U.S. Department of ENERGY

Natural Gas Decarbonization and Hydrogen Technologies Multi-Year Program Plan

January 2025

List of Acronyms

ANL	Argonne National Laboratory
AOI	Areas of Interest
CO_2	Carbon Dioxide
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
FECM	Office of Fossil Energy and Carbon Management
FOA	Funding Opportunity Announcements
FY	Fiscal Year
GHG	Greenhouse Gas
GHGI	U.S. Greenhouse Gas Inventory
GHGRP	Greenhouse Gas Reporting Program
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
H_2	Hydrogen
H_2PCOM	Hydrogen Pipeline Transport Cost Model
HFTO	Hydrogen and Fuel Cells Technologies Office
IRA	Inflation Reduction Act
NETL	National Energy Technology Laboratory
NGDHT	Natural Gas Decarbonization and Hydrogen Technologies
PHMSA	Pipeline and Hazardous Materials Safety Administration
PNNL	Pacific Northwest National Laboratory
R&D	Research and Development
RDD&D	Research, Development, Demonstration, and Deployment
SHASTA	Subsurface Hydrogen Assessment, Storage, and Technology Acceleration
TRL	Technology Readiness Level
WIPP	Waste Isolation Pilot Plant

Table of Contents

List of Figures

List of Tables

1. Overview

1.1 Introduction and Background

Hydrogen is an essential feedstock and fuel that helps to enable the utilization of the Nation's natural energy resources. Opportunities to improve the value proposition of hydrogen technologies are dependent on expanding hydrogen infrastructure and determining applications where hydrogen has a competitive business case. Beyond petrochemical and fuel cell transportation sectors, an expanded hydrogen value chain will include emerging market opportunities like metals and advanced alloys manufacturing, fertilizer and chemicals production, fuel use for marine, rail, and heavy-duty vehicle applications, and power generation for a variety of electrical applications.

The Natural Gas Decarbonization and Hydrogen Technologies (NGDHT) Multi-Year Program Plan is focused on advancing longer-term reductions in emissions through the wider use of hydrogen as an energy source. The NGDHT Program aims to advance technologies for: (1) groundbreaking technology development to produce clean hydrogen; (2) transportation of hydrogen and hydrogen carriers; and (3) geologic hydrogen storage—all in a manner that leverages existing natural gas resources and infrastructure at a mitigated environmental impact. Technology development and maturation under the NGDHT Program will focus on monetizing the carbon content of natural gas production infrastructure, to ensure safe and effective hydrogen blending within existing natural gas pipeline transportation pathways; and to characterize, demonstrate, and support the deployment of large-scale subsurface storage infrastructure. The Program will also develop analytical tools and models to evaluate potential advanced technology solutions, monitor technology performance metrics, perform technoeconomic and lifecycle analyses, and conduct resource evaluations.

1.2 Alignment with Administration and Congressional Priorities

The NGDHT Program is directly aligned with broader DOE strategy and Congressional direction received through annual funding appropriations, the current state of technology development, and the perspectives of the scientific research community. This alignment is described in the following sub-sections.

DOE Strategy

As the lead agency for energy research and development (R&D), the U.S. Department of Energy (DOE) develops technologies to diversify and increase domestic energy supplies and affordability, improve domestic energy production and use, and enhance the security, reliability, and resilience of energy infrastructure. Technological advancements are necessary to enable an expanding domestic hydrogen economy and DOE is well positioned to accelerate this development.

Administration Policy

In keeping with the new Administration's focus on energy dominance, hydrogen can further enhance U.S. energy security, resiliency and economic prosperity through: (1) variable production from diverse domestic resources across multiple industrial sectors; (2) having the highest energy density of all known fuels and reactivity as a critical feedstock for the chemicals and liquid fuels industries; (3) hydrogen fuel cell technologies can enable zero or near zero emissions in transportation, stationary or remote power, and portable power applications; (4) its potential for "responsive load" on the grid to enable grid stability and gigawatt-hour energy storage, and increase utilization of power generators, including nuclear, coal, natural gas, and renewables; and (5) hydrogen enabled innovations in domestic industries.

Congressional Language

Congressional direction regarding Natural Gas Decarbonization and Hydrogen Technologies research is evident from the Fiscal Year (FY)2025 Congressional budget guidance.

The FY2025 Senate Guidance for NGDHT[1] continues to provide support for hydrogen production, transport, and storage, with particular focus on producing net-negative carbon hydrogen through the processing of produced water and the conversion of various gas streams such as NGLs. The guidance also encourages development of an industry-led effort related to underground hydrogen storage, to mimic the Geothermal Energy Oil and Gas Demonstrated Engineering Program.

The FY2025 House Guidance for NGDHT[2] is focused more on hydrogen transportation, particularly regarding sensor development to ensure the feasibility of using existing pipelines for hydrogen and other low carbon fuels.

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1 "The Committee recommends up to $15,000,000 for a demonstration project focused on producing hydrogen from the processing of produced water and mineral substances and transporting hydrogen using existing energy infrastructure."

"The Committee recommendation provides $23,000,000 for critical research to convert abundant, low-cost natural gas, natural gas liquids, and other gas streams to low-carbon, sustainable products, including chemicals and fuels, such as hydrogen, ammonia, and methanol while reducing or eliminating air emissions. Comprehensive planning approaches for transitioning segments of the economy (e.g., the power sector) using hydrogen and other low-carbon fuels (e.g., ammonia) should be part of the program, including analysis of the infrastructure required to store and transport these fuels and the conversion of today's fossil fuel end users, energy-intensive industries, and disadvantaged communities alike, to safely and effectively adopt these fuels. This may include feasibility assessments on using existing infrastructure such as pipelines and underground storage facilities for low-carbon fuels. The Committee is encouraged by the collaborative efforts with industry under the Geothermal Energy Oil and Gas Demonstrated Engineering Program and recommends up to $20,000,000 for the Department to launch a similar industry-led effort in regard underground hydrogen storage."

"The Committee encourages the Department to continue expanding its research and demonstration capabilities toward the production, storage, transport, and utilization of hydrogen. This work shall focus on net-negative carbon hydrogen production from gasification and co-gasification of mixed wastes, biomass, plastics and traditional feedstocks, reversible solid oxide cell technology development for hydrogen and power production, carbon capture, advanced turbines, natural gas-based hydrogen production, hydrogen pipeline infrastructure, and subsurface hydrogen storage. Research on emerging technologies with low-cost CO_2 capture, such as dry reforming and sorbent enhanced reforming, should be addressed."

2 "The Committee directs the Department to conduct an analysis on the feasibility of utilizing existing natural gas infrastructure such as pipelines and underground storage facilities for low-carbon fuels. The Committee directs the Department to continue to conduct research and development on high-precision hydrogen-sensing technologies for leakage mitigation and includes up to $5,000,000 for this effort."

"The Department is directed to provide to the Committee not later than 120 days after enactment of this Act a report summarizing its efforts to date in these areas and its plans regarding the creation of hydrogen emissions monitoring and verification systems and leakage mitigation protocols in different contexts."

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Emerging Regulatory Framework

To produce real-world benefits from the NGDHT program's research, DOE must stay alongside of and work in cooperation with relevant regulatory agencies and other stakeholders seeking to comply with future regulatory frameworks. The Pipeline and Hazardous Materials Safety Administration (PHMSA), for instance, has a key role in enabling greater utilization of hydrogen in the United States through its pipeline safety regulatory authority and research efforts. In this regard, numerous technical, cost, safety, and institutional challenges must be overcome if hydrogen is to significantly contribute towards meeting the Nation's energy requirements (for details on the scientific communities' perspective on needed research, see Appendix A). Government agencies, many large and small private companies, and other organizations are making investments with the intention of addressing these challenges and facilitating the wider use of hydrogen as a competitive energy carrier (fuel) across a growing number of major energy markets within the next decade.

To enable the introduction of hydrogen as an energy carrier, a key initial focus of the Office of Fossil Energy and Carbon Management (FECM) and PHMSA is on research challenges for hydrogen delivery through local distribution natural gas pipeline infrastructure supported by bulk-volume underground hydrogen storage (UHS). FECM and PHMSA are conducting research and development (R&D) to improve reliability, lower the cost of hydrogen transportation and to reduce both the cost and environmental footprint of hydrogen storage.

1.3 Overarching Goals and Desired Benefits of RD&D Investments

Near Term Actions (FY25/26)

The NGDHT Program coordinates with other DOE offices to accelerate an expanded hydrogen-utilized economy through the monetized decarbonization of natural gas conversion, transportation, and storage. The program's near-term objectives are to:

- Support transformational concepts for clean hydrogen production from domestic natural gas resources, with emphasis on decarbonization technologies with marketable carbon product opportunities.
- Validate technologies for producing hydrogen from the processing of produced water, while also emphasizing technology opportunities for the concurrent application of economically viable mineral extraction.
- Ensure the suitability of existing natural gas pipelines and associated infrastructure for hydrogen transportation while emphasizing technology opportunities to detect and mitigate emissions.
- Identify underground storage infrastructure capable of handling high volumes of hydrogen, while seeking demonstration opportunities for other novel bulk storage mechanisms.

Mid-Term Actions (Fy26-Fy30)

The NGDHT program's mid-term actions are designed to accelerate the development, scale-up, and field validation of technologies, to enable commercial implementation by 2030:

Clean Hydrogen Production

- Develop new catalysts and processes that advance the production of clean hydrogen, with the potential to reach a cost target of $1/kg by 2030.
- Advance transformational and disruptive technologies for clean hydrogen production processes offering the greatest decarbonization benefits for fuels and chemicals derived from natural gas.
- Demonstrate technologies for producing hydrogen and mineral products from the processing of produced water.
- Demonstrate the production of hydrogen and valuable nanocarbons from the catalytic pyrolysis of associated gas that would otherwise be flared, with an NETL-patented catalyst, in a pilot project.
- Complete the assessment of state-of-the-art hydrogen production via pyrolysis as a cost-effective route to hydrogen production, with detailed analyses that fully assess the technology's viability.

Clean Hydrogen Transportation

- Support adapting existing natural gas pipeline transportation systems to transport hydrogen blends.
- Develop technologies to mitigate hydrogen leaks in pipeline infrastructure and handling equipment, including new materials designed to reduce hydrogen leakage from otherwise methane-tight systems.
- Determine the effectiveness of various leak detection technologies for hydrogen-natural gas mixtures and assess leakage rates for higher operating pressures (e.g., transmission level) and/or blends greater than 20% hydrogen.
- Design and develop highly sensitive and selective hydrogen sensing materials as an enabling component for leak detection sensors, for integration with multiple sensing platforms (e.g., optical fiber sensors, passive wireless surface acoustic wave sensors).
- Further develop a multi-functional, membrane-based, electrochemical, hydrogen sensor prototype developed under a previous national lab program, to incorporate hydrogen quantification, corrosion rate, and environmental humidity monitoring capabilities.
- Validate a real-time, in-pipe, spectroscopic gas analyzer for application to natural gas pipeline measurement and blending station monitoring of multiple hydrogen/natural gas blends.
- Develop techno-economic models in support of NETL Strategic Systems Analysis and Engineering collaborative efforts to model the full range of pipeline transport options for hydrogen hubs by calculating the technical performance and cost of a pipeline transporting pure hydrogen and blends of natural gas and hydrogen using NETL's Hydrogen Pipeline Transport Cost Model (H2_P_COM).
- Complete comparison of commercial, state-of-the-art, fossil-based ammonia production technologies in support of validating its use as a hydrogen carrier domestically and internationally, to enable hydrogen use.

Clean Hydrogen Storage

- Characterize high-potential subsurface hydrogen storage reservoirs (depleted oil and natural gas reservoirs, aquifers, salt caverns, and hard rock caverns).
- Conduct basin-specific hydrogen storage capacity estimates for large-scale, long-term hydrogen storage, coupling information on hydrogen production potential to establish the viability of hydrogen hubs for regional hydrogen production, transportation, and subsurface storage.
- Generate data from relevant literature and assessments to accelerate the development of pilot-scale field demonstrations for subsurface hydrogen storage projects, to validate storage and extraction efficiency.
- Implement recommendations of regional analyses for the scale-up of subsurface storage of hydrogen to support hydrogen markets and demonstrations at hydrogen hubs.

Long-Term Plan (FY30+)

Long-term plans for NGDHT include an increased focus on end-use needs and fully economic decarbonized natural gas technologies:

- **Clean Hydrogen Production**: Support pre-commercial technology options for decarbonized natural gas products beyond 2030.
- **Clean Hydrogen Transportation**: Continue to develop knowledge on fundamental hydrogen interactions with plastic and metal materials, as well as a comprehensive understanding of the performance limits of compression systems across a range of hydrogen blend ratios within the natural gas pipeline infrastructure.
- **Clean Hydrogen Storage**: Continue to support demonstrations of the safe and efficient injection, storage, and extraction of hydrogen from subsurface reservoirs at hydrogen hubs through 2035.

Program Snapshot

As of January 31, 2025, the NGDHT Program includes 15 active projects, which are distributed across the following four categories: (1) Hydrogen Production, (2) Hydrogen Production from Produced Water, (3) Hydrogen Transport, and (4) Hydrogen Subsurface Storage.

2. Technical Plan – Natural Gas Decarbonization and Hydrogen Technologies Program

2.1 Clean Hydrogen Production and Infrastructure for Natural Gas Decarbonization Description and Goals

New processes, new catalysts, and novel equipment designs will support the realization of DOE's production cost target of $1 per kilogram (kg) of hydrogen. This effort is focused on technologies that dissociate methane and light hydrocarbons into hydrogen and solid carbon through novel separation and improvements to energy and material efficiency techniques. Methods of interest include thermal pyrolysis, hot or cold plasma-based methane decomposition, or other novel approaches to break hydrocarbons into hydrogen and some form of marketable solid carbon product. Methods of thermochemical or biological hydrogen production from natural gas, either at the well head or in the reservoir, as well as production of naturally occurring hydrogen (natural hydrogen) are also included in this area. Concepts that use other means of reforming natural gas, or methods that produce a hydrogen carrier as the end-product, are also of interest.

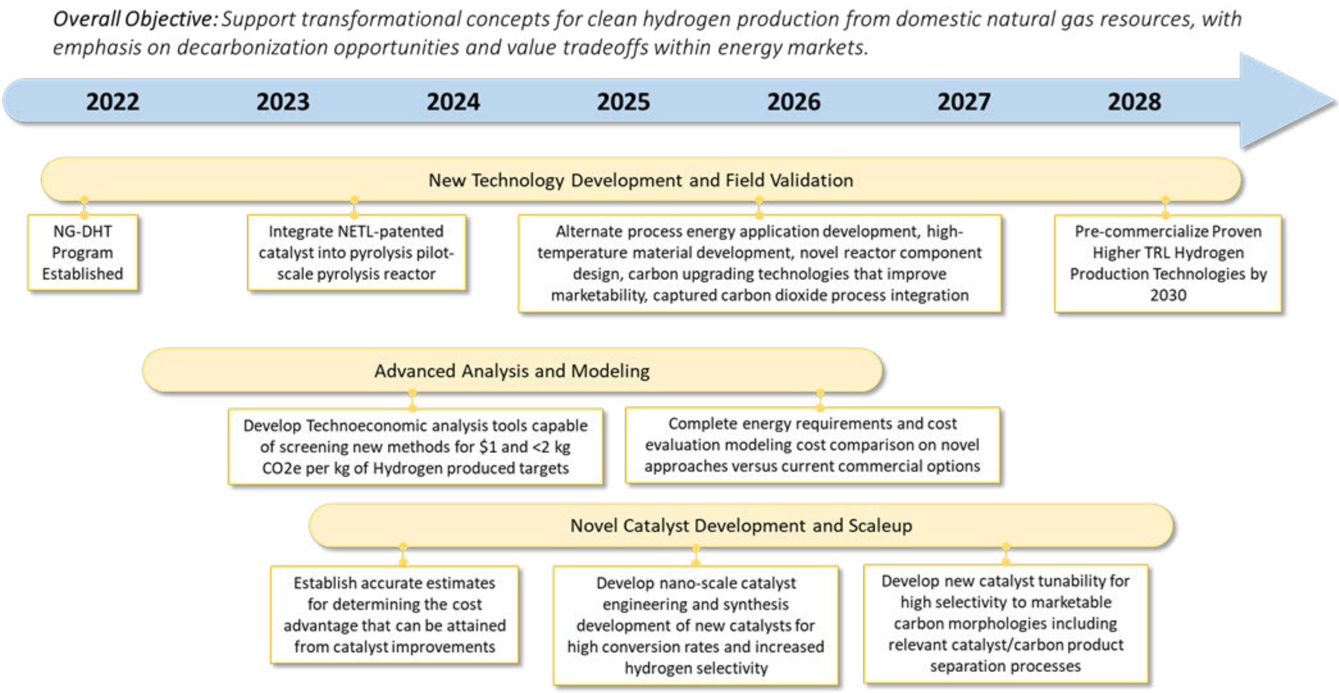
DOE's rationale for clean hydrogen production from natural gas is based on two themes.

- The first focuses on reducing the cost of hydrogen by supporting both low technology readiness level (TRL) innovation and pre-commercial scale-up, stimulating private sector investments, and spurring development across the hydrogen supply chain. Efforts will also address critical material and supply chain vulnerabilities and design for efficiency, durability, and recyclability. A key focus will be on coupling these new production methods together with investments in midstream infrastructure (storage, distribution) to reduce not only the production cost, but also the delivered cost of clean hydrogen.
- The second is a focus on regional networks through investments in scaling hydrogen hubs[1] , which will enable large-scale clean hydrogen production close to high-priority hydrogen users, allowing the sharing of a critical mass of infrastructure. Additionally, these investments will drive scale in production, distribution, and storage to facilitate market liftoff. Priorities will include reducing environmental impacts, creating jobs, securing long-term offtake contracts, and jumpstarting domestic manufacturing and private sector investment.

TIMELINE

Figure 1 illustrates the timing of the Hydrogen Production and Infrastructure for Natural Gas Decarbonization research program sub-elements over the 2022 to 2028 time period.

Figure 1. Research Timeline –Clean Hydrogen Production and Infrastructure for Natural Gas Decarbonization



Multi-Year Plan (FY25-FY29)

During the near term, research will be focused on three areas:

- **New Technology Development and Field Validation**: Key research in this area includes material development for high-temperature thermochemical processes, novel reactor component design, and evaluation of the viability of alternate energy options for methane dissociation. Processes producing solid carbon may need to consider innovative approaches for carbon upgrading technologies to effectively improve the morphology or structure of the carbon to ensure marketability, while processes producing carbon dioxide as a side product will need to advance integrated technologies for carbon dioxide separation and utilization technologies. Efforts in this area also include advancement of an NETL-patented catalytic pyrolysis process that will be integrated and evaluated in a pilot scale system. Future efforts in this area will include a heavy focus on accelerating the development of viable new methods and reactor designs from lower and mid-level TRL development stages to full-scale pilot field validations in support of establishing pre-commercial status.
- **Advanced Analysis and Modeling**: The development of technoeconomic and life cycle emission analytical methodologies will be critical for evaluation of the ability of technologies for converting natural gas to hydrogen to adequately achieve DOE's targets for production cost and emissions at the point of clean hydrogen production. These analytical methods must consider emissions not only from chemical reactions and any associated process energy requirements, but also from any ancillary processes, such as feedstock transport, pre-reforming, or contaminant removal. Any coincident

systems associated with carbon dioxide or solid carbon capture, storage, and/or utilization must also be accounted for. Energy requirement comparisons, economic viability assessments, and quantification on the scalability of new methods and how they directly compare to the current commercial options will be key to establishing the viability of these new processes for industry. Advanced technologies that rely on the sale of carbon nanofibers, carbon nanotubes, graphene sheets, and other high-grade carbon products as means to offset operational costs will especially benefit from accurate economic modeling. The development of these analysis methods and models will also allow the NGDHT program to directly integrate with other tools that consider the full life cycle of fuels, products, and energy systems. , such as the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed at Argonne National Laboratory. These efforts will anchor the development of novel approaches with potential to lower energy requirements and cost, versus commercial options that simply support the environmental and regulatory targets for clean hydrogen production at industrial scale.

- **Novel Catalyst Development and Scaleup**: Catalysts are critical for current commercial hydrogen production using steam methane reforming and future advancements in catalytic chemistry related to converting natural gas to decarbonized hydrogen will require nanoscale engineering and multidisciplinary approaches to enable high conversion rates, increased hydrogen selectivity, and mitigation of unwanted side or reverse reactions. Accurate kinetic models and experimental validation will allow the impact of new catalyst designs on overall hydrogen production costs to be quantified. Research targeting an increased understanding of realistic catalyst attrition rates, synthesis costs, and the practicality of using higher-cost transition metals supported on nano-engineered structures will enable transformative new catalysts technologies to be used at industrial scales. New synthesis technologies will enable the design of support materials and active sites at the atomic level to optimize production rates of hydrogen. In the case of pyrolysis methods, new methods for effective and continuous catalyst separation will ensure that market use cases for carbon nanostructures and morphologies will be realized and differentiated from the potentially saturated market for standard amorphous carbon black.

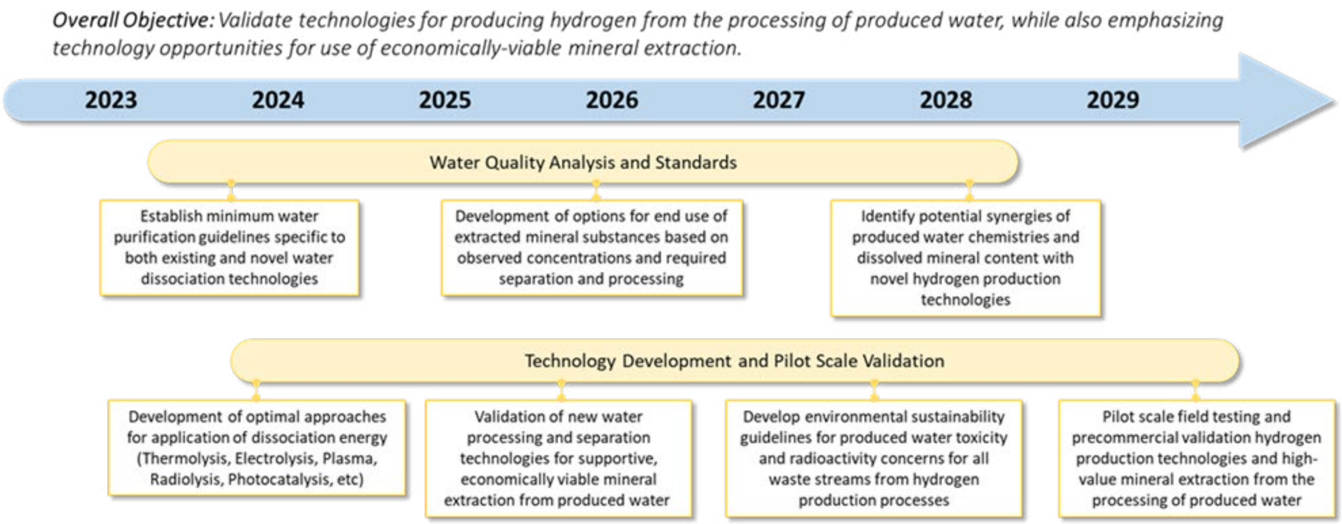
2.2 Hydrogen Production from Produced Water Description and Goals

FECM's approach for producing hydrogen from fossil energy related produced water is focused on understanding the impact of water quality on the sustainability and performance of novel processes that can be used to dissociate the water molecule into hydrogen and oxygen gas, while also leveraging any potential economic benefits of recovering dissolved mineral constituents. The laboratory validation and pilot scale demonstration of technologies that can create hydrogen from produced water and recover associated dissolved substances will enable the utilization of a major fluid waste stream resulting from the fracturing of oil and natural gas-bearing formations. Depending on the chemistry of the lithofacies in the reservoirs, produced water may contain many potentially useful chemical constituents like dissolved mineral salts and rare earth metals. At the same time, it may also contain harmful substances like radionuclides and heavy metals that introduce significant concerns associated with utilizing the water for hydrogen production. Advancing technology-based solutions that can integrate purification, avoid deactivation and catalyst poisoning, and efficiently convert water into clean hydrogen has the potential to monetize a major oilfield waste stream while supporting the development of a hydrogen "economy".

TIMELINE

Figure 2 illustrates the timing of the Hydrogen Production from Produced Water program sub-elements over the 2023 to 2030 time period.

Figure 2. Research Timeline – Hydrogen Production from Produced Water



Multi-Year Plan (FY25-FY29)

Future DOE-funded R&D efforts regarding hydrogen production from produced water will focus on two areas:

- **Water Quality Analysis and Standards**: The type of soluble constituents found in produced water include dissolved hydrocarbon gases, microbes, and other dissociable and non-dissociable organic compounds. There can also be inorganic dissolved gases, radionuclides, heavy metals, charged salts, and non-charged inorganic compounds. Produced water may also contain insoluble organic compounds like oil, wax, and grease, as well as inorganic scale, precipitates, grit, and colloids. For technology-based solutions that utilized produced water to be implemented, research is needed to develop a fundamental understanding of how to mitigate the presence of these compounds, many of which will likely have adverse effects on any electrochemical, catalytic, or other conversion processes implemented. In addition, processing and converting produced water will introduce significant considerations related to the handling of a feedstock with potential health, safety, and environmental concerns. Guidelines are needed for water purity, sustainability, and the environmental impact of using hydrogen production processes on oil field water waste streams with these chemistries; guidelines that are specific to both existing and innovative water dissociation technologies. In addition, research in this area can shed light on options for the use of extracted constituents based on observed concentrations, and the likelihood that any compounds present in produced water could possibly have a positive interaction with novel hydrogen production processes or catalysts.
- **Technology Development and Pilot-Scale Validation**: Another primary goal of the NGDHT program is to advance the state-of-the-art with laboratory and pilot scale validation of new technologies for producing hydrogen from wastewater. Evaluating alternative energy input options, such as thermolysis, radiolysis, photocatalytic, or other approaches, may reveal synergies, enable more economic mineral

extraction, or allow the isolation and removal of hazardous materials. Projects in this area that are currently being validated include a plasma-based approach for dissociating produced water into hydrogen and electricity. This method is targeting 80% efficiency for operation at a smaller modular scale, a reactor size that is more challenging for traditional thermochemical processes to maintain efficient operation. Another project is validating the use of a more conventional steam reforming process to produce hydrogen, but in a reactor configuration that optimizes heat integration with a water desalination and oxidation treatment that is specific to the contaminants in produced water. This research will identify optimal conversion approaches, validate the economic viability of mineral extraction, and properly quantify the environmental sustainability considerations of any additional waste streams created by producing hydrogen from produced water.

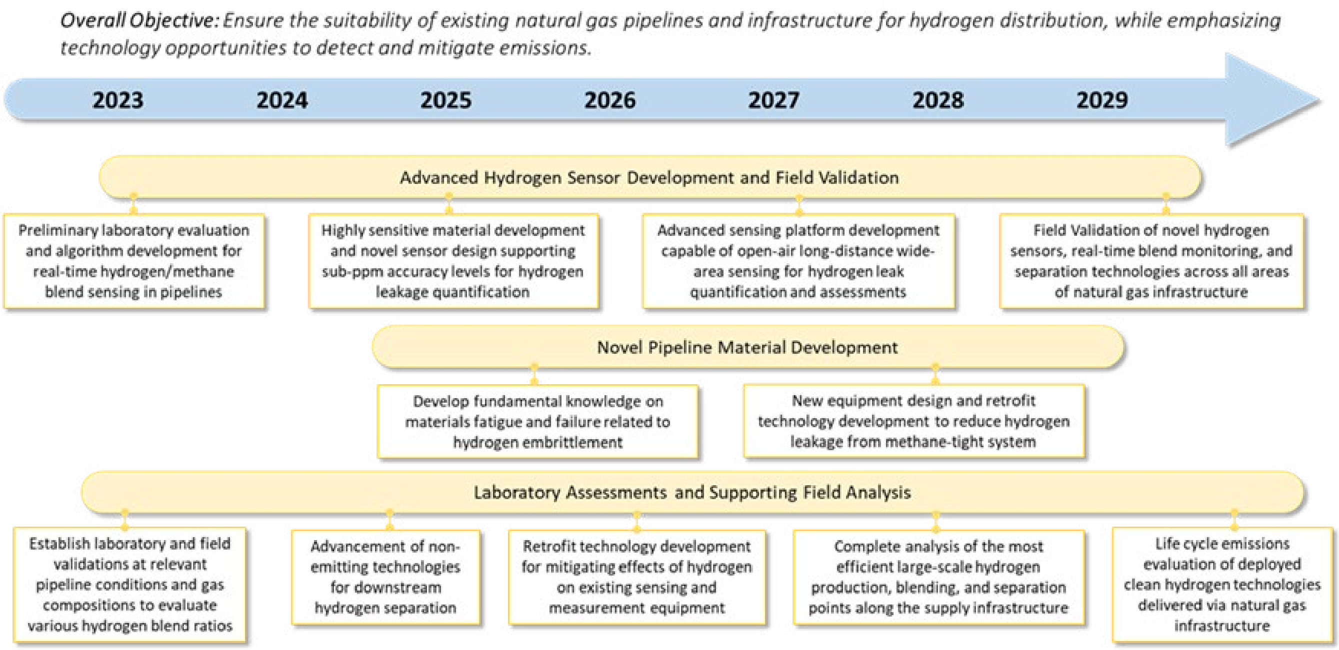
2.3 Technologies for Enabling Safe and Efficient Transportation of Clean Hydrogen within the U.S. Natural Gas Pipeline System Description and Goals

The existing natural gas infrastructure has the potential to provide a cost-effective near-term solution to enable nationwide hydrogen transport. Research is needed to further develop our understanding of the practice of hydrogen blending into natural gas streams to ensure safety and effectiveness when utilizing natural gas pipelines and equipment in this manner. To fully realize the decarbonization benefits of hydrogen transport within natural gas systems, robust sensor systems with sufficient sensitivity and spatial resolution for leakage detection over long distances and in ambient conditions will be required. Such sensors are necessary to ensure that the integrity of natural gas pipelines is maintained during hydrogen transport and to provide reliable leak quantification assessments sufficient to ensure leak mitigation efforts are minimizing system losses. Materials and equipment that are typically resilient and leak-tight under conditions of extended exposure to natural gas may require retrofit solutions and new materials to ensure safe and effective operation when handling hydrogen blends. Laboratory- and field-testing will be key to understanding the most effective blending ratios across a range of equipment options, natural gas compositions, and pipeline operating conditions. FECM research will develop the required supporting fundamental knowledge, validate relevant technical solutions for hydrogen sensor materials, develop new materials for pipelines and gas handling equipment, and perform laboratory assessments and field analyses that establish optimal hydrogen production, blending, and separation points within the natural gas supply infrastructure.

TIMELINE

Figure 3 illustrates the timing of the sub-elements for Enabling Hydrogen Transport Using Natural Gas Pipeline System Program over the 2023 to 2030 time period.

Figure 3. Research Timeline – Technologies for Enabling and Safe and Efficient Transportation of Clean Hydrogen within the U.S. Natural Gas Pipeline System



Multi-Year Plan (FY25-FY29)

The following descriptions provide details about efforts that will be pursued across three primary areas:

- **Advanced Hydrogen Sensor Development and Field Validation**: Laboratory evaluations of sensor electronics, new sensor materials, and algorithmic development for leak detection and measurement of hydrogen concentrations in pipelines are key areas of research for enabling hydrogen transport across the natural gas grid. Advancement of these systems to sub-ppm accuracy levels in the face of environmental interference will enable hydrogen leakage quantification over long distances and over wide areas in open air and allow for associated data management systems to alert operators for repair and leak mitigation actions. The deployment of these new sensor designs across a variety of scales, from handheld tools to autonomous drones and satellites, will allow for the validation of new sensor platforms to accurately monitor hydrogen transport across the entire natural gas pipeline system. Accurate and real time measurement of blend ratios at all points along the infrastructure, from production through transport and distribution to the end use application, will ensure efficient and safe utilization and, if required, proper separation of hydrogen and natural gas blends at the point of use. Research into new highly sensitive materials capable of safe operation in various gas compositions under pipelines conditions will be critical to developing novel sensor designs. The field validation of these new sensors will accelerate solutions that will power blend optimization, leak detection systems, and separation technologies across all areas of the natural gas infrastructure. Existing work in this area includes efforts at NETL to develop materials for an optical fiber hydrogen sensor platform capable of detecting hydrogen concentrations down to 0.5%, with associated model development for determining optimal sensor deployment locations for leakage detection.

- **Advanced Pipeline Material Development**: External activities via cooperative agreements in this area include projects to determine mechanical property qualification metrics across several alloys and microstructures to correlate to hydrogen embrittlement resistance in pipeline steels. FECM's continuing research on fundamental knowledge on material failure related to long term hydrogen exposure will be critical in the development of new materials, new equipment designs, and retrofit technologies to reduce failures and hydrogen leaks from otherwise methane-tight systems.
- **Laboratory Assessments and Supporting Field Analysis**: Establishing laboratory and field validations of new technologies and materials at relevant pipeline conditions and gas compositions with various hydrogen blend ratios is a critical effort for ensuring safe and effective hydrogen transport in natural gas pipelines. Existing awards in this area include testing with blended hydrogen in a natural gas pipeline test loop operating at relevant temperatures and pressures with blends up to 20% hydrogen by volume to evaluate the effects of hydrogen on the real-world performance of existing natural gas components like compressors, meters, gaskets, valves, and pulsation control systems. The application of the results from tests like these and laboratory evaluations will support industry adoption by demonstrating effective mitigation of the adverse effects from hydrogen on existing and new natural gas sensing and measurement equipment. This area will also develop and assess methods for emissions-free technologies for hydrogen separation from natural gas blended streams for downstream applications that require pure hydrogen. Field analysis of the most efficient hydrogen production, blending, and separation points along the supply infrastructure will allow for the effective large-scale deployment of clean hydrogen.

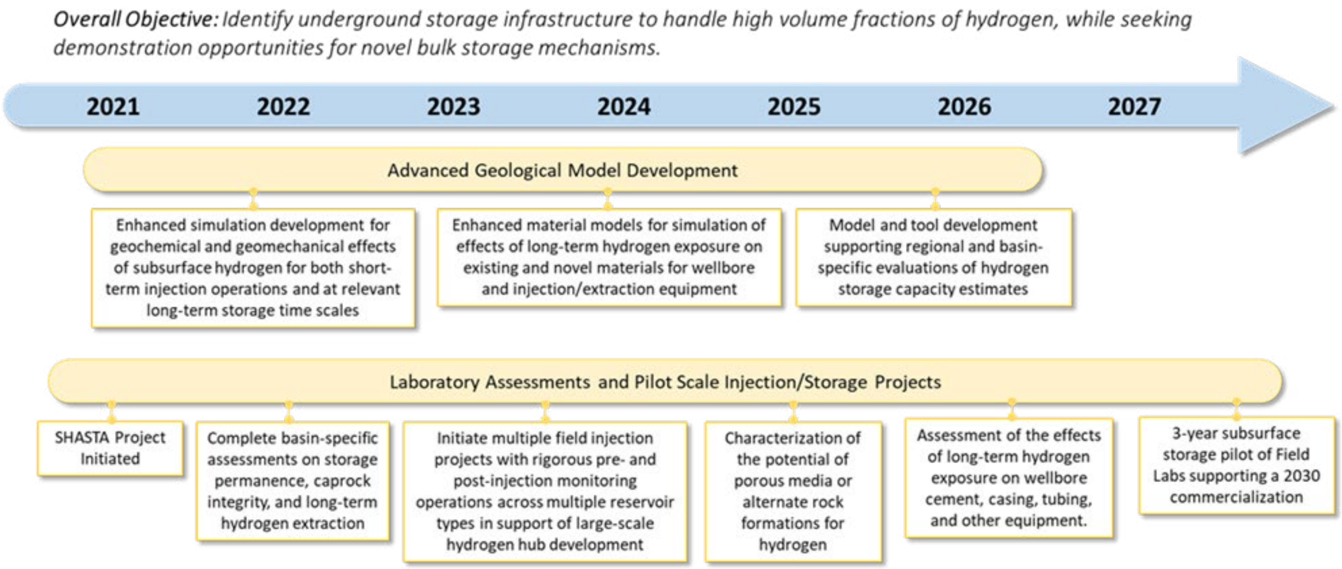
2.4 Fundamental Research to Enable High-Volume Subsurface Hydrogen Storage Description and Goals

DOE and FECM are committed to research on the fundamental concepts that will enable the high-volume, long-term subsurface bulk hydrogen storage needed to support regional hydrogen hubs and the eventual deployment of a nationwide hydrogen supply. This effort will be supported by the development of high-fidelity geological models capable of simulating the impact of hydrogen exposure on specific reservoirs and formation fluids in depleted oil and natural gas reservoirs, saline formations, and salt structures for the purpose of evaluating storage permanence and long-term hydrogen delivery potential. Assessments of the effects of long-term hydrogen exposure on associated wellbore materials, well completion equipment, and other injection/delivery equipment will directly support pilot-scale field demonstrations of the efficiency of geological storage and delivery of hydrogen. This work will culminate in basin-specific hydrogen storage capacity estimates and viability assessments for Hydrogen Hubs and their utility in a future hydrogen supply chain for industrial or power sector end-users.

TIMELINE

Figure 4 illustrates the timing of Fundamental Research to Enable High-Volume Subsurface Hydrogen Storage program sub-elements over the 2021 to 2028 time period.

Figure 4. Research Timeline – Fundamental Research to Enable High-Volume Subsurface Hydrogen Storage



Multi-Year Plan (FY25-FY29)

DOE's fundamental research to enable high-volume subsurface hydrogen storage is focused on two areas:

- **Advanced Geological Model Development**: Modeling tools that can capture the geochemical and geomechanical effects of introducing hydrogen into the subsurface during short-term injection operations and for long-term storage will be a key focus of FECM's research into large volume geological hydrogen storage. Selected efforts include fundamental laboratory and modeling studies in the Anadarko, Williston, Permian, and Appalachian Basins, and the evaluation of multiple geological formations such as saline reservoirs, salt formations, and depleted oil and gas reservoirs, including fractured shale formations. These modeling efforts include the validation of underground hydrogen storage through experimental techniques, numerical simulation of multiphase fluid flow, and validation on the economics of injection and extraction including the impact of hydrogen loss through permeation and potential microbial metabolic processes that consume hydrogen. Work in this area will need continual R&D to improve constitutive models for existing and novel materials, to ensure accurate time scale representations of all relevant geological influences, and to accurately simulate the effects of cyclic hydrogen exposure on equipment. This work will target the development of models and tools capable of basin-specific evaluations of geological formations for their ability to meet the storage needs for safe and reliable nationwide industrial hydrogen utilization.
- **Laboratory Assessments and Pilot Scale Injection/Storage Projects**: Evaluation of modeling results in the laboratory and under field conditions will also be a key aspect of identifying technological hurdles, adequately quantifying the operational risks, and enabling broad acceptance of the subsurface storage

of pure hydrogen and hydrogen/natural gas blends. Ongoing projects include an extramural full-scale field test with a hydrogen injection borehole and monitoring wells in DOE's Waste Isolation Pilot Plant (WIPP) and an NETL Field Labs three-year effort that will include the injection of thousands of metric tons of hydrogen coupled with rigorous pre- and post-injection monitoring operations to better characterize reservoir conditions, ensure reservoir integrity and eliminate contact with underground sources of drinking water and other sensitive receptors. Research in this area will need to continue and expand to multiple field injection projects in a variety of reservoir types to support large-scale regional hydrogen hub development and complete accurate assessments of storage permanence, caprock integrity, and long-term hydrogen delivery performance from basin-specific formations. Characterization work will also need to continue to support the evaluation of alternate subsurface rock formations for hydrogen storage in areas with limited options geologically but where long-term storage is needed to support end-users.

3. Future R&D Opportunities

Hydrogen can complement other energy and manufacturing technologies in reducing emissions across industry, transportation, and electricity generation.

Production

Hydrogen produced from the Nation's large natural gas reserves offers a viable near-term means to help monetize the carbon content of electricity production with firm, dispatchable generation. Future research efforts will need to continue to accelerate the advancement of new technologies towards commercialization. Continued research can support the utilization of fossil-derived hydrogen and drive large-scale commercial validation of new technology-based solutions that ensure a sustainable and decarbonized hydrogen supply from natural gas production and delivery.

The NGDHT Program's validation of methods for creating hydrogen from produced water also establishes an important foundation for future production research. The processes developed can spawn new applications of similar technologies on other industrial wastewaters and other naturally occurring impure water sources (e.g., brackish subsurface or surface water sources). Future research that focuses on scaling up these water treatment methods, water dissociation processes, and mineral recovery technologies will expand use to other waste streams, particularly the utilization of potentially highly hazardous waste streams that are not typically seen as viable feedstocks (e.g., mine runoff).

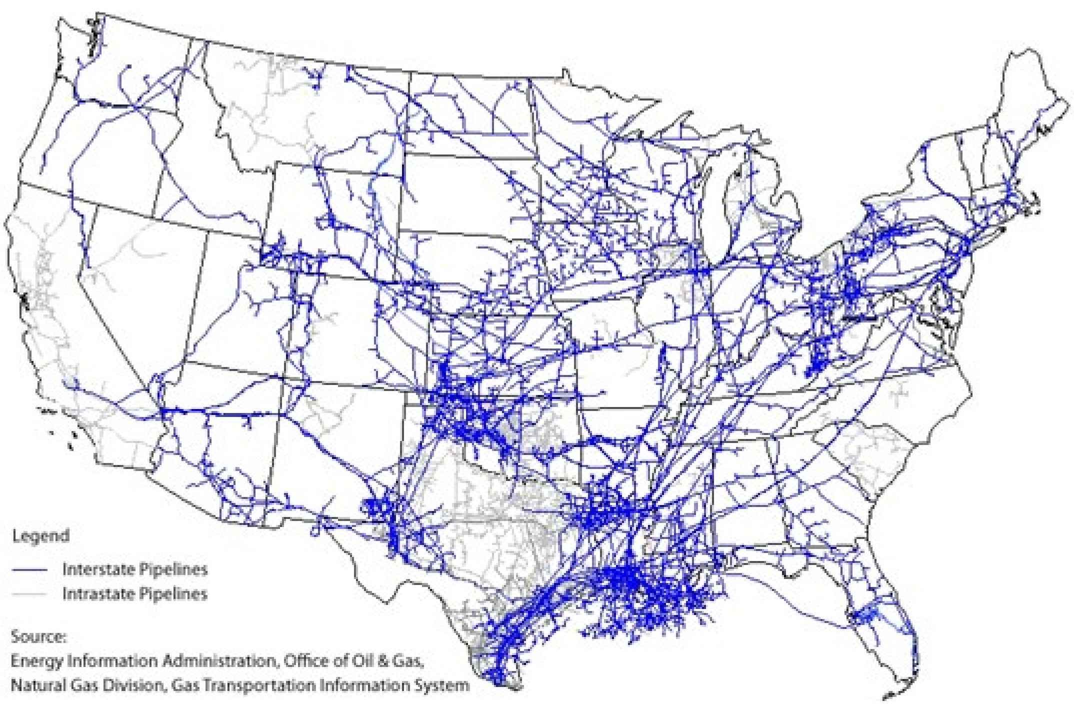
Transport

The risk reduction, material development, and pilot-scale validation of the use of natural gas infrastructure for nationwide distribution of hydrogen in the NGDHT Program is the first step in enabling commercially viable decarbonization in almost any location in the lower forty-eight states. The transportation system consists of over 305,000 miles of transmission pipelines and 2.2 million miles of distribution pipelines (as seen in Figure 6). The efforts to validate new pipeline materials, coatings, retrofit technologies, sensor platforms, and separation methods will enable future research for the long-term utilization of the natural gas grid and for hydrogen transport at blends beyond 20% while integrating appropriate emissions guidelines for pure hydrogen and hydrogen blends. Continued R&D can enable the safe and effective transport and use of hydrogen at higher blend ratios through real time monitoring and analysis with integrated data collection and sensor deployment that allows optimization from the point of production to the downstream utilization.

Future research will provide technology that can address the challenges that arise for blended natural gas streams when hydrogen concentrations exceed 20% of the total volume, either for increased decarbonized fuel use or for applications where the hydrogen content is separated before end use. While hydrogen has a higher energy density than methane per unit mass, it is three times less energy dense than methane on a volume basis, so as the ratio of hydrogen rises in a pipeline the volume of energy being delivered effectively decreases. Additionally, because hydrogen will combust across a wider range of air concentrations than methane, making combustion more difficult to control, equipment must be made intrinsically safe, or explosion proof, when hydrogen volumes exceed 25%.[2]

Future research can also focus on hydrogen transport extending beyond the use of the domestic natural gas grid to support U.S. economic growth through global hydrogen exports. Technology development that can reduce the costs of conversion to ammonia, other hydrogen carriers, or solid-state storage before export and the conversion back to hydrogen after import, can promote the United States as an enabler of global decarbonization, particularly for countries with high domestic hydrogen production costs.

Figure 5. U.S. National Gas Pipeline Network (EIA)



The NGDHT Program will continue to support R&D to determine the viability of utilizing or retrofitting existing natural gas pipelines to transport natural gas and hydrogen blends. Simultaneously, FECM's Methane Mitigation Technologies program (MMT) will expand its R&D activities to investigate blended natural gas stream transmission throughout the U.S. by developing advanced materials and coatings, as well as gas separation and leak detection technologies.

Storage

The NGDHT Program's effort to characterize, model, and field test regional hydrogen geological storage will advance the state-of-the-art and promote further research efforts in understanding fluid-water-rock interactions, biogeochemical impacts, and relevant equipment and material degradation considerations. Future research can also extend to quantify other relevant areas more fully, such as the potential for induced seismicity, reservoir degradation, long term hydrogen migration, and optimal cushion gas utilization. Continued R&D will enable a more comprehensive understanding across the processes that impact the recoverability of subsurface hydrogen and develop pathways and business cases for commercial validation and scale-up to fully integrate subsurface storage into the Nation's energy system. This research will also enable industry to develop in accordance with potential future regulations surrounding injection and recovery operations, proper post-injection reservoir monitoring, and the protection of sensitive receptors like nearby groundwater.

FECM's Subsurface Hydrogen Assessment, Storage, and Technology Acceleration (SHASTA) effort will develop technologies and address key technological hurdles to enable broad public acceptance and the technical and economic viability for subsurface storage of pure hydrogen and hydrogen/natural gas mixtures. A potential Phase II research agenda for SHASTA post-2025 includes several hypothetical research areas. These could include extramural funding for pilot-scale testing of supporting technologies, establishing industry consortia, a meso-scale demonstration led by national laboratories, and additional R&D focused on infrastructure investment.

4. Collaboration

While Congress required DOE to develop a national strategy and roadmap, DOE will undertake these activities in collaboration with multiple federal agencies, including the U.S. Departments of Agriculture, Commerce, Defense, Energy, Interior, Labor, State, Transportation, and Treasury, Environmental Protection Agency, National Aeronautics and Space Administration, National Science Foundation, and Office of Science and Technology Policy, in close coordination with the Executive Office of the President (see Appendix B for details on NGDHT collaborative efforts).

Appendix A – Science Community Perspectives

The 2022 National Academy of Sciences study titled "*Greenhouse Gas Emissions Information for Decision Making: A Framework Going Forward*, made the following recommendations:

Greenhouse gas emissions information (e.g., observations, data analysis, activity data, emission factors) development at more granular temporal and spatial scales with source-level detail should be accelerated to meet the rapidly increasing needs of cities, states, and provinces for managing their emissions.

The accuracy and representativeness of all underlying data used to estimate greenhouse gas emissions (e.g., emission factors, activity data) should be further improved.

Greenhouse gas emissions estimation research efforts should transition with urgency to operational capabilities with institutions to maintain and ensure longevity.

Greenhouse gas emissions data collection, modeling, and information development should be designed and implemented to enable a fuller integration and "hybridization" of information and approaches.

The 2021 International Energy Agency's (IEA) "Global Hydrogen Review" made several near-term policy recommendations to achieve net-zero emissions milestones by 2050. These include, among others, recommendations to:

- Develop hydrogen energy strategies and roadmaps for deployment.
- Advance new hydrogen technologies to commercialization scale as quickly as possible.
- Develop a policy framework that stimulates demand for low-carbon hydrogen to promote investment in production plants and infrastructure.
- Create incentives for using low-carbon hydrogen.
- Establish hydrogen certifications, standards, and regulations.

In 2019, IEA's report on the "*The Future of Hydrogen*" noted that offsetting 5% of the volume of natural gas supply in a given country would be significant, but noted several challenges related to the storage, transmission, and distribution of hydrogen, such as:

The cost of long-distance hydrogen transmission and storage will potentially be three times the cost of hydrogen production alone.

A large-scale intercontinental hydrogen value chain will require the availability of adequate storage capacity and geological storage is the best option for large-scale and long-term storage situations.

Viable long-distance transmission and local distribution of hydrogen may require lower cost compression options, the use of liquefaction, or the use of liquid hydrogen carriers (e.g., ammonia).

Truck transport of hydrogen is not likely to be cost effective over the long term for local distribution and the use of pipelines will likely be required if there is large, localized demand.

Blending hydrogen into existing natural gas pipeline networks is a viable option to lower investment costs and risks associated with dedicated hydrogen infrastructure but presents its own challenges due to hydrogen's tendency to escape methane-tight seals and hydrogen embrittlement of steel.

Safety and public acceptance issues can be deterrents for using hydrogen carriers like ammonia and liquid organic hydrogen carriers.

Hydrogen imports could be cheaper than domestic production for some areas of the world using electrolysis (e.g., Japan).

In its 2023 Technology Monitor Report, the IEA Hydrogen Technology Collaboration Program's Task 42 presents the current state-of-the-art for the underground storage of hydrogen and discusses the need for large-scale underground storage of hydrogen to maintain a secure, stable, and affordable supply for the nation. The report addresses the challenges for development and future upscaling of geological hydrogen storage, and makes several recommendations:

Use laboratory experimentation, modeling, and pilot scale tests on multiple geological environments under various operational conditions to increase technological confidence in UHS.

- Identify and resolve UHS market gaps.
- Improve and validate UHS risk assessments and methodologies for quantifying uncertainty.

Establish a systematic approach to promote societal acceptance of UHS.

Appendix B – Collaborative Efforts

Hydrogen Production

DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) launched the H2@Scale initiative in 2016 to fund projects and activities for national laboratories and industry to accelerate early-stage hydrogen technologies across the areas of hydrogen production, hydrogen surface infrastructure, grid integration, safety, codes, and standards.[3] This funding has advanced several promising hydrogen production technologies building on natural gas technologies that have advanced to higher TRLs, such as the natural gas pyrolysis projects launched under the Advanced Research Projects Agency–Energy's (ARPA-E) Methane Pyrolysis Program (see Table 2). FECM participated in the annual review meetings, including representation on the panel discussion for scaling up methane pyrolysis technologies at the final annual review meeting in 2022. FECM is committed to bringing the most promising early-stage processes that produce clean hydrogen and advanced carbon materials from fossil fuels to pre-commercial status through continued support and collaboration with other offices, national laboratories, and industry. The ARPA-E pyrolysis projects were divided up into two groups based on their primary target products—hydrogen production-focused and carbon product-focused—and included methods of upgrading less structured pyrolysis carbon to higher value structures. These projects predate DOE's Hydrogen Earthshot goal, hence many projects achieved cost estimates that are higher than $1.00 per kilogram of hydrogen. Table 1 provides a description of each project that was presented, with notes on the pyrolysis method being used, hydrogen cost estimates achieved, and the status of the latest prototype. FECM's collaboration and review of these projects focused on identifying key challenges for future programs that would likely to be funded through FECM. The potential areas for further development by FECM included process performance increases and cost reductions, support for scale-up from bench scale to pilot scale, design of ancillary carbon build-up removal techniques and catalyst separation processes, and further catalyst design for increased activity.

Table 1. ARPA-E Hydrogen Production Projects

	Project Title	Performer	ARPA-E Funding	FECM "Related Project"	Method	Hydrogen Production Cost Goals	Prototype Status
"Hydrogen Focused"	High-Throughput Methane Pyrolysis for Low-Cost, Emissions-Free Hydrogen	PARC	OPEN 2018	FE0031868	**Thermocatalytic Pyrolysis** - Zinc droplets serve as homogeneous thermal mediator and catalyst for methane decomposition.	Targeting **$3.00/ kg** pure hydrogen (with modeling showing **$1.37/kg** hydrogen if value of carbon product can be increased)	Bench Scale Reactor without required continuous carbon removal
"Hydrogen Focused"	Carbon Dioxide-Free Hydrogen and Solid Carbon from Natural Gas Via Metal Salt Intermediates	Johns Hopkins University	OPEN 2018	-	**Thermocatalytic Pyrolysis + Metal Salt Reduction and Reclamation** - Methane reacts with $NiCl_2$ to provide heat and create a Ni/C intermediate catalyst for methane decomposition, followed by a low temperature $NiCl_2$ reclamation step that further generates hydrogen.	Targeting less than **$1.00/kg** pure hydrogen	Finalizing $6 million investment for demonstration scale plant (100-1,000 metric tons/year)
"Hydrogen Focused"	Molten-Salt Methane Pyrolysis Optimization Through in-situ Carbon Characterization Reactor Design and Binary Chloride Salts as Catalysts for Methane to Hydrogen and Graphitic Powder	C-Zero	TINA 2019 H2@scale	-	**Thermocatalytic Pyrolysis** - Molten salt serves as heterogeneous thermal mediator and catalyst for methane decomposition in bubble column reactor.	Targeting large scale hydrogen production for power generation	Pilot Scale Plant planned operational by end of 2022
"Hydrogen Focused"	Extremely Durable Concrete using Methane Decarbonization Nanofiber Co-products with Hydrogen	University of Colorado	H2@ scale	FE0031870	**Thermocatalytic Pyrolysis** - Atomic Layer Deposition of metal on fumed silica serves as heterogeneous thermal mediator and catalyst for methane decomposition and carbon nanofiber synthesis.	Targeting **$2.00/ kg** hydrogen (offset with carbon fiber concrete additive product)	TRL 5 planned for late fall 2022

	Project Title	Performer	ARPA-E Funding	FECM "Related Project"	Method	Hydrogen Production Cost Goals	Prototype Status
"Carbon Focused"	Converting Hydrocarbons to Recyclable Materials for Metal Replacement with Positive Hydrogen Output	Rice University	OPEN 2018	-	**Thermocatalytic Pyrolysis** - Solid particles serve as heterogeneous catalyst for methane decomposition and carbon nanotube synthesis subsequently spun into fibers.	No hydrogen production targets. Focusing on high performance Carbon Nanofiber synthesis	Bench Scale Reactor not yet meeting targets
	Structural, High Value Carbon and Hydrogen from Natural Gas	Nanocomp	OPEN 2018	-	**Thermocatalytic Pyrolysis** - Solid iron nanoparticles form in a fluidized stream and serve as heterogeneous catalyst for methane decomposition and carbon nanotube synthesis.	Targeting **$1.50/kg** hydrogen (offset by Carbon Nanotube fiber product) but process requires H2 recirculation	Bench scale reactor meeting targets
	Energy-Efficient Conversion of Methane-Derived Carbon into Valuable Carbon Fibers	Johns Hopkins University	TINA 2019	-	**Fiber Spinning Process** - Gel or blow spinning of fibers using carbon black derived from pyrolysis, followed by heating that upgrades to graphitized carbon fibers (GCFs).	No hydrogen production targets. Focusing on high performance Carbon fiber synthesis	Bench scale reactor meeting targets
	Co-Synthesis of Hydrogen and High-Value Carbon Products from Methane Pyrolysis	Stanford University	TINA 2019	-	**Thermocatalytic Pyrolysis** - Solid Fe/Al203 serves as heterogeneous catalyst for methane decomposition and carbon nanotube synthesis.	Targeting **$1.50/kg** hydrogen (can be further offset by Carbon Nanotube product)	Bench Scale Reactor without required product separation

Hydrogen Transport

DOE's HFTO launched the HyBlend[4] collaboration in support of the H2@Scale initiative in 2021. HyBlend includes several R&D projects being conducted by a team of National Laboratories, led by the National Renewable Energy Laboratory (NREL), and in collaboration with over 30 industrial partners. Key aspects of HyBlend include:

- Structural Integrity and risk assessment of hydrogen pipelines (Sandia National Laboratories [SNL])
- Degradation of structural properties–metals (SNL)
- Degradation of structural properties–polymers (Pacific Northwest National Laboratory [PNNL])
- Lifetime prediction of polymer materials in hydrogen and blends (PNNL)
- Life-cycle analysis of natural gas/hydrogen blends (Argonne National Laboratory [ANL])
- Life-cycle analysis of synthetic methane production from CO_2 + H_2 (ANL)

- Techno-economic analysis of pipeline preparation cost for hydrogen blending (NREL)
- Value proposition of hydrogen blending (NREL)
- Summary comparison of Hydrogen blending using alternative pathways like synthetic natural gas (NREL)
- Water heater burner design, integration, and evaluation (Oak Ridge National Laboratory).

HFTO actively collaborates with FECM on topics relevant to HyBlend, and the NGDHT program plan includes efforts that will directly support the sub-elements within the HyBlend research project, specifically contributions, such as:

- Identification of variables that contribute to risk of transmission and distribution of hydrogen/natural gas blends
- Identification of operational conditions for transmission and distribution systems
- Evaluation of critical parameters of hydrogen-assisted fatigue and fracture of pipeline metals and joints
- Lifecycle analysis support for areas related to hydrogen production emissions and hydrogen blend pipeline transmission emissions
- Cost estimates for required pipeline infrastructure retrofits for hydrogen blending, including economics of new material options
- Gas blend composition data along pipelines to support materials management model development
- Support for identification of natural gas networks, regions, and time scales of interest for using hydrogen blends.

Subsurface Storage of Hydrogen

A recent Inter-Agency Agreement between the DOE's FECM and the DOT's PHMSA is focused on collaborative efforts to develop safe and effective regulatory guidance and oversight for UHS. The scope of work is to establish the technical criteria for pure and blended hydrogen storage in subsurface geologic reservoirs by: (1) identifying sources for potential hydrogen resource and storage reservoir asset loss; and (2) identifying possible mitigation options or remedies for consideration by governing entities that may have regulatory primacy or authority. The work is being executed by NETL, Lawrence Livermore National Laboratory (LLNL), PNNL, and SNL, with each funded at $250,000 per year ($2 million total) through a two-year period of performance through February 2025.

The objectives of this collaboration are to: (1) identify and understand existing PHMSA regulatory functions and needs as they relate to characterizing, permitting, and assessing underground natural gas storage (UGS) operations; (2) quantify the suitability of existing UGS facilities (both well and geologic systems) for storing pure and blended hydrogen; and (3) characterize operational expectations and quantify risk of hydrogen resource loss and UGS asset degradation, as functions of geologic and operational conditions.

The agreement defines seven tasks funded through FECM's SHASTA project, with 24 milestones spread between November 2023 and February 2025. The seven tasks are focused on determining geologic suitability, understanding regulatory considerations, developing monitoring recommendations, predicting delivery performance, assessing potential for caprock leakage, understanding gas dynamics within storage caverns, and developing functional requirements and mockups for a web-based tool to gather the data necessary for assessment of an existing UGS asset for UHS. The task breakdown by assigned laboratory is shown below:

- Geologic Suitability (NETL)
- Regulatory Considerations (PNNL)
- Monitoring Recommendations (SNL)
- Delivery Performance (LLNL)
- Caprock Leakage (NETL)
- Cavern Storage Gas Dynamics (SNL)
- Web-Based Tool Design (PNNL)

References

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