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HyBlend Collaborative Research Partnership

Cooperative Research and Development Final Report

CRADA Number: CRD-21-17525

NREL Technical Contact: Todd Deutsch

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated under Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-7A10-94949
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Suggested Citation
Deutsch, Todd. 2025. *HyBlend Collaborative Research Partnership: Cooperative Research and Development Final Report, CRADA Number CRD-21-17525.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A10-94949. https://www.nrel.gov/docs/fy25osti/94949.pdf.

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Cooperative Research and Development Final Report

Report Date: March 27, 2025

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement:

1. National Technology & Engineering Solutions of Sandia, LLC (a wholly owned subsidiary of Honeywell International, Inc.), as operator of Sandia National Laboratories (SNL)
2. Battelle as operator of Pacific Northwest National Laboratory (PNNL)
3. UChicago Argonne, LLC, as operator of Argonne National Laboratory (ANL)
4. Air Liquide
5. Chevron U.S.A., Inc.
6. DNV GL USA, Inc.
7. Electric Power Research Institute, Inc. (EPRI)
8. Enbridge
9. ExxonMobil Research and Engineering Company
10. Gas Technology Institute
11. Hawaii Gas
12. Hydril Company
13. National Grid USA Service Company, Inc.
14. New Jersey Natural Gas Company
15. ONE Gas, Inc.
16. Operations Technology Development, NFP (OTD)
17. Pipeline Research Council International
18. Sacramento Municipal Utility District
19. Southern Company Services, Inc.
20. Southwest Research Institute
21. Stony Brook University
22. Utilization Technology Development, NFP (UTD)

CRADA Number: CRD-21-17525

CRADA Title: HyBlend Collaborative Research Partnership

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Hydrogen Fuel Cell Technologies Office

Joint Work Statement Funding Table Showing DOE Commitment:

Estimated Costs	NREL Shared Resources, a/k/a Government In-Kind
Years 1–2 Year 3, Modification #1	$10,900.00 $0.00
TOTALS	$10,900.00

Executive Summary of CRADA Work:

This agreement assembles a multi-lab, multi-industry team to address high-priority research topics related to the blending of hydrogen (H_2) into the U.S. natural gas (NG) pipeline network. There are four main research objectives:

1. Compatibility of metals (SNL) – Develop general principles for operation of HyBlend™ delivery systems in the context of structural integrity and assess the role of gas impurities on degradation of metal pipelines.

2. Compatibility of polymers (PNNL) – Assess gas impurities in HyBlend for polymer pipeline degradation and lifetime predictions.

3. Life cycle analysis (LCA) (ANL) – Analyze the life cycle of technology pathways for hydrogen and NG blends, as well as alternative pathways.

4. Techno-economic analysis (TEA) (NREL) – Quantify the costs and opportunities for hydrogen production and blending with the NG network, as well as alternative pathways.

CRADA Benefit to DOE, Participant, and U.S. Taxpayer:

This agreement leverages the core competencies at four national laboratories to enhance U.S. competitiveness by utilizing DOE capabilities to advance low-carbon energy solutions.

Summary of Research Results:

Purpose

The variety of research objectives is indicative of near-term technical barriers that need to be addressed and identified by industry partners as high priority. Blending hydrogen into NG infrastructure (HyBlend) has national and regional benefits by using clean hydrogen for energy storage, resiliency, and emissions reduction.

Reasons for Cooperation

There are multiple partners from industry, academia, and state entities across the U.S. on this project. Each partner has unique reasons for joining this collaborative project, and the initiative is primarily focused on high-level, industrywide solutions to hydrogen blending.

Scope of Work:

Technical Objective

The laboratory team identified top research priorities with a research and design ranking exercise. They aggregated industry responses from the ranking exercise with the following summary:

- The top four research areas were related to pipeline materials compatibility and degradation.
- The next two research areas consisted of TEA and the environmental impact of blending versus alternative pathways like producing synthetic methane (CH_4).

This project addressed the top six identified priorities through experimental testing of pipeline materials and analysis focused on the techno-economics and LCA of blending hydrogen into NG infrastructure.

The research outcomes from this CRADA have been documented in several public reports, presentations, conference papers, and journal publications. References to these documents from all four participating national laboratories are provided after each task description below, with a summary of the principal outcomes from each of the four research tasks: (1) compatibility of metals, (2) compatibility of polymers, (3) LCA, and (4) TEA. Additional details, methods, assumptions, and outcomes can be found in the listed project-supported documents.

TASK DESCRIPTIONS

TASK 1: Pipeline Compatibility of Metals

Subtask 1.1: Structural Integrity and Risk Assessment of Hydrogen Pipelines – Description

Structural integrity assessment of gas delivery systems requires a detailed description of the systems and operating envelope for all elements of a given system. SNL will develop general principles for the operation of blended H_2/NG delivery systems (transmission and distribution) in the context of structural integrity. SNL will identify operational conditions for these systems (e.g., pressure ranges, gas composition, defect populations) and implement these characteristics along with fracture-mechanics-based models of hydrogen embrittlement into the existing probabilistic fracture mechanics (PFM) modular framework developed by SNL for the Nuclear Regulatory Commission. SNL will consider the role of gaseous inhibitors to hydrogen embrittlement (e.g., oxygen) in the model formulations. This probabilistic tool is designed to enable a sensitivity analysis to assess the structural integrity risk of blended H_2/NG delivery systems and thereby inform inspection and repair schedules of H_2/NG infrastructure and provide adequate assurance of system safety. This subtask draws from and feeds into Task 2 on evaluation of materials properties.

Degradation of Structural Properties – Technology Advance/Outcomes

Industry partners will identify the structural and operational characteristics of H_2/NG systems with sufficient detail for structural assessment. The outcome of this work will be a risk assessment tool to evaluate pipelines and piping systems for use with H_2/NG-blended fuel streams and identify the variables that most strongly contribute to system risk.

Structural Integrity and Risk Assessment of Hydrogen Pipelines – Subtasks Performed by SNL

1. *Assessment of literature data, gaps, and industrial relevance:* Assess available data necessary to develop a modeling framework and identify gaps in data to inform experimental activities. Survey industry, codes, and standards for relevant materials—as well as materials of concern—structural/design requirements, and operational conditions.
2. *PFM framework for hydrogen embrittlement:* A PFM modular framework will be developed to assess the structural integrity of NG infrastructure for the transmission and distribution of H_2/NG blends. Hydrogen embrittlement models will be implemented in an existing framework previously developed for the Nuclear Regulatory Commission. The goal is a publicly available resource for structural integrity and risk assessment of hydrogen systems.
3. *Performance and sensitivity analysis of variables that contribute to the risk of transmission and distribution of* H_2*/NG blends:* PFM tool will be used in this subtask to characterize variability in crack growth rate and fracture toughness of representative materials of construction in NG infrastructure. The PFM framework will also be to rank material parameters and mechanisms dominating the fracture process in transmission and distribution infrastructure for H_2/NG blends.

Subtask 1.2: Degradation of Structural Properties – Description

The basic structural properties of pipeline steels in gaseous H_2 are well documented in the literature, especially at high pressure (>100 bar). Additionally, the fatigue and fracture of carbon steels is known to be strongly affected by low concentrations of gaseous H_2 (approximately 1 bar). The dependence of fatigue and fracture properties on the partial pressure of H_2 in the low-pressure regime (<10 bar), however, is not well described in the literature. The uncertainties in the low-pressure regime are complicated by the competing effects of impurities (e.g., oxygen from air), which can be present in laboratory testing and tend to mitigate the effects of H_2. The mitigation effect of impurities, however, is dependent on the conditions of the H_2 exposure (e.g., loading rate). Even impurities at the level of parts per million can influence fatigue and fracture measurements in H_2 and may be intrinsically present in NG. An understanding of the relationship between H_2 partial pressure and the concentration of other surface-active species aids prediction of materials performance in long-term service with significant H_2 concentration (although this can be extremely challenging to quantitatively assess). SNL will critically assess the role of gas impurities in blended H_2/NG mixtures in controlled laboratory environments, including the development of a pressure loop to induce failures in pipe with engineered defects through pressure cycling (i.e., fatigue). SNL will complement evaluation of pipe specimens with testing of standardized fatigue and fracture mechanics test coupons in gaseous H_2 to determine properties typically used in design and required by The American Society of Mechanical Engineers (ASME) B31.12 (Code for Hydrogen Piping and Pipelines). In particular, testing of materials coupons will enable controlled laboratory assessment of materials performance, where environmental, materials, and mechanical variables can be assessed individually with high rigor. Additionally, fundamental characterization of damage accumulation and micro mechanisms of hydrogen-assisted fracture will improve the fidelity of physics-based models and facilitate extrapolation of materials coupon tests to real-world conditions.

Degradation of Structural Properties – Technology Advance/Outcomes

Inducing failure in representative pipe (up to 50-mm in diameter) enables the comparison of fracture mechanics tests in static-pressure environments with a comparatively dynamic gas environment, which is more characteristic of service conditions in the pipe geometry. SNL will instrument pipe specimens to evaluate the growth of cracks from the engineered defects and compare them to standardized materials test data. In particular, SNL will use the pressure loop to provide a platform to interrogate gas impurity effects, as well as fracture-based design strategies based on the materials coupon testing. A fundamental description of H_2 effects on fatigue and fracture can also reduce uncertainty and design margins, thus reducing the cost of infrastructure and aiding management of structural risk.

Degradation of Structural Properties – Subtasks Performed by SNL

1. *Failure assessment of pipe specimens with engineered defects in* H_2 *and* H_2 *mixtures:* Evaluate the failure response of the pipe in representative conditions and assess the conservatism of design strategies based on materials coupon testing.
2. *Evaluation of critical parameters contributing to hydrogen-assisted fatigue and fracture of metals used in NG infrastructure:* Evaluate the sensitivity of hydrogen-assisted fatigue and fracture of materials from NG infrastructure to operational variables such as H_2 partial pressure, temperature, and gas composition. SNL will focus on materials of concern as identified in Task 1 (e.g., vintage seam welds and low-fracture-toughness grades in existing infrastructure).
3. *Development of physics-based models of hydrogen embrittlement processes in structural metals:* Enumerate degradation mechanisms through advanced characterization techniques (e.g., high-resolution microscopy) to inform structural risk assessment. SNL will include detailed microstructural characterization of materials and representative damage mechanisms.

Task 1: Compatibility of Metals Outcomes

The PFM framework (Subtask 1.1) in this project is known as Hydrogen Extremely Low Probability of Rupture (HELPR), an open-source software code with a graphical user interface to evaluate structural integrity (available for download at helpr.sandia.gov). HELPR uses fracture mechanics and reduced-order models of longitudinal cracks in cylindrical geometries to evaluate fatigue crack growth and failure assessment diagrams. The framework allows calculation of tens to thousands of scenarios based on user inputs for uncertainty to establish probabilistic assessments of fatigue and fracture. The user inputs include the geometry of the pipe and defects, pipe material properties, and the operating conditions of the pipeline. Currently, HELPR includes only longitudinal (elliptical) internal crack-like defects subject to pressure loading. The fatigue life of a pipe is determined by propagating the crack due to pressure cycling (fatigue), assuming the fatigue design curves defined in the ASME Hydrogen Piping and Pipelines Code (B31.12 Code Case 220). In addition to assessing the probability of rupture, HELPR can be used for deterministic calculations of fatigue life, the creation of a basic failure assessment diagram, and sensitivity analysis. An example of sensitivity analysis was documented in a manuscript co-authored with industry and presented at the 2024 ASME Pressure Vessels and Piping Conference.

HELPR was designed with a modular form, such that it can be expanded in the future with additional capability and sophistication. The basic structure of HELPR is described in several presentations noted below, along with tutorials demonstrating its use. Additional releases and documentation are planned for the end of the 2024 calendar year, which include the implementation of stress intensity factor solutions for simple axial cracks and failure assessment diagram formulation from American Petroleum Institute (API) 579-1/ASME FFS-1.

In Subtask 1.2, the materials testing was intended to elucidate basic fatigue and fracture responses and trends for line pipe steels in gaseous hydrogen, using state-of-the-art capabilities and methods developed in the Hydrogen Effects on Materials Laboratory at SNL in Livermore, California. More than a dozen pipe materials were acquired for testing as part of this project, including both vintage steels extracted from service and modern steels, as well as historical data generated from previous testing. The team developed an innovative testing campaign to measure both fatigue crack growth and fracture resistance from the same specimen utilizing K-controlled testing procedures. Moreover, these procedures utilized K-control to optimize a range of testing segments within the test, thus allowing mechanics variables (e.g., stress ratio and frequency) to be varied between the segments in a single test specimen. In this manner, a single test specimen can be used to access multiple stress ratios (R), rather than the conventionally used methods that require a single specimen for each testing condition. In addition, by controlling the conditions at the end of the fatigue test, a fracture test could be conducted without removing the specimen from the H_2 environment (essentially, the fatigue test becomes the pre-cracking step for the fracture test). These methods are described in more detail in San Marchi et al., PVP2022-84757.

Objectives and outcomes of Subtask 1.2 include:

- Assess pressure dependence of fatigue and fracture; Agnani et al., PVP2024-123477.
    - Hydrogen-assisted fatigue crack growth consists of two regimes: a pressure-dependent regime proportional to the square root of the fugacity/pressure and a regime at higher fatigue driving force (higher ΔK) that is pressure independent between 1 and 200 bar.
    - At low pressure and low fatigue driving force (ΔK), fatigue crack growth rates converge with measurements in moist air. Thus, under some conditions, fatigue in gaseous H_2 is the same as in moist air (likely a result of moisture in the hydrogen).
    - Hydrogen-assisted fracture is weakly dependent on pressure: testing scatter can be as large as the average difference between pressure of 1 and 200 bar.
- Characterize microstructural influences on fatigue and fracture; Ronevich et al., IJHE (2024); Agnani et al., 3rd Intern. Symp. Recent Developments in Plate Steels; Agnani et al., AMPP 2024; Agnani et al., PVP2023-105622.
    - Hydrogen-assisted fatigue crack growth is nominally independent of microstructure and essentially the same for common grades of line pipe steel, as well as experimental high-strength grades (API 5L X42–X120)
    - Resistance to hydrogen-assisted fracture depends on the strength of the steel: Higher-strength steels/microstructures are generally more sensitive to H_2.
    - Vintage steels (1970s and older) show modest reduction of fracture resistance in gaseous hydrogen compared to air; modern steels show a large reduction of fracture resistance in gaseous hydrogen compared to air but greater resistance to hydrogen-assisted fracture than vintage steels.
- Evaluate hydrogen-assisted fatigue and fracture of welds and heat-affected zones in line pipe steels.

    - Welding does not appear to affect the fatigue crack growth of line pipe steels, consistent with a lack of microstructural sensitivity; this conclusion is based on materials testing assuming no structural (>1-mm) defects and no residual stresses.
    - Fracture behavior of welds and heat-affected zones is nominally similar to base metal of the same strength; this conclusion is based on limited data confounded by the challenge of positioning cracks reliably in the heat-affected zones.
    - Large defects are commonly associated with welding, and these defects will compromise structural integrity, but our materials testing did not sample structural (>1-mm) defects.
    - More testing is needed to verify these trends and the role of hardness on reduced fracture resistance of welds and heat-affected zones.
- Implement models of embrittlement into the PFM framework.
    - Fatigue design curves were developed to capture the effects of H2 partial pressure and stress ratio in line pipe steels; these curves provide a nominal upper bound on fatigue for all conditions tested in this project.
    - With the aid of other projects, these design curves were approved in Code Case 220 for ASME B31.12; San Marchi et al., PVP2024-122529.
    - Implementation of the fatigue design curves in HELPR enabled prediction of the fatigue life of subscale pipe; San Marchi et al., IPC2024-134173.
- Demonstrate the subscale H_2 test system and compare hydrogen-induced failure of geometrically equivalent internal and external engineered flaws; San Marchi et al., IPC2024-134173.
    - Test system for pressure cycling National/Nominal Pipe Size (NPS) 2 Schedule 40 pipe was developed and demonstrated at pressures greater than 300 bar; high pressure is used to achieve stresses comparable to large-diameter pipe.
    - Engineered defects on the outside of the pipe induce hydrogen-assisted failure, even though the defect is not directly exposed to H_2; therefore, native oxides and surface scale do not prevent H_2 uptake and hydrogen-assisted fracture.
    - Fracture mechanics predictions of fatigue life are conservative for the tested internal crack-like defect, which is likely due to the cycles required to nucleate a growing crack (predictions assume cracks grow from the first cycle).

A comprehensive overview of test results from the materials testing activities is being prepared for public release. The fatigue and fracture results are complemented by extensive metallography performed by EPRI as cost-share for this project.

Software:

1. Benjamin B. Schroeder, Cianan Sims, Benjamin R. Liu, Michael C. Devin, and Bailey Lucero. 2024. "HELPR (Hydrogen Extremely Low Probability of Rupture), Version 1.1.0." Sandia National Laboratories, April 16, 2024. Initial release (v1.0.0) November 2023. Software available at helpr.sandia.gov; open-source code publicly available at github.com/sandialabs/helpr.

Archival papers:

2. C. San Marchi, J.A. Ronevich, B. Schroeder, and B.C. Davis. 2024. "Hydrogen pressure cycling of subscale pipes to simulate full-scale testing of transmission pipelines." Accepted to ASME 2024 International Pipeline Conference, 23–27 Sept. 2024, Calgary AB, Canada.
3. M. Agnani, et al. 2024. "Comparison between behavior of pipeline steels in pure and blended hydrogen with equivalent fugacity." Paper no. PVP2024-123477, ASME Pressure Vessels and Piping Conference, 28 July–2 Aug. 2024, Bellevue, WA.
4. C. San Marchi, et al. 2024. "Technical basis for fatigue crack growth rules in gaseous hydrogen for ASME B31.12 Code Case 220 and for revision of ASME VIII-3 Code Case 2938-1." Paper no. PVP2024-122529, ASME Pressure Vessels and Piping Conference, 28 July–2 Aug. 2024, Bellevue, WA. [*funded by HFTO Safety, Codes and Standards program, but important reference*]
5. B. Schroeder, et al. 2024. "Utilizing probabilistic analyses to explore performance margins of natural gas infrastructure for the transport and delivery of hydrogen and hydrogen blends." Paper no. PVP2024-125226, ASME Pressure Vessels and Piping Conference, 28 July–2 Aug. 2024, Bellevue, WA.
6. M. Agnani, J. Ronevich, and C. San Marchi. 2024. "Comparison of fatigue and fracture behavior of welded and seamless pipe steel in gaseous hydrogen." Presented to the 3rd International Symposium on the Recent Developments in Plate Steels, 2–5 June 2024, Vail, CO.
7. M. Agnani, J. Ronevich, and C. San Marchi. 2024. "Fatigue and fracture resistance of different line pipe grade steels in gaseous H_2 environment." Presented at the AMPP Annual Conference, 2–7 March 2024, New Orleans, LA.
8. J. Ronevich, M. Agnani, and C. San Marchi. 2024. "Consistency of fatigue crack growth behavior of pipeline and low-alloy pressure vessel steels in gaseous hydrogen." *International Journal of Hydrogen Energy*. doi.org/10.1016/j.ijhydene.2024.06.287.
9. F.D. León-Cázares, M. Agnani, J. Ronevich, and C. San Marchi. 2024. "Effects of hydrogen partial pressure on crack initiation and growth rate in vintage X52 steel." *International Journal of Hydrogen Energy*. doi.org/10.1016/j.ijhydene.2024.02.292.
10. M. Agnani, J.A. Ronevich, J. Parker, M. Gagliano, S. Potts, and C. San Marchi. 2023. "Fatigue and Fracture Behavior of Vintage Pipelines in Gaseous Hydrogen Environment." Paper no. PVP2023-105622, ASME Pressure Vessels and Piping Conference, 16–21 July 2023, Atlanta, GA. doi.org/10.1115/PVP2023-105622. Presentation document: SAND2023-11547C.

11. C. San Marchi and J.A. Ronevich. 2022. “Fatigue and fracture of pipeline steels in high-pressure hydrogen gas.” Paper no. PVP2022-84757, ASME Pressure Vessels and Piping Conference, 17–22 July 2022, Las Vegas, NV. doi.org/10.1115/PVP2022-84757.

Presentations and posters

12. J.A. Ronevich et al. 2024. “Hydrogen Assisted Fracture of Ferritic and Martensitic Steels in Pipelines and Pressure Vessels.” Presentation (SAND2024-7712PE) at the Oxford – EPRI Workshop on Hydrogen Embrittlement, 23–26 June 2024, Oxford, UK.

13. C. San Marchi, J. Ronevich, B. Schroeder, M. Devin, B. Davis, and M. Agnani. 2023. “Hydrogen-assisted fatigue and fracture of line pipe steels.” Overview presentation (SAND2023-14266PE) at the Pipeline Blending CRADA Phase 2 Kick-Off, 6 Dec. 2023, Downey, CA.

14. B. Schroeder. 2023. “HELPR v1.0.0 Demonstration.” Presentation and software demonstration (SAND2023-14270PE) at the Pipeline Blending CRADA Phase 2 Kick-Off, 6 Dec. 2023, Downey, CA.

15. C. San Marchi and K.L. Simmons. 2023. “Hydrogen permeation trends in piping.” Presentation (SAND2023-14265PE) at the Pipeline Blending CRADA Phase 2 Kick-Off, 6 Dec. 2023, Downey, CA.

16. B. Schroeder, R. Dingreville, C. San Marchi, and J. Ronevich. 2023. “Probabilistic Fracture Mechanics Toolkit for Hydrogen Blends in Natural Gas Infrastructure.” Poster SAND2023-08941C (abstract SAND2023-11297A), International Hydrogen Conference, 17–20 Sept. 2023, Park City, UT.

17. M. Agnani, J. Ronevich, and C. San Marchi. 2023. “Microstructural effects on fracture resistance of vintage pipeline steels in gaseous hydrogen.” Poster SAND2023-8655D, International Hydrogen Conference, 17–20 Sept. 2023, Park City, UT.

18. J. Ronevich, M. Agnani, and C. San Marchi. 2023. “Fatigue crack growth behavior of pipeline and pressure vessel steels in gaseous hydrogen.” Invited talk (SAND2023-9388C; abstract SAND2023-863A) at International Hydrogen Conference, 17–20 Sept. 2023, Park City, UT.

19. Fernando D. León-Cázares, Milan Agnani, Joseph Ronevich, and Chris San Marchi. 2023. “Effect of hydrogen partial pressure on crack initiation and growth rate in x52 vintage steel.” Poster, Internal Hydrogen Conference, 17–21 Sept. 2023, Park City, UT.

20. Ben Schroeder, Chris San Marchi, Remi Dingreville, and Joe Ronevich. 2023. “Probabilistic Fracture Mechanics Toolkit for Hydrogen Blends in Natural Gas Infrastructure.” Presentation (SAND2023-3992C) at Emerging Fuels Symposium, 5–8 June 2023, Orlando, FL.

21. Joe Ronevich, Milan Agnani, and Chris San Marchi. 2023. “Fatigue and Fracture Behavior of Line Pipe Steels in Pressurized Gaseous Hydrogen.” Presentation (SAND2023-3962C) at Emerging Fuels Symposium, 5–8 June 2023, Orlando, FL.

22. Joe Ronevich, Milan Agnani, and Chris San Marchi. 2023. “Behavior of Steel Pipelines in Gaseous Hydrogen.” Presentation (SAND2023-919PE) to the AMPP Hydrogen Technical Community of Interest (TCI), 23 March 2023, Denver, CO.

23. C. San Marchi, M. Agnani, and J. Ronevich. 2023. “Metallic piping and pipelines for hydrogen service.” Presentation (SAND2023-11780C) at Hydrogen and Fuel Cell Seminar, 9 Feb. 2023, Long Beach, CA.

24. C. San Marchi and J.A. Ronevich. 2022. “Design and Operation of Metallic Pipelines for Service in Hydrogen and Blends.” Invited presentation (SAND2022-9015PE) to Emerging Fuels Institute (EFI) Leadership meeting, 6 July 2022.

25. C. San Marchi and J. Ronevich. 2022. “Design and Operation of Metallic Pipelines for Service in Hydrogen and Blends.” Invited talk (SAND2022-8369PE) to HyLINE Workshop, 22 June 2022.

26. C. San Marchi. 2022. “Design and Operation of Metallic Pipelines for Service in Hydrogen and Blends.” H2IQ Webinar (SAND2022-3598PE; sponsored by HFTO), 28 March 2022.

27. C. San Marchi and J. Ronevich. 2022. “Hydrogen-assisted fatigue and fracture of carbon steels and the implications of blending hydrogen into natural gas transmission infrastructure.” Invited talk (SAND2022-0993PE) at 2022 HYDROGENIUS, I2CNER, HydroMate and SINTEF Joint Research Symposium, 27 Jan. 2022, Kyushu, Japan (presented remotely).

28. C. San Marchi and J. Ronevich. 2022. “Implications of Gaseous Hydrogen on Welded Construction of Pipelines.” Invited talk (SAND2022-0429PE) to 2022 API/AGA Joint Committee on Oil and Gas Pipeline Welding, 26 Jan. 2022.

29. C. San Marchi and J. Ronevich. 2022. “Implications of Gaseous Hydrogen on Welded Construction of Pipelines.” Invited overview presentation (SAND2022-0820PE) for 2022 API/AGA Annual Meeting, Hydrogen Fuel Gas Pipelines Task Group, 24 Jan. 2022.

TASK 2: Pipeline Compatibility of Polymers

Subtask 2.1: Degradation of Materials Structural Properties in Polymers – Description

The basic structural properties of distribution pipelines in gaseous NG are well documented in the literature, but there are limited data for H_2 or H_2/NG blends on plastic pipes, welds, and mechanical joints. Our industry partners will provide valuable input in material selection, operational conditions (e.g., pressure, gas composition) for evaluating material property degradation, and vintage piping in H_2/NG blend-aged conditions. The effects of the H_2/NG blend on polymer systems—which contain additives for long-term performance such as antioxidants, stabilizers, and other additive packages—are not well known. In addition to the impact of additives, joining is another area of critical interest, with the fusion joint morphology being influenced over time. Localized stress concentration in mechanical connectors can result in accelerated material degradation upon the addition of H_2 and contaminants in NG. PNNL will identify gaps in the available mechanical property database for polymer distribution gas delivery systems. Additionally, PNNL will critically assess the role of gas impurities in blended H_2/NG mixtures in controlled laboratory environments and measure changes in material activation energy, pressure and time effects, and stabilizer depletion in relation to the material property performance.

Degradation of Materials Structural Properties in Polymers – Technology Advance/Outcomes

Industry partners will identify the material properties and operational characteristics of H_2/NG systems for detailed material performance and pipe assessments. The outcome of this work will be a materials performance comparison of changes in activation energies, slow crack growth changes, full rate process models, and a determination of what variables strongly contribute to the material performance.

SNL will work with PNNL on evaluating material morphology in new, vintage, and post-H_2-exposure pipe materials to assess changes in materials that affect the property performance.

Degradation of Materials Structural Properties in Polymers – Subtasks Performed by SNL and PNNL

1. Evaluation of distribution pipe fracture in H_2 and H_2/NG blends.
    a. Evaluate sections of pipe samples on coupon sections and test for material sensitivity to fracture in temperature, pressure, and gas compositions.
    b. Test slow crack growth in H_2 and H_2/NG blends with gas contaminants on medium-density polyethylene (MDPE), high-density polyethylene (HDPE), and polyamide pipe materials.
2. Correlation of polymer additive depletion effects with H_2, H_2/NG blends, and contaminants of polymer materials related to fracture initiation and the effect on slow crack growth.
3. H_2 and H_2/NG effects on joining technology in welded and mechanically fastened pipe joints.
    a. Evaluate the effects of H_2 and H_2/NG blends on creep effects from mechanically fastened joints and high localized stress concentrations in materials.
4. Development of understanding on the impacts on material changes in pipe morphology and chemistry from the testing in previous subtasks.

Subtask 2.2: Lifetime Prediction of Polymer Materials in Hydrogen and Blends – Description

Typical requirements for NG polyethylene pipes are to provide structural performance beyond 50 years. The integrity of aging polyethylene pipes can be solved by lifetime prediction methods. A number of studies on aging test methods and lifetime prediction of polyethylene pipes have been extensively carried out both domestically and abroad. Quasi-brittle failure is the critical failure mechanism in long-term applications. Stress rupture curves have been developed for NG polymer piping; however, the development of stress rupture curves to determine the long-term failure behavior under the H_2/NG environmental stress conditions has not. Lifetime prediction curves for these polymeric materials subjected to H_2/NG mixtures are needed to better understand the effects of the gas blend and their contaminants to compare against the baseline curves to evaluate long-term effects for 50 years and beyond.

Lifetime Prediction of Polymer Materials in Hydrogen and Blends – Technology Advance/Outcomes

PNNL will develop aging test conditions similar to actual working conditions of pressure (pipe stresses) and H_2 gas blends with predetermined contaminant levels by our collaborators and stress rupture curves. The test conditions will be designed to accelerate aging under these gas and stress conditions at elevated temperature conditions that will determine the thermal oxidative state of the unaged and aged pipe conditions. The intended outcome is to develop stress rupture curves, aging material evaluation of pipes in H_2 gas blends, and an assessment to address concerns of our industry partners of NG infrastructure when considering H_2 and pipeline performance. SNL will work with PNNL on H_2 exposure of polymer samples in cyclic fatigue and fracture testing to determine lifetime predictions.

Lifetime Prediction of Polymer Materials in Hydrogen and Blends – Subtasks Performed by SNL and PNNL

1. Assess literature data for H_2 and H_2/NG; identify gaps and industrial relevance for NG infrastructure.
2. Stress rupture curves in H_2 and H_2/NG blends: Estimate long-term hydrostatic strength by extrapolation of a stress-time regression line.
3. Develop a series of short- and long-term time-to-failure tests of plastic pipe under constant internal pressure in a research environment to determine the effects of H_2 and H_2/NG and contaminants.

Task 2: Compatibility of Polymers Outcomes

Degradation of Materials Structural Properties – Polymers (Subtask 2.1)

Subtask 2.1 identified gaps in the available mechanical property database for polymer distribution gas delivery systems. Localized stress concentration in mechanical connectors can result in accelerated material degradation upon the addition of H_2 and contaminants in NG. This subtask did not look critically at the role of gas impurities in blended H_2/NG mixtures in controlled laboratory environments and measure changes in material activation energy, pressure and time effects, or stabilizer depletion in relation to the material property performance due to the focus on gas influence. Future work could include impurities; however, it is understood that impurities in gas and their influence are a much larger, complex problems. This topic has provided insight into Subtask 2.2 for input on lifetime prediction model experiments.

Principal subtasks performed:

- Evaluation of pipe section samples using test coupons and testing for material sensitivity to fracture in temperature, pressure, and gas compositions.
- Testing of slow crack growth in H_2 and H_2/NG blends with gas contaminants on MDPE and HDPE pipe materials.
- H_2 and H_2/NG effects on joining technology in welded, fastened pipe joints.

- Evaluate the effects of H_2 and H_2/NG blends on creep effects from mechanically fastened joints and high localized stress concentrations in materials.
- Development of understanding on the impacts on material changes in pipe morphology and chemistry from the testing.

Lifetime prediction curves for these polymeric materials were developed (Subtask 2.2) after being subjected to H_2/NG mixtures to better understand the effects of the gas blend and were compared against the baseline curves to evaluate long-term effects for 50 years and beyond.

Principal subtasks:

- Assess literature data for H2 and H2/NG; identify gaps and industrial relevance for NG infrastructure.
- Complete model assessment of lifetime prediction tools and compare their performance against each other.
- In situ test to develop stress rupture curves in H2 and H2/NG blends.
- Develop a series of short- and long-term time-to-failure tests of plastic pipe under constant internal pressure in a research environment to determine the effects of H2 and H2/NG and contaminants.

The study involves testing various MDPE and HDPE materials sourced from current NG distribution networks. The tests performed include quasi-static uniaxial tension tests, single-edge notch bending tests, and slow crack growth evaluations (Figure 1).

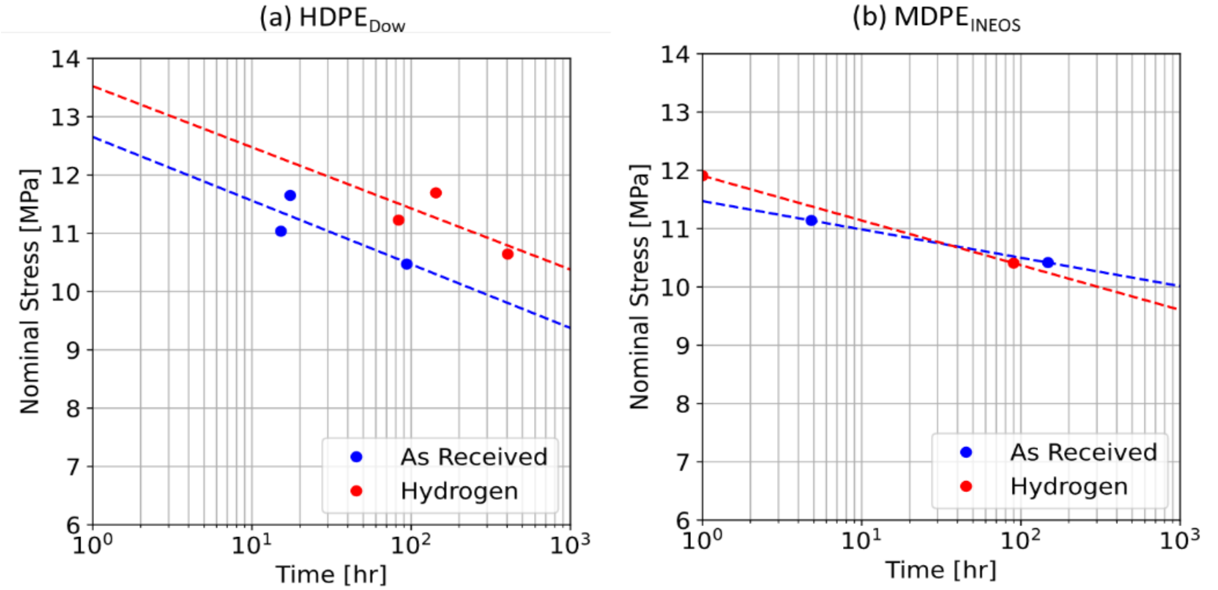

Figure 1. Slow crack growth of (a) Dow HDPE and (b) INEOS MDPE using the single-edge notch bending specimens. The shifted trend line in Dow indicates that the hydrogen environment slows the crack propagation.

Materials characterizations such as nanoindentation, desorption analysis, degree of crystallinity, and oxidation induction time measurements were also conducted to evaluate the compatibility of hydrogen with existing polymeric pipeline materials and assess the mechanical and structural integrity of MDPE and HDPE in hydrogen environments.

Lifetime prediction models were developed based on experimental data and literature reviews (Figure 2). These models aim to predict the long-term behavior of polymeric materials under hydrogen and hydrogen-methane blend environments. Stress rupture curves for MDPE and HDPE in hydrogen environments were also developed to assess the materials' reliability over time.

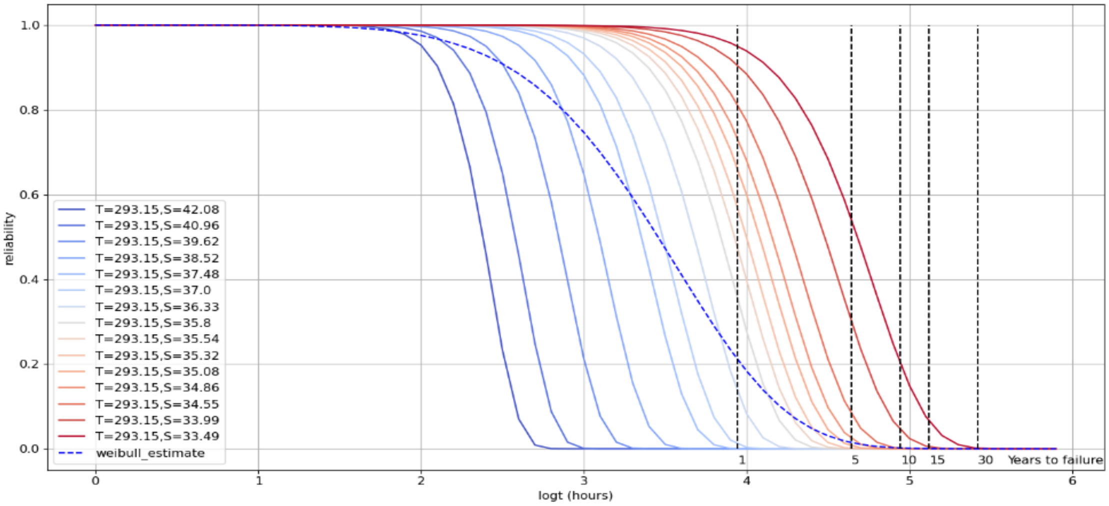

Figure 2. Lifetime reliability distribution for literature dataset. The plot includes the regular Weibull profile (blue dashed line) and the Weibull accelerated failure time profile at 20°C and various hoop stresses (S) in MPa. The black dashed lines indicate 1, 5, 10, 15, and 30 years to failure.

This project has provided a comprehensive analysis of the potential challenges associated with blending H_2 into the existing NG infrastructure. Through a multidisciplinary approach, encompassing materials science, engineering, and economics, we have identified key factors that influence the feasibility and impact of hydrogen blending. Below is a summary of the key findings.

- A review article has been published: K. L. Simmons, L. D. Fring, W. Kuang, Y. Shin, Y. S. Chou, Y. Ni, et al. 2022. *Gap Analysis on the Impacts of Hydrogen Addition to the North American Natural Gas Infrastructure Polyethylene Pipelines*.
- Morphological and physical changes:
  - Two MDPE materials were provided and tested. The initial decrease in density and crystallinity was over 80 days in an H2 environment and shows to stabilize over time. This decrease often recovers within 48 hours after H2 exposure is removed. Extended exposure (over 80 days) leads to increased H2 equilibrium contents and decreased diffusion coefficients.

  - Aldyl-A 91: Similar trends as the two MDPEs with a decrease in density and crystallinity. The antioxidant levels in Aldyl-A 91 are significantly lower than MDPE 1, but there is no change in antioxidant levels for Aldyl-A 91 before and after 250-psi (pounds per square inch) hydrogen exposure.

- Mechanical properties:
  - Two MDPE materials where uniaxial tensile testing showed higher ultimate strain after H2 exposure, with no difference in yield strength compared to baseline. This extended ultimate strain quickly converged to baseline levels within an hour of gas exposure.
  - Single-edge notch bending testing:
    - MDPE 1 showed negligible difference between H_2 and argon exposure.
    - MDPE 2 exposed to H_2 demonstrated higher maximum load and work of fracture compared to argon.
    - HDPE materials have significantly larger plastically deformed and fractured surfaces when they are exposed to H_2 and blended gas. It causes a significant reduction of the specific fracture energy.
  - No crack extension was observed in the slow crack growth tests in MDPE 1 specimens after 500 hours.
  - Butt-fusion joint testing: MDPE 2 joints showed a 12% decrease in yield strength, but negligible effects on modulus, yield strength, and failure strain due to H_2.
- Nanoindentation studies:
  - HDPE 1: 20%–30% drop in elastic modulus after 72 hours of 250-psi hydrogen exposure, with no recovery over time. This effect was not observed with argon exposure.
  - Aldyl-A 91: 30%–40% increase in local elastic modulus after H2 exposure, which appears to be permanent.
- Hydrogen diffusion and crystalline rearrangement:
  - Hydrogen concentration: HDPE 1 reaches maximum H2 concentration in 1 hour, whereas MDPE 1 takes 3–4 hours.
  - Crystalline rearrangement: Occurs within 1 day for HDPE 1 and 14 days for MDPE 1. Methyl groups in MDPE 1 become more interactive and entangled than in HDPE 1 upon H2 exposure.
- Effect of methane exposure:
  - Slight drop in density after exposure to 250 psi methane for various durations, with recovery in 2 days. Similar trends were observed in crystallinity and d-spacing.
  - Single-edge notch bending testing:
    - Decreased average peak loads in MDPE 1 and Aldyl-A 91 with methane exposure.

    - Increased peak load in HDPE 1, although variations were within standard deviation.
  - Oxidation induction time studies: No significant impact from methane exposure on antioxidants in MDPE 1, HDPE 1, and Aldyl-A 91.
- Slow crack growth resistance:
  - HDPE 2: Improved resistance to slow crack growth by 646% in terms of failure time with hydrogen exposure.
  - MDPE 2: Decreased failure time with hydrogen exposure.
- Lifetime prediction:
  - Several physical/acceleration models were carefully investigated to evaluate and predict the lifetime of the polymer pipes. The evaluated models were (1) rate process method, (2) the Gas Technology Institute, and (3) the Eyring models. The Gas Technology Institute model could fit all three datasets with $R^2 > 0.7$.
  - Reliability assessment was conducted using the Weibull distribution with a four-parameter rate process method model. Using the Weibull accelerated failure time model, we can predict the probability of a product reaching its lifetime.

Additional Documentation

R. Shrestha, J.A. Ronevich, L. Fring, K. Simmons, N.D. Meeks, Z.E. Lowe, T.J. Harris Jr., and C. San Marchi. 2022. "Compatibility of medium density polyethylene (MDPE) for distribution of gaseous hydrogen." Paper no. PVP2022-84791, ASME Pressure Vessels & Piping Conference, 17–22 July 2022, Las Vegas, NV.

TASK 3: LCA

Subtask 3.1: LCA of H_2/NG Blends for Various End Use Applications – Description

The NG pathways considered will include both conventional and shale gas production; gas processing and separation; and gas compression, storage, and transmission/distribution to the H_2 injection point. The H_2 pathways will include all renewable and near-zero-carbon production technology options (e.g., low-temperature electrolysis and high-temperature electrolysis using solar, wind, and nuclear power), as well as H_2 compression, storage, and transmission to the injection point into NG pipelines. The downstream pathway for the H_2/NG blend will include transmission/distribution, compression via gas reciprocating engines and electric motors, and storage and combustion at-end use applications such as building appliances, industrial boilers, and gas turbines for power generation. ANL will perform LCA to evaluate energy use by type (e.g., fossil, nuclear, renewable), pathway energy efficiency, greenhouse gas (GHG) emissions (e.g., carbon dioxide [CO_2] and [CH_4]), and criteria air pollutant (CAP) emissions (e.g., nitrogen oxides [NO_x], carbon monoxide, volatile organic compounds, sulfur oxides) for each step in the technology pathways of the H_2/NG blend and at a wide range of blending ratios spanning 0%–100% H_2.

LCA of NG/H_2 Blends for Various End Use Applications – Technology Advance/Outcomes

The LCA in this subtask aims to answer the following research questions when comparing with conventional NG pathways:

1. What are the impacts of hydrogen primary energy sources and production technology pathways on life cycle total and fossil energy use and associated emissions?
2. What are the implications of hydrogen storage types, delivery methods, injection pressure, and associated energy use and emissions?
3. What are the impacts of the combustion of H_2/NG blends on the efficiency and emissions of existing internal combustion engines driving the pipeline compressors?
4. What are the implications of leakage and fugitive emissions of various H_2/NG blends?
5. What are the implications of various blending ratios and end-use applications on GHG and CAP emissions?
6. Are there regional preferences or differences associated with H_2 production, delivery, and storage pathways?
7. What are the implications of pipeline modification, materials, and construction to accommodate various blending ratios of H_2/NG compared to building new pipelines for H_2 delivery to end use in a counterfactual scenario of no H_2 blending?

LCA of H_2/NG Blends for Various End Use Applications – Subtasks Performed by ANL

1. *Evaluate energy use and emissions of H_2 production pathways to injection point:* ANL will evaluate the impacts of primary energy sources and technology pathways of H_2 on total and fossil energy use and GHG and CAP emissions. The technology pathways will include renewable and near-zero-carbon H_2 production via low-temperature electrolysis and high-temperature electrolysis using solar, wind, and nuclear power. The evaluation will also include H_2 compression technologies for various storage types, including geologic and physical storage options, as well as compression for various H_2 pipeline transportation distances to the injection point, which will be informed by TEA and regional analysis conducted by NREL.
2. *Evaluate energy and emissions of delivering H_2/NG blends from injection point to end-use applications:* ANL will evaluate the impacts of the combustion of various H_2/NG blend ratios on the efficiency and emissions of existing internal combustion engines driving the pipeline compressors. Such evaluation will leverage the most recent experiments at ANL and will benefit from a thorough literature review of using H_2/NG blends in internal combustion engines. ANL will also evaluate the implications of leakage and fugitive emissions of H_2/NG gas blends in lieu of CH_4 leakage associated with conventional gas pathways. While CH_4 leakage is a major contribution to life cycle GHG emissions for conventional NG pathways due to its high global warming potential (30), H_2 leakage could be of greater magnitude due to it being a smaller molecule and would represent energy and economic loss, in addition to its impact on changing the blending ratio along the pathway of the blend to end use. Finally, ANL will evaluate the energy and environmental implications of pipeline modification, materials, and construction to accommodate various blending ratios in lieu of a counterfactual scenario where H_2 is delivered in a newly dedicated pipeline to various end uses.

3. *Evaluate emissions of H_2/NG combustion at various end-use applications:* ANL will evaluate the life cycle impacts of H_2/NG combustion at various end-use applications, including building appliances, turbines, engines, and industrial boilers and heating applications. The evaluation will span varying blending ratios because it impacts both flame temperature and combustion characteristics, with consequent impacts on energy efficiency and emissions. In particular, NO_x emissions are strongly impacted by combustion temperature, and its mitigation may have a negative impact on energy efficiency at end use.

4. *LCA of various H_2/NG blending pathways:* ANL will develop the various H_2/NG blends pathways in the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model using the energy and emissions inventory data from Subtasks 1.1–1.3 to conduct a thorough LCA with respect to important metrics such as energy use, GHG emissions, and CAP emissions. The results of the various pathways will be compared to the conventional and shale gas pathways. From the LCA, key environmental performance parameters will be identified and evaluated using uncertainty and stochastic analyses. The LCA will be combined with the TEA by NREL so that the life cycle carbon intensity reduction by various H_2/NG blends compared to baseline conventional NG pathways will be used with the levelized cost of the NG/H_2 blend to calculate the abatement cost of CO_2 while also considering the impacts of possible GHG credits under various existing and hypothetical low-carbon fuel frameworks.

Subtask 3.2: Analysis of Synthetic Methane Production from CO_2 + H_2 as an Alternative to Blending H_2 *With NG – Description*

While blending H_2 with NG can leverage existing NG infrastructure and thus eliminate the need to build costly infrastructure dedicated to H_2 delivery, such blending will likely incur costs downstream of the blending point, depending on the blending ratio. These include possible costs associated with modifying NG infrastructure components (e.g., pipeline coating, storage, compressors, engines driving compressors, leak detection, and safety devices), as well as possible costs associated with modifying end-use equipment (e.g., burner designs, heat exchangers, NO_x mitigation). An alternative approach to using clean H_2 to reduce the carbon intensity of conventional NG is to use H_2 with CO_2 to synthesize methane, which can be injected into existing NG pipelines while being fully compatible with existing NG infrastructure components and end-use applications. While this synthetic NG production scenario eliminates all downstream costs associated with the H_2 blending alternative, there is additional cost associated with the synthesis of methane (e.g., CO_2 capture and purification, CO_2 compression and transmission, in addition to the synthesis process). However, the synthesis process has a carbon conversion ratio >95% and energy efficiency >80%, while also producing high-quality heat (approximately 300°C, due to the exothermic reaction of CO_2 + H_2), which can be used for building or industrial heating applications. Furthermore, the synthetic natural gas (SNG) alternative can use an unlimited and varying amount of H_2 production with no impact on downstream processes. Additionally, the SNG pathway avoids the dilemma of a H_2 blending scenario created by the much lower volumetric energy density of an H_2 compared to CH_4.

Analysis of Synthetic Methane Production from CO_2 + H_2 as an Alternative to Blending H_2 *With NG – Technology Advance/Outcomes*

This subtask aims to answer the following research questions when comparing with the H_2/NG blending pathways:

1. What are the cost and environmental implications of synthetic methane production from zero-carbon H_2 and various CO_2 sources vs. blending H_2 into NG pipeline?
2. What are the scale and purity level of various CO_2 sources, and the cost, energy, and emissions associated with the capture and purification of CO_2 for CH_4 synthesis process?
3. What are the cost and energy/emissions associated with the transportation of CO_2 to the CH_4 synthesis plant?
4. What are the cost and energy/emissions associated with the CH_4 synthesis process?
5. What are the levelized delivered energy costs and GHG and CAP emissions of the CH_4 synthesis pathway compared to H_2/NG blending pathways?
6. Are there regional synergies associated with CO_2 sources and H_2 production pathways?

Analysis of Synthetic Methane Production from CO_2 + H_2 as an Alternative to Blending H_2 *With NG – Subtasks Performed by ANL and NREL*

1. *Evaluate the cost, energy use, and emissions of capturing, purifying, and transporting CO_2 from various sources:* This subtask will evaluate the scale and regional availability of CO_2 from various sources, including nearly pure CO_2 sources (e.g., ethanol, ammonia, and NG processing plants), high-concentration CO_2 sources (e.g., refinery steam methane reforming plants, cement plants), and low-concentration CO_2 sources (e.g., power plants). This subtask will also evaluate the cost, energy use, and GHG emissions associated with capturing and purifying CO_2 from these various sources, as well as the direct air capture of CO_2. The cost of compressing and transporting H_2 and CO_2 to the CH_4 synthesis plant will also be evaluated.
2. *Model CH_4 synthesis process:* In this subtask, ANL will develop a detailed Aspen Plus model for evaluating the SNG production process from clean H_2 and CO_2 pathways. The Aspen model will provide the GREET model with material and energy balance, carbon conversion ratio, and synthetic CH_4 product yield. ANL will also use the model to size and cost the major equipment needed for the SNG production needed by the TEA model. ANL will integrate NREL analysis on available clean energy sources for H_2 production with available sources of CO_2 to estimate potential H_2 demand by region for blending and for SNG production.
3. *TEA of SNG production:* ANL will leverage the Hydrogen Analysis (H2A) modeling framework with TEA models using detailed capital and operation costs from the Aspen Plus process model, along with common economic and financial assumptions, to calculate the cash flows and levelized cost of the final SNG product. ANL, with support from NREL, will obtain current and future energy and utility costs from the U.S. Energy Information Administration's Annual Energy Outlook and estimates by NREL and other national labs. Key parameters influencing the cost of synthetic CH_4 products will be identified. ANL will

conduct a sensitivity analysis to evaluate the impact of various cost drivers on the levelized cost of CH_4 production. The information from the sensitivity analysis will inform and guide the process design for further optimization until a final optimized process is achieved.

4. *LCA of synthetic NG production:* In this subtask, ANL will develop synthetic NG pathways in GREET using different CO_2 sources and H_2 production options. The energy and emissions inventory data from Subtasks 2.1–2.3 will be used by ANL to conduct a thorough LCA with respect to important metrics such as energy use, GHG emissions, and CAP emissions. The results of the various pathways will be compared to the NG/H_2 blending pathways and the conventional and shale gas pathways. From the LCA, key environmental performance parameters will be identified and evaluated using uncertainty and stochastic analyses. The LCA will be combined with the TEA from Subtask 2.3 so that the life cycle carbon intensity reduction by the various SNG pathways compared to baseline conventional NG pathways can be used with the levelized cost of SNG to calculate the abatement cost of CO_2. The analysis will also consider the impacts of possible GHG credits under various existing and hypothetical low-carbon fuel frameworks.

Task 3: LCA Outcomes

In Subtask 3.1, ANL evaluated the injection of low-carbon H_2 into the existing NG pipeline networks and delivered blended NG/H_2 gas, which maintained either the same volumetric flow or the same energy flow as the baseline NG system. While a significant reduction in life cycle GHG emissions can be achieved by delivering the blended gas, maintaining the energy throughput instead of volumetric throughput in the pipeline would require significant modification of the NG pipeline infrastructure.

ANL quantified the life cycle GHG emissions of transmitting a blend of H_2 and NG in an existing NG pipeline. The analysis was based on a high-capacity NG transmission pipeline operated by Alliance Pipeline that delivers Canadian NG to the United States via 42-in. and 36-in. steel pipes. Four low-carbon H_2 production pathways were considered: (1) low-temperature electrolysis using renewable energy (e.g., solar, wind), (2) low-temperature electrolysis using nuclear energy, (3) high-temperature electrolysis using nuclear energy, and (4) steam methane reforming of NG followed by carbon capture and storage.

The life cycle GHG emissions at different concentrations of H_2 are provided in Figure 3. Maintaining the same volumetric flow rate as baseline NG delivery, the GHG emissions decreased with increasing H_2 mole fraction in the blend, mainly due to the decrease in the downstream combustion emissions associated with a lower emission factor of H_2. At H_2 mole fractions higher than 0.6, the transmission and distribution emissions showed a decrease with H_2 ratio as well. However, the advantage of blending a gas with lower emission factor was offset by the increase in emissions associated with transmission and distribution when the energy throughput was maintained to be the same as baseline NG delivery. In this case, the life cycle GHG emissions decreased by 6% at an H_2 mole ratio of 0.3, while the blend combustion emissions decreased by 11%. The life cycle GHG emissions considering several H_2 production pathways are shown in Figure 4. For H_2 production via steam methane reforming and carbon capture and storage, the reduction of life cycle GHG emissions was less than 2% due to the higher upstream H_2 production emissions. More details of the LCA of the NG/H_2 blend are provided in a peer-reviewed publication by ANL [1].

In Subtask 3.2, ANL evaluated SNG production (using low-carbon H_2 and captured CO_2) as an alternative scenario, as it can eliminate downstream costs associated with the H_2 blending (e.g., capital cost in infrastructure upgrade, retrofitting of compression stations, and end-user equipment). However, such scenarios incur additional costs associated with capturing CO_2 and synthesizing methane. ANL considered various sources of captured CO_2, including from ethanol plants, ammonia plants, and iron and steel manufacturing, as well as high-temperature and low-temperature direct air capture.

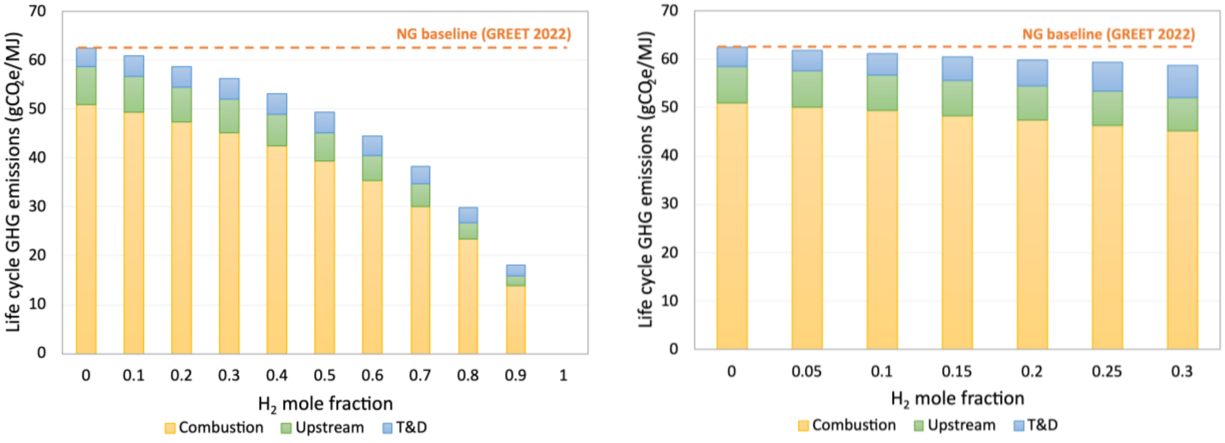

Figure 3. Breakdown of GHG emissions for constant volume flow rate and constant energy throughput at different concentrations of H2 produced via water electrolysis using renewable electricity from solar or wind power. T&D stands for transmission and delivery.

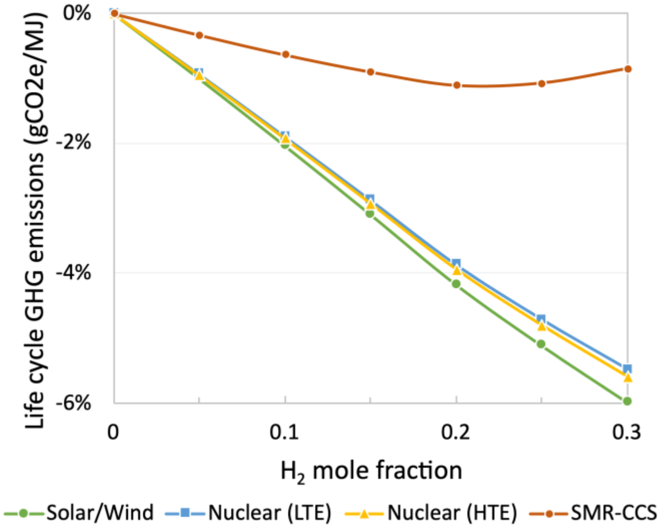

Figure 4. Life cycle GHG emissions of mixing H_2 from different production pathways for the constant energy throughput scenario. LTE and HTE stand for low- and high-temperature electrolysis, respectively.

ANL developed an engineering process model of SNG production using Aspen Plus to calculate the levelized cost and life cycle GHG emissions of SNG. SNG synthesis from CO_2 and H_2 through the Sabatier reaction, a thermochemical catalytic methanation process that is highly exothermic, was considered as follows:

$$CO_2 + 4H_2 \xrightarrow[catalyst]{} CH_4 + 2H_2O\ (\Delta H = -165\ kJ/mol).$$

ANL conducted TEA of SNG production using equipment and material balance from the engineering process model. Considering an electricity price of \$0.03/kWh for the water electrolysis pathways, the SNG production cost was \$27–\$58/MMBtu-HHV, as shown in Figure 5, where the SNG production cost was compared with fossil NG and renewable natural gas (RNG) production costs. The range of RNG costs was based on data from a 2019 American Gas Foundation report [2]. ANL identified that the SNG production cost without potential tax credits was higher than the costs of fossil NG and RNG.

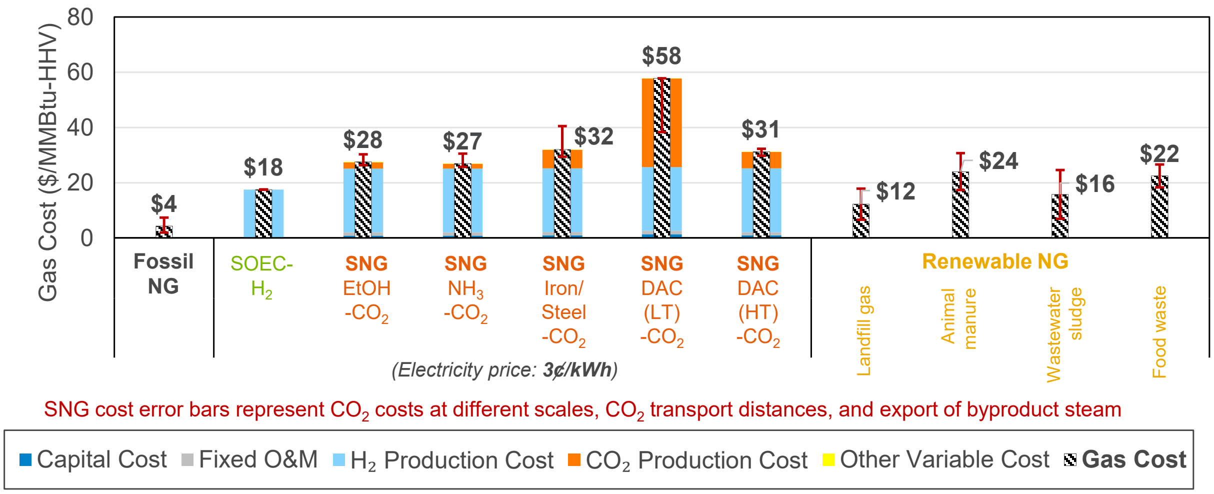

Figure 5. SNG production cost with an electricity price of \$0.03/kWh and comparison with fossil NG and RNG costs.

Life cycle GHG emissions of SNG were evaluated using mass and energy balance information obtained from the engineering model, along with supply chain emissions data (e.g., grid electricity) from ANL's GREET model. LCA results for fossil NG and RNG were obtained from GREET 2022 [3]. As depicted in Figure 6, SNG had the potential to significantly reduce life cycle GHG emissions, ranging from 8 to 32 $kgCO_2e$/MMBtu-HHV, resulting in a reduction of 52%–88% compared to fossil NG. More details of the TEA and LCA of the NG/H_2 blend are provided in a peer-reviewed publication by ANL [4].

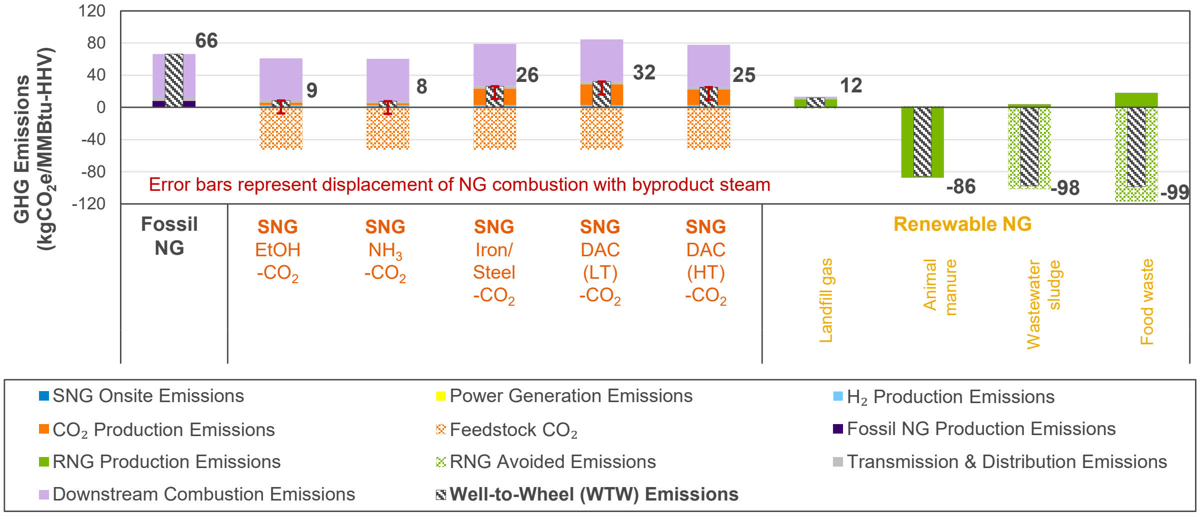

Figure 6. Life cycle GHG emissions of SNG and comparison with fossil NG and RNG.

Task 3 References

1. Vincenzo Cappello, Pingping Sun, and Amgad Elgowainy. 2024. "Blending low-carbon hydrogen with natural gas: impact on energy and life cycle emissions in natural gas pipelines." *Gas Science and Engineering* 128: 205389. doi.org/10.1016/j.jgsce.2024.205389.

2. American Gas Foundation. 2019. *Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment*.

3. M. Wang, et al. 2023. *Summary of Expansions and Updates in R&D GREET® 2023*. doi.org/10.2172/2278803.

4. Kyuha Lee, Pingping Sun, Amgad Elgowainy, Kwang Hoon Baek, and Pallavi Bobba. 2024. "Techno-economic and life cycle analysis of synthetic natural gas production from low-carbon H_2 and point-source or atmospheric CO_2 in the United States." *Journal of CO_2 Utilization* 83: 102791 doi.org/10.1016/j.jcou.2024.102791.

TASK 4: TEA

Subtask 4.1: Pipeline Preparation Cost Analysis for Hydrogen Blending – Description

The costs associated with preparing different pipelines for H_2 blending have been studied but have typically focused on the transmission pipeline segment of the NG supply chain. Each aspect of the NG supply chain (transmission, distribution mains, distribution service lines, compressors, storage, offtake to industrial customers, end-use local customers, and auxiliary equipment such as meters and sensors) must be evaluated to understand the key cost drivers and tipping points of blending H_2 into NG systems. For example, transmission lines are higher pressure and typically use steels that are susceptible to hydrogen-induced cracking, which could impact replacement lifetimes, while distribution lines made up of plastic pipes have minimal cracking risk but higher leakage rates, potentially impacting monitoring costs, as they are closer to population centers. Additionally, as the impact of H_2 blending depends on the concentration, certain areas in the pipeline network may require more upgrades (e.g., at the injection point), and gas composition modeling along the network could be important in some supply chain segments. It is likely that due to different pipeline materials, designs, and NG compositions and contaminants, the economic impact of H_2 blending will need to be analyzed on a case-by-case basis.

Pipeline Preparation Cost Analysis for Hydrogen Blending – Technology Advance/Outcomes

As case-by-case analyses are often needed in this research area, a flexible, open-source TEA tool will be developed to support this need based on NREL's TEA expertise.

Pipeline Preparation Cost Analysis for Hydrogen Blending – Subtasks Performed by NREL

1. Work with industry partners to identify the most critical NG supply chain segments from an economics perspective (e.g., storage, compressors, piping materials, pressures).
2. Work with the materials research components (SNL and PNNL) of this project to help prioritize materials testing from an economics perspective
3. Obtain and incorporate techno-economic data from a variety of sources including the materials research results, discussions and surveys with industry partners, review of global experience operating H_2-blended pipelines, and bottom-up economic modeling
4. Build on or develop, as needed, a gas composition state model to understand the H_2 concentration along the pipeline network and its impact on materials management.
5. Develop an open-source, flexible techno-economic tool for public consumption with case-by-case analysis capability.

Subtask 4.2: Estimating the Value Proposition of Hydrogen Blending – Description

The production and blending of H_2 creates new value propositions that need to be further investigated for each use case. For example, installing an electrolyzer to produce H_2 for blending also provides the firm with a flexible asset to optimize demand-side energy management and participate in demand reduction programs in certain locations Additionally, questions arise about how low-cost, dispatch-constrained electricity from renewable energy production facilities (e.g., wind, solar) could be leveraged in flexible electrolyzers and H_2 blending, providing another value proposition that should be evaluated. As the production of H_2 relies on inputs that vary regionally and over time (e.g., electricity price and carbon intensity), these questions need to be evaluated across regions and over time.

Estimating the Value Proposition of Hydrogen Blending – Technology Advance/Outcomes

To complete this subtask, NREL will expand on existing models (e.g., H2A, Revenue Operation and Device Optimization [RODeO]) and analysis frameworks that are integrating electrolyzer operation models with NG and electrical grid simulation models.

Estimating the Value Proposition of Hydrogen Blending – Subtasks Performed by NREL

1. Identify and align on key value streams with industry partners (e.g., grid management, demand response, option value of H_2 blending).
2. Identify the NG networks, regions, and time scales of interest and determine a set of scenarios to evaluate those systems.
3. Integrate the techno-economic pipeline preparation model into the combined NG and electrical grid simulation framework.
4. Complete scenario analysis and co-simulations to quantify the value proposition of H_2 blending.

Subtask 4.3: Comparing Hydrogen Blending with Alternative Pathways – Description

Hydrogen blending must be compared with alternative pathways to NG system decarbonization and uses of H_2 production—specifically, the economic trade-offs of blending H_2 into NG systems compared to the production and use of SNG are of interest. Carbon mitigation cost (\$/tonne CO_2e avoided) will be quantified and used to compare the environmental return of the pathways of interest. The economics of both the pipeline system and the end-use application should be considered to understand the total system's economic impact; upgrades to household appliances or changes to industrial processes are important to characterize and account for when deciding the cost-optimal approach.

Comparing Hydrogen Blending with Alternative Pathways – Technology Advance/Outcomes

A better understanding of the costs associated with H_2 blending in NG pipelines is critical to large-scale adoption of this technology. Understanding the economic tipping points for H_2 blending and how those tipping points change with respect to factors like H_2 concentration, materials, system design, and contaminants is essential to understanding how to best incorporate H_2 into the NG system. The TEA framework, once developed, will provide a flexible tool to facilitate rapid, informed decision-making on the economics of various options, how to best manage economic risks, and areas of opportunity and low-hanging fruit when blending. Combined, these insights will lead to more rapid deployment of this technology, potentially leading to more industry experience and learning in this area.

Comparing Hydrogen Blending with Alternative Pathways – Subtasks Performed by NREL

1. Develop a flexible TEA framework to compare alternative pathways (e.g., SNG).
2. Integrate the analysis framework with ANL's environmental impact modeling.
3. Assess the economics of H_2 blending with concentrations of 0%–50% and alternative decarbonization pathways, including SNG and 100% H_2 pipelines, relative to the benchmark business-as-usual NG system.
4. In collaboration with ANL, develop carbon mitigation cost metrics (e.g., \$/tonne CO_2e avoided) to assess the environmental return on capital employed.

Task 4: TEA Outcomes

NREL's effort in Subtask 4.1 involved developing a comprehensive state-of-technology report on H_2 blending, a TEA tool to assess the modifications and costs of blending H_2 on a case-by-case basis, and an initial TEA of blending H_2 at a representative U.S. NG transmission pipeline case study.

The NREL TEA team-initiated progress on this subtask by conducting and publishing a comprehensive literature review to assess the state of knowledge regarding the impacts of H_2 blending on the NG supply chain. The literature review details how the presence of H_2 impacts the following topics: pipeline gas properties, transmission pipelines and equipment, distribution pipelines and equipment, underground gas storage, and end-use appliances. Furthermore, the review discusses recent H_2 blending TEA studies, network analysis studies, and applied demonstrations. This review was published as an NREL technical report and is freely available on OSTI.gov [1]. Though not discussed here, the outcomes of the literature review informed NREL's subsequent development of the Blending Pipeline Analysis Tool for Hydrogen (BlendPATH), a TEA program designed to assess the technical and economic impacts of blending H_2 into NG transmission pipelines on a case-by-case basis.

NREL developed BlendPATH to have three major model components (as shown in Figure 7): gas network model simulation, pipeline design assessment, and pipeline preparation analysis. Through the pipeline design assessment model, BlendPATH applies a network segmentation approach and ASME B31.12, the industry standard for H_2 pipelines and piping, as conservative pipeline design guidelines to assess existing pipeline infrastructure and establish operating condition limits when transporting H_2. If segments of the pipeline network design are determined insufficient for transporting H_2, BlendPATH provides users three pipeline network modification methods (through the pipeline preparation analysis model) to enable H_2 blending while also meeting end-use energy demand and ASME B31.12 operation limits. BlendPATH's modified pipeline network design output and re-simulated operating conditions are factored into a cost model to provide users with estimates for modified pipeline network capital costs, operating costs, and levelized cost of transport. NREL released BlendPATH [7] as an open-source Python program (available for download at github.com/nrel/BlendPATH) and has published a webinar detailing an overview of BlendPATH's techno-economic model and a demonstration of the tool on a literature-derived transmission pipeline case study [8]. BlendPATH is described in several presentations noted below with case studies demonstrating its use [2–6, 9]. Additional releases and documentation are planned for the end of the 2024 calendar year, which include an open-source pipeline network hydraulic simulation model and capabilities to assess H_2 blending up to 100%.

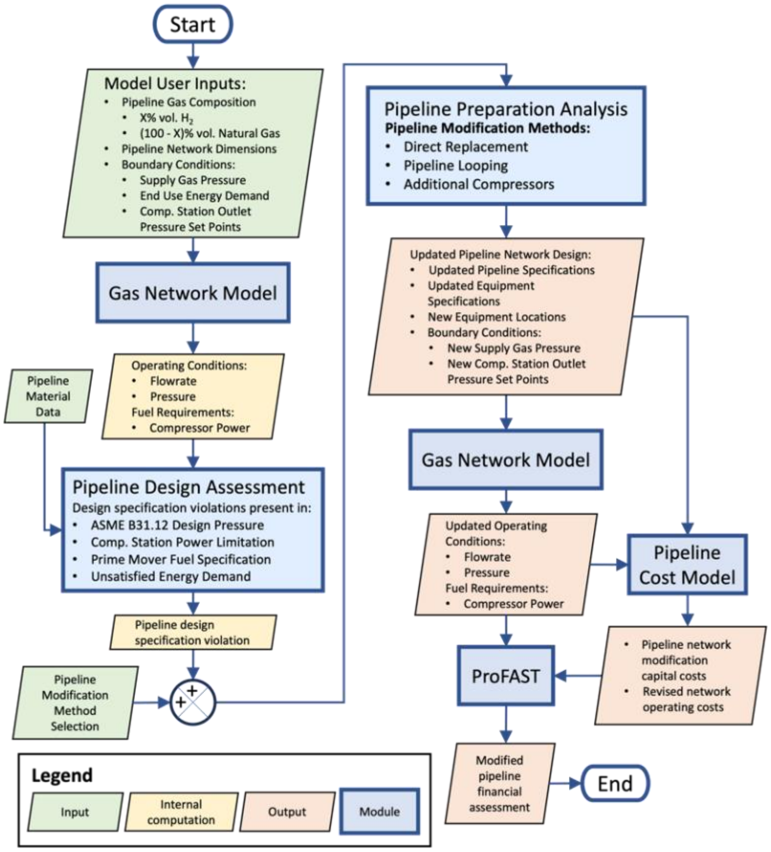

Figure 7. BlendPATH framework

Furthermore, NREL has applied BlendPATH to an industry case study, the Alliance Pipeline, to demonstrate the technical and economic outcomes of blending H_2 into a high-capacity pipeline. This case study considered a 327-mile portion of the Alliance Pipeline with an assumed H_2 injection point in southern Minnesota and gas delivery in Chicago. NREL's Alliance Pipeline case study considers location-specific NG and H_2 cost estimates, as well as a sensitivity analysis on blended gas composition prior to meeting pipeline hydraulic constraints (40 vol % H_2), applied ASME B31.12 design options, and BlendPATH pipeline network modification options. Figure 8 displays a sample of the Alliance Pipeline case study results; they suggest that despite significant capital investment for pipeline modification (not discussed here), the levelized costs of transporting blended gas are marginal compared to NG and H_2 injection costs. This case study analysis has been presented at multiple meetings [2–6, 9]. A report providing greater detail of this analysis and coverage of H_2 blending up to 100% is being prepared for public release [10].

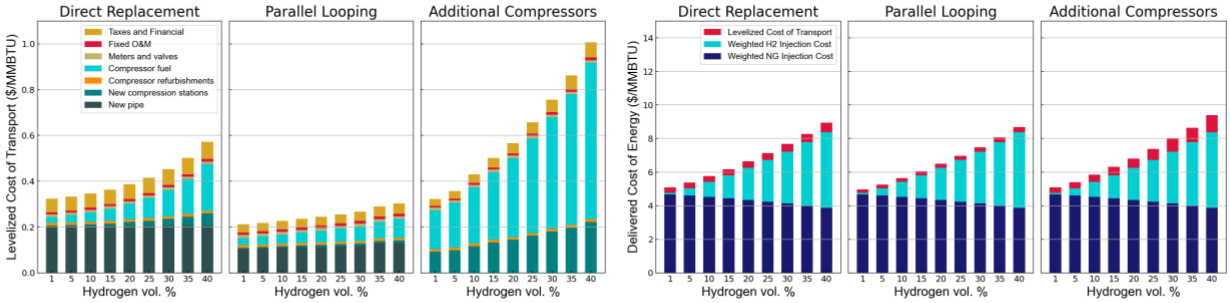

Figure 8. Levelized cost of transport (left) and delivered cost of energy (right) for each pipeline modification method applied to the Alliance Pipeline case study when limiting existing pipeline hoop stress to 40% (termed in BlendPATH as "no fracture control") and transporting blended gas to meet end use energy demand with H2 content from 1 to 40 vol %.

Subtask 4.2 involved expanding upon existing NREL models such as H2A, the System Advisor Model (SAM), the Hydrogen Financial Analysis Scenario Tool (H2FAST), and BlendPATH to identify key value opportunities for blending H_2 within the United States. This subtask called for identifying NG networks, regions, and time frames, as well as potential scenarios conducive to H_2 blending. Recent events such as the U.S. Environmental Protection Agency's Clean Air Act Section 111 regulation proposal and the Inflation Reduction Act renewable energy tax credit passage have also informed NREL analysis within this subtask.

NREL approached Subtask 4.2 by proposing a methodology for suggesting early adoption opportunities given identification and prioritization of key external market and regional resource drivers. Subsequent to driver identification and prioritization, this methodology involved compiling public data sources detailing external market and regional resource drivers into a geographic information system (GIS) database for driver mapping and region down selection given driver prioritization. The last step in this methodology called for defining case studies for blending H_2 in NG transmission pipelines located within the down selected regions that have publicly available and current pipeline design and operating data.

This analysis identified High Desert Lateral, located in Southern California, as a case study in which our methodology suggests a near-term opportunity, and which has sufficient data to support BlendPATH application. NREL has applied H_2 production, storage, and transport cost methods to quantify the cost of energy to end users and presented the results [9]. Figure 9 displays a sample of the BlendPATH analysis results for the High Desert Lateral case study and suggests that major pipeline modification may not be required if blending H_2 to ≤30 vol % in pipeline gas and limiting existing pipeline hoop stress to 40% of pipeline-specific minimum yield strength. The results of this case study analysis are described in more detail in a forthcoming article [11] to provide a sufficiently contrasting case study to the Alliance Pipeline.

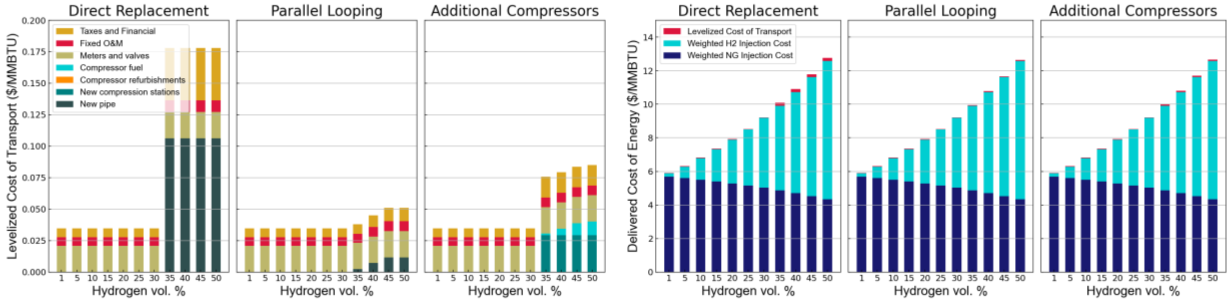

Figure 9. Levelized cost of transport (left) and delivered cost of energy (right) for each pipeline modification method applied to the Alliance Pipeline case study when limiting existing pipeline hoop stress to 40% (termed in BlendPATH as "no fracture control") and transporting blended gas to meet end use energy demand with H2 content from 1 to 50 vol %.

NREL's analysis in Subtask 4.3 was performed through collaboration and coordination with ANL regarding Subtask 3.2. NREL coordinated analysis with ANL by presenting the bespoke wind power H_2 production, storage, and transportation costs used within the Alliance Pipeline case study for incorporation into ANL's SNG cost model. NREL complemented ANL's model analysis by assessing H_2 blending up to pipeline hydraulic limitations (up to 40 vol % H_2 in pipeline gas) for the Alliance Pipeline. A preliminary TEA comparison between H_2 blending and SNG production was presented [4], noting a consistent H_2 production, storage, and transport costs basis. TEA results for blending H_2 at the Alliance Pipeline have subsequently been updated [9].

Task 4 References and Project-Supported Documentation (in Chronological Order)

[1] Kevin Topolski, Evan Reznicek, Burcin Cakir Erdener, Chris San Marchi, Joe Ronevich, Lisa Fring, Kevin Simmons, Omar Guerra, Bri-Mattias Hodge. and Mark Chung. 2022. *Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology*. Golden, CO: National Renewable Energy Laboratory. NREL/TP5400-81704. www.nrel.gov/docs/fy23osti/81704.pdf.

[2] Mark Chung, Amgad Elgowainy, Kevin Topolski, and Pingping Sun. 2022. "HyBlend: Pipeline CRADA Cost and Emissions Analysis." U.S. Department of Energy Hydrogen Program 2022 Annual Merit Review and Peer Evaluation Meeting, 6–8 June 2022, Arlington, VA.

[3] Mark Chung, Evan Reznicek, Kevin Topolski, Amgad Elgowainy, Pingping Sun, Chris San Marchi, Kevin Simmons, and Nicolas Huerta. 2023. "Blending Hydrogen into Natural Gas Pipelines and Underground Geologic Storage." Proceedings of the 2023 Fuel Cell and Hydrogen Energy Association Seminar and Workshop, 7–9 Feb. 2023, Long Beach, CA.

[4] Mark Chung, Amgad Elgowainy, Kevin Topolski, and Pingping Sun. 2023. "HyBlend: Pipeline CRADA Cost and Emissions Analysis." U.S. Department of Energy Hydrogen Program 2023 Annual Merit Review and Peer Evaluation Meeting, 5–8 June 2023, Arlington, VA.

[5] Kevin Topolski, Evan Reznicek, Jamie Kee, and Mark Chung. 2023. "Techno-economic Analysis of Blending Hydrogen into Natural Gas Transmission Networks." Proceedings of

the Pipeline Safety Research and Development Forum 2023, 31 Oct.–1 Nov. 2023, Crystal City, VA.

[6] Todd Deutsch, Chris San Marchi, Kevin Simmons, Kevin Topolski, and Amgad Elgowainy. 2023. "Pipeline Blending CRADA – A HyBlend™ Project Overview." NREL webinar, 26 Oct. 2023. www.energy.gov/eere/fuelcells/october-h2iq-hour-hyblend-initiative.

[7] Jamie Kee, Evan Reznicek, Mark Chung, and Kevin Topolski. 2024. "BlendPATH (Blending Pipeline Analysis Tool for Hydrogen)." NREL Software No. SWR-24-10.

[8] Kevin Topolski and Jamie Kee. 2024. "Pipeline Blending CRADA BlendPATH Webinar." NREL webinar, 16 Jan. 2024. www.youtube.com/watch?v=yorvh7MfZps.

[9] Kevin Topolski, Amgad Elgowainy, and Mark Chung. 2024. "HyBlend: Pipeline CRADA Cost and Emissions Analysis." U.S. Department of Energy Hydrogen Program 2024 Annual Merit Review and Peer Evaluation Meeting, 6–9 May 2024, Arlington, VA.

[10] Jamie Kee, Evan Reznicek, Kevin Topolski, and Mark Chung. n.d. *Blending Pipeline Analysis Tool for Hydrogen (BlendPATH) Documentation and User Manual*. Golden, CO: National Renewable Energy Laboratory. TBD.

[11] Evan Reznicek, Kevin Topolski, Jamie Kee, Omar Guerra, and Mark Chung. n.d. "A techno-economic model to assess the feasibility and cost of repurposing natural gas transmission pipeline networks to accommodate hydrogen." Journal article forthcoming.

TASK 5: Program Management

Subtask 5.1: NREL Program Management Will Provide Quarterly Reports.

In addition to submitting quarterly reports that detailed project progress from all the national labs, the program management team engaged in several other project-supporting activities. They organized and executed monthly meetings to provide all CRADA partners progress updates that also featured topical, external guest speakers. They also conducted outreach, giving more than two dozen overview presentations to educate the community on the goals of this CRADA project.

Subtask 5.2: NREL Program Management Will Provide a CRADA Final Report as per Article X of the Terms and Conditions.

This report meets the CRADA final report deliverable to complete the requirement in accordance with Article X.

Subject Inventions Listing: None

ROI #: None