HARNESSING HYDROGEN

A Key Element of the U.S. Energy Future

VOLUME I • REPORT SUMMARY • National Petroleum Council • 2024

National Petroleum Council

An Oil and Natural Gas Advisory Committee to the Secretary of Energy

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April 23, 2024

The Honorable Jennifer M. Granholm
Secretary of Energy
Washington, D.C. 20585

Dear Madam Secretary,

In response to your request dated November 8, 2021, the National Petroleum Council (Council) conducted a comprehensive study on the deployment of low carbon intensity (LCI) hydrogen at scale in the United States across the entire value chain, including production, storage, transportation, and end uses, to support decarbonization of various energy and key market sectors. If deployed at scale, LCI hydrogen technology applications in the hard-to-abate sectors can support achieving U.S. carbon emissions reduction ambitions at a lower cost to society.

This report, *Harnessing Hydrogen: A Key Element of the U.S. Energy Future*, evaluated the key economic, policy, regulatory, technical, and public acceptance challenges and critical enablers along the hydrogen value chain that must be addressed to achieve at-scale LCI hydrogen deployment. The study effort involved a diverse team of approximately 300 experts from more than 100 organizations, 70 percent of which come from outside of the oil and gas industry. This study leveraged scenario-based modeling, partnering with the Massachusetts Institute of Technology (MIT) Energy Initiative.

The report generates unique insights due to the diverse perspectives of the study participants, many of whom have practical experience executing large-scale projects, informing the technoeconomic and life cycle assessment models. The Council would like to highlight three key findings from the report:

First, LCI hydrogen can play a key role in reducing emissions in hard-to-abate sectors at a lower cost to society. The study determined that, while existing policies and legislation are expected to double the current U.S. demand for hydrogen by 2050, these levers, along with anticipated cost reductions, are insufficient to stimulate the growth of LCI hydrogen deployment needed to support the country's net zero ambitions by 2050 at a lower cost to society. LCI hydrogen, when applied in hard-to-abate applications within the Industrial, Transportation, and Power sectors, could abate approximately 8 percent of total U.S. emissions by 2050, but achieving net zero ambitions by deploying multiple technology solutions could cost up to 3 percent of the Gross Domestic Product (GDP) annually. Achieving that same outcome without leveraging LCI hydrogen would likely increase this annual cost by an incremental 0.5 to 1 percent of GDP.

Second, the LCI hydrogen production mix will be driven by multiple aspects of the various hydrogen production pathways, including their relative speed to scale, delivery cost reductions, and carbon intensities. LCI hydrogen production is expected to be initially driven by hydrogen produced via natural gas reforming with carbon capture and storage, due to its lower production cost and the ability to rapidly scale production and infrastructure. The production mix under a net zero emissions scenario is expected to include an increasingly larger share of renewable electrolytic hydrogen due to its lower carbon emissions and the projected higher future cost of carbon. Deployment of LCI hydrogen from the two key production pathways will be needed to support net zero objectives and will require addressing specific constraints for each pathway.

Third, LCI hydrogen deployment will be marked by regional variation in production development and demand activation by sector. LCI hydrogen production can activate now in regions with abundant renewable or natural gas resources, existing anchoring demand, access to infrastructure, or supportive policies. Expanding LCI hydrogen more broadly across the United States will require additional federal policy and investment in technologies and infrastructure.

Significant and rapid progress across many areas must occur to move through three phases of LCI hydrogen market development: Activation, Expansion, and At-Scale. This report identifies three categories of critical enablers that could aid in rapid LCI hydrogen deployment and progression across all regions: policy and regulation; societal considerations, impacts (SCI) and safety; and targeted investments in technology and research, development, and deployment (RD&D). The Council provides key recommendations for the critical enablers:

- **Policy and Regulation:** Develop additional legislation to overcome cost gaps between incumbent fuels and feedstocks and LCI hydrogen, increase investor confidence, and streamline regulatory frameworks.

- **SCI and Safety:** Ensure reliable value chains while providing societal benefits, improving community engagement, and enabling workforce development.

- **Technology and RD&D Investments:** Prioritize investments to close technology gaps across the LCI hydrogen value chain, address technical bottlenecks, and support public/private research programs.

The recommendations provided by the Council in this *Harnessing Hydrogen* report aim to accelerate the deployment of LCI hydrogen in the United States, contributing to the country's net zero target by 2050. The Council identifies clear areas of opportunity and challenge, while maintaining a focus on how the United States can leverage its existing infrastructure, abundant resources, and capabilities to reach at-scale deployment of LCI hydrogen. The Council looks forward to sharing additional details with you, your colleagues, and broader government and public audiences about the critical enablers.

Respectfully submitted,

Alan S. Armstrong
Chair
National Petroleum Council

Enclosure

HARNESSING HYDROGEN

A Key Element of the U.S. Energy Future

A Report of
the National Petroleum Council
April 2024

Committee on Deployment
of Low Carbon Intensity Hydrogen At-Scale
Mike Wirth, Chair

The National Petroleum Council is a federal advisory committee to the Secretary of Energy.

The sole purpose of the National Petroleum Council is to advise, inform, and make recommendations to the Secretary of Energy on any matter requested by the Secretary relating to oil and natural gas or to the oil and gas industries.

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OUTLINE OF FULL REPORT

VOLUME I – REPORT SUMMARY

VOLUME II – REPORT CHAPTERS

VOLUME III – REPORT APPENDICES

The Report Summary, Chapters, Appendices, and other study materials can be downloaded at no charge from the NPC report website, harnessinghydrogen.npc.org.

PREFACE

NATIONAL PETROLEUM COUNCIL

The National Petroleum Council (NPC) is an organization whose sole purpose is to provide advice to the federal government. After successful cooperation during World War II, President Harry Truman requested this federally chartered and privately funded advisory group to be established by the Secretary of the Interior to represent the oil and natural gas industry's views to the federal government by advising, informing, and recommending policy options. Today, the NPC is chartered by the Secretary of Energy under the Federal Advisory Committee Act of 1972, and the views represented are broader than those of the oil and natural gas industry.

Council members, about 200 in number, are appointed by the Energy Secretary to assure well-balanced representation from all segments of the oil and natural gas industry, from all sections of the country, and from large and small companies. Members are also appointed from outside the oil and natural gas industry, representing related interests such as large consumers, states, Native Americans, and academic, financial, research, and public interest organizations and institutions. The NPC promotes informed dialogue on issues involving energy, security, the economy, and the environment of an ever-changing world.

STUDY REQUEST AND OBJECTIVES

By letter dated November 8, 2021, Secretary of Energy Jennifer M. Granholm formally requested the NPC to conduct a study on the deployment of low and zero carbon hydrogen energy at-scale through the entire value chain, including production, storage, liquefaction, transportation, and end uses. She noted that this effort should focus on production and delivery (both from fossil fuel and renewable sources); the potential impact on the Power generation, Industrial process, Residential, Commercial, and Transportation sectors; and the needed infrastructure and storage requirements. She further noted that policy, regulatory, and technical challenges to the use of hydrogen should be identified and recommendations provided to enable use at-scale.

The Secretary specifically requested the council's advice on seven key questions:

1. What policy, regulatory, and other actions are needed to move technically ready hydrogen technologies into deployment to enable this energy system transition?

2. What are the range and key drivers of hydrogen demand forecasts (including forecasts that are tied to a rapid decarbonization objective, such as the Paris Agreement) to use in evaluating infrastructure needs, technology opportunities, and relevant policy aspects?

3. What integration and infrastructure requirements are needed to maximize hydrogen deployment for the identified market sectors and across the value chain?

4. What hydrogen transportation carrier alternatives exist or could be developed and deployed, e.g., ammonia or other hydrogen carriers, in addition to the liquefaction, transportation, and use of elemental hydrogen?

5. What health, safety, and environmental concerns need to be addressed to facilitate the

acceptance of hydrogen in various market sectors or geographic regions?

6. What are the environmental and economic footprints of hydrogen versus alternatives? Which end uses and technologies are most advantaged in greenhouse gas and other pollutant reductions, environmental justice, and job creation?

7. What research gaps exist, and what is the path to address those gaps, including potential research roles for industry, academia, government, and national laboratories?

Appendix A contains a copy of the Secretary's request letter and a description of the NPC.

STUDY CONTEXT

As the United States explores options to promote economic growth and ensure energy security while protecting the environment by reducing emissions of carbon dioxide over time, hydrogen has the potential to abate a variety of energy market sectors as well as serve as a renewable energy storage mechanism. Secretary Granholm directed the NPC to undertake and deliver a comprehensive study on low carbon intensity hydrogen, defining potential pathways for deploying and integrating low carbon intensity hydrogen at-scale into energy and industrial marketplaces in the United States. Scaling low carbon intensity hydrogen in the United States will require significant investments and infrastructure, as well as the cooperation of multiple industries. The oil and gas industry has unique capabilities to contribute to hydrogen at the scale required, including the construction of pipeline infrastructure, deploying world-scale equipment, and managing construction and operation of large capital-intensive projects. As such, the NPC is well suited to lead a study on the deployment of low carbon intensity hydrogen that incorporates the perspectives of oil and gas and nonoil and gas industries, representatives, and stakeholders.

In addition to the seven questions asked, Secretary Granholm's letter suggested other areas of inquiry, advice, and comment, including the following:

- Development of a road map of remaining technology and project development challenges that can enable successful economic deployment of low carbon intensity hydrogen at-scale across the spectrum of industries and fuel types.
- Recognition that integrating technology and deploying hydrogen at-scale will require significant capital investment, major new infrastructure, and cooperation of multiple industries and government institutions.
- Coverage of the entire hydrogen value chain, including production, storage, liquefaction, transportation, and end uses. The value chains should cover hydrogen production from both fossil fuel and renewable sources. It should also consider the potential impact on Power generation, Industrial processes, and Transportation sectors—as well as the infrastructure and storage requirements to deliver across these.
- Identification of the policy, regulatory, and technical challenges to the use of hydrogen, as well as corresponding recommendations to address these and enable use at-scale.
- Factors to be considered should include technology options and readiness, market dynamics, cross-industry integration and infrastructure, legal and regulatory issues, policy mandates, economics and financing, environmental footprint, environmental justice issues, and public acceptance.

STUDY SCOPE AND PROCESS

The objective of the NPC study on hydrogen energy was to define potential pathways leading to low carbon intensity hydrogen deployment at-scale. While emphasis was on accelerating deployment in the United States, the NPC learned from and applied insights from other countries' efforts in progress.

This NPC study addressed the entire hydrogen value chain from production through storage, conversion, transportation, and end uses. The NPC understood that the success of hydrogen at-scale requires economic and operational integration across industries, harmonized local/state/federal regulations, a strong health and safety record, and broad public acceptance. The study addressed the technology advances and choices needed, infrastructure requirements, economics, cross-sector integration, regulations, policy options, health and safety, and public acceptance necessary for at-scale deployment of low carbon intensity hydrogen.

The NPC drew on available analyses from a variety of sources such as the International Energy Agency (IEA), the U.S. Energy Information Administration (EIA), U.S. Department of Energy (DOE) and national labs studies and reports, other peer-reviewed and research and development reports, and data from demonstration and commercial-scale projects. The study also drew on the methodological approach used in previous NPC studies, such as those on infrastructure and carbon capture use and storage.

While this report's emphasis is on accelerating deployment in the United States, the study learned from and applied insights from other countries' efforts in progress. While many of the report's findings are global in nature, its recommendations are the NPC's response to the Secretary's request for advice and, therefore, are U.S. focused.

Based on lessons learned from recent NPC studies and other hydrogen activities, the following principles were used to guide the study process:

- Assess hydrogen value in terms of energy security, economic growth, and jobs, in addition to environmental benefits
- Maximize use of prior studies and previous research
- Engage broad participation from industries, government, nongovernmental organizations (NGOs), and academia
- Leverage organizational strengths, drawing upon collective resources and expertise
- Involve global perspectives to ensure a comprehensive study that leverages learnings from abroad
- Coordinate closely with the concurrent NPC study on U.S. greenhouse gas (GHG) emissions in the natural gas supply chain (entitled *Charting the Course: Reducing Greenhouse Gas Emissions from the U.S. Natural Gas Supply Chain*)
- Ensure comprehensive communication of the report's assumptions and conclusions via tailored presentations delivered to multiple interested parties

As a key part of the study process, the NPC engaged the Massachusetts Institute of Technology (MIT) to provide computer modeling support for the study. Using inputs and assumptions provided or approved by the study groups, the MIT Modeling support provided systems-level insights about the cost and performance parameters that low-carbon hydrogen technology must deliver to become a substantial contributor to carbon emissions reductions at the national scale. It assessed the role of hydrogen technology in a portfolio of mitigation options as a basis for strategies to advance the low-carbon hydrogen option. Two MIT models were used for the NPC analyses:

1. SESAME: A multilevel platform used to explore the impacts of relevant technological, operational, temporal, and geospatial characteristics of the energy system and various low carbon hydrogen integration options
2. USREP: United States-focused Economic Projection and Policy Analysis model—a national computable general equilibrium energy-economic model designed to analyze energy and environmental policies used to examine long-term scenarios to estimate the importance of factors influencing hydrogen energy deployment and its role in reducing carbon emissions from energy and the economy

The *Charting the Course* NPC study was completed simultaneously with this study. The two studies collaborated to ensure that the carbon intensity of natural gas used to reform hydrogen was aligned. The two studies also collaborated on framing of the societal considerations and impacts (SCI).

The SCI topic represents a significant development for the NPC itself as it, together with the concurrent *Charting the Course* study's SCI Chapter 2, is the first time NPC studies have undertaken a dedicated SCI review of issues related to a study topic. While both studies' SCI treatments are an important step forward, more work needs to be done to thoroughly understand the social, community, and environmental justice issues involved in energy systems and energy infrastructure.

This NPC study was conducted in full compliance with all regulations and laws, including antitrust laws and provisions and the Federal Advisory Committee Act. It did not include evaluations of commodity prices, despite the important role these play in encouraging research and technology investments required for the widespread deployment of low carbon intensity hydrogen at-scale.

STUDY GROUP ORGANIZATION

In response to the Secretary's request, the NPC established a Committee on Hydrogen Energy composed of approximately 60 members of the council. The committee's purpose was to conduct a study on this topic and to supervise the preparation of a draft report for the council's consideration. This study committee was led by a steering committee consisting of the committee's chair, government cochair, the chair and vice chair of the NPC, the chair of the companion NPC Committee on GHG Emissions, and 10 members representing a cross section of the committee. The steering committee provided timely guidance and resolution of issues during the course of the study.

A coordinating subcommittee, including seven analytical chapter task groups, were also established to assist the committee in conducting the study. These study groups were aided by multiple study teams and subgroups focused on specific subject areas, supplemented by technical workshops and other outreach. Figure P-1 provides an organization chart for the groups that conducted the study's analyses, and Figure P-2 lists organizations that led these groups.

The members of the various study groups were drawn from NPC member organizations as well as from many other industries, state and federal agencies, NGOs, other public interest groups, financial institutions, consultancies, academia, and research groups. Approximately 300 people served on the study's committee, subcommittee, task groups, teams, and subgroups. While all have relevant expertise for the study, less than 30% are from the oil and natural gas industry. Figure P-3 depicts the diversity of participation in the study process, and Appendix B contains rosters of the participants in each of the study groups. This broad participation was an integral part of the study, with the goal of soliciting input from an informed range of interested parties.

Participants in this study contributed in a variety of ways, ranging from work in all study areas, to involvement in a specific topic, to reviewing proposed materials, to participating in the aforementioned technical workshops. Involvement in these activities should not be construed as a participant's or their organization's endorsement or agreement with all the statements, findings, and

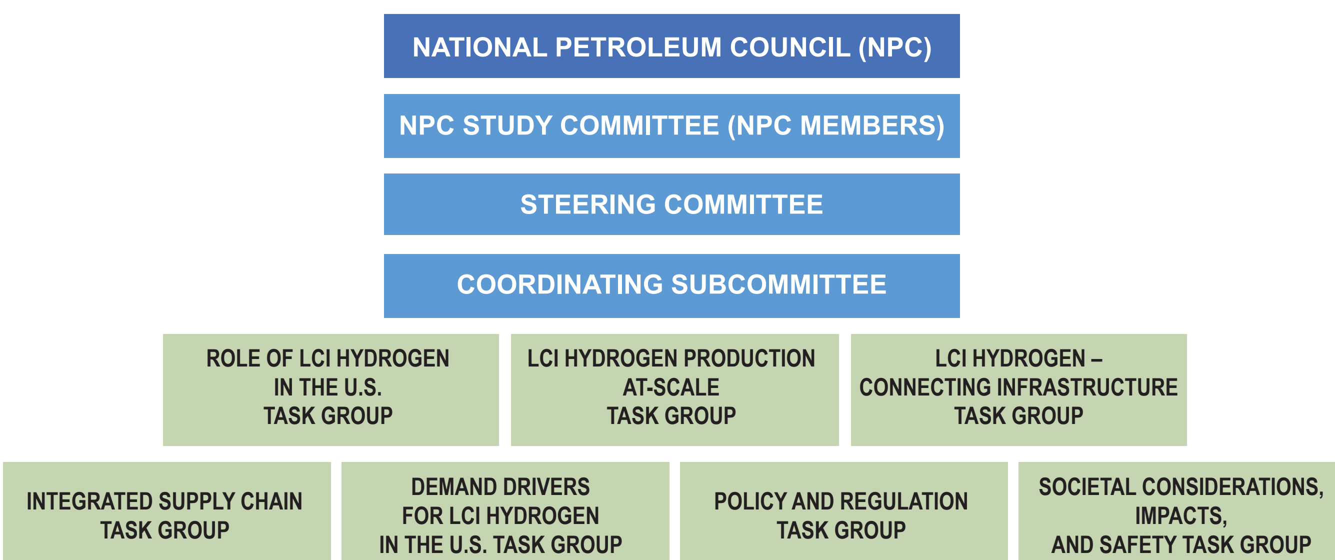


Figure P-1. *Organization Chart for the Groups That Contributed to the Study's Analyses*

NPC COMMITTEE ON DEPLOYMENT OF LOW CARBON INTENSITY HYDROGEN AT-SCALE

CHAIR
Michael K. Wirth
Chairman of the Board and Chief Executive Officer
Chevron Corporation

GOVERNMENT COCHAIR
David M. Turk
Deputy Secretary of Energy
U.S. Department of Energy

ALTERNATE GOVERNMENT COCHAIR
Bradford J. Crabtree
Assistant Secretary, Office of Fossil Energy and Carbon Management
U.S. Department of Energy

STEERING COMMITTEE

Alan S. Armstrong, Ex Officio – NPC Chair
President and Chief Executive Officer
The Williams Companies

Ryan M. Lance, Ex Officio – NPC Vice Chair
Chairman and Chief Executive Officer
ConocoPhillips Company

Filipe Barbosa
Senior Partner
McKinsey & Company, Inc.

Jason E. Bordoff
Cofounding Dean, Columbia Climate School
Founding Director, Center on Global Energy Policy
Professor of Professional Practice in International and Public Affairs
Columbia University

Maryam S. Brown
President
Southern California Gas Company

Deborah H. Caplan
Retired Executive Vice President of Human Resources
and Corporate Services
NextEra Energy, Inc.

Edmund Crooks
Vice-Chair, Americas
Wood Mackenzie Inc.

Michael J. Graff
Chairman and Chief Executive Officer
American Air Liquide Holdings, Inc.
Executive Vice President, Americas and Asia-Pacific
Air Liquide Group

Mark E. Lashier
President and Chief Executive Officer
Phillips 66 Company

Richard G. Newell
President and Chief Executive Officer
Resources for the Future

Meg E. O'Neill
Chief Executive Officer and Managing Director
Woodside Energy Group Ltd.

Lorenzo Simonelli
Chairman and Chief Executive Officer
Baker Hughes Company

Darren W. Woods
Chairman, President and Chief Executive Officer
Exxon Mobil Corporation

COORDINATING SUBCOMMITTEE

CHAIR
Austin Knight
Vice President, Hydrogen
Chevron New Energies, a division of Chevron U.S.A. Inc.

GOVERNMENT COCHAIR
Jennifer Wilcox
Principal Deputy Assistant Secretary
Office of Fossil Energy and Carbon Management
U.S. Department of Energy

ALTERNATE CHAIR
Darin Rice
General Manager, Hydrogen Strategy
Chevron New Energies, a division of Chevron U.S.A. Inc.

GOVERNMENT COCHAIR
Sunita Satyapal
Director, Hydrogen and Fuel Cell Technologies Office
U.S. Department of Energy

TASK GROUPS

CHAIR – ROLE OF LCI HYDROGEN IN THE U.S.
Mark Shuster
University of Texas, Bureau of Economic Geology

CHAIR – LCI HYDROGEN PRODUCTION AT-SCALE
Bob Brinkman
Air Liquide Group

CHAIR – LCI HYDROGEN – CONNECTING INFRASTRUCTURE
Vijai Atavane
Southern California Gas Company

CHAIR – INTEGRATED SUPPLY CHAIN
Melany Vargas
Wood Mackenzie Inc.

CHAIR – DEMAND DRIVERS FOR LCI HYDROGEN IN THE U.S.
Mike Kerby
Exxon Mobil Corporation

CHAIR – POLICY AND REGULATION
Poh Boon Ung
bp

COCHAIRS – SOCIETAL CONSIDERATIONS, IMPACTS, AND SAFETY

Matt Fry
Great Plains Institute for Sustainable Development

David Monsma
George and Cynthia Mitchell Foundation

Figure P-2. *Leaders of the Groups That Contributed to the Study's Analyses*

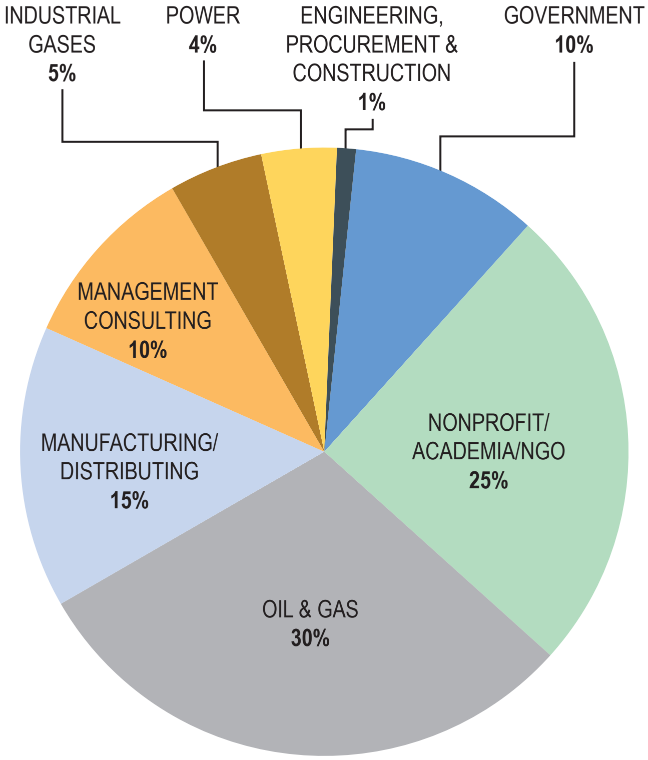


Figure P-3. *Diversity of Participants in the Study Process*

recommendations in this report. Additionally, while U.S. government participants provided significant assistance in the identification and compilation of data and other information, they did not take positions on the study's recommendations. Likewise, some other participants from certain nonadvocacy, nonprofit organizations did not take positions on the study's recommendations.

As a federally appointed and chartered advisory committee, the NPC is solely responsible for the final advice provided to the Secretary of Energy. However, the NPC believes that the broad and diverse participation has informed and enhanced its study and advice. The NPC is very appreciative of the commitment and contributions from all who participated in the process.

III. REPORT STRUCTURE

In the interest of transparency, and to help readers better understand this study, the NPC is making the study results available through its website to all interested parties. To provide interested parties with the ability to review this report and supporting materials in various levels of detail, the report is organized in multiple layers, as follows.

Volume I, Report Summary includes the report transmittal letter, outline of the entire report, Preface, Executive Summary, and several appendices. This volume provides three levels of summarization:

1. Report Transmittal Letter is the first level that submits the report to the Secretary of Energy as the council's response to her request for advice on at-scale low carbon intensity hydrogen deployment. It provides a very brief, high-level overview of the report's key messages.

2. Executive Summary is the second level and provides an overview of the study's findings and recommendations for at-scale deployment of low carbon intensity hydrogen.

3. Appendices A, B, and C, which provide the study request letter and NPC description and roster, study group rosters, and Executive Summary findings and recommendations, plus abbreviations and acronyms used in the report.

Volume II, Analysis of the LCI Hydrogen Value Chain, includes all seven chapters of the report, providing an additional level of detail.

Volume III, Supporting Appendices, includes Appendices D through W (Appendices G and N will not be in printed volumes; they are only available via the web).

The Executive Summary, report chapters, and appendices may be individually downloaded from the NPC report website at https://harnessinghydrogen.npc.org. The public is welcome and encouraged to visit the site to download the entire report or individual sections for free. Printed copies of the report can be purchased from the NPC report website.

EXECUTIVE SUMMARY

I. INTRODUCTION

Hydrogen can play a key role in reducing U.S. carbon emissions, particularly in the hard-to-abate sectors,[1] at a lower cost to society than alternative abatement methods. Current policies and legislation, including the Inflation Reduction Act (IRA) and Infrastructure Investment and Jobs Act (IIJA, including the H_2Hubs program), are expected to stimulate market activation, doubling the current hydrogen demand by 2050. However, these policy levers are insufficient to deploy low carbon intensity (LCI)[2] H_2 at the scale necessary to support the U.S. net zero target by 2050. Thus, immediate actions are required to accelerate the uptake of LCI H_2. These actions fall into three categories: (1) policy and regulation; (2) societal considerations, impacts, and safety (SCI and Safety); and, (3) investments in technology and research, development, and demonstration (RD&D).

The U.S. Secretary of Energy requested the National Petroleum Council (NPC) address seven questions related to identifying key challenges and critical enablers to achieve at-scale deployment of LCI hydrogen in the United States (Appendix A). To answer these questions, NPC assembled a diverse team of experts from a broad range of organizations, including oil and gas, industrial gas, power, manufacturing and heavy industry, nongovernmental organizations, academia, management consulting, and engineering, procurement, and construction. NPC also partnered with the Massachusetts Institute of Technology's (MIT) Energy Initiative to conduct scenario-based Modeling to support this study. Two Modeling scenarios, Stated Policies and Net Zero by 2050 (NZ2050), were created to support the development of study insights; the outcome of the latter scenario is often referred to as "reaching at-scale deployment of LCI H_2."[3] Wherever the study refers to the "Model" or "Modeling," it is this work to which the study is referring.

This study generates unique insights due to the diverse perspectives of the study participants, many of whom have practical experience executing large-scale projects, informing the technoeconomic and life cycle assessment models. It describes the targeted role of LCI H_2 to support meeting U.S. net zero ambitions at a lower cost to society, including recommendations to enable reaching at-scale LCI H_2 deployment. Additionally, this study extensively examines regional differences with the United States across the LCI H_2 value chain (which includes production, infrastructure, and demand).

1 For this study, hard-to-abate applications include those in the Industrial, Transportation, and Power sectors. More detail on hard-to-abate applications can be found in Table ES-1.

2 This study defines low carbon intensity hydrogen following the IRA definition for LCI H_2. However, the study recognizes that the 4 kg carbon dioxide equivalents (CO_2e)/kg hydrogen metric threshold is subject to change and views any significant reduction in CO_2e as beneficial, even if the 4 kg CO_2e/kg H_2 threshold is not met for production tax credit purposes.

3 The reader should not presume that reaching at-scale deployment of LCI H_2 means that net zero has been achieved or that net zero can only be achieved when LCI H_2 is deployed at-scale. However, at-scale deployment of LCI H_2 will not be achieved unless the United States is on a net zero trajectory, inclusive of needed policy, technology advancements, etc.

A. Study Findings

This study's findings can be organized into four main themes.

1. **LCI H_2 can play a key role in reducing emissions in the hard-to-abate sectors at a lower cost to society.** If deployed at-scale, LCI H_2 could abate approximately 8% of U.S. carbon emissions by 2050. Achieving net zero in the United States will require deploying multiple technologies, including LCI H_2, and could cost up to 3% of the gross domestic product (GDP) annually. Reaching net zero in the United States without leveraging LCI H_2 could increase the annual cost to society by approximately 0.5 to 1% of GDP, ranging between $160-$260 billion.[4]
2. **Significant and immediate actions beyond current policies are necessary to unlock various LCI H_2 demand sectors at the scale needed to support U.S. net zero by 2050 aspirations.** Hydrogen demand would need to increase by nearly 7x compared to the current market to enable cost-effective achievement of U.S. net zero ambitions. Additional policies recognizing the value of carbon emissions reductions can support this demand growth by helping LCI H_2 achieve sector-specific cost parity with higher-carbon incumbent fuels and feedstocks. The Industrial sector is expected to activate first, along with transportation in regions supported by current policies. However, without additional policies, further unlocking of the Industrial, Transportation, and Power sectors will not occur.
3. **The LCI H_2 production mix will be driven by multiple aspects of the various H_2 production pathways, including their relative speed to scale, delivery cost reductions, and carbon intensities.** Relevant production technologies are available and are being deployed today. LCI H_2 production is initially expected to be driven by hydrogen produced via natural gas reforming with carbon capture and storage (NG+CCS), due to its lower production cost and the ability to rapidly scale production and infrastructure. The production mix under the NZ2050 scenario is expected to include an increasingly larger share of renewable electrolytic (RE) hydrogen due to its lower carbon emissions and the projected higher future cost of carbon. Deployment of LCI H_2 from these two key production pathways will be needed to support the U.S. net zero objectives and will require addressing specific constraints for each pathway.
4. **LCI H_2 deployment will be marked by regional variances in production development and demand activation by sector.** The Modeling shows LCI H_2 initiates in regions with abundant renewable or natural gas resources, existing anchoring demand, access to infrastructure, and/or supportive policies. Expanding LCI H_2 more broadly across the United States will require additional federal policy.

B. Critical Enablers

Significant and rapid progress across many areas must occur to move through the three phases of LCI H_2 market development: Activation, Expansion, and At-Scale. The Department of Energy (DOE), along with other agencies, legislators, policymakers, and industry, must coordinate actions across policy, SCI and safety, and investments in technology and RD&D to achieve at-scale deployment of LCI H_2. These actions should broadly consider the following:

- Policy and regulation
  - Developing additional legislation, which recognizes the value of abating carbon emissions, to help overcome the large cost gap between incumbent feedstocks or fuels and LCI H_2, particularly in hard-to-abate applications
  - Creating policies that increase investors' certainty and confidence, thus supporting the activation of LCI H_2 across the value chain
  - Developing efficient regulatory frameworks primarily associated with permitting processes that streamline navigation of administrative and legal complexities across jurisdictions
- SCI and safety
  - Developing reliable value chains while ensuring public safety and providing societal

4 Assumes reaching a 2050 U.S. GDP of $38 trillion in real 2020 dollars, an approximate growth rate of 2% since 2023. See Figure ES-3 for more detail.

SCENARIO MODELING FOR CARBON EMISSIONS TARGETS AND REGIONAL OPTIMIZATION

To inform this study, NPC deployed established, peer-reviewed MIT Energy Initiative Modeling methodology and platforms. Specifically, MIT's USREP and SESAME platforms were leveraged to deliver a coupled macroeconomic energy demand and greenhouse gas (GHG) emissions projections Model. Herein, the MIT Modeling platforms and their output for this NPC study will simply be referred to as "the Model" and "the Modeling," respectively.

This study has modeled regional distinctions for the role of LCI H_2 to support U.S. GHG emissions reduction under two scenarios, Stated Policies and U.S. Net Zero by 2050 (NZ2050). The Model delivers key region-specific outputs, including LCI H_2 demand by sector, supply by technology, infrastructure needs, levelized cost, value chain life cycle assessment, and carbon intensity. Those outputs are used to inform a regional distribution system that is optimized within Modeling assumption boundaries. This study is believed to be one of the first to evaluate regional production pathways with sector-level granularity through 2050.

The Stated Policies scenario is calibrated to the International Energy Agency (IEA) World Energy Outlook (WEO) 2022 Stated Polices (STEPS) scenario and includes incentives from the IRA signed into U.S. law in 2022, clean energy standards in the United States, and selected state-specific policies, such as Low Carbon Fuel Standard (LCFS) in California and state-level renewable portfolio standards.

The U.S. Net Zero by 2050 (NZ2050) scenario includes the same set of policies as in the Stated Policies scenario, and it is calibrated to IEA WEO 2022 Announced Pledges Scenario (APS). For the U.S., the APS is set to achieve a policy objective of net zero emissions by 2050. The NZ2050 scenario is modeled to highlight the gap between current emissions projections and the emissions trajectory required to reach U.S. net zero by 2050.

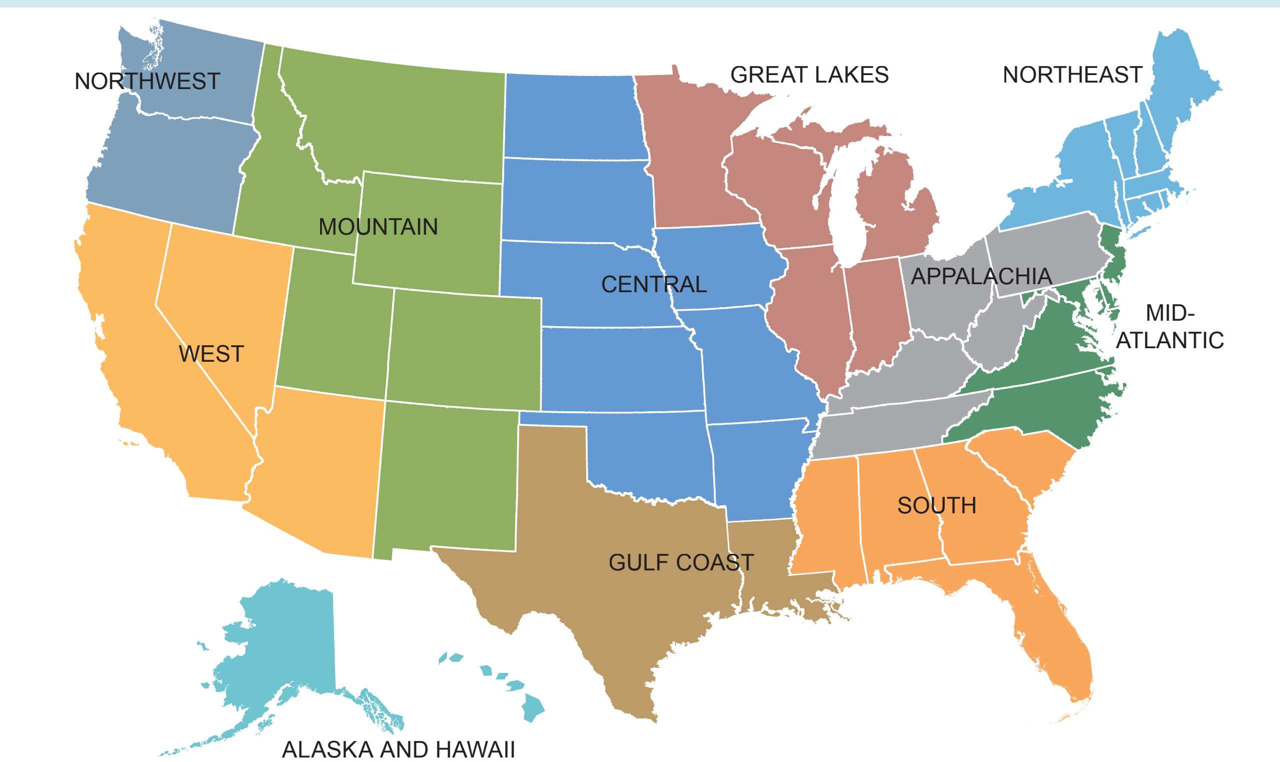


Figure ES-1. *Regions Included in the Modeling Conducted as Part of This Study*

SCENARIO MODELING FOR CARBON EMISSIONS TARGETS AND REGIONAL OPTIMIZATION (continued)

There are two distinct aspects of the Modeling and subsequent analysis:

- The Modeling used input parameters and assumptions informed by numerous experts. NPC has leveraged the expertise of the NPC council members, industry, academia, non-governmental organizations, and government officials and used published data (e.g., IEA, Environmental Protection Agency [EPA], national labs) to align inputs.
- The analysis of the Model's region-specific outputs provides insights to enable decision-makers to develop localized LCI H_2 deployment solutions. The 11 regions modeled are indicated in Figure ES-1.

Readers are advised to be cognizant that the Modeling is based on assumptions that are informed by expert perspectives but that it retains levels of uncertainty, specifically regarding: emissions projections, technology learning rates, technology-specific market growth with time, optimum carbon emissions-reduction pathways based on variations in levelized cost, and other macroeconomic factors on the U.S. economy. The Modeling cannot consider all constraints and has made some simplifying assumptions. The goal of the Modeling was to project how the U.S. economy could most cost-effectively meet the emissions-reduction trajectory adopted for each scenario. The results are a product of the methodology and inputs adopted to meet this objective. In particular, an implied price of carbon was used as a proxy for unspecified policies that would produce the imposed emissions reduction over time, which drove adoption of low-carbon technologies, including hydrogen. Therefore, projected costs for renewables and traditional energy sources, like natural gas, do not align with current market dynamics. The report will address these considerations in the narrative. More details on the Modeling methodology, key input parameters, and assumptions are available in Appendix D: Modeling Methodology. Additionally, comparison of the Modeling to other published reports is provided in Appendix E: Contextualizing of Modeling Results.

benefits, including consideration of environmental, health, and economic impacts

  - Transforming frontline community and stakeholder engagement planning, practices, and two-way communication
  - Enabling workforce development and labor engagement

- Investments in technology and RD&D
  - Prioritizing targeted technology and RD&D investments with national labs and public/private programs in areas with gaps in commercially available technology across the LCI H_2 value chain
  - Addressing potential technical bottlenecks related to materials sourcing, technical codes and standards, and the electrical grid that could inhibit deployment of commercially available technologies

Study findings and recommendations are identified throughout this Executive Summary. These findings and recommendations are also summarized in Appendix C: Findings and Recommendations for ease of review.

II. THE CRITICAL ROLE OF HYDROGEN

Hydrogen can play a key role in reducing U.S. carbon emissions while meeting energy demands and addressing societal considerations, impacts, and safety. However, deploying LCI H_2 at-scale could entail an economic scope and impact that is rarely, if ever, seen. Significant and immediate action must be taken, including supporting the growth and scale-up of all aspects of the H_2 market: production, demand, and infrastructure.

FINDING 1: LCI hydrogen could account for 8% of the United States' emissions

reductions, primarily in hard-to-abate applications in the Industrial, Transportation, and Power sectors. Addressing these emissions without leveraging LCI hydrogen would cost society approximately an additional 0.5-1% of gross domestic product.

Despite the momentum from the U.S. federal legislation (e.g., IRA and IIJA), increased energy efficiency, and increased electrification with low carbon intensity (CI) power, the United States is not projected to meet its net zero CO_2 emissions goal under the Stated Policies scenario (Figure ES-2).[5] Electricity generated from low-carbon resources (e.g., solar, wind, nuclear, hydroelectric) will be a key approach for abating carbon emissions from U.S. energy use and closing this emissions gap to net zero. However, electrification is not suitable for decarbonizing all end-use applications across different sectors. In particular, certain hard-to-abate applications in the Industrial, Transportation, and Power sectors will need to use additional low CI sources, such as LCI H_2, to reduce their emissions and achieve net zero. As shown in Figure ES-2, deploying LCI H_2 at-scale could address up to 8% of emissions reductions required to reach net zero.

Based on the Modeling, the cost of achieving net zero in the U.S. economy—i.e., abating ~4,600 million metric tons per annum (MMTpa) of CO_2 as of 2020—rises over time to approximately 3% of GDP in 2050 (Figure ES-3). Reaching net zero will require deploying a suite of different technologies, and the Modeling demonstrates that LCI H_2 can more cost-effectively abate carbon emissions from certain hard-to-abate sectors than competing alternatives. Even with aggressive adoption of abatement technologies, achieving a net zero outcome will require residual emissions to be addressed through negative carbon technologies such as direct air capture (DAC), which directly removes CO_2 from ambient air. In the Modeling, DAC, which is a relatively expensive technology, serves as the backstop carbon abatement technology necessary to reach net zero CO_2 emissions for the United States.[6, 7, 8, 9] As part of the Modeling, a NZ2050 scenario sensitivity was evaluated that excluded the deployment of LCI H_2. This alternative presents a significantly more expensive trajectory to net zero compared to the NZ2050 scenario with LCI H_2 (Figure ES-3). The NZ2050 scenario sensitivity without LCI H_2 represents a broader deployment of DAC and other technologies and additional energy demand response to achieve emissions targets. In other words, not deploying LCI H_2 at-scale, particularly in hard-to-abate sectors, could increase the cost of achieving net zero by ~0.5–1% of GDP annually.[10]

Table ES-1 summarizes potential end uses of LCI H_2 by sector as well as incumbent fuels and relevant technologies that LCI H_2 could displace. A summary of existing and emerging end-use applications is available as Appendix F: Hard-to-Abate Applications. Deploying LCI H_2 at-scale can be a more cost-effective way to address these hard-to-abate sectors and will play a necessary role in reducing carbon emissions in the U.S. economy, especially in a net zero future.

Hydrogen's role in addressing up to 8% of the emissions abatement in the NZ2050 scenario will require transitioning from existing,

5 The estimated U.S. CO_2 emissions in 2050 for the Stated Policies scenario are approximately 2,200 million metric tons per annum (MMTpa), while the net CO_2 emissions in 2050 in the Net Zero by 2050 scenario are close to zero. The baseline year for comparison is 2020, when U.S. emissions were approximately 4,600 MMTpa CO_2.

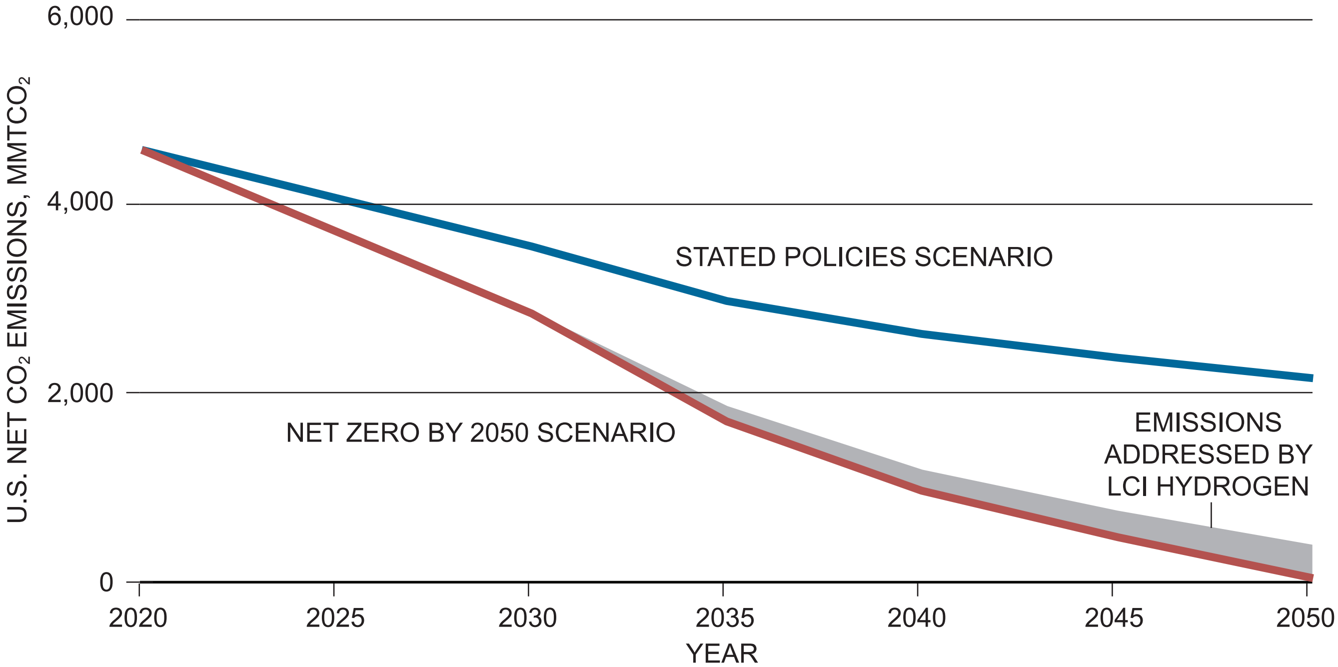
6 The cost of DAC is assumed to be around $700 per metric ton of CO_2 (2020 dollars) at the time of deployment based on the medium cost scenario in: Desport, L., Gurgel, A., Morris, J., Herzog, H., Chen, Y-H.H., Selosse, S., and Paltsev, S. 2024. "Deploying Direct Air Capture at Scale: How Close to Reality?" *Energy Economics*. January. https://doi.org/10.1016/j.eneco.2023.107244.

7 The cost of DAC declines in the USREP model via learning and other factors. In the Net Zero by 2050 scenario, the Model begins to incorporate DAC at an observable scale in 2040, which results in DAC abating approximately 700 MMTpa CO_2 per annum by 2050.

8 More optimistic assumptions about the costs and availability of technologies (e.g., lower DAC costs, introduction of fusion power generation) would lower the costs of the U.S. economy achieving net zero. Due to the iterative nature of the Modeling and the variety of carbon abatement technologies and assumptions included in the Model, it is not possible to define a simple correlation between total carbon emissions abatement costs and adjustments to a Model input assumption.

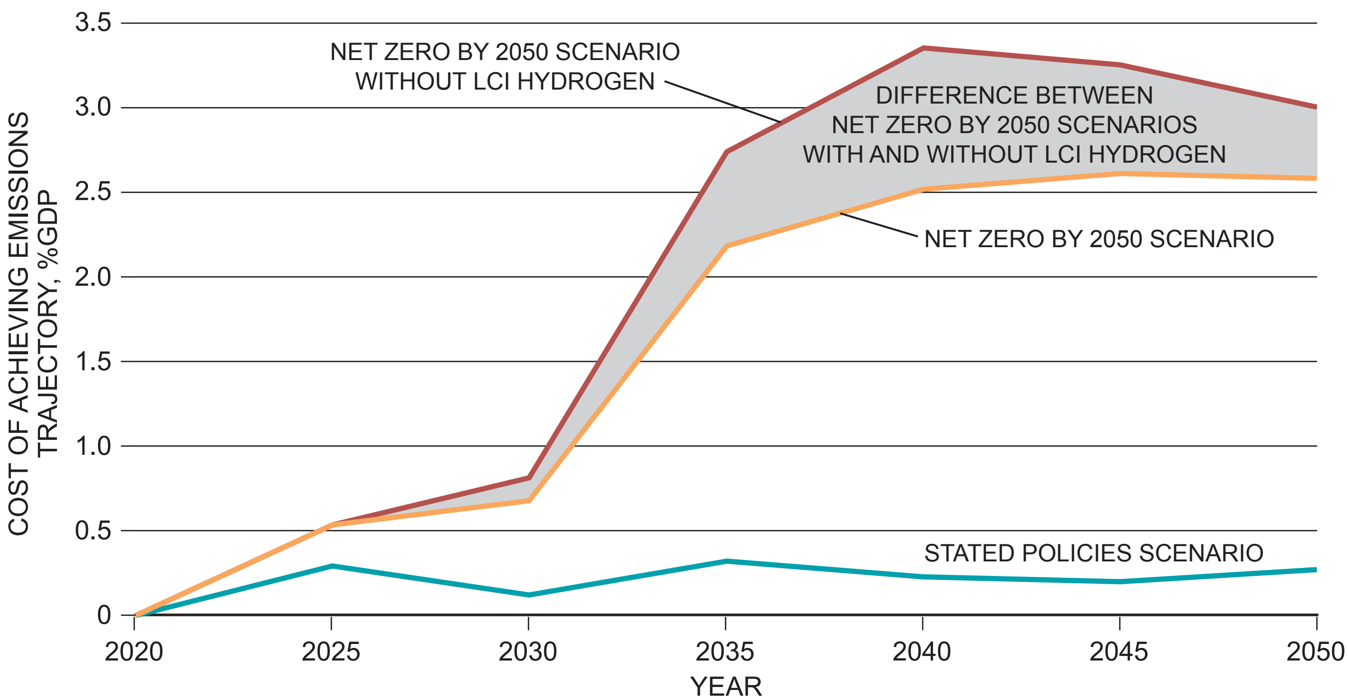
9 Desport et al. (2024) provides sensitivities related to the impact of DAC costs on global carbon emissions abatement costs.

10 U.S. GDP is assumed to grow reaching $38 trillion by 2050 (in real 2020 dollars), and the cost impact of not deploying LCI H_2 is approximately 0.5% of the 2050 GDP. The impact of not deploying LCI H_2 to achieve emissions targets changes by year and ranges in cost from $160 to $260 billion between 2035 and 2050.



Note: The gray shading represents anticipated emissions reductions resulting from the deployment of LCI hydrogen. The overall reduction in emissions occurs as a result of deploying a portfolio of emissions abatement technologies. LCI hydrogen eliminates only a fraction of total emissions reduction in the U.S. economy.

Figure ES-2. *Emissions Trajectories and the Role of LCI Hydrogen in the Stated Policies and Net Zero by 2050 Scenarios*



Notes: The gray area indicates an additional cost burden to society to reach net zero if LCI hydrogen is not deployed.
GDP = Gross Domestic Product.

Figure ES-3. *Cost to Society to Achieve the Stated Policies and Net Zero by 2050 Scenarios*

Demand Sector	End Use of LCI H_2	Incumbent Fuel/Technology That LCI H_2 Could Replace
Industrial	Refining	Unabated H_2 for feedstock & natural gas and internally produced fuel gases for heat
	Chemicals production and others	Unabated H_2 for feedstock to chemicals (e.g., ammonia) and natural gas for process heat
	Iron and steel	Coal or natural gas as a reductant and heat source
Transportation	Heavy-duty trucking, buses, rail	Diesel
	Aviation	Unabated jet fuel
	Marine	Diesel, unabated bunker fuel, LNG
Power	Dispatchable power and long-duration energy storage	Natural gas or coal-fired power plants

Notes: Aviation: LCI hydrogen use is anticipated primarily as a feedstock for production of Sustainable Aviation Fuel. Dispatchable power: power generated from sources that are flexible and controllable to supply power on demand.

Table ES-1. *LCI Hydrogen Could Help Reduce Carbon Emissions from Specific End Use Applications in Hard-to-Abate Sectors*

unabated H_2 use cases and activating new H_2 uses in these hard-to-abate sectors. Demand growth is essential for incentivizing the necessary production buildout, as current policies are insufficient to trigger investment at the level needed to reach at-scale deployment of LCI H_2. According to the Modeling, the deployment of ~75 MMTpa of LCI H_2 will be needed to reach the emissions-reduction targets in the NZ2050 scenario at a lower cost to society. Reaching this scale will require a significant undertaking to increase production and demand by nearly 7x from today's MMTpa[11] level while transitioning from existing unabated H_2 to LCI H_2. This scale of market shift in demand and production will not occur under the Stated Policies scenario, and additional policy is needed to enable this multifold increase in the buildout of the hydrogen value chain for the Industrial, Transportation, and Power sectors, including hydrogen carriers (e.g., ammonia, methanol).

Delivering LCI H_2 production at-scale will require an evolving split between H_2 from two key production pathways: natural gas reformed hydrogen with carbon capture and storage and renewable electrolytic hydrogen. The hydrogen production mix for reaching 2050 net zero objectives will be driven by speed to scale, cost reduction, and the CI of different H_2 pathways. Carbon emissions abated today generate a larger compounding impact toward net zero than carbon emissions abated in the future due to the accumulative effect of greenhouse gases.[12] LCI H_2 production will initially be driven by NG+CCS H_2 due to lower cost feedstock availability and the ability to rapidly scale production. NG+CCS H_2 can provide the initial large-scale production and local distribution needed to support reliable LCI H_2 supply to early end users, thus helping establish the LCI H_2 economy. To achieve net zero, the CI of the LCI H_2 production mix must see continued reductions over time. As the economy moves toward net zero, the marginal cost of abatement will rise (see Section IV.A). Ultimately, the production mix in the NZ2050 scenario will have a higher proportion of RE H_2 due to its lower carbon emissions, the projected higher future cost of carbon, and anticipated cost reductions for RE H_2.

III. GROWTH OF THE LCI HYDROGEN VALUE CHAIN

LCI H_2 could reach at-scale deployment if economics and technical viability are improved with additional policy support, along with SCI

11 Fuel Cell and Hydrogen Energy Association. 2020. "Road Map to a U.S. Hydrogen Economy." https://www.fchea.org/us-hydrogen-study.

12 Sun, T., Ocko, I.B., Sturcken, E., and Hamburg, S.P. 2021. "Path to Net Zero Is Critical to Climate Outcome." *Scientific Reports* 11 (1). https://doi.org/10.1038/s41598-021-01639-y.

and safety commitments and investments in technologies and RD&D. This report details a roadmap with key attributes, signposts, barriers to remove, and enablers to account for the requisite growth in demand, production, and infrastructure to reach at-scale deployment (i.e., 75 MMTpa of LCI H_2). This report underscores the enormous challenge of reaching at-scale deployment in the timeline to achieve national net zero targets by 2050. To accelerate the current pace of progress, all stakeholders in both the public and private sectors need to coordinate action to enable deployment at-scale and ensure LCI H_2 can play a key role in both carbon abatement and economic efficiency. This section summarizes the Modeling findings along the LCI H_2 value chain (e.g., production, infrastructure, and demand) across the Activation, Expansion, and At-Scale phases.

A. Hydrogen Demand Growth Addressing Hard-to-Abate Sectors

FINDING 2: Current policies and anticipated cost reductions for LCI hydrogen could increase total hydrogen demand by nearly 2x by 2050. However, current policies and anticipated economics are not sufficient to catalyze the nearly 7x demand growth required by 2050 to reach LCI hydrogen deployment at-scale and support U.S. net zero ambitions at a lower cost to society. Achieving this goal will require significant and immediate action to support the growth and scale-up of all aspects of the hydrogen market: production, infrastructure, and demand.

Current U.S. H_2 demand is approximately 11 MMTpa, which is largely unabated H_2. Although the Modeling indicates approximately 2x growth in H_2 demand under the Stated Policies scenario, the current growth trajectory of H_2 demand will not be sufficient to reach LCI H_2 deployment at-scale. Reaching deployment at-scale is not synonymous with reaching net zero, but a net zero trajectory is required to realize at-scale deployment. To reach at-scale deployment, LCI H_2 must not only replace existing demand but also address expanding future demand under the NZ2050 scenario (Figure ES-4).

1. Three-Phase Roadmap of LCI Hydrogen Growth

This study describes the 7x growth required to reach U.S. LCI H_2 deployment at-scale under the NZ2050 scenario in three phases: Activation, Expansion, and At-Scale (Figure ES-5). This three-phase roadmap provides a framework to drive clarity around the sequencing of the critical items needed to advance to the next phase and ultimately reach the at-scale deployment in the most economically efficient and expedient manner. Catalyzing the market transition between phases will require a broad set of policy and regulatory actions, SCI and safety commitments, and investments into technology and RD&D across demand, production, and infrastructure.

This phased approach is similar to that described in the DOE's *Pathways to Commercial Liftoff: Clean Hydrogen* report. The high-level characteristics for each phase in this report are as follows:

- **Activation:** Transitioning from unabated H_2 in select industrial applications (e.g., feedstock to industrial process) to LCI H_2. This is enabled by existing policies (e.g., IRA, IIJA and the H2Hubs program, and state-level policies) with some uptake in other sectors, such as Transportation within policy-enabled regions, supported by existing hydrogen infrastructure, and colocation of hydrogen production and demand, and exports of LCI H_2 carriers (e.g., ammonia, methanol) to select countries seeking early carbon abatement goals.
- **Expansion:** Extending LCI H_2 deployment into more diversified applications, namely industrial heat and dispatchable power. This is enabled by supporting policy and infrastructure that connects advantaged production to multiple demand centers within each region. Use in heavy-duty transportation grows, as does the export of LCI H_2 carriers (e.g., ammonia and methanol) to countries needing it to achieve their carbon abatement goals.
- **At-Scale Deployment:** Deploying LCI H_2 into more diversified applications to support the remaining heavy-duty transportation sectors (e.g., marine, rail), energy storage for grid integration of renewables, and off-grid applications. This is enabled by policies, infrastructure

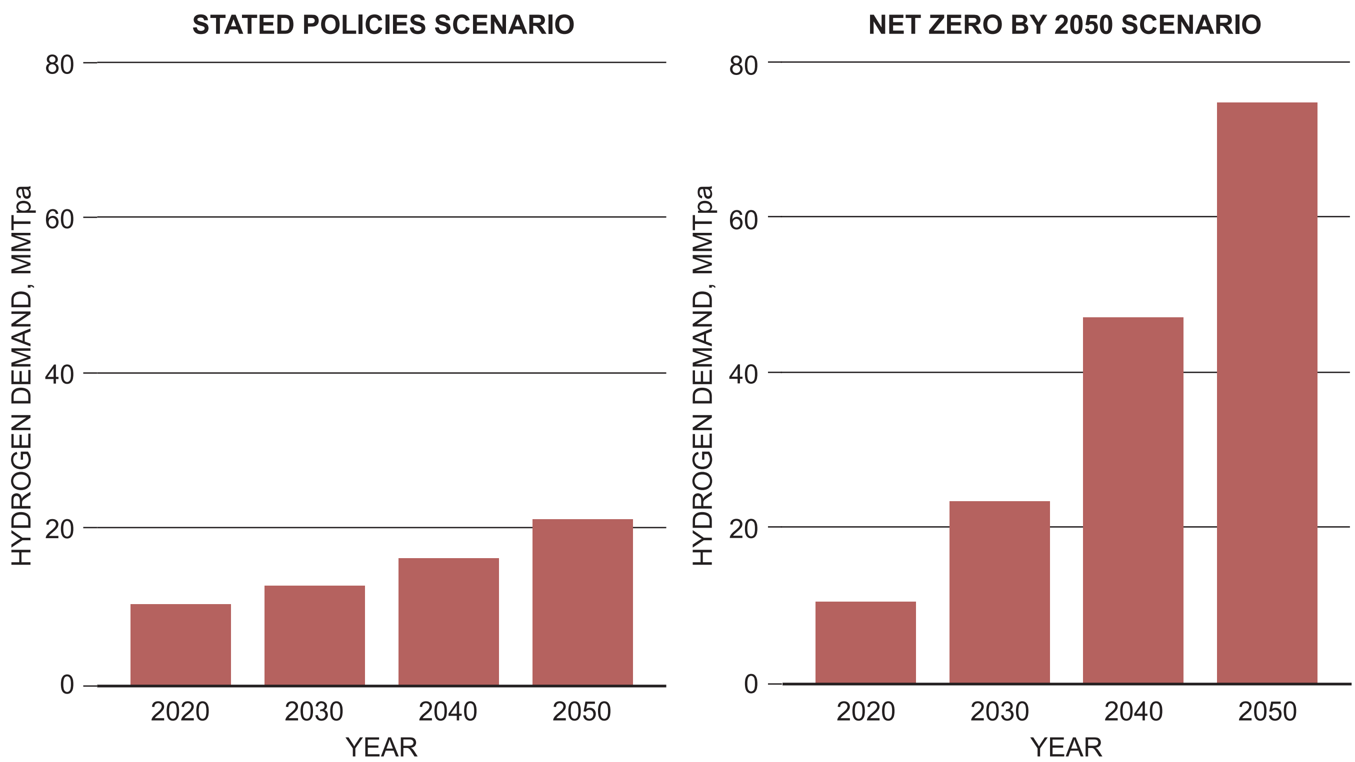


Figure ES-4. Hydrogen Growth Under the Stated Policies and Net Zero by 2050 Scenarios

that connects advantaged production to multiple regional demand centers, and technology advancement. LCI H_2 carriers (e.g., ammonia, methanol) for export will continue to expand as other countries start or further advance their carbon abatement goals.

FINDING 3: The Industrial sector is projected to be the largest demand segment, but deploying LCI hydrogen at-scale requires demand growth in hard-to-abate sectors, including heavy-duty Transportation and dispatchable Power.

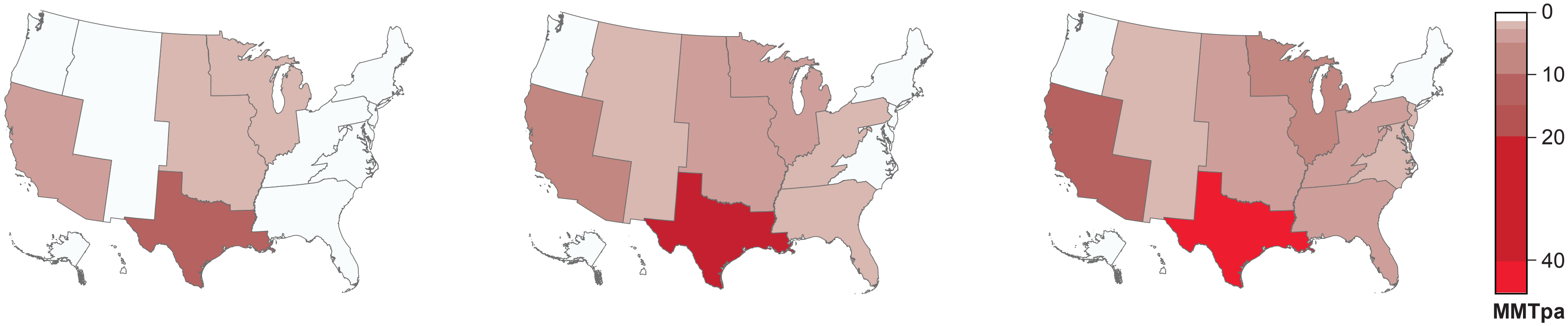
2. The Industrial Sector

The Industrial sector could serve as the single largest demand segment for LCI H_2 (Figure ES-6). The Industrial sector represents existing demand for unabated H_2 (11 MMTpa in 2021) and likely drives LCI H_2 deployment in the Activation phase. LCI H_2 in this phase, supported by IRA incentives, could replace unabated hydrogen as a feedstock for hydrotreating transportation fuels and the production of ammonia and methanol. Demand-centric industrial hubs will likely serve as "anchors" to support incremental production for secondary market demand (e.g., heavy-duty transportation).

Full decarbonization of the Industrial sector will require the deployment of multiple abatement and alternative technologies, including, but not limited to, electrification, CCS, and the use of H_2 for process heat. However, all technologies have limitations: Electrification is challenged when addressing high-heat industrial needs, CCS is challenged when addressing emissions sources with low CO_2 concentrations or in locations with limited land space, and LCI H_2 does not compete economically with natural gas for use as process heat with the current policies. Hydrogen's potential deployment for process heat is sizable, but a large cost gap between natural gas and LCI H_2 remains, even with current policies. Therefore, additional policy support (e.g., a price on carbon or a national low carbon intensity industry standard, see Chapter 6: Policy) will be needed. These types of policies

ACTIVATION PHASE → EXPANSION PHASE → AT-SCALE PHASE

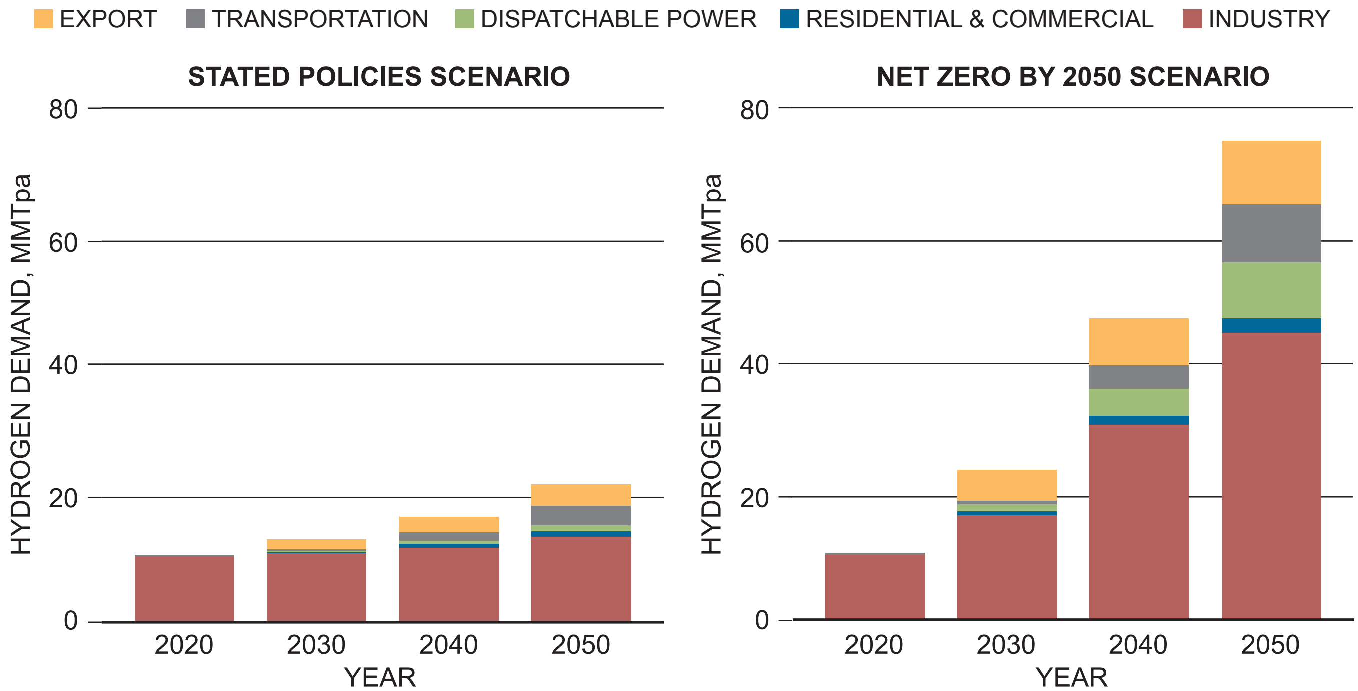
Growth of H_2 Demand in the Net Zero by 2050 Scenario



Key Events

ACTIVATION PHASE	EXPANSION PHASE	AT-SCALE PHASE
• Industrial demand growth around local infrastructure	• Establishment of regional hubs along with demand growth in Transportation and Power	• Interregional infrastructure coupled with full scale-up across Industrial, Transportation, and Power sectors
Regions Activated		
4	7	9
H_2 Demand Volume (MMTpa)		
25	50	75

Figure ES-5. *Three-Phase Roadmap for LCI Hydrogen Deployment*



Note: The demand projections for exports are taken from "Houston as the epicenter of a global clean hydrogen hub" (May 2022) and are applied as constraints in USREP.

Figure ES-6. *Hydrogen Demand by Sector Under Stated Policies and Net Zero by 2050 Scenarios*

could help to drive the carbon emissions reductions of industrial heat, steel production, and other Industrial sectors in the Expansion phase by promoting the use of all abatement technologies, including LCI H_2. Additionally, hydrogen carriers (e.g., ammonia, methanol) enable production of LCI H_2 for export markets (see Section III.A.5) to help reduce carbon emissions from industrial applications in other countries.

The At-Scale phase, supported by policy, as well as cost reductions of emerging technologies, will continue the carbon abatement of the Industrial sector, supported by synergies from connecting hubs, widely available infrastructure, and increased demand across other sectors.

3. The Transportation Sector

The Transportation sector could become the second-largest demand segment for LCI H_2. Adoption in the Activation phase could be supported by incremental production from industrial hubs (where industrial applications "anchor" demand in the region) and by supportive transportation-related state policies. Increased adoption of LCI H_2 fuel cells would be realized in the 2040s, particularly in long-haul transportation with higher payloads (e.g., heavy-duty trucking). All relevant technologies to fuel this sector have limitations: Batteries require longer refueling times and offer lower-density energy storage; incumbent fuels have high CI; and H_2 is not currently cost competitive to incumbents. Hydrogen-based fuel cell electric vehicles (FCEVs) in heavy-duty trucking have a significant cost gap to overcome compared to diesel-based incumbent internal combustion engine vehicles (ICEVs), as shown in Section IV. A.

In some use cases, LCI H_2's fast refueling, high-energy density, and low CI can make it an attractive low CI alternative to the adoption of battery electric vehicles (BEVs). Assuming supportive policies (e.g., a national low carbon intensity transportation standard, see Chapter 6: Policy), LCI H_2 near demand-centric industrial hubs and ports could support the transportation of heavy goods (e.g., trucking, shipping) in the Activation phase.

In addition, as indicated in the Modeling, the use of LCI H_2, along with other low CI alternatives, could continue to grow in select states (e.g., California) that support transportation-focused regulations (e.g., the Advanced Clean Trucks Rule, the Innovative Clean Transit Rule, the Advanced Clean Fleets Rule), coupled with incentives (e.g., the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project). However, due to significant gaps in the total cost of ownership (TCO), LCI H_2 will need cost support and the buildout of supporting infrastructure (e.g., H_2 retail stations) to enable sector growth in subsequent Expansion and At-Scale phases.[13] Demand policies (detailed in Chapter 6: Policy) could lead to an Expansion phase characterized by the buildout of H_2 refueling stations along major distribution routes for heavy-duty trucking, and potential synergies with medium- and heavy-duty transportation modes ranging from buses to rails. A mature, national-scale distribution network will provide LCI H_2 for heavy-duty trucking supported by policy and emerging technology. During the At-Scale phase, LCI H_2 carriers for shipping and aviation applications could develop.

4. The Power Sector

In the Power sector, LCI H_2 could serve as a low-carbon, dispatchable power source. Hydrogen turbines and fuel cells could provide grid-firming capacity that supports increased penetration of renewable generation. In the Activation phase, continued development of turbines and fuel cells using LCI H_2 (and blends) could lead to their deployment in states with renewable grid mandates (e.g., California) and in locations with high-quality wind and solar renewables (e.g., Midwest, Texas) to enhance grid stability. Renewable power generation is impacted by intermittency issues, such as diurnal fluctuation and seasonal variations in solar and wind generation profiles. While battery energy storage could help solve day-to-day intermittency challenges, longer-duration variances (e.g., monthly, seasonal) could be addressed by using H_2 for longer-duration energy storage. In the Expansion phase, LCI H_2, supported by renewable power policies, can provide reserve dispatchable energy and serve as a long-duration energy storage complement to batteries. By the At-Scale phase, LCI H_2 could play a key role in capturing excess generation and for dispatchable power (e.g., via fuel cells, H_2 combustion systems) into the grid as needed. This grid-firming capability of LCI H_2 could support a fully decarbonized electric grid.

LCI H_2 use in the Power sector will likely extend to off-grid power generation. Some applications for off-grid power generation will occur near hub locations in Activation; growth in backup power could continue in Expansion and ultimately support the development of microgrids.

13 Total cost of ownership includes the costs of purchasing, maintaining, operating, installing, and disposal/recycling associated with the asset.

SAFE USE OF HYDROGEN

The United States hydrogen industry has demonstrated the ability to transport, store, deliver, and use hydrogen safely over several decades in refining, chemical, and petrochemical applications. However, many new hydrogen users might not be familiar with the special challenges, safeguards, and infrastructure required with hydrogen. Increasing the awareness of hydrogen safety will be critical in ensuring adoption of safety measures and practices as the use of hydrogen in the economy increases. Ensuring infrastructure and operational safety of the hydrogen ecosystem across all aspects of the value chain is essential.

FINDING 4: The United States has the opportunity not only to secure its own carbon emissions-reduction goals via LCI hydrogen but also to be a leader in advancing the global hydrogen economy.

5. Exports

A key opportunity during both the Activation and Expansion phases for U.S.-based LCI H_2 production is the export of LCI H_2. Because of its endowment in abundant natural resources and supportive production polices, the United States is intrinsically well positioned to ramp up domestic production of LCI H_2 to meet its national carbon abatement targets and become a global leader as a net exporter via several potential H_2 carriers (e.g., ammonia, methanol, liquid organic hydrogen carriers, liquefied hydrogen).[14] During the Activation phase, ammonia and methanol producers near regions with major ports (e.g., Gulf Coast) could build out additional production for export of LCI H_2 carriers; ports would prepare the necessary infrastructure to enable transport to international markets. During the Expansion phase, these LCI H_2 carrier exports are expected to support targeted countries, primarily in Asia and Europe, working to meet their net zero goals by addressing their hard-to-abate sectors. In addition, this demand enhances the U.S. role in providing energy security to favored nations. By the At-Scale phase, in the NZ2050 scenario, U.S. LCI H_2 exports could be approximately 15% of the total LCI H_2 demand in 2050 (10 MMTpa).[15] To give an appreciation, the role the U.S. plays in the global LNG market represents ~12% of the U.S. domestic natural gas production and is projected to be ~25-30% by 2050.

B. Characteristics of LCI H_2 Production

FINDING 5: The LCI hydrogen production mix will be driven by multiple aspects of the various hydrogen production pathways, including their relative speed to scale, delivery cost reductions, and carbon intensities.

The volume of LCI H_2 needed in the NZ2050 scenario will require growing U.S. LCI H_2 production through multiple production pathways. This study has focused on two key LCI H_2 production pathways: RE H_2 and NG+CCS H_2.[16] These two production pathways will evolve throughout the three growth phases and optimize around variables of speed to scale, cost to deliver, and CI of H_2. Both major production pathways must increase at an aggressive pace compared to historical norms to achieve LCI H_2 deployment at-scale by 2050. Any delays will prevent the United States from reaching its net zero ambitions in the desired timeline at the lowest cost to society.

NG+CCS H_2 leads the way in the Activation and early Expansion phases of LCI H_2 deployment, followed by a significant increase in RE H_2 volumes in the NZ2050 scenario (Figure ES-7). This production characteristic is primarily driven by NG+CCS H_2's ability to rapidly scale up, the near-term lower costs, and infrastructure advantages. To reach deeper levels of carbon abatement, the residual emissions associated with NG+CCS H_2 need to be mitigated, requiring adding costs of negative emissions technologies, like DAC, to the effective production cost of NG+CCS H_2. RE H_2, by comparison, has a lower CI than NG+CCS H_2 and would have lower residual emissions to mitigate for net zero. According to the Modeling, growing production of RE H_2 will be needed in the production mix as the mitigation costs associated with NG+CCS H_2 increase, driving the effective costs[17] of NG+CCS H_2 above RE H_2.

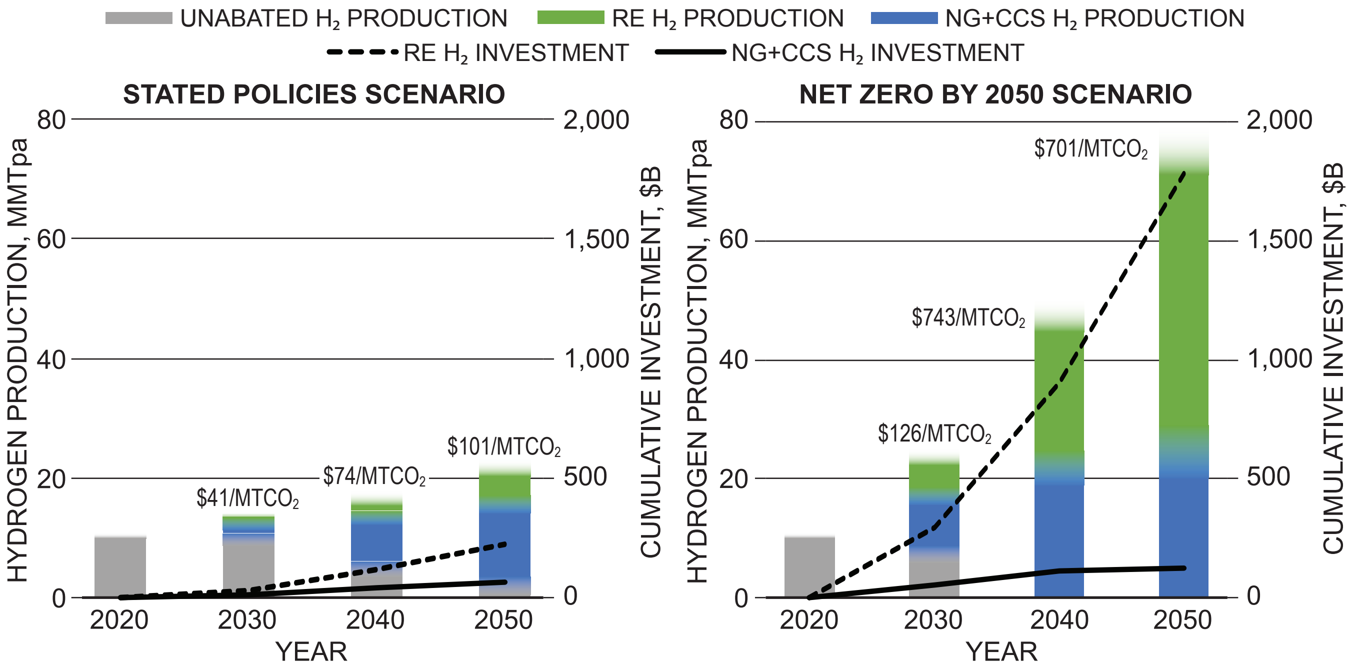
It is crucial to acknowledge the unique challenges that exist to scale up the production of LCI H_2 from each of the two key production pathways at the desired pace and magnitude needed under the NZ2050 scenario. Key hurdles for scaling up RE H_2 production include reducing the capital and operational costs of electrolysis-based production facilities, expanding renewables on the grid, increasing grid capacity and resilience, establishing supportive supply chains for manufacturing electrolyzers at-scale, sourcing critical metals, and ensuring sustained efficiency and performance across various operational conditions. Additionally, RE H_2 requires greater build-out of H_2 pipelines and salt caverns to match high-capacity renewable power with LCI H_2 demand. Scaling up NG+CCS H_2 could face hurdles associated with development of infrastructure related

14 Natural resources range from low-carbon energy resources (e.g., wind, solar, etc.) to natural gas and large-scale geologic storage options.

15 The Modeling did not attempt to define global trade flows. Instead, this study leveraged demand projections for exports from a May 2022 study by the Center for Houston's Future, the Greater Houston Partnership, and input from ammonia manufacturing experts. "Houston as the Epicenter of a Global Clean Hydrogen Hub." Center for Houston's Future. 2022. https://www.futurehouston.org/houston-hydrogen-hub/.

16 While multiple production pathways are anticipated to be leveraged in the United States, the Model considers two primary production pathways, including NG+CCS leveraging Autothermal Reforming (ATR) technology with CCS and RE H_2 produced with intermittent renewable electricity feedstocks (wind and solar). Chapter 4: Integrated Supply Chain provides more detail on why these pathways were selected.

17 While not explicitly modeled, the effective costs include both the delivered costs and the cost of carbon associated with the carbon intensity of the LCI H_2.



Notes: The Modeling assumed that the solar and wind renewable power for RE H_2 production was fully additional, developed in the same region as the H_2 production occurs, and functionally hourly time matched.
$B = billions of U.S. dollars; $X/MTCO₂ = Implied cost of carbon at indicated year and policy scenario in real 2020 dollars per metric ton of CO_2 abated.

Figure ES-7. *LCI Hydrogen Production Pathways Mix for Stated Policies and Net Zero by 2050 Scenarios*

to CCS, enhancement of the efficiency and CO_2 capture performance of reformers, and reduction in the CI of natural gas feedstock. Particularly, challenges related to CCS infrastructure—including availability and proximity to CO_2 storage and transporting CO_2—could lead to increased cost and limited growth potential. The uncertainties and challenges in scale-up will dictate the actual mix of RE and NG+CCS hydrogen.

To approach net zero, addressing the remaining hardest-to-abate sectors will require ever-lower CI H_2, which will come at a cost. In the longer term, a significant volume increase of RE H_2 is driven by emissions-reduction requirements under the NZ2050 scenario that NG+CCS H_2, with a non-zero CI, could not fulfill without leveraging negative emissions technologies (e.g., DAC).

Scaling H_2 production to ~75 MMTpa while transitioning ~11 MMTpa of unabated H_2 into LCI H_2 will be a significant challenge. It will require the massive buildout of the relevant facilities and infrastructure, as well as changes in existing policy frameworks to incentivize the buildout.

For RE H_2, both renewable power and electrolyzer capacities will require extensive growth. To meet the electrolytic H_2 production rates estimated under the NZ2050 scenario (~7 MMTpa in 2030 increasing to ~50 MMTpa in 2050), installed electrolysis capacity has to grow from less than 1 GW today to about 65 GW in 2030 to nearly 400 GW by 2050, with annual capacity additions of 12 to 18 GW per year over that period.

To supply sufficient renewable energy to run these electrolyzers at a capacity factor[18] in the 60-65% range, a renewable overbuild ratio of 1.5 to 2.6 is needed (depending on the region, averaging 1.8), so the required renewable resource capacity is over 700 GW by 2050, with annual capacity additions of 22 to 33 GW over that period.[19]

18 The capacity factor is the ratio of actual output to maximum potential output over a specific period. It is often expressed as a percentage and represents the efficiency and utilization of the production equipment (e.g., electrolyzers)

19 For context, the current North American electricity grid is approximately 1,200 GW.

For NG+CCS H_2, a single world-scale autothermal reformer with CCS could produce 0.2-0.4 MMTpa of H_2. To produce approximately 25 MMTpa of NG+CCS H_2 by 2050 would require the buildout of approximately 100 world-scale autothermal reforming systems and the associated infrastructure and storage for carbon capture.

According to the Modeling, the NZ2050 scenario would require $1.9 trillion in cumulative capital investment by 2050 for production of RE and NG+CCS H_2.[20] The challenge is increased when considering the 2050 time constraint under the NZ2050 scenario. This will require significant and immediate actions to support the growth and scale-up of the H_2 market. For example, RE H_2 production will require installed electrolyzer capacity to grow at a compound annual growth rate of 27% over the next 25 years. While the required investment and growth rate to reach net zero supported by LCI H_2 is formidable, it is comparable to the North American capital investment in upstream oil and gas ($1.9 trillion) and solar installation (30% compound annual growth rate) in the last decade.[21, 22]

C. Infrastructure to Connect Demand with Production

FINDING 6: Pipelines should connect advantaged production to diverse demand centers to support a regionally optimized infrastructure configuration.

The geographical separation of production and demand poses additional challenges for deploying LCI H_2 at-scale, a challenge that is especially acute for RE H_2 (see Chapter 4: Integrated Supply Chain for more detail). Some of these challenges include building infrastructure connecting the geographically separated production and demand (e.g., pipelines), developing reliable supply (e.g., leveraging salt cavern storage) to reach the desired scale, and reducing the overall infrastructure cost. Transporting molecules from production to demand sites further increases the existing cost gap between LCI H_2 and incumbent fuels or feedstocks. While the Activation phase will likely leverage existing infrastructure by transitioning from movement of unabated to LCI H_2 and the close proximity of production and demand, future demand and production centers for LCI H_2 are unlikely to have these advantages. Minimizing the cost impact of dislocated production and demand will necessitate the development of a diverse and well-balanced portfolio of LCI H_2 infrastructure. Without this infrastructure buildout to connect advantaged production to demand, the H_2 value chain stalls, jeopardizing deployment of LCI H_2 at-scale to meet the U.S. net zero by 2050 target.

The buildout of the infrastructure connecting production and demand will leverage various transport mechanisms based on transport distance. There are three primary domestic transport mechanisms: short-distance molecule transport (e.g., trucks), long-distance molecule transport (e.g., pipelines), and energy transport (e.g., electric transmission[23]). Among the three primary transport mechanisms to connect production and demand, pipelines tend to provide the most affordable mode of connection.

Energy transfer with electricity transmission could incur extra costs due to electrical efficiency-related power losses. On the other hand, molecule transport with trucks has limitations on the volume that can be transported by each vehicle and may necessitate transportation as liquid H_2. The choice of moving energy either as molecules (hydrogen) or as electrons (electricity) is driven by several factors, including regional constraints, siting/land-use restrictions, environmental impacts, technoeconomics, and transporting distance. Therefore, this choice requires analysis of the trade-offs at the individual project level. Further discussion of this topic is included in Chapter 3: Infrastructure.

20 RE H_2 requires $1.8 trillion and NG+CCS H_2 $0.1 trillion out of the total cumulative investment by 2050 ($1.9 trillion), according to the Modeling.

21 "Renewable Capacity Statistics 2023." International Renewable Energy Agency (IRENA). 2023. https://www.irena.org/Publications/2023/Mar/Renewable-capacity-statistics-2023.

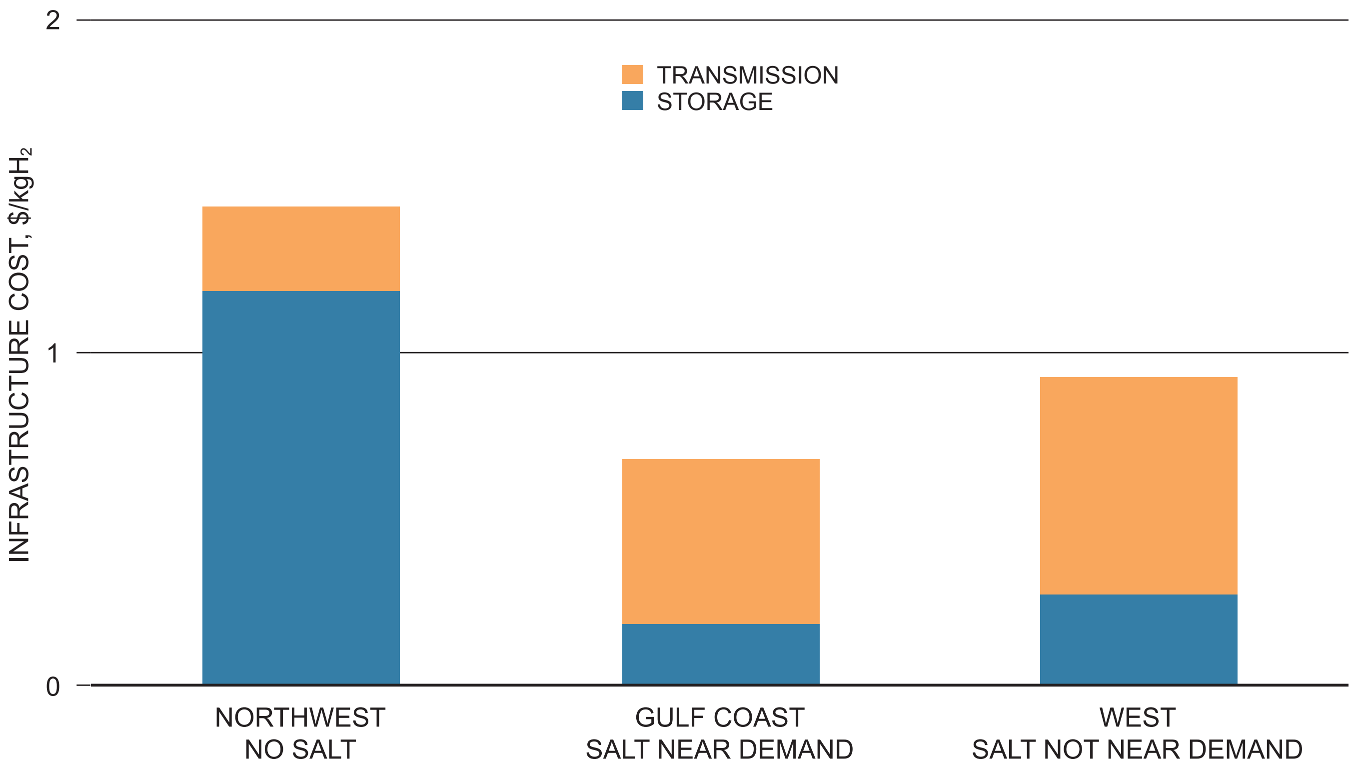
22 "Upstream Exploration Solution." Rystad Energy. 2023. https://www.rystadenergy.com/services/upstream-solution.

23 Electric transmission is energy transport in the form of high-voltage electricity delivered through a power transmission network, followed by electrolytic hydrogen production in proximity to end users.

FINDING 7: **Incorporating large-scale hydrogen storage infrastructure could enable a more cost-effective LCI hydrogen energy system design across the United States.**

The infrastructure cost can be divided into two major segments: H_2 transportation and storage (Figure ES-8). Storage is vital for reliable, cost-optimized energy systems, particularly for RE H_2. It ensures efficient design and addresses the intermittent nature of renewable power in electrolytic H_2 production. Regional H_2 storage needs vary based on renewable energy capacity factors. Multiple storage options exist or are emerging. Two key options for further discussion are subsurface salt caverns and liquefied H_2 tank storage (see Chapter 3: Infrastructure for more details on storage technologies). Salt cavern storage offers a cost-effective way to store H_2 at-scale; however, its availability is geographically limited, often leading to challenges in matching it with renewable power or demand locations. The availability, or lack thereof, of salt cavern storage affects the levelized cost of infrastructure in the H_2 value chain. Geographical regions with easy access to salt cavern storage (e.g., the Gulf Coast) have relatively lower storage costs than regions without salt cavern storage (e.g., the Northwest), as the latter regions must rely on liquefied H_2 tank storage.

The type and location of storage impacts the delivered cost of LCI H_2. In the Northwest, which lacks salt cavern storage and relies on liquefied H_2 tanks, storage costs exceed $1/kg in the levelized cost of delivered H_2. In the Gulf Coast and West regions, the RE H_2 would be most economically produced near the available salt cavern storage and transported via pipelines to distant demand sectors. Even with the additional transportation cost, the incremental cost of storage in salt caverns in the Gulf Coast and West regions remains lower than leveraging liquefied H_2 tank alternatives.



Note: Levelized infrastructure cost in 2030. Assumes use of above-ground liquid H_2 storage when salt caverns are unavailable.

Figure ES-8. *Levelized Infrastructure Cost of Hydrogen Based on Location and Availability of Subsurface Salt Cavern Storage*

D. Advantaged Regions to Lead Deployment

FINDING 8: The LCI hydrogen market in the United States has entered the Activation phase, aided by recent legislation such as the Inflation Reduction Act and Infrastructure Investment and Jobs Act, and is poised to increase LCI hydrogen production in advantaged regions.

Certain advantaged regions within the United States possess attributes that may catalyze early LCI H_2 production in the Activation phase. These key regions exhibit one or more of four factors:

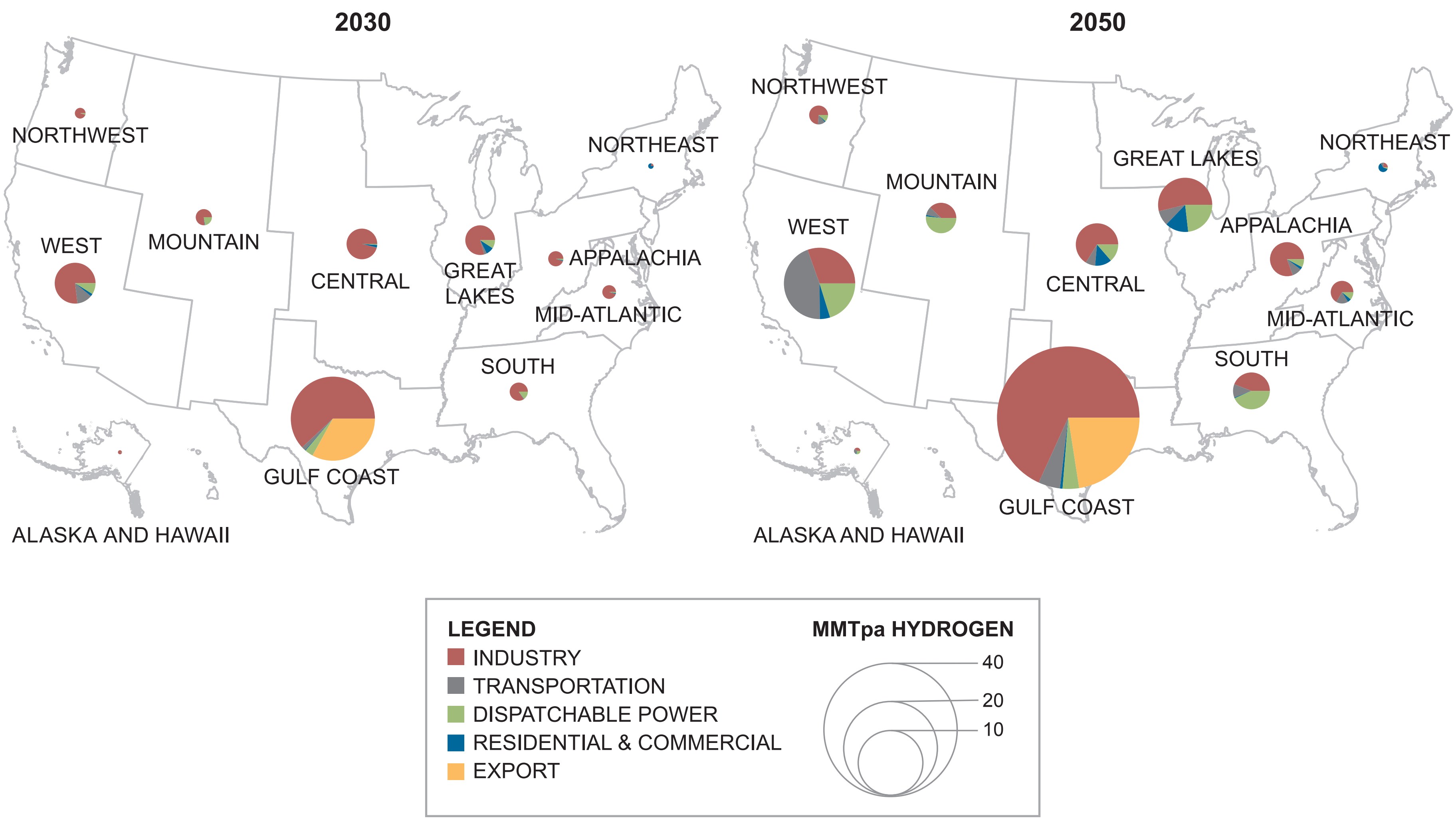
1. Proven demand due to existing unabated H_2 users or proximity to sectors where the adoption of LCI H_2 is relatively more attractive and technically feasible during the Activation phase
2. Potential for lower production costs under both reforming and electrolysis pathways due to abundant natural resources (e.g., solar, wind, natural gas)
3. Faster scalability at a lower cost due to the availability of existing infrastructure or ease of construction for new infrastructure (e.g., pipelines, geologic storage)
4. Cost competitiveness due to existing supportive state policy that supplements federal policy, narrowing the cost gap between incumbent and LCI H_2

The underlying economics, influenced by these factors, will likely shape the production of LCI H_2 and favor the production of certain H_2 pathways in various regions during the Activation phase. In the U.S., three advantaged regions will likely stand out during the Activation phase and could lead the U.S. LCI H_2 market development across all phases: Gulf Coast, West, and Great Lakes. Each region has a unique combination of the preceding factors that will likely lead to different regional patterns of demand, production, and infrastructure development (Figures ES-9 and ES-10).

While not explicitly factored into the Modeling, the seven selected DOE Regional Clean Hydrogen Hubs, announced October 2023, generally overlap with the advantaged regions identified through the Modeling and should serve to positively reinforce development of the LCI H_2 economy in these areas. Refer to Chapter 4: Integrated Supply Chain for details on the impacts of the characteristics of each region.

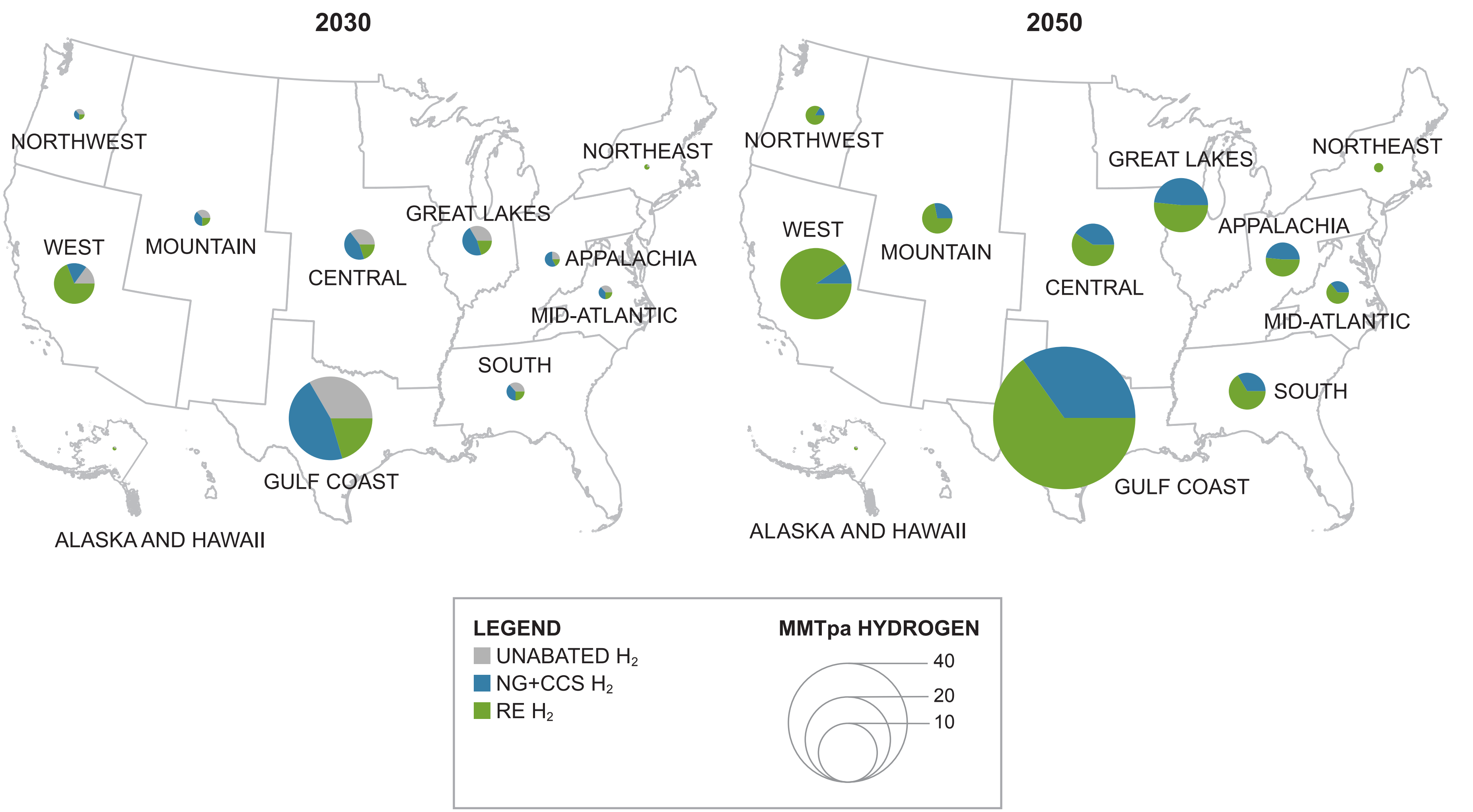
Under the NZ2050 scenario, the Industrial sector leads the demand growth of LCI H_2 in the Activation phase. Replacing the Industrial sector uptake of unabated H_2 with LCI H_2 is projected to drive LCI H_2 adoption across different regions. Regional differences in sectoral demand will become more distinctive as the market progresses through the Expansion and At-Scale phases. On these subsequent phases, additional and new demand for LCI H_2 in end-use applications (e.g., using H_2 as a fuel) is projected to be activated. In the Gulf Coast, the Industrial sector continues to dominate regional demand due to existing and newly enabled end-use applications in the industrial centers, primarily for refining and chemicals production. For similar reasons, industrial demand in the Great Lakes is also projected to dominate regional demand, albeit to a lesser extent than the Gulf Coast. On the West Coast, the Transportation sector accounts for nearly half of LCI H_2's projected regional demand. In that region, state policies incentivize the switch to low CI transportation options, including FCEVs (e.g., California's LCFS, Advanced Clean Trucks and Fleet regulations).

In addition, under the NZ2050 scenario, the optimal production mix could vary by region based on a region-specific combination of factors. The CI of different H_2 pathways, emissions-reduction targets and projected cost of carbon will also heavily influence the optimal H_2 production mix. As shown in Figure ES-10, in most regions, NG+CCS H_2 leads the adoption of LCI H_2 during the Activation and early Expansion phases, while the RE H_2 value chain scales up. However, in the West region, RE H_2 leads LCI H_2 adoption due to significant RE H_2 demand created by state-level transportation policies. After the RE H_2 value chain scales up, RE H_2 deployment increases significantly in all regions to reach net zero.



Note: Existing and future anchor demand will impact regional sectoral adoption.

Figure ES-9. Outlook of Regional Demand Development by Sector in 2030 and 2050 under the Net Zero by 2050 Scenario



Note: For the Modeling, the LCI H_2 production in California within the West region is constrained to RE H_2.

Figure ES-10. *Outlook of Regional Production Development by Hydrogen Pathway in 2030 and 2050 under the Net Zero by 2050 Scenario*

REGIONAL VARIABILITY IN SUPPORTING INFRASTRUCTURE BUILDOUT

Regional variability plays a significant role in developing the LCI H_2 value chain, especially for RE H_2. Factors that have the highest impact on the delivered cost of RE H_2 include the location of high-quality renewable energy resources (particularly solar and wind), geographic separation between high-quality renewables, subsurface salt caverns for H_2 storage and demand centers, along with regional cost of pipeline infrastructure and electrical transmission. Given the intermittent nature of solar and wind energy, RE H_2 necessitates overbuilding renewable capacity relative to electrolyzer capacity. It also requires the addition of sufficient H_2 storage to meet constant demand while maximizing electrolyzer utilization.

Renewable energy, salt cavern storage, and demand centers are not always in the same location and often require transmission—as H_2 molecules or electrons—over long distances. The Model analyzed three priority regions (the Gulf Coast, West, and Great Lakes) to understand the interregional complexities of building out a H_2 value chain and determined a cost-optimal supply chain architecture to efficiently meet LCI H_2 demand. The optimized LCI H_2 value chain is different in each region, due to differences in the highest impact factors. For example:

- In the Gulf Coast region, the optimal supply of RE H_2 involves the production of H_2 in northwest Texas near high-capacity wind power and salt cavern storage; H_2 is transmitted as a molecule via a pipeline to the demand centers of Houston, Beaumont, and south Louisiana.
- In the West Region, production coincides with the location of salt storage (northwest Arizona), rather than the most advantaged renewables; transmission remains in a pipeline as a molecule but reaches a more distributed transportation demand.
- In the Great Lakes region, the location of salt cavern storage and the lower cost of electrical transmission results in the movement of electrons from areas with advantaged renewables to produce H_2 near salt cavern storage.

All regional optimizations showed the important role of H_2 pipelines and salt cavern storage in developing the RE H_2 value chain at a lower cost than other alternatives.

By comparison, the production of NG+CCS H_2 is expected to be near the demand center, reducing the importance of long-distance H_2 pipelines and storage. This is driven by the ability to leverage existing infrastructure to move natural gas to demand centers, where it can be reformed into LCI H_2 and used locally. Instead, the focus shifts to the significant impact of developing CO_2 transport pipelines and carbon sequestration sites.

IV. CRITICAL ENABLERS TO UNLOCK LCI HYDROGEN AT-SCALE

The NZ2050 scenario requires nearly 7x growth in H_2 deployment by 2050 while simultaneously reducing the CI of the H_2 deployed. This monumental challenge will require unlocking new demand, developing production, and building infrastructure at a scale rarely seen in the U.S. economy during the last several decades. Achieving LCI H_2 deployment at-scale requires a significant change from the current trajectory, led by policy that drives low-carbon solutions to displace unabated alternatives—and doing so at an aggressive pace. This study has highlighted a set of three categories of critical enablers that could aid in rapid LCI H_2 deployment across all regions: policy and regulation, SCI and safety, and targeted investments in technology and RD&D. First, policy measures are likely to be the most critical lever for achieving scale for LCI H_2, and an effective regulatory framework is required for the timely deployment of LCI H_2 projects. Second, addressing SCI and safety concerns is critical to increasing public acceptance and collaboration, which supports the timely development of LCI H_2 projects. Third, targeted technology and RD&D investments will help expand the use of LCI H_2 to new applications and enable its wider deployment; nevertheless, targeted technology investments are not a substitute for policy actions. The following subsections summarize the enablers largely aimed at the Activation phase and NPC's recommendations related to implementing these enablers.

A. Policy and Regulation

Without policy support, the end-user cost of LCI H_2 is not competitive with higher-carbon incumbents, nor will it be for the foreseeable future. The incumbent energy sources that LCI H_2 may replace in different end-use applications within each sector across the economy are summarized in Table ES-1. In general, the cost gap between incumbents and lower-carbon alternatives can be attributed to two factors: (1) the additional cost to produce and abate carbon emissions along existing production pathways and (2) the utilization of new production pathways that do not yet benefit from economies of scale. This cost differential could widen further due to sector-specific switching costs incurred by end users to adopt low CI alternatives.

FINDING 9: A large cost gap exists between incumbent fuels and feedstocks and LCI hydrogen in hard-to-abate applications. Technology advancement will continue to support closing the cost gap; however, current federal and state policies, as well as modeled system cost reduction, will not be sufficient to close the cost gap to parity by 2050.

The current policy measures (e.g., renewable production tax credit, IRA 45V, 45Q) will significantly reduce LCI H_2 production costs. However, these incentives will be insufficient to drive down LCI H_2 costs to consumers for some end-use applications compared to the cost of incumbents. While cost reductions from technological advancements, learning rates, and economies of scale are anticipated, these reductions will be insufficient to bridge the gap between LCI H_2 for end-use applications and incumbents by 2050 (refer to the inset titled "Cost Gaps Between Incumbents and Low-Carbon Alternatives" for a discussion of cost gaps in the Industrial and Transportation sectors). Continued policy support is needed to develop a level playing field for all low-carbon technologies. Without sustained policies beyond the IRA expiry, there is a risk that demand momentum will be disrupted by increased LCI H_2 costs to consumers, particularly for RE H_2 (Figure ES-11).

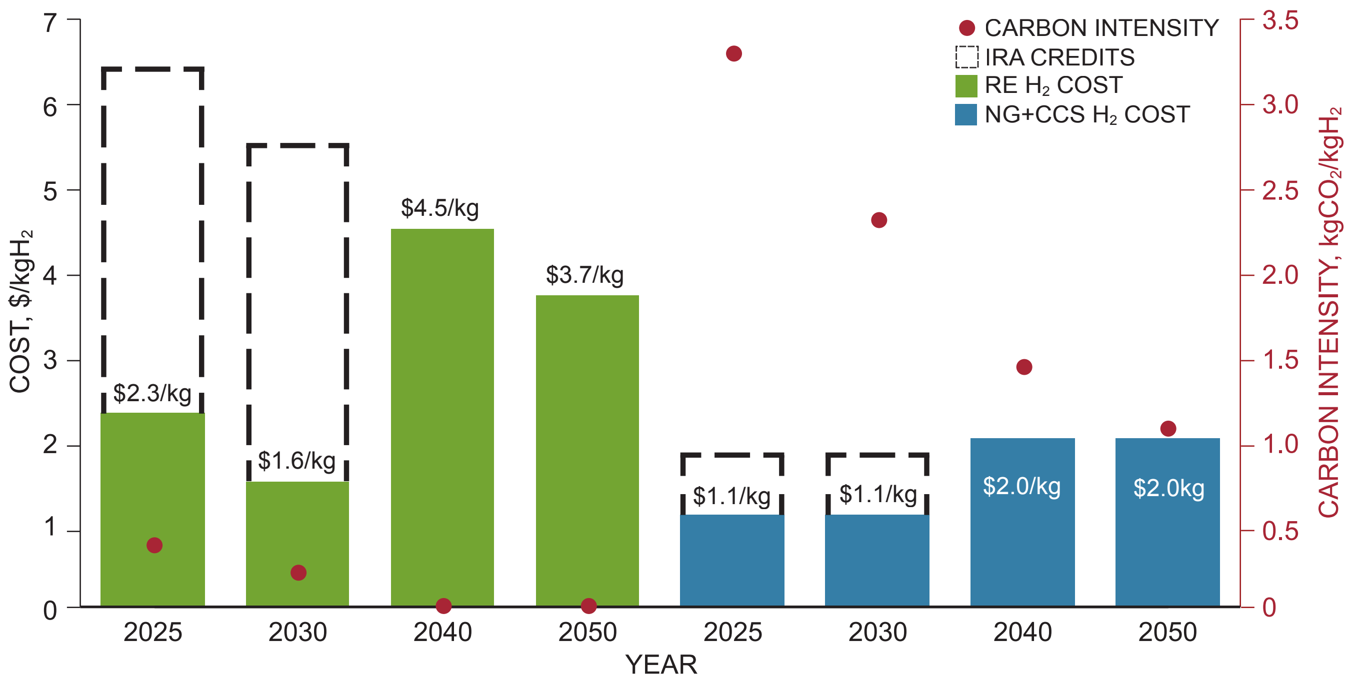
Over time, the delivered CI from both H_2 production pathways decreases, but NG+CCS H_2 consistently maintains a higher CI than RE H_2.[24] The CI of NG+CCS H_2 reduces over time due to improvements in the CI of the natural gas value chain and through the decarbonization of the grid in a net zero scenario. The CI of RE H_2 is driven by electricity needed for transmission and storage in the H_2 supply chain and is directly related to the electric grid's CI. This CI, which excludes embedded manufacturing emissions,[25] drops to zero after the grid decarbonizes in a net zero scenario. Achieving net zero emissions requires addressing all emissions, including residual emissions from NG+CCS H_2. This entails reducing NG+CCS H_2 emissions to match RE H_2 levels. As a result, NG+CCS H_2 requires offsetting with negative emissions technology, such as DAC, which would raise the effective cost of NG+CCS H_2 above that of RE H_2 in most regions for many applications.

Explicit Carbon Price: NPC continues to support long-term, technology-neutral, economy-wide, explicit carbon pricing, as recommended in the 2011 *Prudent Development* report, for cost-effective emissions reductions of the economy. This study introduces the idea of well-designed sector policies as a bridging strategy prior to implementation of carbon pricing.

Modeling shows that a long-term, effective, economy-wide, transparent price on carbon would shift the driving force of the energy transition from shorter-term government incentives to a more efficient market mechanism (i.e., pricing). Explicit carbon pricing would consider the carbon emissions associated with incumbent fuels and feedstocks as part of their end-use costs, provide the most economically efficient climate policy, and unlock a suite of carbon emissions

24 The carbon intensity of NG+CCS and RE H_2 considered in the study does not include embedded emissions.

25 See Chapter 2: Production, Section IV for further discussion on embedded manufacturing emissions.



Notes: IRA credits include both 45Y and 45V for RE H_2 and assume use of 45Q for NG+CCS H_2. IRA credits are assumed to have expired and are not included in the delivered cost results for 2040 or 2050. Carbon intensity values do not include embedded emissions. Results shown from the Net Zero by 2050 Scenario.

Figure ES-11. *Delivered Costs and Carbon Intensity of RE and NG+CCS Hydrogen in the Gulf Coast Region for the Industrial Sector Pre- and Post-IRA Credit Application*

abatement levers including, but not limited to, LCI H_2. An explicit carbon-pricing mechanism would incorporate the source's full life cycle carbon emissions so that a higher-carbon emitter has higher pricing than lower-emissions options.

Both Modeling scenarios incorporate an "implied price of carbon," which is defined as the marginal cost of abating carbon. This "implied price" represents the cost of reducing CI in the overall energy system. It is equivalent to the required cost of carbon to reach cost parity when abating the next marginal CO_2 emitter along the timeline required to achieve net zero. The Modeling demonstrates how applying a cost of carbon could enable least-cost technologies to reach emissions targets within both scenarios; the carbon cost profile is increased in certain years to match emissions-reduction targets and the cost to offset carbon increases as net zero is approached

PREVIOUS NPC RECOMMENDATION ON CARBON PRICING

The main aspects of the 2011 Prudent Development report carbon-pricing recommendation are as follows:

"As Congress, the administration, and relevant agencies consider energy policies, they should recognize that the most effective and efficient method to further reduce GHG emissions would be a mechanism for putting a price on carbon emissions that is national, economy wide, market based, visible, predictable, transparent, applicable to all sources of emissions, and part of an effective global framework."

"Any policy should include consideration of the impacts on the national economy and industry and should provide a predictable investment climate. To minimize adverse impacts on energy security and affordability, implementation should address the need for phase-in of carbon prices and emission controls."

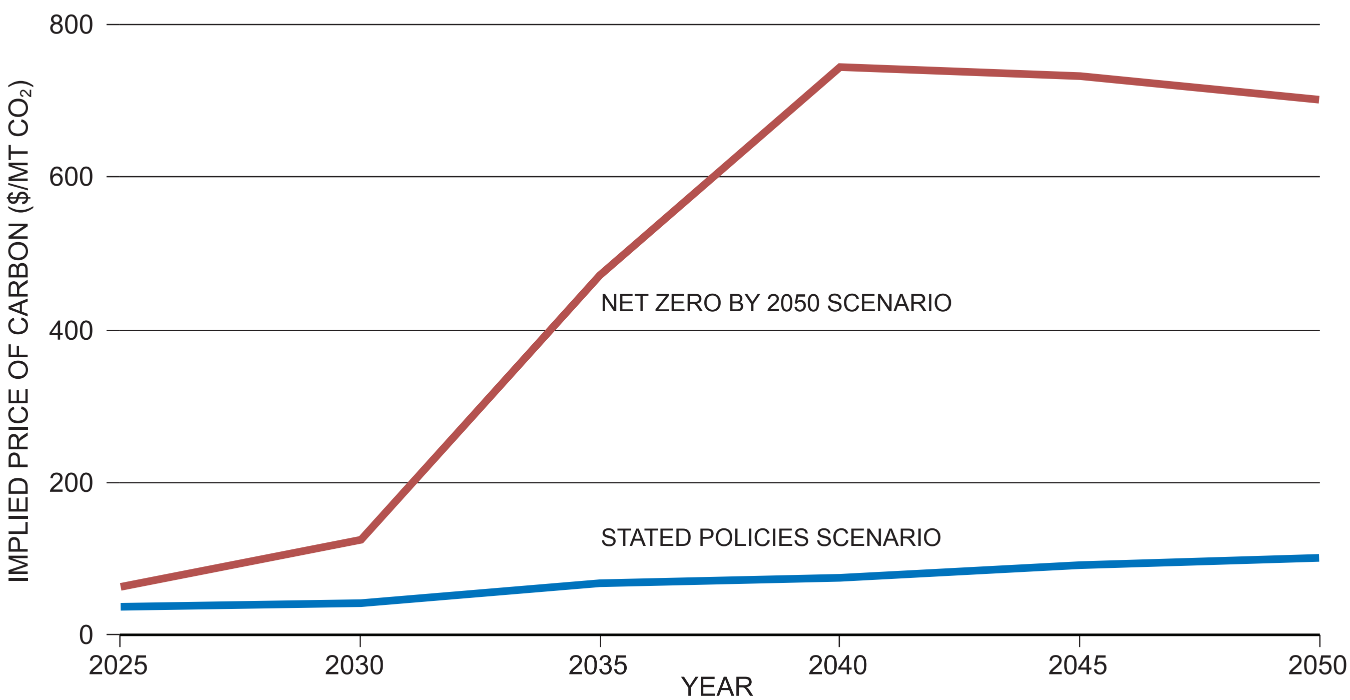
(Figure ES-12). A gradual increase in a carbon cost could encourage optimal system buildouts for the net zero economy. It could indicate to investors how to best sequence the deployment of technologies to enable carbon emission reductions at the desired speed and scale. Therefore, a gradual ramp-up of the carbon cost would help mitigate economic inefficiencies. As a result, the Model estimates an explicit cost on carbon needed to support deployment of LCI H_2 at-scale.

In the NZ2050 scenario, the implied price of carbon increases rapidly post-2030. This increase is driven by the emissions-reduction trajectory and the corresponding need to deploy a suite of more expensive technologies, including LCI H_2, CCS, and DAC, to accelerate the U.S. carbon emissions-reductions trajectory. From 2030 to 2040, as emissions continue to decline, the marginal reduction becomes harder, requiring deployment of more costly or complex abatement options, leading to a higher cost of carbon. In the NZ2050 scenario, the CI of grid power is assumed to reach zero by 2035 and, by 2040, the deployment of DAC begins to play a significant role in incremental emissions reductions, essentially operating as a price-setting mechanism for the implied price of carbon. As the deployment of DAC continues to grow, learning curves and scale-up enable costs to come down through 2050.

A direct, explicit carbon price is the most efficient approach toward decarbonization. A phased-in approach could combine implicit cost measures to support developing demand, production, and infrastructure.

RECOMMENDATION 1: PRICE ON CARBON

Recommendation: As more fully described in Chapter 6: Policy, the NPC recommends that the administration work with Congress to establish an economy-wide price on carbon well before current incentives, such as 45V, expire. This economy-wide price on carbon should be:



Notes: Implied price of carbon required to reach cost parity when abating the next marginal CO_2 emitter to achieve the emissions-reduction targets under the Stated Policies and Net Zero by 2050 scenarios. Implied price of carbon shown in real 2020 U.S. dollars.

Figure ES-12. *Estimated Implied Price of Carbon under the Stated Policies and Net Zero by 2050 Scenarios*

- Phased-in and coordinated to minimize adverse impacts on energy security, reliability, and affordability
- Well-designed to provide predictable signals for decisions about long-lived capital investment
- Market based, and applicable to imports as well as domestic production, with a rebate for exports
- Visible, predictable, and transparent
- Enabling all technologies to compete and cost effectively lower carbon emissions intensity by focusing on reducing emissions per unit of energy while delivering meaningful emissions reductions
- Considering key protections and assurances for communities that are disadvantaged and could be overburdened by climate and air pollution
- An emissions intensity border fee considered in the context of a complementary explicit carbon-pricing policy to address/mitigate potential emissions leakage

While a direct, explicit carbon price is the most efficient approach toward decarbonization, the United States might not be ready to activate this lever. Therefore, additional demand and production-side incentives are necessary to bridge the price gap between low CI technologies, including LCI H_2, and other energy sources. A sector-based, technology-neutral, low CI standard that targets a life cycle CI reduction profile could act as a bridge toward a price on carbon. Standards as described in the following two recommendations would support all low CI technologies. Those standards have been prioritized in this study, as they address two key sectors—Industrial and Transportation—with the highest potential for reducing emissions with LCI H_2.[26]

Demand-Side Incentives—National Low Carbon Intensity Industry Standard: In the absence of an economy-wide price on carbon, a

26 According to EPA, the Industrial and Transportation sectors account for 30% and 29% of the total U.S. GHG emissions as of 2021, respectively.

COST GAPS BETWEEN INCUMBENTS AND LOW-CARBON ALTERNATIVES

Further policy is required to help close large gaps that exist in cost parity between LCI H_2 and higher-carbon incumbents in many of the potential demand use cases. Two examples are provided to articulate this concept. Figures ES-13 and ES-14 show the cost gap between incumbents and LCI H_2 in Industrial and Transportation applications, respectively. In these figures, (A) and (B) show the projected ranges in levelized delivered cost of hydrogen for both the NG+CCS and RE H_2 production pathways. Items (C) show the ranges of delivered H_2 cost that would make LCI H_2 competitive with incumbents. Of note, the RE H_2 levelized cost ranges were developed as sensitivities tested outside of the Model, related to flexing variables around electrolyzer capital, electrolyzer efficiency, overbuild ratios, and renewable energy capex. These ranges are driven by regional variations in cost and modeled scenario. The indicated “Reference RE H_2 cost” represents the levelized costs of RE H_2 used in the iterations to develop the NZ2050 scenario. It should be noted that the Modeling was completed prior to rulemaking for IRA 45V implementation and the costs for RE H_2 assumed a “behind-the-meter” dedicated renewable power source. This functionally assumes that the solar and wind renewable power for RE H_2 was fully additional, developed in the same region as the H_2 production occurs, and hourly time matched. Reduced stringency in electricity accounting could increase the electrolyzer capacity factor and reduce the amount of storage needed, which might result in lower delivered costs of RE H_2 to end users. However, those lower delivered costs would be contingent on the grid being fully decarbonized or sufficient access to and accounting of renewable energy credits to ensure low CI of the resulting H_2.

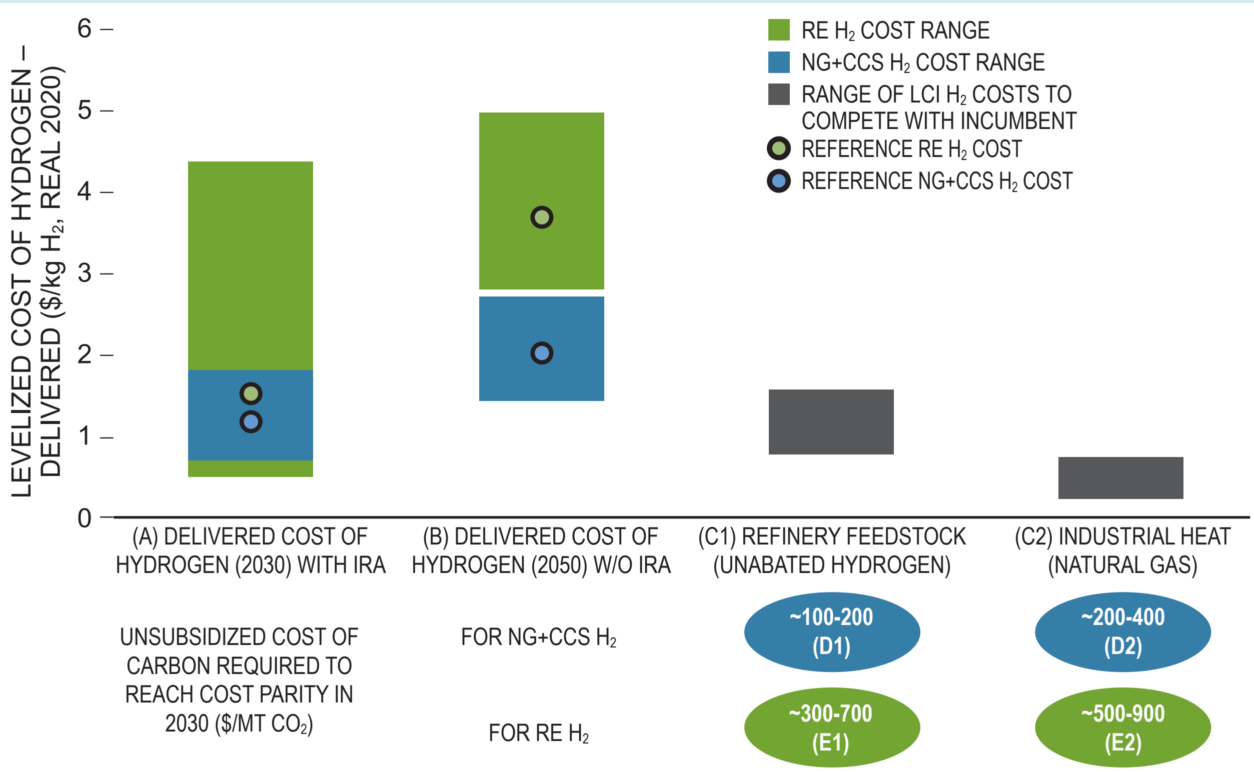
A. Industrial Sector

The Industrial sector is projected to be the largest demand segment for LCI H_2 under both the Stated Policies and NZ2050 scenarios. However, specific end-use applications within that sector cannot be activated due to a large gap in cost parity without policy support (Figure ES-13). In the example shown for a Gulf Coast industrial user, LCI H_2 must compete with incumbent unabated hydrogen for refinery feedstocks (C1) and with natural gas for industrial heat (C2).

For refinery feedstock applications, both RE and NG+CCS H_2 might reach parity with the incumbent unabated H_2 cost with incentives from current policy support, primarily the IRA (A compared to C1). When current policies expire (B compared to C1), H_2 from both delivery pathways will face challenges to compete as an alternative for industrial feedstock, as the delivered cost is required to drop below $2/kg.

For industrial heat, neither RE nor NG+CCS H_2 will compete as an alternative unless its delivered cost drops below $1/kg. The Modeling suggests that reaching this cost threshold is unlikely without additional policy support. Cost competitiveness, while challenged with the incentives from current policies (A compared to C2), becomes increasingly difficult when those policies expire (B compared to C2).

Unabated energy sources are, and will remain, more economical than low-carbon alternatives if carbon is not valued. Introducing an explicit carbon price on emissions from incumbents is an approach that could enable cost competitiveness for all low-carbon alternatives, including LCI H_2, compared to unabated incumbents. Figure ES-13 shows the approximate cost of carbon needed for LCI H_2 to reach parity in 2030 with incumbents for refinery feedstock and industrial heat. NG+CCS H_2 could reach cost parity with incumbents with carbon prices of ~$100-200/MT CO_2 (D1) for refinery feedstock or ~$200-400/MT CO_2 (D2) for industrial heat.



Notes: Levelized cost ranges for delivered RE and NG+CCS H_2 (A and B), alongside H_2 delivered cost ranges needed (C1 and C2) to compete with incumbents in refinery feedstock and industrial heat applications. The cost of carbon required to reach cost parity is shown for NG+CCS and RE H_2 (D1/D2 and E1/E2, respectively) if a reduction in delivered cost cannot be achieved. Graph generated based on Net Zero by 2050 Scenario.

Figure ES-13. *Gulf Coast Comparison of Levelized Delivered Cost Ranges of LCI H_2 to Industrial Incumbents*

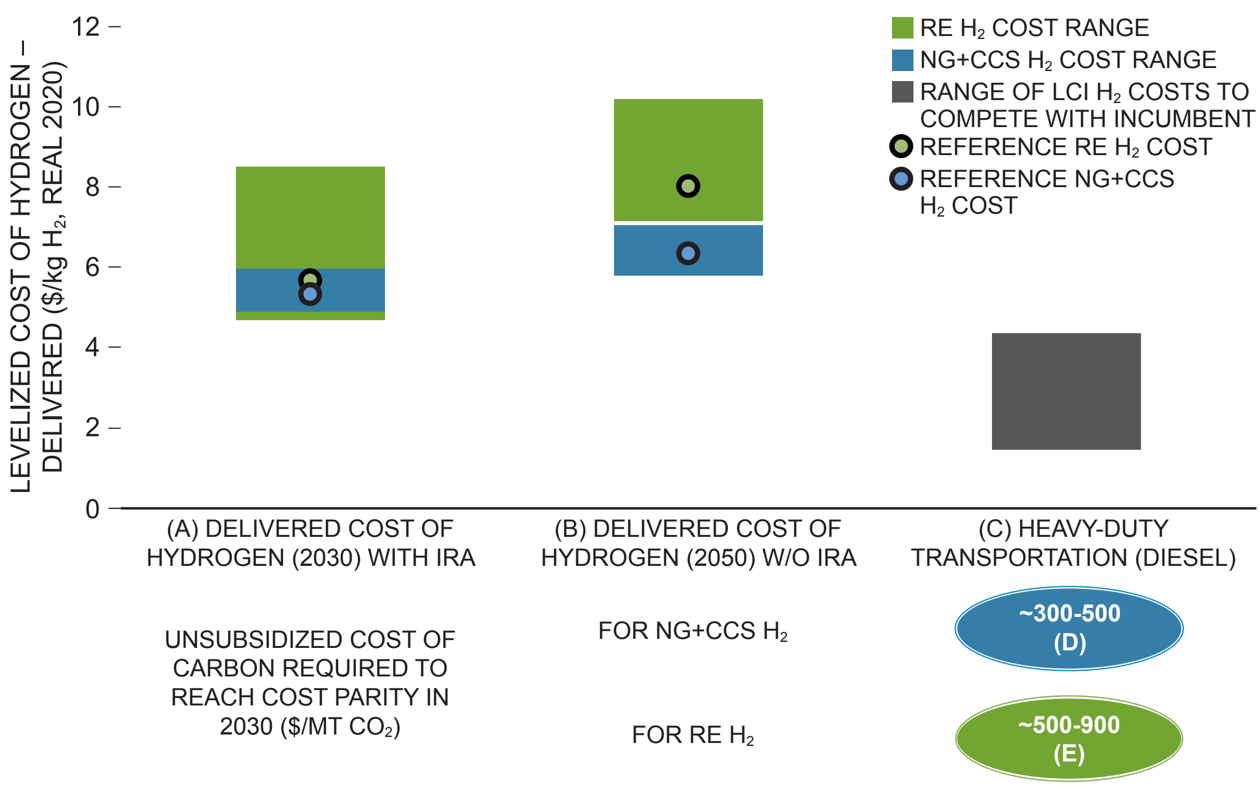
RE H_2 could reach cost parity with incumbents with carbon prices of ~\$300-700/MT CO_2 (E1) for refinery feedstock or ~\$500-900/MT CO_2 (E2) for industrial heat.

A wider cost parity gap between incumbent and LCI H_2 demands either a higher carbon price or a more substantial combination of LCI H_2 cost reductions or incentives to achieve cost parity.

B. Transportation Sector

In the Heavy-Duty Transportation sector, H_2-based FCEVs have a significant cost gap to overcome with diesel-based ICEVs. Figure ES-14 illustrates the \$/kg cost of H_2 needed to compete with the unabated ICEV fuel cost (C). Under current policies, a cost gap remains between both RE and NG+CCS H_2 delivered costs and the incumbent (A compared to C). The Modeling indicates that the cost parity gap may persist despite economies of scale and learning curve gains when current policies expire (B compared to C). Although the NG+CCS H_2 has a more favorable cost position than the RE H_2, achieving further cost reduction remains imperative to making NG+CCS H_2 competitive with ICEV. Further comparison of cost parity gaps between FCEVs, BEVs, and ICEVs, including consideration of lower CI fuels for ICEVs, is provided in Chapter 5: Demand.

Closing this cost gap requires a higher carbon price on incumbent emissions or a substantial combination of LCI H_2 cost reductions and incentives to achieve cost parity. For instance, the delivered cost of H_2 in 2050 must decrease from the \$6-10/kg range (B) to the \$1-4/kg range (C) to be competitive with incumbents. Alternatively, imposing an explicit carbon price of ~\$300-500/MT CO_2 (D) or ~\$500-900/MT CO_2 (C) on incumbents (e.g., diesel) would make NG+CCS or RE H_2, respectively, cost competitive.



Notes: Levelized cost ranges for RE and NG+CCS H_2 (A and B), alongside LCI H_2, delivered cost ranges (C) needed to compete with diesel incumbent. The cost of carbon required to reach cost parity for NG+CCS and RE H_2 (D and E, respectively) indicates that a reduction in delivered cost cannot be achieved. Graph generated based on Net Zero by 2050 Scenario.

Figure ES-14. *Gulf Coast Comparison of Levelized Delivered Cost Ranges of LCI H_2 to Heavy-Duty Transportation Incumbents* transparent and technology-neutral national low CI industry standard could offer an Industrial sector-focused incentive. Such a driver would promote meaningful reductions in life cycle emissions at potentially lower costs than alternatives. That standard should recognize global trade concerns and be funded through carbon credit markets without burdening taxpayers. In doing so, it will encourage market-driven innovation while reducing the CI on emissions.[27]

RECOMMENDATION 2: DEMAND-SIDE INCENTIVES FOR INDUSTRY: NATIONAL LOW CARBON INTENSITY INDUSTRY STANDARD

Recommendation: As more fully described in Chapter 6: Policy, the NPC recommends Congress and the administration consider a national low carbon intensity (CI) industry standard to address GHG emissions from the Industrial sector. This transparent, technology-neutral, life cycle-based standard would be funded through carbon credit markets and applied within different segments of the Industrial sector to reduce the CI of products by considering well-to-gate emissions associated with the sector. This policy may require specific CI standards to address various Industrial subsegments and provisions to ensure the Industrial sector remains globally competitive. This recommendation would be in lieu of an economy-wide explicit price on GHG emissions, which is the preferred policy approach.**

** "Well-to-gate" shall only include emissions through the point of production, as determined under the most recent Greenhouse gases, Regulated Emissions, and Energy use in Technologies model (commonly referred to as the "GREET model") developed by Argonne National Laboratory, or a successor model (as determined by the Secretary).

27 Incentivizing industrial applications to convert to higher-cost LCI H_2 will be complex given the competitive pressures between companies within the U.S. and global markets. Countries seeking to export to the U.S., or import from the U.S., might not have comparable policies. This is particularly critical for heavily traded products (e.g., ammonia, methanol) that are exported globally.

Demand-Side Incentives—National Low Carbon Intensity Transportation Standard: A market-based, tech-neutral policy at the federal level to reduce life cycle emissions to support a broader portfolio of low CI technologies is needed. Such a policy is potentially needed for all forms of transportation, including vehicles, shipping, rails, and aviation. Current United States policies do not fully incentivize the market to reduce emissions from all transportation modes currently in use and their associated life cycle emissions.

No comprehensive, life cycle, emissions-based, low CI standard exists at the federal level. For example, for vehicles, the Renewable Fuel Standard focuses on biofuel volumes rather than GHG emissions reduction; vehicle standards—e.g., Corporate Average Fuel Economy, state electric vehicle (EV) mandates—only focus on tailpipe emissions, thus neglecting upstream life cycle emissions. The EPA has proposed rules designed to exclude ICEVs, leading to state-level mandates for EV sales.

California policies could be an indicator of how federal-level policies could function. The state has enacted a state-wide LCFS, which, while focused on tailpipe-only emissions and BEVs, has been reported to result in a reduction in vehicle emissions' CI over time. California's initiative accounts for full life cycle reduction and is agnostic to low-carbon vehicle and fuel options. This mechanism could show how a nationwide implementation of a CI standard could further accelerate the deployment of low CI technologies—including LCI H_2—in the Transportation sector.

RECOMMENDATION 3: DEMAND-SIDE INCENTIVES FOR TRANSPORTATION: NATIONAL LOW CARBON INTENSITY TRANSPORTATION STANDARD

Recommendation: As more fully described in Chapter 6: Policy, the NPC recommends Congress and the administration establish linked life cycle fuel and well-to-wheels vehicle carbon dioxide standards,* This policy would include:

- **A low-carbon fuels standard program, driving down the carbon intensity of different** fuel pathways (e.g., liquid fuel, hydrogen, or electricity)

- Vehicle carbon dioxide standards, which would use the well-to-wheels emissions of the vehicle based on the actual/projected low-carbon fuel standards performance of the energy source for the vehicle

As a result, the combined programs funded through carbon credit markets could drive down actual transport emissions in a holistic and efficient way, helping to accelerate emissions reduction and delivering reductions at a lower cost than the current siloed fuel and vehicle policies. This recommendation would be in lieu of an economy-wide explicit price on GHG emissions, which is the preferred policy approach.

At this time, NPC does not recommend including vehicle manufacturing emissions due to the current complexity of tracking these emissions across large supply chains but recognizes that other regulatory actions in the future may address these types of emissions and, if implemented, will need to be harmonized with standards such as those described in this recommendation.

Production-Side Incentives: The passage of the IRA has created momentum for an LCI H_2 economy in the United States. However, uncertainty remains in areas that could further encourage investment and enhance the IRA's impact. Three specific focus areas are provided:

Duration of credits: Major projects producing LCI H_2 or its carriers will be operational for decades. However, the current credits (e.g., 45V, 45Q) only provide 10- to 12-year tax credits. Extending the duration of credits to match asset life cycles could encourage these long-term investments by providing the support necessary for facilities to bring production online and realize a return.

Impacts of credit tiering: Current policy offers a four-tiered credit, with the top tier allowing up to 0.45kg CO_2/kg of qualified LCI H_2. This policy creates potential for investment uncertainty, as the steep step changes in credits for achieving different CI tiers introduces project economic risk during design/construction and operations should a facility fail to qualify for a planned tier (the cliff effect).[28]

Driving innovation: GREET provides limited built-in options to reflect different investments and verifiable actions a company may take to reduce the emissions intensity of its H_2 production. The lack of flexibility in accommodating user-defined inputs could limit innovation and where investments are made to reduce emissions intensity in LCI H_2 production pathways. However, when incentivizing emissions reductions through user-defined inputs, this can create the unintended consequence that national average emissions could become artificially lower than reality. As such, some members of the NPC are concerned about the following recommendation due to the potential to undermine the accuracy of methane accounting within GREET. Establishing verifiable values in GREET—incorporating coproduct allocation accounting, reliable monitoring, reporting and verification methods and functionality, and routine updates to ensure accurate default GREET values that reflect revisions to the national average emissions intensity rates—could speed and support this modification.

RECOMMENDATION 4: PRODUCTION-SIDE INCENTIVES

Recommendation: As more fully described in Chapter 6: Policy, the NPC recommends:

- To provide further certainty on the investment commitments that developers must take to come to a final investment decision for a LCI hydrogen project, the IRS should consider implementing measures to reduce the risk that the "cliff effect" or even concerns over the "cliff effect," which arises due to the steep step changes in 45V between the different carbon intensity tiers and may negatively affect the bankability of a LCI hydrogen project. To ensure that qualifying LCI hydrogen projects are bankable while retaining the structure of 45V

28 In this context, the cliff effect is used to describe the steep drop in 45V credit values and corresponding eligibility between tiers as H_2 CI changes based on the variable inputs to the GREET model or model-specific updates.

tiers, the IRS should consider implementing measures such as:

  - Allowing a reasonable uncertainty range for the 45V tiers so that true border case projects can qualify for the lower carbon intensity tier and have greater financial viability as a result.
  - Allowing companies to have a six-month period to appeal life cycle assessment findings during which the company can take additional actions to reduce the carbon intensity of the project (e.g., purchasing additional renewable natural gas, etc.).

- Congress: Lengthen the 45V credit-claiming period to 20 years to more closely match the incentive with the asset life cycle.
- DOE: Improve and fully utilize Greenhouse gases, Regulated Emissions, and Energy use in Technologies model (GREET) capability to incentivize emissions intensity reductions by allowing taxpayers to substitute default values in GREET with verifiable values based on coproduct allocation accounting (of methane emissions between oil, gas, and other hydrocarbon products) and reliable measurement, reporting, and verification methods (e.g., differentiated natural gas used, efficient electrolyzers).

Mutually Recognized, Transparent Global Trade Certificate: With supportive policies that can accelerate investments, the U.S. can create broad demand for LCI H_2 and its carriers. The U.S. is expected to be a major production source and demand market for LCI H_2 and has the potential to grow exports of LCI H_2 carriers (e.g., ammonia) to select countries with limited carbon emissions-reduction options.

Hydrogen derivative products are already highly traded commodities in a competitive global marketplace. However, existing global trade rules have yet to focus on the environmental attributes of H_2 and its derivatives and do not have a framework to transparently compare higher and lower CI products.

Beyond global considerations, there are also no federal CI accounting standards for H_2 or its carriers used in products within the U.S. At the state level, there are discrepancies in regulation from one state to another, which could stall progress. Some states' policies directly target certain H_2 transactions. For example, beginning on July 1, 2026, a Maryland statute prohibits the sale of H_2 motor fuel made from natural gas. In addition, while nearly every state levies some form of sales or other tax on different varieties of fuels, it is unclear which, if any, of these taxes applies to H_2. In some cases, H_2 may be specifically exempted. This data deficiency and discrepancy in regulation impedes domestic market activation in the short term.

In the medium term, lack of clear and mutually recognized trade rules supporting low CI H_2 products and carriers— both globally and among U.S. states—could stall LCI H_2 development. Details are discussed in Chapter 6: Policy.

RECOMMENDATION 5: GLOBAL TRADE

Recommendation: As more fully described in Chapter 6: Policy, NPC recommends the administration and Congress:

- Support the development by business and other stakeholders of transparent certification systems on the carbon intensity of hydrogen and hydrogen carriers (e.g., ammonia, methanol), and work to ensure their mutual recognition globally
- Support (with technical input and consultations) foreign mutual recognition of U.S. certification schemes (including use of accredited verifiers in different jurisdictions) with key trading partners
- Evaluate trade infrastructure needs and move forward key port, bunkering, transportation, storage, and other related infrastructure—including needed regulatory changes—to meet expected growth, particularly through major trade corridors
- Develop plurilateral agreements to promote trade in low-emissions products, including H_2 and its derivatives, and work to build support beyond the core group of countries that have developed this approach

- Urge the DOE, working with other appropriate U.S. agencies and international organizations, to develop and make public data on the carbon intensity of hydrogen and hydrogen carriers' production in the United States and globally
- Develop and implement an emissions intensity border fee for hydrogen and hydrogen derivative products aligned with an explicit price on carbon or, in the absence of an explicit price on carbon, consistent with the effects

Infrastructure Development Incentives: Hydrogen-related infrastructure (e.g., pipelines, storage, export terminals, electricity transmission lines) must expand to accommodate the growth and deployment of LCI H_2 at-scale. However, the development of LCI H_2 infrastructure cannot be considered in isolation due to the interconnectedness of the wider energy ecosystem in the U.S. That ecosystem includes liquid fuels, natural gas, and the electricity grid. The development of market-based, commercially driven infrastructure enablers—based on location requirements and interactions with the wider energy system—can enable the development of an efficient, flexible, and resilient LCI H_2 market. The factors enabling the infrastructure development include:

1. **Production/demand certainty:** Supporting market development incentives and adopting legally binding production targets to ensure long-term production and demand certainty that could boost investor confidence
2. **Funding support:** Providing financial support to mitigate risk-return valuations of project investments
3. **Policy, regulatory, and commercial framework:** Structuring the right policies, strengthening regulatory certainty, and fast-tracking funding to accelerate project development
4. **Market partnership with key stakeholders:** Promoting market partnership consortiums with key stakeholders and supporting long-term offtake agreements with clear market pricing and incentive structures to facilitate project development

Stability of the policy and regulatory environment through project development and the operating life of assets will support investment (see Chapter 3: Infrastructure). While comprehensive recommendations were not developed for all policy mechanisms supporting infrastructure development, the NPC endorses the following recommendation addressing capital constraints and encourages the reader to review other recommendations in Chapter 3: Infrastructure.

RECOMMENDATION 6:
INFRASTRUCTURE INCENTIVES

Recommendation: As more fully described in Chapter 6: Policy, NPC recommends Congress create an Investment for Clean Hydrogen Infrastructure Projects Program to facilitate access to capital that stimulates LCI hydrogen infrastructure. Funding should be made available to qualifying LCI hydrogen infrastructure projects in the form of grants, loans, and loan guarantees administered through the DOE Loan Programs Office and/or the introduction of an investment tax credit.

FINDING 10: Administrative and legal complexity across multiple jurisdictions in the current permitting process could delay development and deployment of necessary facilities and infrastructure.

While policy support is a crucial first step toward sustainable LCI H_2 project economics, it's equally vital to establish a straightforward and efficient regulatory framework. Given the long lead times and regionally varying developmental pathways for LCI H_2 facilities and infrastructure, a clear, durable, and timely permitting process framework is essential to facilitating the practical implementation of policy measures for at-scale deployment of LCI H_2 and, ultimately, decarbonizing the entire energy system. Streamlining criteria for project evaluations across federal, state, and local authorities will mitigate conflicting regulatory guidance. Permitting constraints, including siting and right-of-way restrictions, could negatively impact the speed of LCI H_2 and its supporting infrastructure development in the United States (e.g., interstate pipelines, geologic

H_2 storage, CO_2 transportation and sequestration). Infrastructure project development at the needed scale could be at risk because these projects often require streamlined permitting and timely project execution across multiple jurisdictions. Approved permits—interstate and intrastate—are currently subject to litigation after approval, with few limitations on eligible parties to bring suit. If left unaddressed, this risk could derail the development and scaling of the necessary infrastructure required to support carbon emissions-reduction goals.

General Permitting Reforms: Permitting delays can derail project timelines, inflate costs, jeopardize financing, and delay carbon abatement. Achieving timely scale-up of infrastructure requires a streamlined permitting process for the development of facilities and infrastructure. NPC has identified four primary challenges:

1. Ever-changing and often-conflicting federal, state, and local permitting processes and guidance
2. Lack of a designated lead federal authority for enforcing statutory timelines
3. Lack of clarity on the post approval litigation window for communities
4. Absence of a regulatory means to secure/obtain land rights for large facilities and infrastructure, especially for interstate assets

As outlined in the 2019 NPC Dynamic Delivery report, multiple jurisdictions (e.g., federal, state, local) are often involved in the permitting process, contributing to long delays.[29] Two significant changes impacted permitting requirements in early 2023:

1. The Supreme Court ruling in Sackett vs. EPA substantially restricted federal jurisdictional limits in the Clean Water Act.[30, 31]
2. Congress passed the Fiscal Responsibility Act, which includes provisions to help streamline environmental project reviews under the National Environmental Policy Act. The Fiscal Responsibility Act requires designating a single federal lead agency and consolidating work into a single National Environmental Policy Act document during the review process.[32]

The White House, Congress, and report recommendations from several organizations have all called for a wide variety of changes to improve the effectiveness and efficiency of the permitting process—including some that go beyond Sackett vs. EPA and the Fiscal Responsibility Act.[33] Any additional measures should be balanced with the need to maintain core environmental protections and enhance the protections for applicable communities.

The recommendation that follows reflects the perspective of many—but not all—NPC members. Some NPC members believe a more inclusive outlook on H_2-specific permitting needs is warranted requiring a broader dialogue on the ideas included in this recommendation as a mechanism for balancing proposed changes with the need to maintain core environmental protections and enhance protections for affected communities.

RECOMMENDATION 7: GENERAL PERMITTING REFORM

Recommendation: As more fully described in Chapter 6: Policy, the NPC recommends that the administration and/or Congress:

- Improve communications related to, and the implementation of, state and/or federal eminent domain; eminent domain should only be used as an option of last resort along with effective community engagement

29 "Dynamic Delivery: America's Evolving Oil and Gas Transportation Infrastructure Summary." National Petroleum Council. 2019. https://www.npc.org/reports/trans.html.

30 "Sackett vs. the Environmental Protection Agency." Supreme Court of the United States. 2022. https://www.supremecourt.gov/opinions/22pdf/21-454_4g15.pdf.

31 U.S. EPA. "National Environmental Policy Act Review Process." July 31, 2013. https://www.epa.gov/nepa/national-environmental-policy-act-review-process.

32 Schneider, J., Buffa, N., O'Connor, D., and Homrighausen, K. "Congress Advances Federal Environmental Permitting Reform in Fiscal Responsibility Act of 2023." Latham & Watkins LLP. June 7, 2023. https://www.globalelr.com/2023/06/congress-advances-federal-environmental-permitting-reform-in-fiscal-responsibility-act-of-2023/.

33 Including the Brookings Institution, Aspen Institute, Bipartisan Policy Center, U.S. Chamber of Commerce, World Resources Institute, and the Center for American Progress.

- Establish an integrated federal, state, and local permitting portal (whole-of-government permitting portal, e.g., expanding on the existing Federal Permitting Improvement Steering Council [FPISC] permitting portal) to avoid duplication and provide efficient coordination and sharing of data among permitting authorities and projects
- Expand use of Programmatic Environmental Impact Statements to help accelerate the permitting process for low-carbon energy projects and expand permitting agency capacity by adopting the FPISC and ensuring adequate staffing resources
- Consolidate litigation, specifically apply the same two-year or other shorter statute of limitations for filing lawsuits against federal agency actions for all low-carbon energy projects and develop a timeline for agencies to act on judicial remands
- Provide adequate funding for appropriate agencies to ensure they have resources and staffing to administer permitting programs
- Expand responsible use of administrative categorical exclusions: Congress should require federal agencies to examine existing categorical exclusions and consider proposing additional categorical exclusions for LCI hydrogen/clean energy projects where appropriate

FINDING 11: Reaching the Expansion and At-Scale phases of LCI hydrogen deployment will require construction of interstate hydrogen pipelines to cost effectively move LCI hydrogen from supply to demand centers and will require timely permitting and approvals.

The Modeling shows that LCI H_2 market growth from 11 MMTpa to ~75 MMTpa will require significant infrastructure development. This infrastructure, which is anticipated to be needed in the Expansion and At-Scale phases, will allow H_2 production to be sited closer to key feedstocks—such as renewable power or natural gas and carbon sequestration sites—to lower the delivered cost of H_2 to users. Pipelines are generally the most efficient mode of transporting large volumes of gases over medium and long distances (refer to Chapter 3: Infrastructure for details), and the study found that a significant growth of unblended, interstate H_2 pipelines will likely be needed.[34] However, in the last decade many examples exist in which United States pipelines—specifically those for CO_2 and natural gas—were canceled or tabled indefinitely after groundbreaking. This trend could stall LCI H_2 deployment if left unaddressed.

To date, there are ~1,600 miles of unblended H_2 pipelines in the United States, all concentrated on the Gulf Coast. Of these systems, a small fraction of pipelines cross state lines. Given current trends related to pipeline siting and construction, there is concern that a constraint will develop that slows the installation of needed interstate H_2 pipelines. A mechanism to address this potential siting bottleneck is a regulatory framework that allows for application of federal eminent domain authority to enable construction of large-scale interstate H_2 pipelines.

It must be acknowledged that private intrastate and interstate H_2 pipelines exist today that were constructed without the need to leverage federal eminent domain support. These private pipelines were developed to support the current H_2 market, moving a specialty chemical (unabated H_2) from production locations to industrial consumers. These pipelines were and are subject to safety, construction, and operations requirements under the Pipeline and Hazardous Materials Safety Administration. Unlike natural gas pipelines, these private H_2 pipelines were not developed with federal economic oversight. Thus, they operate functionally unregulated regarding their rates, practices, and siting.

As part of reaching the following recommendation, there was much debate regarding the need for additional economic regulatory oversight of unblended interstate H_2 pipelines. Some study members believe that open access pipelines with transparent rates and pricing will be needed to support the scaling of LCI H_2 by allowing smaller

34 These unblended pipelines could be designed and constructed for H_2 service, or existing pipelines could be repurposed after having been retrofitted to safely transport H_2.

suppliers to access the market. Other study members believe the H_2 markets are functioning well under the current regulatory frameworks. Those study members suggest that additional regulation should only come in response to actual issues as they arise and note that premature regulation could risk stalling LCI H_2 market development. This recommendation addresses potential siting bottlenecks by creating a mechanism to provide federal eminent domain authority for interstate H_2 pipelines deemed in the public interest. It does so while maintaining the option for continued pipeline development in which operators comply with local and state permitting requirements but do not leverage federal eminent domain.

RECOMMENDATION 8: UNBLENDED INTERSTATE HYDROGEN PIPELINE REGULATORY AUTHORITY

Recommendation: As more fully described in Chapter 6: Policy, the NPC recommends that Congress deem hydrogen infrastructure to be in the public interest and, except as described in bullet "g.", authorize the Federal Energy Regulatory Commission (FERC) to regulate unblended as well as blended (an existing authority) interstate hydrogen pipelines, addressing the following key criteria for LCI hydrogen:

a. Promote regulatory certainty by establishing an unblended federal LCI hydrogen interstate pipeline framework in the Activation phase that could then be implemented in the Expansion phase in order to encourage investor certainty.

b. Provide a federal framework for eminent domain in conjunction with appropriate stakeholder/community engagement.

c. Ensure permits are approved in a timely manner to accelerate industry growth.

d. Continue to ensure applicable permit requirements (e.g., National Environmental Policy Act) are met.

e. Develop an unblended LCI hydrogen purity definition—clarify the point at which blends of hydrogen and natural gas are classified as "hydrogen" or "natural gas" for regulatory purposes.

f. Promote open access and transparency while ensuring that regulation does not inhibit growth of the nascent LCI hydrogen market. Focus FERC jurisdiction to regulation of LCI hydrogen transportation rates and service terms for energy. Recognize that hydrogen is used as both an energy carrier and as a feedstock for other commodities.

g. Honor the current business model of allowing hydrogen systems (not under FERC regulation) that do not seek federal eminent domain rights to remain exempt from any FERC regulation.

In addition, Congress and the administration should monitor the development of these changes to encourage a regulatory framework that supports development of a robust, competitive LCI hydrogen market.

Class VI Wells and Permitting Process: Another component of midstream infrastructure that needs permitting reform is storage. This especially includes geologic storage of CO_2 to support the NG+CCS H_2 production pathway. The 2019 NPC report *Meeting the Dual Challenge* describes the U.S. as having one of the world's largest-known CO_2 geologic storage endowments.[35] Carbon dioxide storage in deep saline formations can allow for the safe, secure, and permanent storage of large volumes of CO_2. The EPA has developed a Class VI well design and permitting process to protect underground drinking water sources. Timely permitting for Class VI injection wells is a requirement for production of NG+CCS H_2 and is necessary to advance planning and commercial development of new CO_2 pipelines and regional sequestration infrastructure. Infrastructure will be used to transport and store CO_2 from new and existing H_2 production facilities using natural gas reforming pathways (e.g., steam methane reforming [SMR], autothermal reforming [ATR]) and from other carbon-intensive sectors of the economy. However, extended lead time and backlogs in the permitting process of Class VI wells could jeopardize the

35 "Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage." National Petroleum Council, 2019. https://dualchallenge.npc.org/.

scaling of LCI H_2, especially from the NG+CCS production pathway.

As of June 2024, the EPA has issued four Class VI well permits for active projects, with two of them being issued since 2020. The permits issued since 2020 took 2.75 years from initial submission to receipt of a construction permit. There are 139 Class VI injection wells awaiting approval by the EPA.[36] Expedited time frames for review and approval of these Class VI injection-well applications will enable the planning and commercial development of NG+CCS production projects, new pipelines, and sequestration infrastructure. These elements are needed to capture, transport, and sequester CO_2 and meet carbon emissions-reduction objectives.

RECOMMENDATION 9: CLASS VI PRIMACY AND WELL PERMITTING

Recommendation: As more fully described in Chapter 6: Policy, the NPC recommends the administration and Congress improve the Class VI primacy and well-permitting process as follows:

- Hold the Environmental Protection Agency (EPA) accountable to its stated primacy timelines currently in 40 C.F.R. § 145.22 by establishing the following requirements:
  - If EPA has not made a decision on a Class VI primacy application within 90 days of receipt of complete submission, the EPA administrator should be required by Congress to submit a report to the governor of the state seeking primacy, the state agency seeking primacy, the Chair of the White House Council on Environmental Quality (CEQ chair), and the appropriate congressional committees explaining why the decision has exceeded 90 days and when the decision should be expected.
  - If EPA has not decided within 365 days of the application being complete, the appropriate congressional committees should consider holding an oversight hearing in which the EPA administrator and the CEQ chair explain why a decision has not yet been made.
- Congress, in consultation with EPA, should determine and require minimum staffing levels for Class VI primacy reviews/approvals by statute and enable EPA to meet and maintain these staffing targets until such a time when state requests for primacy have ended.
- Congress should improve the permitting process for individual Class VI wells by determining, in consultation with EPA and state agencies, what is adequate funding to support the Class VI program for states and the EPA in a manner that enables permits to be issued within 18 months. After completing this analysis, Congress should ensure both states and the EPA receive adequate funding for permitting work, and EPA shall report to Congress how these funds were used.

B. Societal Considerations and Impacts and Safety

FINDING 12: Inadequate community engagement practices have led to distrust of project developers and delays in projects.

Public understanding and acceptance of low CI energy alternatives are crucial for the successful growth of all low-carbon energy projects in the United States, including LCI H_2. However, the public understanding of energy alternatives remains limited. Inadequate community engagement and historical neglect have generated community dissatisfaction and legal disputes, resulting in increased costs and project delays. For project developers, simply pursuing permit approvals without genuine community involvement will invariably lead to resistance from affected communities. Several examples illustrate how inadequate community engagement led to project delays, including recent CO_2 pipeline projects in the Midwest whose viability has been challenged by communities that question the project's green credentials, safety, and use of eminent domain.

36 EPA Class VI Wells Dashboard, as of June 7, 2024: https://bit.ly/3YaEFsm.

RECOMMENDATION 10: COMMITMENT TO SOCIAL CONSIDERATIONS, TRANSFORMATIVE COMMUNITY ENGAGEMENT, AND NET POSITIVE OUTCOMES

Recommendation: As more fully described in Chapter 7: SCI and Safety, the NPC recommends DOE, decision-makers, corporations, researchers, governments, and regulatory bodies actively commit to comprehensively consider and equitably address societal, environmental, and public health impacts related to the project during the Activation phase of LCI hydrogen deployment.

The energy transition provides an opportunity to engage communities through informed participation that enables feedback-based engagement and demonstrates clear societal benefits—including the Justice40 framework for federally funded projects. In turn, project developers will be better equipped to deliver on community expectations. NPC sees a strong case for a paradigm shift in community engagement by ensuring community readiness, delivering on commitments, and reporting progress throughout the project's life. Well-designed community engagement goes beyond regulatory guidelines to ensure environmental, health, socioeconomic, and societal concerns are addressed and actions are tailored to the affected community.

NPC supports an evolution of the community engagement framework to demonstrate visible collaboration between communities and industry, enabling the best LCI H_2 solutions at speed and with clear societal benefits. NPC sees two primary areas of improvement as the first steps toward a paradigm shift:

1. Prioritize intentional community engagement and considerations over shortened project schedules
2. Actively share accessible educational materials to empower communities with information

Prioritize Intentional Community Engagement and Considerations: Communities in regions likely to lead the demand for LCI H_2 in the Activation phase may have existing environmental, health, and socioeconomic vulnerabilities. This history could naturally foster skepticism, requiring prioritization of intentional community engagement to support new industrial or energy development. Short-term perspectives on project timelines and a failure to involve the community can lead to project delays. Growing concerns about SCI reveal a pressing need for a comprehensive environmental justice framework encompassing policy and statutory requirements. The lack of such a framework (e.g., roles, responsibilities, deliverables, communication channel, frequency) has caused friction between frontline communities and other stakeholders, intensifying opposition to energy projects and causing delays. Therefore, it is critically important to leverage a framework enabling meaningful engagement that articulates and delivers societal benefits to the affected communities.

The community engagement recommendation that follows is well intentioned and upholds the spirit of identifying, developing, and encouraging the adoption of best practices with community engagement. Constructing a framework to effectively address the highly complex and often emotional dynamics between energy project developers, communities, and other stakeholders will be difficult. It will be imperative to ensure members of the council are aligned on a common goal to improve community engagement while enabling critical project development, or this could result in unintended consequences that might not be aligned with the spirit of this recommendation.

RECOMMENDATION 11: COMMUNITY ENGAGEMENT IMPROVEMENT OPPORTUNITIES

Recommendation: As more fully described in Chapter 6: Policy and Chapter 7: SCI and Safety, the NPC recommends the U.S. government charter national and/or regional public/private council(s) of excellence in effective industry-community engagement practices to develop and encourage the adoption of best practices that include equitable representations from industry, nongovernmental organizations (NGOs), and government.

- These councils should be forums where industry, NGOs, and government would keep community engagement best practices up to date by identifying and disseminating effective community engagement practices, leveraging existing best practice resources (e.g., Permitting Council FY22 Recommended Best Practices Report, API RP-1185, and IPIECA) that are cognizant of regional and local needs and considerations. The governance structures, participation processes, and transparency should be designed to promote engagement of industry, NGOs, local governments, and other interested parties and enhance the credibility of a council's products.

- These councils should intentionally support less capitalized operators to implement these best practices inclusive of, but not limited to, experienced resources and training.

While acknowledging that many developers already implement community engagement, there is an opportunity to encourage broader adoption of documented best practices across the industry by providing additional motivation to implement robust community engagement. The NPC further recommends the administration and Congress develop government procedural or permitting timeline incentives for companies that consistently meet established best practices (when developed and documented) for community engagement. As part of the joint industry organization, propose a voluntary program to monitor adherence and adoption of recognized best practices that can be considered for eligibility for procedural or permitting timeline incentives.

Accessible Educational Materials: To enable all low CI project development, including LCI H_2, a strategic approach is needed to educate members of the public, allowing them to have informed perspectives to support decision-making regarding project development. All potential community members will need education on the role and safety of LCI H_2 production, transportation, and usage. Additionally, educational programs need to increase the knowledge of local regulators, various levels of government, and emergency responders so they understand the safety considerations related to H_2 and its carriers. Only education can dispel misconceptions and prevent misinterpretations by local stakeholders.

A key component of educating the public is the distribution of educational materials, which must be broad, simple, easily accessible, and comprehensible. These materials will empower communities with the necessary information to make informed decisions when new projects are proposed. Materials will be more widely accepted and understood if distributed in coordination with public safety education programs and open dialogue.

RECOMMENDATION 12: OUTREACH MATERIALS TO INCREASE COMMUNITY UNDERSTANDING OF LCI HYDROGEN DEVELOPMENT

Recommendation: As more fully described in Chapter 7: SCI and Safety, the NPC recommends DOE should expand support for programs such as the Environmental Justice Technical Assistance Centers programs and/or should develop funding opportunities for community representatives and experts to support the outreach needed to increase community understanding of advanced energy technologies such as LCI hydrogen, carbon capture and sequestration, and direct air capture. Industry and government must ensure a more informed level of community engagement.

FINDING 13: Past experiences may have left communities feeling unheard by project developers, resulting in a deficit of trust, transparency, tracking, and sharing of outcomes.

Communities frequently face challenges in understanding how to engage regarding proposed projects. They might not know who to approach, where to start, what productive and effective engagement looks like, or how to resolve conflicts. Publicly disclosing the community engagement process and the project's desired outcomes early in the project development cycle can build community trust.[37] Highly collaborative community engagement, including dialogue between industry representatives and community stakeholders via feedback channels, brings transparency and trust equity that can reassure communities. Additionally, clarifying roles and responsibilities could promote cooperation and limit misunderstanding among stakeholders during project development, particularly as project owners and communities align on adjacent infrastructure needs.

For project developers, making best practices, case studies, and quantitative analysis from past projects visible and accessible across the industry can foster community engagement among project developers, including new entrants or smaller operators who might not have experience actively engaging communities. In addition, incentivizing community engagement for project owners can accelerate the adoption of best-in-class community engagement practices.

Federal project funding often requires robust community, labor engagement, and benefit programs. However, improved clarity and guidance on the processes, programs, metrics, and specific benefit-sharing agreements could help funding seekers increase their community engagement commitments.

RECOMMENDATION 13: ROLE CLARITY FOR COMMUNITY BENEFITS

Recommendation: As more fully described in Chapter 7: SCI and Safety, the NPC recommends DOE clarify the roles it and project developers each play in addressing community concerns as early and often as possible in project development (for developers) or throughout listening sessions and road shows (for DOE).

RECOMMENDATION 14: COMMUNITY BENEFITS PLANNING

Recommendation: As more fully described in Chapter 7: SCI and Safety, the NPC recommends DOE consider expansion of its Community Benefits Plans/Planning approach, which is currently utilized in scoring competitive grant applications, to reach beyond Justice40 covered programs to other funding streams.

RECOMMENDATION 15: TRACKING AND COMMUNICATING COMMITMENTS TO COMMUNITY ENGAGEMENT TO INCREASE PUBLIC CONFIDENCE

Recommendation: As more fully described in Chapter 7: SCI and Safety, the NPC recommends that, as commitments are made to engage with communities associated with LCI hydrogen project deployment in the Activation stage, DOE make the techniques and results available to the public to better educate on effective engagement techniques and to incentivize their use.

FINDING 14: **Lack of timely workforce development and labor engagement can inhibit the pace of LCI hydrogen growth.**

The growth of the U.S. LCI H_2 economy to reach at-scale deployment hinges on the availability of a skilled workforce supporting all value chain segments, including demand, production, and infrastructure. One promising solution to bridge the workforce demand gap is transitioning labor resources from industries that may lose jobs due to decarbonization. According to DOE's *Commercial Liftoff* report, growth of the LCI H_2 economy could generate about 100,000 net new direct and indirect jobs related to new capital projects and 120,000 direct and indirect jobs related to the operation and maintenance of H_2 assets in 2030.[38] In addition, DOE has recently announced the selection of seven H2Hubs across the nation, which are projected to create approximately 120,000 permanent jobs and 220,000

37 Possibly prior to site selection and at the beginning of the permitting process for a given project.

38 According to DOE's Liftoff report, direct jobs include employment in engineering and construction. Indirect jobs refer to employment in relevant areas, including industrial-scale manufacturing and raw materials supply chain.

jobs related to hub project construction (Table ES-2).[39]

Timely Workforce Development: Thoughtful workforce development requires immediate planning and investment to properly train and equip the workforce at a level that can support the at-scale deployment of LCI H_2. Many occupations, skills, and training frameworks developed in the oil and gas industry will be transferable to the H_2 economy. To that end, DOE could develop a study to identify workforce needs for LCI H_2 enablement, similar to the Workforce Readiness Plan released by the National Energy Technology Laboratory's Regional Workforce Initiative.

RECOMMENDATION 16: WORKFORCE READINESS

Recommendation: As more fully described in Chapter 7: SCI and Safety, the NPC recommends DOE and Department of Labor work to create a more broadly inclusive program for apprenticeships that considers input from various groups such as the National Association of Manufacturers, labor unions, and trade organizations to enable workforce participation in the hydrogen economy.

39 The White House. "Biden-Harris Administration Announces Regional Clean Hydrogen Hubs to Drive Clean Manufacturing and Jobs." October 13, 2023. https://www.whitehouse.gov/briefing-room/statements-releases/2023/10/13/biden-harris-administration-announces-regional-clean-hydrogen-hubs-to-drive-clean-manufacturing-and-jobs/.

Stand-Alone, Comprehensive Societal Considerations and Impacts Study: This study does not aim to encapsulate the myriad perspectives around low CI project development but instead offers high-level observations that may be useful for ensuring robust stakeholder engagement. The observations are based on examples from adjacent sectors and peer-reviewed literature without directly engaging the impacted communities. The subsequent, comprehensive, and stand-alone study, Societal Considerations and Impacts, should build upon our current effort and emphasize frontline communities.

RECOMMENDATION 17: ADDITIONAL STUDY ON SOCIETAL CONSIDERATIONS AND IMPACTS

Recommendation: As more fully described in Chapter 7: SCI and Safety, the NPC recommends DOE undertake a stand-alone, comprehensive societal considerations and impacts study, related to energy development, including, but not limited to, LCI hydrogen H_2 development and GHG

Selected Hydrogen Hubs	Locations	Projected Job Breakdown	Total Projected Jobs
Appalachian Regional Clean Hydrogen Hub	Ohio, Pennsylvania, West Virginia	18,000 construction jobs	21,000 jobs
		3,000 permanent jobs	
Alliance for Renewable Clean Hydrogen Energy Systems	California	130,000 construction jobs	222,000 jobs
		90,000 permanent jobs	
HyVelocity Hydrogen Hub	Texas	35,000 construction jobs	45,000 jobs
		10,000 permanent jobs	
Heartland Hub	Minnesota, North Dakota, South Dakota	3,067 construction jobs	3,880 jobs
		703 permanent jobs	
Mid-Atlantic Clean Hydrogen Hub	Delaware, New Jersey, Pennsylvania	14,400 construction jobs	20,800 jobs
		6,400 permanent jobs	
Midwest Alliance for Clean Hydrogen	Illinois, Indiana, Michigan	12,100 construction jobs	13,600 jobs
		1,500 permanent jobs	
Pacific Northwest Hydrogen Association	Montana, Oregon, Washington	8,050 construction jobs	10,000 jobs
		350 permanent jobs	

Source: The White House. October 13, 2023. https://www.whitehouse.gov/briefing-room/statements-releases/2023/10/13/biden-harris-administration-announces-regional-clean-hydrogen-hubs-to-drive-clean-manufacturing-and-jobs/.

Table ES-2. *Projected Job Creation from DOE-Announced Regional Clean Hydrogen Hubs* emissions-reduction value chains, as well as other facets of energy development. It is recommended that this study be conducted with the National Academy of Sciences, Engineering, and Medicine's Division of Behavioral and Social Sciences and Education and the Board on Energy and Environmental Systems, with coordinated input and concerted effort from the NPC and other stakeholders.

C. Targeted RD&D and Technology Investments

Technology advancements, combined with cost reduction across the H_2 value chain—including production (e.g., reformers, electrolyzers), transport (e.g., pipelines, trucks), storage (e.g., salt cavern, depleted gas field), and end-use applications (e.g., fuel cells for transportation, hydrogen combustion turbines for power)—are needed to scale production pathways and enable new end uses of LCI H_2. These advancements are essential for reaching the At-Scale phase but will not fully close the cost gap between incumbents and LCI H_2.

Given the limited available funding for technology advancements, investment efforts should prioritize removing bottlenecks to optimize the LCI H_2 value chain. Additionally, RD&D needs should be continually reviewed and prioritized to address emerging bottlenecks. A systematic and consistent approach that balances investment size, urgency, and commercialization potential is pivotal for transparency and the cost-effective allocation of RD&D funding within the ever-evolving technology landscape.

FINDING 15: Lack of a prioritized investment roadmap for technology is a hindrance to further levelized cost of hydrogen reduction and reliable LCI hydrogen value chain.

The LCI H_2 value chain requires significant scale-up and reduction in delivered cost for LCI H_2 to become a self-sustaining energy alternative. Several engineering challenges must be prioritized for RD&D investments to overcome these challenges. NPC identified the following priority areas in each element of the value chain:

- **Demand:** Technology advancement to enable end uses with the highest potential across sectors (i.e., Industrial, Transportation, and Power). Cost reductions in technologies needed to address potential NOx emissions when hydrogen is combusted.
- **Production:** Targeted technology development to reduce the cost of electrolytic hydrogen through lower cost and more accessible alternatives while ramping up electrolyzer manufacturing capabilities through gigafactories; improvements in efficiency or commercialization of new technologies for NG+CCS H_2
- **Infrastructure:** Technology development to increase the reliability and scale-up of H_2 and CO_2 pipeline infrastructure
- **Storage:** Technology development to support the commercial scale-up of bulk storage by finding new, more universally present storage types (e.g., aquifers, depleted gas fields)

RECOMMENDATION 18: TECHNOLOGY—REDUCING THE COST GAP

Recommendation: As more fully described in Chapter 6: Policy, the NPC recommends DOE invest in research, development, and deployment (RD&D) in the following areas:

- Demand: Support national laboratory and university research to fast-track the development of robust, low-cost materials to enhance the performance of the hydrogen end uses identified to have the highest potential by the MIT Model results (e.g., advanced fuel cells). RD&D should focus on reducing costs, increasing efficiency, improving safety performance, and addressing the environmental impact (e.g., nitrogen oxides emissions) of end-use applications.
- Supply: Support materials research for electrolysis, including alternative catalysts and nanotechnology-based solutions to reduce costs, reduce reliance on critical minerals, improve performance,

and enable scale. Technology improvements to methane-based production solutions, such as pyrolysis and carbon capture, should be an integral part of DOE's RD&D portfolio.

- Infrastructure: Support national laboratory and university research to understand the effect of hydrogen on natural gas pipeline infrastructure, particularly vintage pipelines (embrittlement, corrosion) through the DOE-sponsored Hydrogen Materials Consortium. Perform RD&D on monitoring systems for improved accuracy and cost reduction of these technologies. Support research to further enhance the properties of nonmetallic, composite pipe for hydrogen and carbon dioxide applications while improving life cycle emissions.
- Storage: Support research for underground storage of hydrogen (e.g., in engineered caverns, depleted oil and natural gas fields, and deep saline formations). Support ongoing national laboratory (Hydrogen Materials Advanced Research Consortium) and university research on hydrogen storage materials to enable cost reduction and compatibility with high volume or variable end uses.

FINDING 16: Without long-term sourcing and supply of critical materials, a robust and resilient LCI hydrogen value chain might not materialize.

Development of a Reliable Supply Chain, Particularly for Electrolytic Hydrogen: Approaching at-scale deployment of LCI H_2 in the U.S. will require deployment of many critical technologies along the LCI H_2 value chain on a massive scale. The current challenges of sourcing critical minerals and essential supplies for manufacturing critical equipment (e.g., fuel cell, electrolyzer) hinder the development of the LCI H_2 value chain. A series of potential actions could ensure a robust and resilient value chain for critical equipment and could be addressed within the federal and state levels, thus mitigating some investment risk and unlocking capital:

- Identifying vulnerable elements within the H_2 production and utilization value chain that could create production-related challenges (e.g., essential supplies for electrolyzer manufacturing)
- Fostering research to replace difficult-to-source materials (e.g., critical metals) with those more readily available domestically or through stable international sources
- Assistance with the development and deployment of alternative materials and methods to prepare for the potential risk of supply disruptions (e.g., natural disasters)
- Coordinated and strategic procurement of rare materials (e.g., platinum, iridium) essential for different types of fuel cells and electrolyzers in consultation with companies that already make regular bulk purchases or have existing long-term agreements, crucial for maintaining stable markets and prices

Furthermore, any onshoring efforts within the LCI H_2 value chain should adhere to responsible sourcing commitments as part of the Activation phase.

RECOMMENDATION 19: SUPPLY CHAIN

Recommendation: As more fully described in Chapter 6: Policy, the NPC recommends:

- The government should form a multi-agency taskforce to analyze vulnerable supply chains and recommend strategies that focus on ensuring security of supply of critical materials and manufacturing capacity for scaling up hydrogen production. These strategies could and should incorporate supporting U.S. domestic and allied supply and more diversified import options.
- Allow the market to play a role in addressing routine economic challenges and reserve the use of the Defense Production Act for critical and exceptional circumstances to avoid unnecessary intervention in market dynamics.

In addition, limited emissions measurements and measurement technology exist across the H_2

value chain. These limitations present challenges for H_2's handling, transportation, and storage. Hydrogen's unique physical properties (e.g., low density, viscosity, autoignition temperature, and wide flammability range) indicate the importance of minimizing leakage to ensure safety and minimize potential climate impacts.

FINDING 17: There is no commercially accessible technology for measuring and mitigating low-flow-rate hydrogen emissions that are relevant to possible climate impacts.

Hydrogen emissions could indirectly contribute to climate change by increasing the amount of other GHGs in the atmosphere that cause global warming.[40, 41] Because of H_2's potential indirect warming effect, especially in the near term, any emissions—including leakage, venting, and purging—will offset some intended climate benefits of H_2 deployment.[42, 43] Of note, the scenarios modeled as part of the study do not include the potential impact of H_2 emissions when evaluating or generating their respective emissions trajectories. Although the industry has safely managed H_2 production, distribution, and use for decades, measurement tools for monitoring fugitive emissions have focused on safety and economics, not on quantifying total H_2 emissions at the site level. This level of monitoring specificity is central to determining and addressing potential climate impacts.

Improved leak detection technology and documented measurements are needed to better understand H_2 leak rates. Adjustments to operating practices and improved technologies to minimize leakage during routine maintenance operations are also needed to manage intentional H_2 releases. To fully understand the climate impacts associated with deploying H_2, emissions from real world facilities must be quantified, requiring highly sensitive H_2 sensors that are not yet widely available.

40 Derwent, Richard G. 2022. "Global Warming Potential (GWP) for Hydrogen: Sensitivities, Uncertainties and Meta-Analysis." *International Journal of Hydrogen Energy* 48 (22): 8328-41. https://doi.org/10.1016/j.ijhydene.2022.11.219.

41 Ocko, Ilissa B., and Steven P. Hamburg. 2022. "Climate Consequences of Hydrogen Emissions.*" Atmospheric Chemistry and Physics.* 22 (14): 9349–68. https://doi.org/10.5194/acp-22-9349-2022.

42 The near-term (20-year) climate benefit of electrolytic hydrogen compared to traditional fossil fuel sources can be over 90% if the hydrogen leakage rate is 1%, but the benefit is only 60% if the hydrogen leakage rate is 10%.

43 Hauglustaine, D., Paulot, F., Collins, W., Derwent, R., Sand, S., and Boucher, O. 2022. "Climate Benefit of a Future Hydrogen Economy." *Communications Earth & Environment.* 3 (1). https://doi.org/10.1038/s43247-022-00626-z.

RECOMMENDATION 20: TECHNOLOGY—DETECTING, QUANTIFYING, AND MITIGATING ENVIRONMENTAL IMPACT

Recommendation: As more fully described in Chapter 6: Policy, the NPC recommends that, in order to better understand the impact of hydrogen emissions, the DOE should direct the national labs, as soon as possible, in conjunction with other public and private researchers, to undertake additional research and development to develop and improve leak detection, prevention, and abatement technologies; the accuracy of monitoring technologies; and to measure, quantify, and validate actual hydrogen emissions rates. The EPA can utilize insights to recommend hydrogen emissions reporting standards to develop guidance for monitoring and repair.

FINDING 18: The industry requires clear safety standards and guidelines to allow for the safe use of existing or repurposed natural gas lines for the movement of unblended LCI hydrogen or blends of LCI hydrogen and natural gas. Without clear standards, the deployment of LCI hydrogen could be slowed.

Blending Hydrogen and Repurposing Natural Gas Pipelines: From the outset, LCI H_2 infrastructure should prioritize safety and environmental considerations as it is planned, built, and managed. Likewise, these considerations apply to repurposed natural gas infrastructure. Repurposing natural gas pipeline infrastructure for LCI H_2 is a potentially effective strategy for scaling H_2 transport capability, although further research is required to assess safety concerns associated with these conversions.

LCI H_2 blending within the natural gas infrastructure aims to leverage existing infrastructure to incorporate LCI H_2 into the overall energy mix. Previous studies claimed that a H_2 blend of up to 20% by volume would often not require modification of the existing natural gas pipeline or end-user applications.[44] However, there are no established safety standards for blending LCI H_2 into the existing natural gas pipeline infrastructure, and the blending of LCI H_2 at any concentration into the natural gas network will require evaluation and potential mitigation to address technological, metallurgical, operational, and safety impacts to the system. NPC recommends the following to accelerate our efforts toward developing standards on blending H_2 into or repurposing existing pipeline infrastructure for H_2 service.

RECOMMENDATION 21: PIPELINE SAFETY CODES AND STANDARDS

Recommendation: As more fully described in Chapter 3: Infrastructure and Chapter 6: Policy, the NPC recommends DOE and the Pipeline and Hazardous Materials Safety Administration convene interagency efforts to develop clear requirements for converting existing natural gas pipelines to transport LCI hydrogen or LCI hydrogen and natural gas blends and for converting other infrastructure to hydrogen service, including, with industry input, integrity-based quality specifications for hydrogen transported in pipelines.

FINDING 19: **Integrating LCI hydrogen with the electrical grid and other energy systems can support the grid's transition to a low carbon intensity energy system.**

Grid Integration: Electric grid integration with LCI H_2 infrastructure could promote the development of decentralized power generation and enable load-balancing capabilities.

LCI H_2-based power generation systems (e.g., fuel cells, internal combustion engines, H_2-combustion turbines) can be deployed at varying capacity scales, allowing for localized power generation. By decentralizing LCI H_2 production and utilizing it locally, the need for long-distance electricity transmission can be reduced, minimizing transmission losses and grid congestion. This decentralization of power generation could enhance grid resilience and enable local renewable resource integration, increasing low-carbon energy autonomy.

At the same time, electric grid integration with LCI H_2 infrastructure could enable energy storage and load-balancing capabilities, further enhancing the resilience and reliability of the electric grid. Excess electricity, particularly during periods of low demand or high renewable energy generation, can produce H_2 through electrolysis—producing LCI H_2 that can be stored and later converted into electricity or used outside the Power sector. Hydrogen's flexibility can help balance the grid load when demand exceeds supply (e.g., hot summer days, extreme weather events) and take advantage of surplus production when supply exceeds demand.

Additionally, grid integration with electrolyzers for RE H_2 production would impact the cost and relative volumes of RE H_2 and could have significant implications for the electrical load on the grid. The Modeling conducted for this study assumed "behind-the-meter" dedicated renewables. The Modeling did not account for grid-connected RE H_2 and assumed that the solar and wind renewable power for RE H_2 was fully additional, developed in the same region as the H_2 production occurs, and functionally hourly time matched. The impacts of grid connectivity to the cost and carbon intensity of RE H_2 are complex and driven by the costs of electricity, the utilization of the electrolyzer, and the implications of the CI of the grid. As previously highlighted, the amount of renewable energy anticipated by 2050 in the NZ2050 scenario to generate RE H_2 is roughly half the size of the current electric grid in 2020 and would have a significant impact on grid operations.

Successful electric grid integration with LCI H_2 infrastructure requires planning, coordination, and optimization. Intricate and data-intensive

44 Lipiäinen, S., Lipiäinen, K., Ahola, A., and Vakkilainen, E. 2023. "Use of Existing Gas Infrastructure in European Hydrogen Economy." *International Journal of Hydrogen Energy*. 48 (80): 31317–29. https://doi.org/10.1016/j.ijhydene.2023.04.283.

power-flow modeling of the grid system is imperative for addressing infrastructure upgrades. Such modeling will need to simulate hourly energy supply and dispatch variability and identify potential congestion points. To optimize future deployment, the electric system's integrated resource planning may need to incorporate Power sector demand, supply forecasts, and product demand (e.g., H_2) from other economic sectors. This effort calls for coordination among many stakeholders, ranging from local electricity and gas utilities, independent system operators (ISOs)/regional transmission operators (RTOs), FERC, and even DOE.

While this study included informed assumptions for the role of LCI H_2 in the Power sector, detailed power-flow analysis modeling of the grid system was outside the scope of the analysis. A subsequent evaluation could offer the potential to evaluate the role of LCI H_2's benefits in relation to the electric grid infrastructure as part of the overall energy ecosystem. NPC recommends pursuing the following actions.

RECOMMENDATION 22: GRID INTEGRATION

Recommendation: As more fully described in Chapter 6: Policy, the NPC recommends DOE and the Federal Energy Regulatory Commission (FERC), in consultation with the independent system operators/regional transmission operators, commission an energy-flow modeling study to assess grid energy system capabilities and resiliency. This study should specifically develop and implement a transmission and distribution grid planning roadmap to assess and support future national grid demands and integrate renewables, hydrogen, storage, natural gas, and the regional electric grid systems. This study should also address the potential benefits, costs, and impacts on accelerating U.S. decarbonization goals by broadly addressing:

- Expanding existing grid capacity
- Interconnection delays
- Long-distance transmission capabilities and transmission planning reform
- Microgrids
- Distributed energy resources
- Electrolyzer production and use demand
- Growing power demands, e.g., artificial intelligence, cryptocurrency, battery manufacturing

RECOMMENDATION 23: GRID RESILIENCY

Recommendation: As more fully described in Chapter 6: Policy, the NPC recommends:

- Federal Energy Regulatory Commission (FERC), North American Electric Reliability Corporation, and regional transmission operators implement available and proven technologies and adopt clear policies to enhance existing grid capacity using grid enhancing technologies, e.g., dynamic line ratings, advanced power-flow control, and topology optimization
- FERC continue to expand and improve interconnection reform beyond FERC Order 2023, in order to expand transmission and distribution grid improvements and more rapidly integrate renewables, hydrogen, storage, natural gas, and the regional electric grid systems
- The administration, Congress, FERC, and states work to pass power transmission and distribution grid reforms to incentivize transmission efficiency and capacity development that incorporate new technologies that enhance grid capacity and resiliency, e.g., grid enhancing technologies

IV. CONCLUSION

As detailed above, the at-scale deployment of LCI H_2 can play a key role in reducing U.S. carbon emissions, particularly in hard-to-abate sectors, at a lower cost to society. However, current policies and anticipated cost reductions fall short of providing the support needed to deploy LCI H_2 at a scale necessary to cost effectively achieve the U.S. net zero target by 2050. Significant and immediate steps must be taken to support the growth and scale-up of all aspects of the H_2 market (e.g., production, demand, and infrastructure).

This report answers questions posed by the U.S. Secretary of Energy to the NPC. As outlined above, NPC believes framing a three-phased approach—Activation, Expansion, and At-Scale—provides actionable insights into the opportunities and challenges associated with at-scale LCI H_2 deployment.

As discussed earlier, this report's Modeling indicates that reaching the targets of the NZ2050 scenario will require at-scale LCI H_2 deployment of ~75 MMTpa. This market scale will require an increased production and demand for H_2 nearly 7x from today's level, while transitioning from existing unabated H_2 to LCI H_2. This market shift will require a massive increase in the buildout of the H_2 value chain that is not yet insufficient supported by policy.

LCI H_2 has a unique and key role to play in supporting U.S. carbon emissions reductions goals and will play an important role alongside other technologies and low-carbon solutions. The chapters that follow provide an in-depth analysis of LCI H_2 within this context. Topics include the role of LCI H_2 (Chapter 1) in reducing carbon emissions in our economy, its production (Chapter 2), midstream infrastructure (Chapter 3), technoeconomic considerations for the integrated LCI H_2 supply chain (Chapter 4), demand (Chapter 5), policy and regulations (Chapter 6), and societal considerations, impacts, and safety (Chapter 7).

NPC's findings, as detailed herein, reveal clear areas of opportunity and challenge. Our recommendations provide specific actions so the U.S. can leverage its abundant resources and capabilities to reach at-scale deployment of LCI H_2. This study identifies actionable recommendations to ensure sufficient RD&D investments and the incorporation of societal considerations, impacts, and safety as part of the LCI H_2 economy development. Finally, one lever—policy action—remains a necessary lynchpin. Therefore, NPC recognizes the importance of urgent policy action; without it, LCI H_2 is unlikely to achieve scale or fulfill its potential to support U.S. net zero ambitions.

APPENDICES

Appendix A:
Request Letter and Description of the NPC

Appendix B:
Study Group Rosters

Appendix C:
Executive Summary Findings and Recommendations

Acronyms and Abbreviations

The Secretary of Energy
Washington, DC 20585

November 8, 2021

Mr. J. Larry Nichols
Chair
National Petroleum Council
1625 K Street, NW
Washington, DC 20006

Dear Mr. Nichols:

To meet the world's need for affordable energy while reducing greenhouse gas (GHG) emissions to net zero by 2050 will require deploying a variety of technologies. One essential set of technologies encompasses Carbon Capture, Use, and Storage (CCUS). I have been impressed by the recent National Petroleum Council (NPC) report that provides a roadmap for deployment of CCUS at scale. Hydrogen energy involves another essential set of technologies presenting opportunities and challenges for deployment at scale.

Hydrogen has the potential to decarbonize a variety of energy market sectors for energy, including industrial, power, residential, commercial, and transportation, and serve as a renewable energy storage mechanism. Technologies exist today to produce low-carbon and renewable hydrogen at reasonable scale, but economically supplying these market sectors at significant scale poses commercial, logistical, regulatory, and technical challenges. Meeting these challenges will require collaboration from multiple industries, academia, government institutions, and other stakeholders to conduct additional research and to define the needed policy frameworks, market mechanisms, production pathways, and delivery systems.

Petroleum, chemical, industrial gas, infrastructure, and power companies have experience developing and deploying the technologies required to deliver hydrogen energy. Accordingly, I request the NPC conduct a study on the deployment of low and zero carbon hydrogen energy at scale through the entire value chain, including production, storage, liquefaction, transportation, and end uses. This effort should focus on production and delivery (both from fossil fuel and renewable sources); the potential impact on the power generation, industrial process, residential, commercial, and transportation sectors; and the needed infrastructure and storage requirements. Policy, regulatory, and technical challenges to the use of hydrogen should be identified and recommendations provided to enable use at scale.

Key questions to be addressed by the study include:

- What policy, regulatory, and other actions are needed to move technically ready hydrogen technologies into deployment to enable this energy system transition?

- What are the range and key drivers of hydrogen demand forecasts (including forecasts that are tied to a rapid decarbonization objective, such as the Paris Agreement) to use in evaluating infrastructure needs, technology opportunities, and relevant policy aspects?

- What integration and infrastructure requirements are needed to maximize hydrogen deployment for the identified market sectors and across the value chain?

- What hydrogen transportation carrier alternatives exist or could be developed and deployed, e.g., ammonia or other hydrogen carriers, in addition to the liquefaction, transportation, and use of elemental hydrogen?

- What health, safety, and environmental concerns need to be addressed to facilitate the acceptance of hydrogen in various market sectors or geographic regions?

- What are the environmental and economic footprints of hydrogen versus alternatives? Which end uses and technologies are most advantaged in GHG and other pollutant reductions, environmental justice, and job creation?

- What research gaps exist and what is the path to address those gaps, including potential research roles for industry, academia, government, and national laboratories?

For the purposes of the study, I am designating Deputy Secretary David Turk to represent me. As my designee, in coordination with you, as the NPC Chair, he can approve the establishment and membership of subcommittees or working groups, as well as designate Government employees as Cochairs for any subcommittees or working groups, as required. The Assistant Secretary for Fossil Energy and Carbon Management will work with Deputy Secretary Turk to identify Government Cochairs.

Sincerely,

Jennifer M. Granholm

DESCRIPTION OF THE NATIONAL PETROLEUM COUNCIL

In May 1946, the President stated in a letter to the Secretary of the Interior that he had been impressed by the contribution made through government/industry cooperation to the success of the World War II petroleum program. He felt that it would be beneficial if this close relationship were to be continued and suggested that the Secretary of the Interior establish an industry organization to advise the Secretary on oil and natural gas matters. Pursuant to this request, Interior Secretary J. A. Krug established the National Petroleum Council (NPC) on June 18, 1946. In October 1977, the Department of Energy was established and the Council's functions were transferred to the new Department.

The purpose of the NPC is solely to advise, inform, and make recommendations to the Secretary of Energy and the Executive Branch on any matter requested or approved by the Secretary, relating to oil and natural gas or the oil and gas industries. Matters that the Secretary would like to have considered by the Council are submitted in the form of a letter outlining the nature and scope of the study. The Council reserves the right to decide whether it will consider any matter referred to it.

Examples of reports of studies undertaken by the NPC at the request of the Secretary include:

- *Charting The Course – Reducing GHG Emissions from the U.S. Natural Gas Supply Chain* (2024)
- *Harnessing Hydrogen: A Key Element of the U.S. Energy Future* (2024)
- *Principles, and Oil & Gas Industry Initiatives and Technologies for Progressing to Net Zero* (2022)
- *Petroleum Market Developments – Progress and Actions to Increase Supply and Improve Resilience* (2022)
- *Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage* (2019)
- *Dynamic Delivery: America's Evolving Oil and Natural Gas Transportation Infrastructure* (2019)
- *Supplemental Assessment to the 2015 Report – Arctic Potential* (2018)
- *Arctic Potential: Realizing the Promise of U.S. Arctic Oil and Gas Resources* (2015)
- *Enhancing Emergency Preparedness for Natural Disasters* (2014)
- *Advancing Technology for America's Transportation Future* (2012)
- *Prudent Development: Realizing the Potential of N. America's Abundant Natural Gas & Oil Resources* (2011)
- *One Year Later: An Update On Facing the Hard Truths about Energy* (2008)
- *Facing the Hard Truths about Energy: A Comprehensive View to 2030 of Global Oil & Natural Gas* (2007)
- *Observations on Petroleum Product Supply* (2004)
- *Balancing Natural Gas Policy – Fueling the Demands of a Growing Economy* (2003)
- *Securing Oil and Natural Gas Infrastructures in the New Economy* (2001)
- *U.S. Petroleum Refining—Assuring the Adequacy and Affordability of Cleaner Fuels* (2000)
- *Meeting the Challenges of the Nation's Growing Natural Gas Demand* (1999)
- *U.S. Petroleum Product Supply—Inventory Dynamics* (1998)
- *Issues for Interagency Consideration: A Supplement to Future Issues* (1996)
- *Future Issues – A View of U.S. Oil & Natural Gas to 2020* (1995)
- *Research, Development, and Demonstration Needs of the Oil and Gas Industry* (1995)
- *Marginal Wells* (1994)
- *The Oil Pollution Act of 1990: Issues and Solutions* (1994)
- *U.S. Petroleum Refining – Meeting Requirements for Cleaner Fuels and Refineries* (1993)
- *The Potential for Natural Gas in the United States* (1992)
- *Petroleum Refining in the 1990s – Meeting the Challenges of the Clean Air Act* (1991)
- *Short-Term Petroleum Outlook – An Examination of Issues and Projections* (1991)
- *Industry Assistance to Government – Methods for Providing Petroleum Industry Expertise During Emergencies* (1991)
- *Petroleum Storage & Transportation* (1989)
- *Integrating R&D Efforts* (1988)
- *Factors Affecting U.S. Oil & Gas Outlook* (1987)
- *U.S. Petroleum Refining* (1986)
- *The Strategic Petroleum Reserve* (1984).

The NPC does not concern itself with trade practices, does not lobby, nor does it engage in any of the usual trade association activities. The Council is subject to the provisions of the Federal Advisory Committee Act of 1972.

Members of the National Petroleum Council are appointed by the Secretary of Energy and represent all segments of the oil and gas industries and related interests. The NPC is headed by a Chair and a Vice Chair, who are elected by the Council. The Council's operations are supported entirely by voluntary contributions from its members. Additional information on the Council is available at www.npc.org.

NATIONAL PETROLEUM COUNCIL MEMBERSHIP

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Appendix B

STUDY GROUP ROSTERS

STUDY PARTICIPATION

Participants in this study contributed in a variety of ways, ranging from work in all study areas, to involvement on a specific topic, or to reviewing proposed materials. Involvement in these activities should not be construed as endorsement or agreement with all the statements, findings, and recommendations in this report. Additionally, while U.S. government participants provided significant assistance in the identification and compilation of data and other information, they did not take positions on the study's recommendations.

As a federally appointed and chartered advisory committee, the National Petroleum Council is solely responsible for the final advice provided to the Secretary of Energy. However, the Council believes that the broad and diverse participation has informed and enhanced its study and advice. The Council is very appreciative of the commitment and contributions from all who participated in the process.

This appendix lists the individuals who served on this study's Committee, Coordinating Subcommittee, Task Groups, Subgroups, and Teams, as a recognition of their contributions. In addition, the NPC wishes to acknowledge the numerous other individuals and organizations who participated in some aspects of the work effort through outreach meetings or other contacts. Their time, energy, and commitment significantly enhanced the study and their contributions are greatly appreciated.

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Marshall W. Nichols	Executive Director	National Petroleum Council

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Maryam S. Brown	President	Southern California Gas Company
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Mark E. Lashier[1]	President and Chief Executive Officer	Phillips 66 Company
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Study Committee Members

Nicholas K. Akins[2]	Executive Chairman	American Electric Power Co., Inc.
Orlando A. Alvarez[3]	Chairman and President	bp America Inc.

1 Replaced Greg C. Garland, who represented Phillips 66 Company through February 2023.

2 Represented American Electric Power Co., Inc., serving through December 2022.

3 Replaced David C. Lawler, who represented bp America Inc. through October 2023.

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Christian S. Kendall[8]	President and Chief Executive Officer	Denbury Inc.
D. Ethan Kimbrel[9]	Senior Advisor to the Director Illinois Department of Natural Resources	State of Illinois

4 Represented the Oklahoma Corporation Commission serving through February 2024.

5 Replaced Thomas A. Blasingame, who represented the Society of Petroleum Engineers through February 2024.

6 Represented KBR, Inc., serving through February 2023.

7 Replaced Sarah O. Ladislaw, who represented the Rocky Mountain Institute through December 2022.

8 Represented Denbury Inc. serving through February 2024.

9 Served as Commissioner, Illinois Commerce Commission, until March 2023.

Arunava J. Majumdar	Dean, Stanford Doerr School of Sustainability Jay Precourt Professor, Professor of Mechanical Engineering, Senior Fellow at the Precourt Institute for Energy, and Senior Fellow, by courtesy, at the Hoover Institution	Stanford University
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Matthew K. Schatzman	Chairman and Chief Executive Officer	NextDecade Corporation
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Ray N. Walker, Jr.[12]	Chief Operating Officer	Encino Energy, LLC
Cynthia J. Warner[13]	Senior Operating Partner	GVP Climate, LLP
Kelcy L. Warren[14]	Executive Chairman	Energy Transfer LP

10 Represented EnergyRev LLC serving through February 2024.

11 Represented Accenture serving through August 2023.

12 Represented Encino Energy, LLC, serving through February 2023.

13 Represented GVP Climate, LLP, serving through February 2024.

14 Represented Energy Transfer LP serving through December 2023.

COMMITTEE ON HYDROGEN ENERGY

Gretchen H. Watkins	President	Shell USA, Inc.
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Richard Clark	Director, Innovation and New Product Development	NextEra Energy, Inc.
Cristina Cordeddu	Vice President, Global Strategic Accounts	Baker Hughes Company
Timothy Cortes	Chief Technology Officer	Plug Power Inc.

15 Represented Air Liquide Group serving through January 2024.

16 Replaced Mansur Zhakupov, who represented TotalEnergies, S.E., through November 2023.

COORDINATING SUBCOMMITTEE (CSC)

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17 Served as Commissioner, Illinois Commerce Commission, until March 2023.

18 Represented EnergyRev LLC serving through February 2024.

19 Replaced A. Scott Anderson, who represented the Environmental Defense Fund through December 2023.

20 Replaced S. Heath DePriest, who represented Phillips 66 Company through March 2023.

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21 Represented Air Products and Chemicals, Inc., serving through November 2023.

22 Represented The Wiliams Companies, Inc., serving through March 2023.

23 Represented Baker Hughes Company serving through February 2024.

24 Represented the Environmental Defense Fund serving through September 2023.

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Appendix C

FINDINGS AND RECOMMENDATIONS

FINDING 1: LCI hydrogen could account for 8% of the United States' emissions reductions, primarily in hard-to-abate applications in the Industrial, Transportation, and Power sectors. Addressing these emissions without leveraging LCI hydrogen would cost society approximately an additional 0.5-1% of gross domestic product.

FINDING 2: Current policies and anticipated cost reductions for LCI hydrogen could increase total hydrogen demand by nearly 2x by 2050. However, current policies and anticipated economics are not sufficient to catalyze the nearly 7x demand growth required by 2050 to reach LCI hydrogen deployment at-scale and support U.S. net zero ambitions at a lower cost to society. Achieving this goal will require significant and immediate action to support the growth and scale-up of all aspects of the hydrogen market: production, infrastructure, and demand.

FINDING 3: The Industrial sector is projected to be the largest demand segment, but deploying LCI hydrogen at-scale requires demand growth in hard-to-abate sectors, including heavy-duty Transportation and dispatchable Power.

FINDING 4: The United States has the opportunity not only to secure its own carbon emissions-reduction goals via LCI hydrogen but also to be a leader in advancing the global hydrogen economy.

FINDING 5: The LCI hydrogen production mix will be driven by multiple aspects of the various hydrogen production pathways, including their relative speed to scale, delivery cost reductions, and carbon intensities.

FINDING 6: Pipelines should connect advantaged production to diverse demand centers to support a regionally optimized infrastructure configuration.

FINDING 7: Incorporating large-scale hydrogen storage infrastructure could enable a more cost-effective LCI hydrogen energy system design across the United States.

FINDING 8: The LCI hydrogen market in the United States has entered the Activation phase, aided by recent legislation such as the Inflation Reduction Act and Infrastructure Investment and Jobs Act, and is poised to increase LCI hydrogen production in advantaged regions.

FINDING 9: A large cost gap exists between incumbent fuels and feedstocks and LCI hydrogen in hard-to-abate applications. Technology advancement will continue to support closing the cost gap; however, current federal and state policies, as well as modeled system cost reduction, will not be sufficient to close the cost gap to parity by 2050.

RECOMMENDATION 1: PRICE ON CARBON

RECOMMENDATION: As more fully described in Chapter 6: Policy, the NPC recommends that the administration work with Congress to establish an economy-wide price on carbon well before current incentives, such as 45V, expire. This economy-wide price on carbon should be:

- Phased-in and coordinated to minimize adverse impacts on energy security, reliability, and affordability
- Well-designed to provide predictable signals for decisions about long-lived capital investment
- Market-based, and applicable to imports as well as domestic production, with a rebate for exports
- Visible, predictable, and transparent
- Enabling all technologies to compete and cost effectively lower carbon emissions intensity by focusing on reducing emissions per unit of energy while delivering meaningful emissions reductions
- Considering key protections and assurances for communities that are disadvantaged and could be overburdened by climate and air pollution
- An emissions intensity border fee considered in the context of a complementary explicit carbon-pricing policy to address/mitigate potential emissions leakage

RECOMMENDATION 2: DEMAND-SIDE INCENTIVES FOR INDUSTRY: NATIONAL LOW CARBON INTENSITY INDUSTRY STANDARD

RECOMMENDATION: As more fully described in Chapter 6: Policy, the NPC recommends Congress and the administration consider a national low carbon intensity (CI) industry standard to address GHG emissions from the Industrial sector. This transparent, technology-neutral, life cycle-based standard would be funded through carbon credit markets and applied within different segments of the Industrial sector to reduce the CI of products by considering well-to-gate[1] emissions associated with the sector. This policy may require specific CI standards to address various Industrial subsegments and provisions to ensure the Industrial sector remains globally competitive. This recommendation would be in lieu of an economy-wide explicit price on GHG emissions, which is the preferred policy approach.

RECOMMENDATION 3: DEMAND-SIDE INCENTIVES FOR TRANSPORTATION: NATIONAL LOW CARBON INTENSITY TRANSPORTATION STANDARD

RECOMMENDATION: As more fully described in Chapter 6: Policy, the NPC recommends Congress and the administration establish linked life cycle fuel and well-to-wheels vehicle carbon dioxide standards,* This policy would include:

- A low-carbon fuels standard program, driving down the carbon intensity of different fuel pathways (e.g., liquid fuel, hydrogen, or electricity)
- Vehicle carbon dioxide standards, which would use the well-to-wheels emissions of the vehicle based on the actual/projected low-carbon fuel standards performance of the energy source for the vehicle

As a result, the combined programs funded through carbon credit markets could drive down actual transport emissions in a holistic and efficient way, helping to accelerate emissions reduction and delivering reductions at a lower cost than the current siloed fuel and vehicle policies. This recommendation would be in lieu of an economy-wide explicit price on GHG emissions, which is the preferred policy approach.

At this time, NPC does not recommend including vehicle manufacturing emissions due to the current complexity of tracking these emissions across large supply chains but recognizes that other regulatory actions in the future may address these types of emissions and, if implemented, will need to be harmonized with standards such as those described in this recommendation.

RECOMMENDATION 4: PRODUCTION-SIDE INCENTIVES

RECOMMENDATION: As more fully described in Chapter 6: Policy, the NPC recommends:

- To provide further certainty on the investment commitments that developers must take

1 "Well-to-gate" shall only include emissions through the point of production, as determined under the most recent Greenhouse gases, Regulated Emissions, and Energy use in Technologies model (commonly referred to as the "GREET model") developed by Argonne National Laboratory, or a successor model (as determined by the Secretary).

to come to a final investment decision for a LCI hydrogen project, the IRS should consider implementing measures to reduce the risk that the "cliff effect" or even concerns over the "cliff effect," which arises due to the steep step changes in 45V between the different carbon intensity tiers and may negatively affect the bankability of a LCI hydrogen project. To ensure that qualifying LCI hydrogen projects are bankable while retaining the structure of 45V tiers, the IRS should consider implementing measures such as:

  - Allowing a reasonable uncertainty range for the 45V tiers so that true border case projects can qualify for the lower carbon intensity tier and have greater financial viability as a result.
  - Allowing companies to have a six-month period to appeal life cycle assessment findings during which the company can take additional actions to reduce the carbon intensity of the project (e.g., purchasing additional renewable natural gas, etc.)

- Congress: Lengthen the 45V credit-claiming period to 20 years to more closely match the incentive with the asset life cycle.
- DOE: Improve and fully utilize Greenhouse gases, Regulated Emissions, and Energy use in Technologies model (GREET) capability to incentivize emissions intensity reductions by allowing taxpayers to substitute default values in GREET with verifiable values based on coproduct allocation accounting (of methane emissions between oil, gas, and other hydrocarbon products) and reliable measurement, reporting, and verification methods (e.g., differentiated natural gas used, efficient electrolyzers).

RECOMMENDATION 5: GLOBAL TRADE

RECOMMENDATION: As more fully described in Chapter 6: Policy, NPC recommends the administration and Congress:

- Support the development by business and other stakeholders of transparent certification systems on the carbon intensity of hydrogen and hydrogen carriers (e.g., ammonia, methanol), and work to ensure their mutual recognition globally
- Support (with technical input and consultations) foreign mutual recognition of U.S. certification schemes (including use of accredited verifiers in different jurisdictions) with key trading partners
- Evaluate trade infrastructure needs and move forward key port, bunkering, transportation, storage, and other related infrastructure—including needed regulatory changes—to meet expected growth, particularly through major trade corridors
- Develop plurilateral agreements to promote trade in low-emissions products, including H2 and its derivatives, and work to build support beyond the core group of countries that have developed this approach
- Urge the DOE, working with other appropriate U.S. agencies and international organizations, to develop and make public data on the carbon intensity of hydrogen and hydrogen carriers' production in the United States and globally
- Develop and implement an emissions intensity border fee for hydrogen and hydrogen derivative products aligned with an explicit price on carbon or, in the absence of an explicit price on carbon, consistent with the effects

RECOMMENDATION 6: INFRASTRUCTURE INCENTIVES

RECOMMENDATION: As more fully described in Chapter 6: Policy, NPC recommends Congress create an Investment for Clean Hydrogen Infrastructure Projects program to facilitate access to capital that stimulates LCI hydrogen infrastructure. Funding should be made available to qualifying LCI hydrogen infrastructure projects in the form of grants, loans, and loan guarantees administered through the DOE Loan Programs Office and/or the introduction of an investment tax credit.

FINDING 10: Administrative and legal complexity across multiple jurisdictions in the current permitting process could delay development

and deployment of necessary facilities and infrastructure.

RECOMMENDATION 7: GENERAL PERMITTING REFORM

RECOMMENDATION: As more fully described in Chapter 6: Policy, the NPC recommends that the administration and/or Congress:

- Improve communications related to, and the implementation of, state and/or federal eminent domain; eminent domain should only be used as an option of last resort along with effective community engagement
- Establish an integrated federal, state, and local permitting portal (whole-of-government permitting portal, e.g., expanding on the existing Federal Permitting Improvement Steering Council [FPISC] permitting portal) to avoid duplication and provide efficient coordination and sharing of data among permitting authorities and projects
- Expand use of Programmatic Environmental Impact Statements to help accelerate the permitting process for low-carbon energy projects and expand permitting agency capacity by adopting the FPISC and ensuring adequate staffing resources
- Consolidate litigation, specifically apply the same two-year or other shorter statute of limitations for filing lawsuits against federal agency actions for all low-carbon energy projects and develop a timeline for agencies to act on judicial remands
- Provide adequate funding for appropriate agencies to ensure they have resources and staffing to administer permitting programs
- Expand responsible use of administrative categorical exclusions: Congress should require federal agencies to examine existing categorical exclusions and consider proposing additional categorical exclusions for LCI hydrogen/clean energy projects where appropriate

FINDING 11: Reaching the Expansion and At-Scale phases of LCI hydrogen deployment will require construction of interstate hydrogen pipelines to cost effectively move LCI hydrogen from supply to demand centers and will require timely permitting and approvals.

RECOMMENDATION 8: UNBLENDED INTERSTATE HYDROGEN PIPELINE REGULATORY AUTHORITY

RECOMMENDATION: As more fully described in Chapter 6: Policy, the NPC recommends that Congress deem hydrogen infrastructure to be in the public interest and, except as described in bullet "g.", authorize the Federal Energy Regulatory Commission (FERC) to regulate unblended as well as blended (an existing authority) interstate hydrogen pipelines, addressing the following key criteria for LCI hydrogen:

a. Promote regulatory certainty by establishing an unblended federal LCI hydrogen interstate pipeline framework in the Activation phase that could then be implemented in the Expansion phase in order to encourage investor certainty.

b. Provide a federal framework for eminent domain in conjunction with appropriate stakeholder/community engagement.

c. Ensure permits are approved in a timely manner to accelerate industry growth.

d. Continue to ensure applicable permit requirements (e.g., National Environmental Policy Act) are met.

e. Develop an unblended LCI hydrogen purity definition—clarify the point at which blends of hydrogen and natural gas are classified as "hydrogen" or "natural gas" for regulatory purposes.

f. Promote open access and transparency while ensuring that regulation does not inhibit growth of the nascent LCI hydrogen market. Focus FERC jurisdiction to regulation of LCI hydrogen transportation rates and service terms for energy. Recognize that hydrogen is used as both an energy carrier and as a feedstock for other commodities.

g. Honor the current business model of allowing hydrogen systems (not under FERC regulation) that do not seek federal eminent domain rights to remain exempt from any FERC regulation.

In addition, Congress and the administration should monitor the development of these changes to encourage a regulatory framework that supports development of a robust, competitive LCI hydrogen market.

RECOMMENDATION 9: CLASS VI PRIMACY AND WELL PERMITTING

RECOMMENDATION: As more fully described in Chapter 6: Policy, the NPC recommends the administration and Congress improve the Class VI primacy and well permitting process as follows:

- Hold the Environmental Protection Agency (EPA) accountable to its stated primacy timelines currently in 40 C.F.R. § 145.22 by establishing the following requirements:
  - If EPA has not made a decision on a Class VI primacy application within 90 days of receipt of complete submission, the EPA administrator should be required by Congress to submit a report to the governor of the state seeking primacy, the state agency seeking primacy, the Chair of the White House Council on Environmental Quality (CEQ chair), and the appropriate congressional committees explaining why the decision has exceeded 90 days and when the decision should be expected.
  - If EPA has not decided within 365 days of the application being complete, the appropriate congressional committees should consider holding an oversight hearing in which the EPA administrator and the CEQ chair explain why a decision has not yet been made.
- Congress, in consultation with EPA, should determine and require minimum staffing levels for Class VI primacy reviews/approvals by statute and enable EPA to meet and maintain these staffing targets until such a time when state requests for primacy have ended.
- Congress should improve the permitting process for individual Class VI wells by determining, in consultation with EPA and state agencies, what is adequate funding to support the Class VI program for states and the EPA in a manner that enables permits to be issued within 18 months. After completing this analysis, Congress should ensure both states and the EPA receive adequate funding for permitting work, and EPA shall report to Congress how these funds were used.

FINDING 12: Inadequate community engagement practices have led to distrust of project developers and delays in projects.

RECOMMENDATION 10: COMMITMENT TO SOCIAL CONSIDERATIONS, TRANSFORMATIVE COMMUNITY ENGAGEMENT, AND NET POSITIVE OUTCOMES

RECOMMENDATION: As more fully described in Chapter 7: SCI and Safety, the NPC recommends DOE, decision-makers, corporations, researchers, governments, and regulatory bodies actively commit to comprehensively consider and equitably address societal, environmental, and public health impacts related to the project during the Activation phase of LCI hydrogen deployment.

RECOMMENDATION 11: COMMUNITY ENGAGEMENT IMPROVEMENT OPPORTUNITIES

RECOMMENDATION: As more fully described in Chapter 6: Policy and Chapter 7: SCI and Safety, the NPC recommends the U.S. government charter national and/or regional public/private council(s) of excellence in effective industry-community engagement practices to develop and encourage the adoption of best practices that include equitable representations from industry, nongovernmental organizations (NGOs), and government.

- These councils should be forums where industry, NGOs, and government would keep community engagement best practices up to date by identifying and disseminating effective community engagement practices, leveraging existing best practice resources (e.g., Permitting Council FY22 Recommended Best Practices Report, API RP-1185, and IPIECA) that are cognizant of regional and local needs and considerations. The governance structures, participation processes, and transparency should be designed to promote engagement of industry, NGOs, local governments, and other interested parties, and enhance the credibility of a council's products.

- These councils should intentionally support less capitalized operators to implement these best practices inclusive of, but not limited to, experienced resources and training.

While acknowledging that many developers already implement community engagement, there is an opportunity to encourage broader adoption of documented best practices across the industry by providing additional motivation to implement robust community engagement. The NPC further recommends the administration and Congress develop government procedural or permitting timeline incentives for companies that consistently meet established best practices (when developed and documented) for community engagement. As part of the joint industry organization, propose a voluntary program to monitor adherence and adoption of recognized best practices that can be considered for eligibility for procedural or permitting timeline incentives.

RECOMMENDATION 12: OUTREACH MATERIALS TO INCREASE COMMUNITY UNDERSTANDING OF LCI HYDROGEN DEVELOPMENT

RECOMMENDATION: As more fully described in Chapter 7: SCI and Safety, NPC recommends DOE should expand support for programs such as the Environmental Justice Technical Assistance Centers programs and/or should develop funding opportunities for community representatives and experts to support the outreach needed to increase community understanding of advanced energy technologies such as LCI hydrogen, carbon capture and sequestration, and direct air capture. Industry and government must ensure a more informed level of community engagement.

FINDING 13: Past experiences may have left communities feeling unheard by project developers, resulting in a deficit of trust, transparency, tracking, and sharing of outcomes.

RECOMMENDATION 13: ROLE CLARITY FOR COMMUNITY BENEFITS

RECOMMENDATION: As more fully described in Chapter 7: SCI and Safety, the NPC recommends DOE clarify the roles it and project developers each play in addressing community concerns as early and often as possible in project development (for developers) or throughout listening sessions and roadshows (for DOE).

RECOMMENDATION 14: COMMUNITY BENEFITS PLANNING

RECOMMENDATION: As more fully described in Chapter 7: SCI and Safety, the NPC recommends DOE consider expansion of its Community Benefits Plans/Planning approach, which is currently utilized in scoring competitive grant applications, to reach beyond Justice40 covered programs to other funding streams.

RECOMMENDATION 15: TRACKING AND COMMUNICATING COMMITMENTS TO COMMUNITY ENGAGEMENT TO INCREASE PUBLIC CONFIDENCE

RECOMMENDATION: As more fully described in Chapter 7: SCI and Safety, the NPC recommends that, as commitments are made to engage with communities associated with LCI hydrogen project deployment in the Activation stage, DOE make the techniques and results available to the public to better educate on effective engagement techniques and to incentivize their use.

FINDING 14: Lack of timely workforce development and labor engagement can inhibit the pace of LCI hydrogen growth.

RECOMMENDATION 16: WORKFORCE READINESS

RECOMMENDATION: As more fully described in Chapter 7: SCI and Safety, the NPC recommends DOE and Department of Labor work to create a more broadly inclusive program for apprenticeships that considers input from various groups such as National Association of Manufacturers, labor unions, and trade organizations to enable workforce participation in the hydrogen economy.

RECOMMENDATION 17: ADDITIONAL STUDY ON SOCIETAL CONSIDERATIONS AND IMPACTS

RECOMMENDATION: As more fully described in Chapter 7: SCI and Safety, the NPC recommends

DOE undertake a stand-alone, comprehensive societal considerations and impacts study, related to energy development, including, but not limited to, LCI hydrogen H2 development and GHG emissions-reduction value chains, as well as other facets of energy development. It is recommended that this study be conducted with the National Academy of Sciences, Engineering, and Medicine's Division of Behavioral and Social Sciences and Education and the Board on Energy and Environmental Systems, with coordinated input and concerted effort from the NPC and other stakeholders.

FINDING 15: Lack of a prioritized investment roadmap for technology is a hindrance to further levelized cost of hydrogen reduction and reliable LCI hydrogen value chain.

RECOMMENDATION 18: TECHNOLOGY—REDUCING THE COST GAP

RECOMMENDATION: As more fully described in Chapter 6: Policy, the NPC recommends DOE invest in research, development, and deployment (RD&D) in the following areas:

- Demand: Support national laboratory and university research to fast-track the development of robust, low-cost materials to enhance the performance of the hydrogen end uses identified to have the highest potential by the MIT Model results (e.g., advanced fuel cells). RD&D should focus on reducing costs, increasing efficiency, improving safety performance, and addressing the environmental impact (e.g., nitrogen oxides emissions) of end-use applications.
- Supply: Support materials research for electrolysis, including alternative catalysts and nanotechnology-based solutions to reduce costs, reduce reliance on critical minerals, improve performance, and enable scale. Technology improvements to methane-based production solutions, such as pyrolysis and carbon capture, should be an integral part of DOE's RD&D portfolio.
- Infrastructure: Support national laboratory and university research to understand the effect of hydrogen on natural gas pipeline infrastructure, particularly vintage pipelines (embrittlement, corrosion) through the DOE-sponsored Hydrogen Materials Consortium. Perform RD&D on monitoring systems for improved accuracy and cost reduction of these technologies. Support research to further enhance the properties of nonmetallic, composite pipe for hydrogen and carbon dioxide applications while improving life cycle emissions.
- Storage: Support research for underground storage of hydrogen (e.g., in engineered caverns, depleted oil and natural gas fields, and deep saline formations). Support ongoing national laboratory (Hydrogen Materials Advanced Research Consortium) and university research on hydrogen storage materials to enable cost reduction and compatibility with high volume or variable end uses.

FINDING 16: Without long-term sourcing and supply of critical materials, a robust and resilient LCI hydrogen value chain may not materialize.

RECOMMENDATION 19: SUPPLY CHAIN

RECOMMENDATION: As more fully described in Chapter 6: Policy, the NPC recommends:

- The government should form a multiagency taskforce to analyze vulnerable supply chains and recommend strategies that focus on ensuring security of supply of critical materials and manufacturing capacity for scaling up hydrogen production. These strategies could and should incorporate supporting U.S. domestic and allied supply and more diversified import options.
- Allow the market to play a role in addressing routine economic challenges and reserve the use of the Defense Production Act for critical and exceptional circumstances to avoid unnecessary intervention in market dynamics.

FINDING 17: There is no commercially accessible technology for measuring and mitigating low-flow-rate hydrogen emissions that are relevant to possible climate impacts.

RECOMMENDATION 20: TECHNOLOGY—DETECTING, QUANTIFYING AND MITIGATING ENVIRONMENTAL IMPACT

RECOMMENDATION: As more fully described in Chapter 6: Policy, the NPC recommends that, in order to better understand the impact of hydrogen emissions, the DOE should direct the national labs, as soon as possible, in conjunction with other public and private researchers, to undertake additional research and development to develop and improve leak detection, prevention, and abatement technologies; the accuracy of monitoring technologies; and to measure, quantify, and validate actual hydrogen emissions rates. The EPA can utilize insights to recommend hydrogen emissions reporting standards to develop guidance for monitoring and repair.

FINDING 18: The industry requires clear safety standards and guidelines to allow for the safe use of existing or repurposed natural gas lines for the movement of unblended LCI hydrogen or blends of LCI hydrogen and natural gas. Without clear standards, the deployment of LCI hydrogen could be slowed.

RECOMMENDATION 21: PIPELINE SAFETY CODES AND STANDARDS

RECOMMENDATION: As more fully described in Chapter 3: Infrastructure and Chapter 6: Policy, the NPC recommends DOE and the Pipeline and Hazardous Materials Safety Administration convene interagency efforts to develop clear requirements for converting existing natural gas pipelines to transport LCI hydrogen or LCI hydrogen and natural gas blends and for converting other infrastructure to hydrogen service including, with industry input, integrity-based quality specifications for hydrogen transported in pipelines.

FINDING 19: Integrating LCI hydrogen with the electrical grid and other energy systems can support the grid's transition to a low carbon intensity energy system.

RECOMMENDATION 22: GRID INTEGRATION

RECOMMENDATION: As more fully described in Chapter 6: Policy, the NPC recommends DOE and the Federal Energy Regulatory Commission (FERC), in consultation with the independent system operators/regional transmission operators, commission an energy-flow modeling study to assess grid energy system capabilities and resiliency. This study should specifically develop and implement a transmission and distribution grid planning roadmap to assess and support future national grid demands and integrate renewables, hydrogen, storage, natural gas, and the regional electric grid systems. This study should also address the potential benefits, costs, and impacts on accelerating U.S. decarbonization goals by broadly addressing:

- Expanding existing grid capacity
- Interconnection delays
- Long-distance transmission capabilities and transmission planning reform
- Microgrids
- Distributed Energy Resources
- Electrolyzer production and use demand
- Other growing power demands e.g., artificial intelligence, cryptocurrency, battery manufacturing

RECOMMENDATION 23: GRID RESILIENCY

RECOMMENDATION: As more fully described in Chapter 6: Policy, the NPC recommends:

- Federal Energy Regulatory Commission (FERC), North America Electric Reliability Corporation, and regional transmission operators implement available and proven technologies and adopt clear policies to enhance existing grid capacity using grid enhancing technologies, e.g., dynamic line ratings, advanced power-flow control, and topology optimization
- FERC continue to expand and improve interconnection reform beyond FERC Order 2023, in order to expand transmission and distribution grid improvements and more rapidly integrate renewables, hydrogen, storage, natural gas, and the regional electric grid systems

- The administration, Congress, FERC, and states work to pass power transmission and distribution grid reforms to incentivize transmission efficiency and capacity development that incorporate new technologies that enhance grid capacity and resiliency e.g., grid enhancing technologies

ACRONYMS AND ABBREVIATIONS

Acronym	Meaning
ACF	Advanced Clean Fleets
ACT	Advanced Clean Trucks Regulation
ANL	Argonne National Laboratory
ATR	Autothermal Reforming
AWE	Alkaline Water Electrolysis
BACT	Best Available Control Technology
BEV	Battery Electric Vehicle
BF-BOF	Blast Furnace and Basic Oxygen Furnace
CAA	Clean Air Act
CAB	Community Advisory Board
CAFE	Corporate Average Fuel Economy
CAISO	California Independent System Operator
CARB	California Air Resources Board
CBAM	Carbon Border Adjustment Mechanism
CBH	Community Benefits Hubs
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization, and Storage
CEJST	Climate and Economic Justice Screening Tool

Acronym	Meaning
CFR	Code of Federal Regulations
CGH_2	Compressed Gaseous Hydrogen
CH_2	Methylene
CI	Carbon Intensity
CIA	Cumulative Impact Assessments
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
DAC	Direct Air Capture
DEIA	Diversity, Equity, Inclusion, and Accessibility
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOT	U.S. Department of Transportation
DRI	Direct Reduction of Iron
EA	Environmental Assessment
EAF	Electric Arc Furnace
EIA	U.S. Energy Information Administration
EJ	Environmental Justice
EPA	U.S. Environmental Protection Agency
EPCRA	Emergency Planning and Community Right-to-Know Act

Acronym	Meaning
ERCOT	Electric Reliability Council of Texas
EU	European Union
FCEV	Fuel Cell Electric Vehicle
FEED	Front End Engineering and Design
FERC	Federal Energy Regulatory Commission
GHG	Greenhouse Gas
GHGRP	Greenhouse Gas Reporting Program
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (LCA Model)
GVWR	Gross Vehicle Weight Ratio
GW	Gigawatt
H_2	Hydrogen
HD	Heavy Duty
HDT	Heavy-Duty Truck
HRI	Hydrogen Refueling Infrastructure
HRS	Hydrogen Refueling Stations
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
IIJA	Infrastructure Investment and Jobs Act
IMO	International Maritime Organization
IRA	Inflation Reduction Act
J40	Justice40
LAER	Lowest Achievable Emissions Rate
LCA	Life Cycle Assessment
LCFS	Low Carbon Fuel Standard
LCI H_2	Low Carbon Intensity Hydrogen

Acronym	Meaning
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Hydrogen
LCOHd	Levelized Cost of Hydrogen Distribution
LCOHp	Levelized Cost of Hydrogen Production
LCOHs	Levelized Cost of Hydrogen Storage
LCOHt	Levelized Cost of Hydrogen Transmission
LEV	Low-Emissions Vehicle
LH_2	Liquefied Hydrogen
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
MGD	Million Gallons per Day
MIT	Massachusetts Institute of Technology
MITEI	Massachusetts Institute of Technology Energy Initiative
MT	Metric Tons
MTpd	Metric Tons per Day
MMT	Million Metric Tons
MMTpa	Million Metric Tons per Annum
MW	Megawatt
N_2O	Nitrous Oxide
NOx	Nitrogen Oxides
NAAQS	National Ambient Air Quality Standards
NEPA	National Environmental Policy Act
NERC	North American Electric Reliability Corporation
NG+ CCS H_2	Natural Gas Reformed with Carbon Capture and Storage Hydrogen

Acronym	Meaning
NHTSA	National Highway Traffic Safety Administration
NPC	National Petroleum Council
NREL	National Renewable Energy Laboratory
NZ2050	Net Zero by 2050 Scenario
OEM	Original Equipment Manufacturers
OSHA	Occupational Safety and Health Administration
PEM	Polymer Electrolyte Membrane
PHEV	Plug-In Hybrid Electric Vehicles
PHMSA	Pipeline and Hazardous Materials Safety Administration
PM2.5	Particulate Matter with Diameter Less Than 2.5 Micrometers
PPA	Power Purchase Agreement
PTC	Production Tax Credits
R&D	Research and Development
RD&D	Research, Development, and Deployment
RE	Renewable Electricity
RE H_2	Renewable Electrolytic Hydrogen
RFS	Renewable Fuel Standard
RIN	Renewable Identification Number

Acronym	Meaning
RNG	Renewable Natural Gas
SAF	Sustainable Aviation Fuel
SCI	Societal Considerations and Impacts
SCR	Selective Catalytic Reduction
SDWA	Safe Drinking Water Act
SESAME	Sustainable Energy System Analysis Modeling Environment Model
SMNR	Small Modular Nuclear Reactors
SMR	Steam Methane Reforming
SO_2	Sulfur Dioxide
SOEC	Solid Oxide Electrolysis Cell
SOFC	Solid Oxide Fuel Cell
SP	Stated Policies Scenario
Tcf	Trillion Cubic Feet
TCO	Total Cost of Ownership
TEA	Technoeconomic Analysis
TRL	Technology Readiness Level
UIC	Underground Injection Control
USGS	U.S. Geological Survey
USREP	U.S. Regional Energy Policy
VRE	Variable Renewable Energy Sources
ZEV	Zero-Emissions Vehicle

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