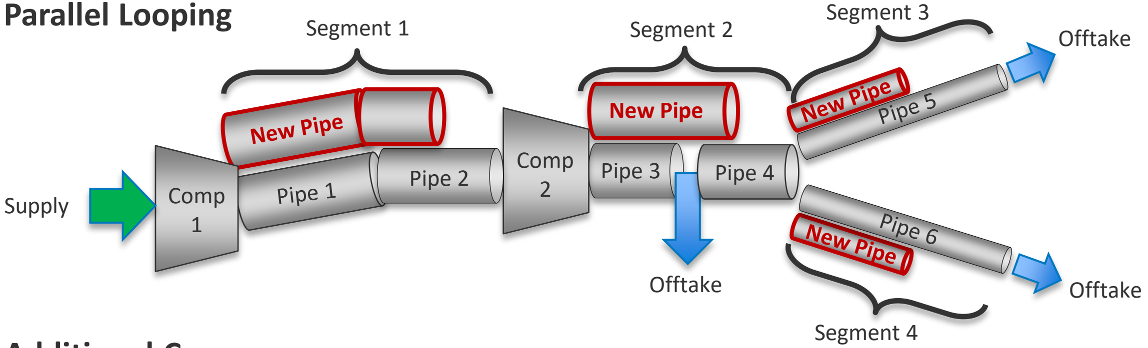
Method 2 – Parallel Looping

- 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

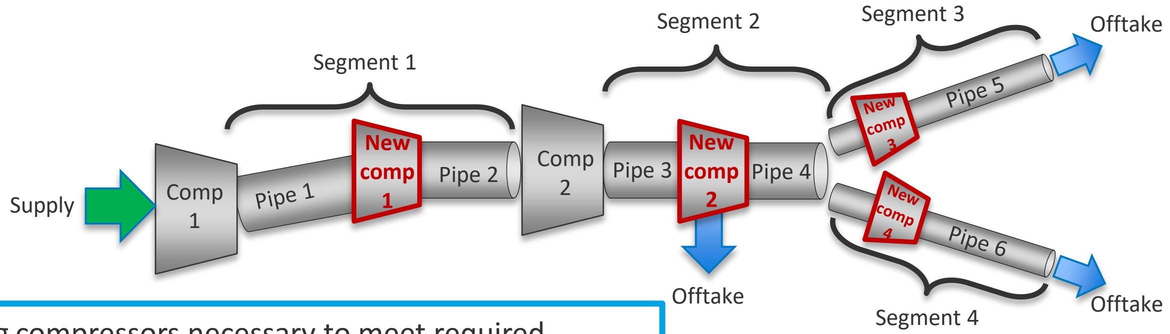
Method 3 – Additional Compressors

- 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