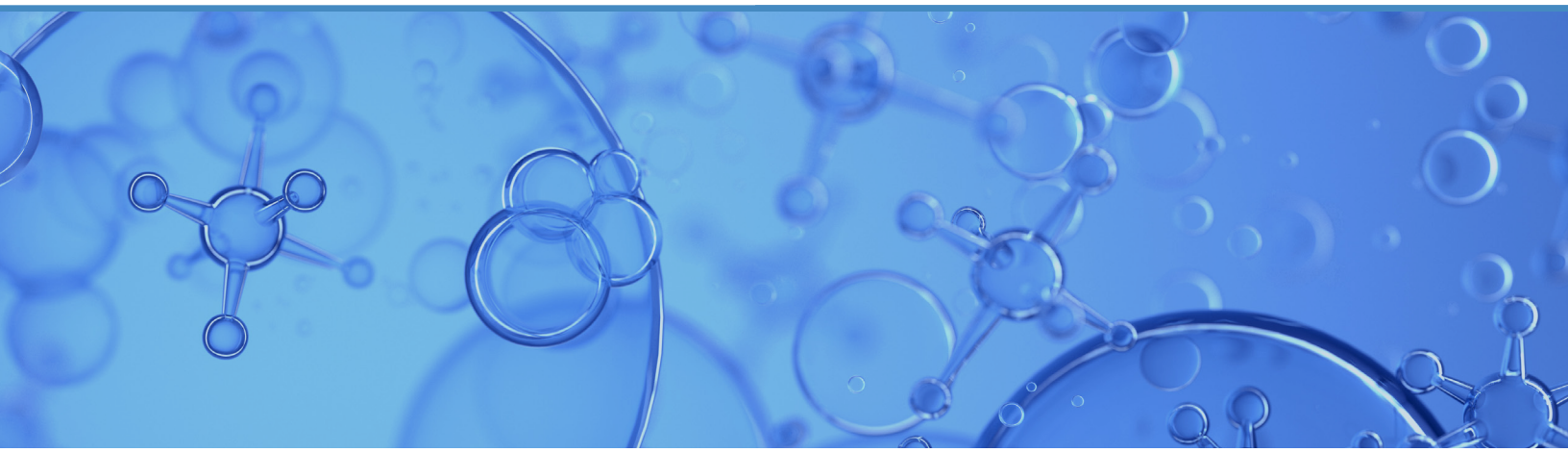

The U.S. Hydrogen Demand

ACTION PLAN

February 2023

ENERGY FUTURES INITIATIVE

About the
ENERGY FUTURES INITIATIVE

The Energy Futures Initiative advances technically grounded solutions to climate change through evidence-based analysis, thought leadership, and coalition-building. Under the leadership of Ernest J. Moniz, the 13th U.S. Secretary of Energy, EFI conducts rigorous research to accelerate the transition to a low-carbon economy through innovation in technology, policy, and business models. EFI maintains editorial independence from its public and private sponsors. EFI's reports are available for download at **www.energyfuturesinitiative.org**

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LIST OF ACRONYMS

AC: Alternating Current

ACES: Advanced Clean Energy Storage

AEM: Alkaline Exchange Membrane

AFL-CIO: American Federation of Labor and Congress of Industrial Organizations

API: American Petroleum Institute

ARIES: Advanced Research on Integrated Energy Systems

ARPA-E: Advanced Research Projects Agency-Energy

ARRA: American Recovery and Reinvestment Act

ATR: Autothermal Reforming

AWARE: Available Water Remaining model

bbl: barrel

BF: Blast Furnace

BIL: Bipartisan Infrastructure Law

BLS: Bureau of Labor Statistics

BOF: Basic Oxygen Furnace

BP: Business Plan

C-I: Carbon Intensity

CAPEX: Capital Expenditure

CBAM: Carbon Border Adjustment Mechanism

CBP: Community Benefits Plan

CCS: Carbon Capture and Storage

CCUS: Carbon Capture, Utilization, and Storage

CEJST: Climate and Economic Justice Screening Tool

CF: Capacity Factor

CHPS: Clean Hydrogen Production Standard

CNG: Compressed Natural Gas

CNR: Catalytic Naphtha Reformer

CO_2: Carbon Dioxide

CO_2e: Carbon Dioxide equivalent

CO: Carbon Monoxide

CS: Carbon Steel

CSP: Concentrated Solar Power

D&D: Disposition and Decommissioning

DC: Direct Current

DEIA: Diversity, Equity, Inclusion, and Accessibility

DHS: Department of Homeland Security

DOE: Department of Energy

DOT: Department of Transportation

DRI: Direct Reduction Iron

EAF: Electric Arc Furnace

EERE: Energy Efficiency and Renewable Energy Office

EIA: Energy Information Administration

EJ: Environmental Justice

EOR: Enhanced Oil Recovery

EPA: Environmental Protection Agency

ESCO: Energy Service Company

ESPC: Energy Savings Performance Contracts

ETS: Emissions Trading Scheme

EU: European Union

EV: Electric Vehicle

FCEV (or FCV): Fuel Cell Electric Vehicle

FCHEA: Fuel Cell & Hydrogen Energy Association

FECM: Fossil Energy and Carbon Management Office

FEED: Front-End Engineering Design

FEMP: Federal Energy Management Program

FERC: Federal Energy Regulatory Commission

FOA: Funding Opportunity Announcement

FP: Financial Plan

FY: Fiscal Year

gal: gallon

GE: General Electric

GHG: Greenhouse Gas Emissions

GICS: Global Industry Classification Standard

GIS: Geographic Information System

GREET: Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies

Gt: Gigaton

GW: Gigawatt

GWh: Gigawatt-hour

GWP: Global Warming Potential

H_2: Hydrogen

HDV: Heavy-duty Vehicle

HERD: Higher Education Research and Development

HFTO: Hydrogen and Fuel Cell Technologies Office

HIFLD: Homeland Infrastructure Foundation-Level Data

HTE: High-Temperature Electrolysis

HyTF: Hydrogen Transition Framework

ICEV: Internal Combustion Engine Vehicle

IEA: International Energy Agency

IGC: Industrial Gas Company

IGCC: Integrated Gasification Combined Cycle

IIJA: Infrastructure Investment and Jobs Act

IPA: Intermountain Power Agency

IPHE: International Partnership for Hydrogen and Fuel Cells in the Economy

IPP: Intermountain Power Project

IPS: Integrated Project Schedule

IRA: Inflation Reduction Act

IRS: Internal Revenue Service

ISO: Independent System Operator

ISO: International Organization for Standardization

ITC: Investment Tax Credit

Kg: kilogram

Khr: thousand hours

kW: kilowatt

kWh: kilowatt-hour

LCA: Life Cycle Analysis

LCFS: Low Carbon Fuel Standard

LCOA: Levelized Cost of Ammonia

LCOE: Levelized Cost of Electricity

LCOM: Levelized Cost of Methanol

LCOS: Levelized Cost of Steel

LDV: Light-duty Vehicle

LHV: Lower Heating Value

LNG: Liquefied Natural Gas

LOHC: Liquid Organic Hydrogen Carrier

LPO: Loan Programs Office

LTE: Low-Temperature Electrolysis

m^3: cubic meter

MDV: Medium-duty Vehicle

MeOH: Methanol

MITEI: Massachusetts Institute of Technology Energy Initiative

MJ: Megajoule

MM: Million

MMBtu: Million British Thermal Units

MP: Management Plan

MRV: Measurement, Reporting, and Verification

Mt: Megaton

MW: Megawatt

MWh: Megawatt-hour

NAICS: North American Industry Classification System

NDC: Nationally Determined Contribution

NE: Nuclear Energy Office

NETL: National Energy Technology Laboratory

NG: Natural Gas

NGCC: Natural Gas Combined Cycle

NH_3: Ammonia

NISAC: National Infrastructure Simulation and Analysis Center

Nm^3: Normal cubic meter

NOI: Notice of Intent

NO_x: Nitrogen Oxide

NREL: National Renewable Energy Laboratory

NSRDB: National Solar Radiation Database

O&M: Operations and Maintenance

O/O: Owner/Operator

O_2: Oxygen

OCED: Office of Clean Energy Demonstrations

OPEX: Operational Expenditure

OTT: Office of Technology Transitions

PADD: Petroleum Administration for Defense Districts

PE: Polyethylene

PEM: Polymer Electrolyte Membrane

PGM: Platinum Group Metals

PHMSA: Pipeline and Hazardous Materials Safety Administration

PM: Particulate Matter

PNNL: Pacific Northwest National Laboratory

PPP: Public-Private Partnership

PTC: Production Tax Credit

PV: Photovoltaic

RD&D: Research, Development, and Demonstration

RDD&D: Research, Development, Demonstration, and Deployment

REC: Renewable Energy Certificate

RFI: Request for Information

RMP: Risk Management Plan

S&P: Standard and Poor's

SAF: Sustainable Aviation Fuel

SBIR: Small Business Innovation Research

SC: Office of Science

SESAME: Sustainable Energy System Analysis Modelling Environment

SI: International System of Units

SMR: Steam Methane Reforming

SPR: Strategic Petroleum Reserve

STB: Surface Transportation Board

STTR: Small Business Technology Transfer

t CO_2: metric ton of CO_2

TC: Tax Credit

TCEQ: Texas Commission on Environmental Quality

TEA: Techno-Economic Analysis

TMF: Technology Modernization Fund

TPC: Total Project Cost

TPWD: Texas Parks and Wildlife Department

TRL: Technology Readiness Level

TSA: Transportation Security Administration

UESC: Utility Energy Service Contracts

UKRI: U.K. Research and Innovation

USD: U.S. Dollars

USPS: United States Postal Service

USMCA: U.S.-Mexico-Canada Agreement

USPTO: U.S. Patents and Trademarks Office

V&V: Verification and Validation

VA: Veteran Affairs

VLCC: Very Large Crude Carrier

WIND: Wind Integration National Dataset

WRI: World Resources Institute

WSF: Water Scarcity Footprint

ZEPHYR: Zero-emissions Electricity System Planning with Hourly Operational Resolution

ZEV: Zero-emission Vehicle

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EXECUTIVE SUMMARY

This decade will define U.S. options for reaching net-zero greenhouse gas (GHG) emissions by midcentury. While the science shows that meeting net-zero emissions economywide by 2050 is critical for avoiding the worst impacts of climate change, boundary conditions of the energy sector make it historically slow to change.[1] It is a highly capitalized, commodity business with robust supply chains, established customer bases, and provides essential services to all levels of society. The timetable for developing and deploying new business models, technologies, and policies means that an immediate nationwide commitment is required. To significantly bend the emissions curve over the next decade, it is necessary to shift to new energy systems, while also rapidly decarbonizing the existing infrastructures.

Hydrogen offers the energy system unique versatility, flexibility, and scalability to rapidly decarbonize existing infrastructure and transition to new clean energy pathways at scale. Hydrogen is a versatile clean energy carrier that can be produced and consumed in sectors and sub-sectors across most regions of the country. There are technical challenges related to its production efficiency, its very low energy density by volume, and its dependence on enabling infrastructure (e.g., carbon dioxide [CO_2] and electricity) that must be considered. However, hydrogen presents large opportunities for the energy sector. It can be used to decarbonize the existing infrastructure and capital stock while also providing breakthrough potential as the backbone of a future clean energy economy. Hydrogen can be used to address emissions in difficult-to-decarbonize sectors, while offering a relatively smooth transition for the U.S. industrial workforce. It complements other clean energy technologies, such as wind and solar, and can be used directly as a fuel or as a feedstock. Finally, hydrogen supports investor scalability, enabling a broad range of incumbents and new players—both small and large—to move quickly up the learning and deployment curve.

> **To significantly bend the emissions curve over the next decade, it is necessary to shift to new energy systems, while also rapidly decarbonizing the existing infrastructures.**

There is unprecedented policy momentum for clean hydrogen in the United States. In April 2021, President Biden pledged to reduce GHG emissions by 50 percent by 2030 from a 2005 baseline and achieve net-zero emissions by midcentury.[2] The $1 trillion Infrastructure Investment and Jobs Act (IIJA), also known as the Bipartisan Infrastructure Law (BIL), and the Inflation Reduction Act (IRA) create new incentives for transitioning the economy to net-zero emissions—with significant opportunities to build the clean hydrogen economy. The IIJA provides $1 billion (B) for clean electrolysis research and development (R&D) and $8B for regional clean hydrogen hubs, and the IRA offers new tax credits for clean hydrogen production and incentives for

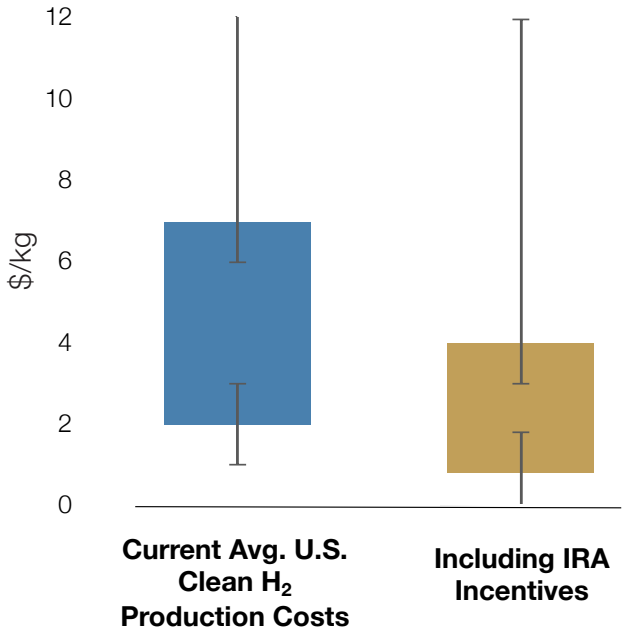
new enabling technologies and systems. These policies, combined with 32 countries pledging more than $500B in policy support in recent years, are spurring increased interest in clean hydrogen (Appendix C). A fundamental next step will be to harmonize the definitions of "clean hydrogen" across policies, which currently vary in terms of scope and magnitude. In September 2022, the U.S. Department of Energy (DOE) issued guidance to support this harmonization.[a]

The IRA incentives can significantly lower the cost of clean hydrogen production. The IRA's new clean hydrogen production tax credit (PTC), also known as 45V, and the expanded 45Q credits ($85/metric ton of carbon dioxide [t CO_2]) for geologic carbon dioxide sequestration, can dramatically lower the costs of eligible clean hydrogen projects. Calculating the cost of clean hydrogen is based on several factors, including technology costs, energy resource costs, and project capacity factors. Modeling performed for this study estimates the average cost of delivered clean hydrogen, based on today's energy cost data for nine different U.S. regions, to be between $2.00-$7.00/kilogram (kg).[b] Regions with abundant renewable energy potential and low-cost CO_2 storage are at the low end of the cost range. Incorporating the IRA incentives, the average cost of production can fall to between $0.80/kg H_2 and $4.00/kg H_2, though specific project configurations, described in Chapter 3, can result in $0.00/kg H_2 (Figure ES1).

The IRA is driving new private sector investment in clean hydrogen. Clean hydrogen accounts for essentially none of the current U.S. hydrogen supply. There has been a major increase in announced clean hydrogen projects over the last two years. As of August 2022, EFI has tracked 374 distinct clean hydrogen project announcements, increasing nearly sevenfold since EFI began tracking projects in June 2021. These announcements include a range of projects, partnerships, and activities across the value chain. A review of the publicly announced projects shows 2.2 million metric tons (megatons [Mt]) of potential clean hydrogen supply, or roughly 21 percent of the current U.S. hydrogen industry's output.

Figure ES1

Estimated Clean H_2 Production Costs with IRA Incentives



IRA incentives: $3/kg green H_2, $0.60/kg blue H_2

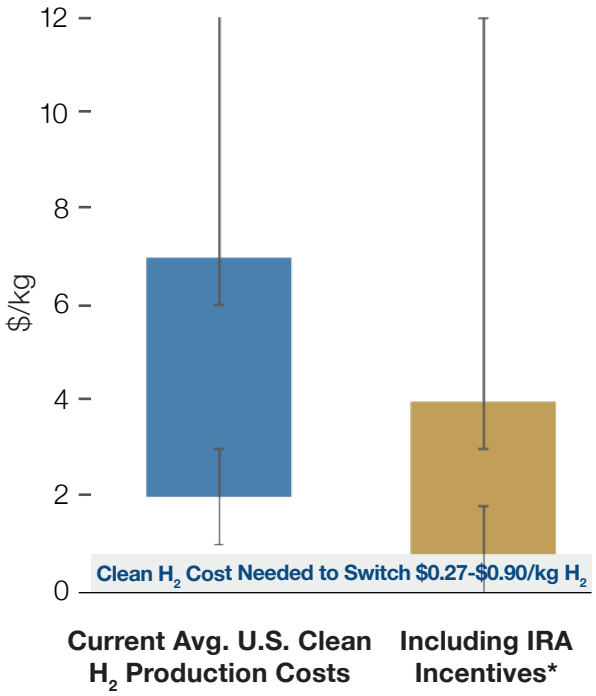
This figure shows the current average range of clean hydrogen production costs (left) and the average range of costs if the tax incentives from the IRA have been applied (right). EFI estimated the cost of clean hydrogen production for nine separate U.S. regions based on regional energy input costs and availability (e.g., for intermittent renewable resources). A supply profile and cost curve was developed for each region assuming 1 megaton (Mt) of hydrogen production. Additional details for this analysis are in Chapter 3.

a In September 2022, DOE issued draft guidance on its Clean Hydrogen Production Standard to solicit industry feedback and guide policy implementation for the IRA and IIJA.

b Sustainable Energy System Analysis Modeling Environment (SESAME) is a simulation and optimization platform developed to accurately estimate life cycle GHG emissions, techno-economic performance, and the feasibility of energy technologies. A central aspect of this scenario analysis framework is the ability to assess key systems interactions and couplings. This framework allows sustainable energy transition options to be compared holistically on the same basis. **https://sesame.mit.edu**

Figure ES2

Average U.S. Clean H_2 Production Costs with IRA and Cost Ranges Needed to Switch for Steelmaking, Refining, and Ammonia and Methanol Production



Steel ($0.90/kg H_2), Ammonia ($0.80/kg H_2), Refining ($0.50/kg H_2), Methanol ($0.27/kg H_2)

*IRA Incentives: $3/kg green H_2, $0.60/kg blue H_2

EFI estimated the cost of clean H_2 production today for nine separate U.S. regions based on regional energy input costs and availability (i.e., for intermittent renewable resources). A supply profile for each region was developed, and the cost was estimated. The impact of the IRA incentives was analyzed based on the regional resources and an estimated life cycle accounting for each pathway. In the gray box, EFI estimated the cost of clean hydrogen needed to reach cost parity with existing sources for select end-users, including refining, ammonia, methanol, and steel. Some of these sectors represent the most "clean hydrogen- ready" based on their current use of hydrogen.

However, recent federal incentives may not create adequate demand to drive national hydrogen market formation; additional policy and regulatory actions are needed. Building new sources of demand is critical for creating a national clean hydrogen network. In its Regional Clean Hydrogen Hubs (H2Hubs) program Funding Opportunity Announcement (FOA), DOE finds that lowering the cost of producing clean hydrogen will help enable demand. This *Action Plan* study estimates there will be a cost gap between the supply-side incentives of the IRA and the conditions needed to kickstart demand for most commercial use cases. A detailed techno-economic analysis of potential end-use sectors on the low end of the cost curve (i.e., steelmaking, refining, ammonia, methanol) shows that clean hydrogen costs may be competitive in the $0.27-$0.90 range, using an assumption that these industries will seek to avoid passing additional costs to their customers (Figure ES2). For most potential sources of new demand, this cost range may not sufficiently de-risk the switch to clean hydrogen, which requires competitive costs with incumbent and alternative technologies, familiarity with and certainty of the technology, as well as durable policy support. Chapter 2 describes the analysis in detail.

Developing new policies and programs that leverage regional hydrogen hubs as engines for market formation is the most efficient way to create demand and build the national hydrogen network. Regional hubs help market players rapidly scale, while jointly managing risk, pooling resources, and coordinating closely on development strategies. Hubs help integrate a broad constellation of projects and activities that comprise the hydrogen value chain, providing organizing principles and structure around which stakeholders can collectively leverage the broad climate policy support of the IRA. Unlocking the full potential of these regional hub demonstrations can help expand these projects into broader regional networks. Doing so leverages the public-private partnership ecosystem to address many of hydrogen's greatest challenges: durable policy support; regulatory frameworks for project siting and permitting; sharing best practices between regional hubs; and efficiently coordinating the building of enabling infrastructures, including new electricity, natural gas, CO_2, and bioenergy.

Hydrogen Demand Action Plan Overview

The *U.S. Hydrogen Demand Action Plan* recommends new policies and industrial strategies for rapidly accelerating hydrogen use across a range of regions and sectors, focusing on leveraging regional hubs as growth engines (Figure ES3). This study estimates there will be a cost gap between the supply-side incentives of the IRA and the conditions required to accelerate demand in most commercial use cases, needed for market formation. Additional policy measures that target **hydrogen-ready applications** in **difficult to decarbonize sectors** can effectively use hydrogen's unique attributes, while reinvesting in America's workforce, and rapidly driving U.S. market formation.

> **This Action Plan study estimates there will be a cost gap between the supply-side incentives of the IRA and the conditions needed to kickstart demand for most commercial use cases.**

The *Action Plan* begins with new analysis of the *U.S. Clean Hydrogen Landscape* (Chapter 1), profiling emerging technologies and business models. It introduces the *Hydrogen Transition Framework* (HyTF), a new EFI analytical tool designed to help policy makers and project developers consider a broad range of market-enabling conditions at the regional level. Chapter 2 includes *Pathways for Accelerating Clean Hydrogen Demand*, with analysis of the IRA incentives and their potential impact on delivered clean hydrogen costs by region and technology. It also assesses industries with near-term hydrogen demand potential, with recommendations for encouraging their switch to clean hydrogen. Chapter 3 offers *Industrial Strategies for Hydrogen Market Formation* with recommendations for hydrogen hub stakeholders that promote scalable market development, based on tested economic frameworks for creating industrial activity.

The *Action Plan* is informed by multiple research activities, including a study of U.S. hydrogen investments, three workshops with regional hydrogen hub stakeholders, and hundreds of interviews with thought leaders in industry, government, and academia. In September 2021, EFI published *The Future of Clean Hydrogen in the United States: Views from Industry, Market Innovators, and Investors*, based on 72 interviews across the current and emerging hydrogen value chain to better understand what is driving investment decisions and what is needed to activate more investment.[3] Between July 2021 and June 2022, EFI convened public and private sector players from three U.S. regions to discuss their clean hydrogen activities and what they see as necessary ingredients and next steps for hydrogen market development. These regions included the Ohio River Valley, the Carolinas and surrounding regions, and the U.S. Gulf Coast.[4,5,6]

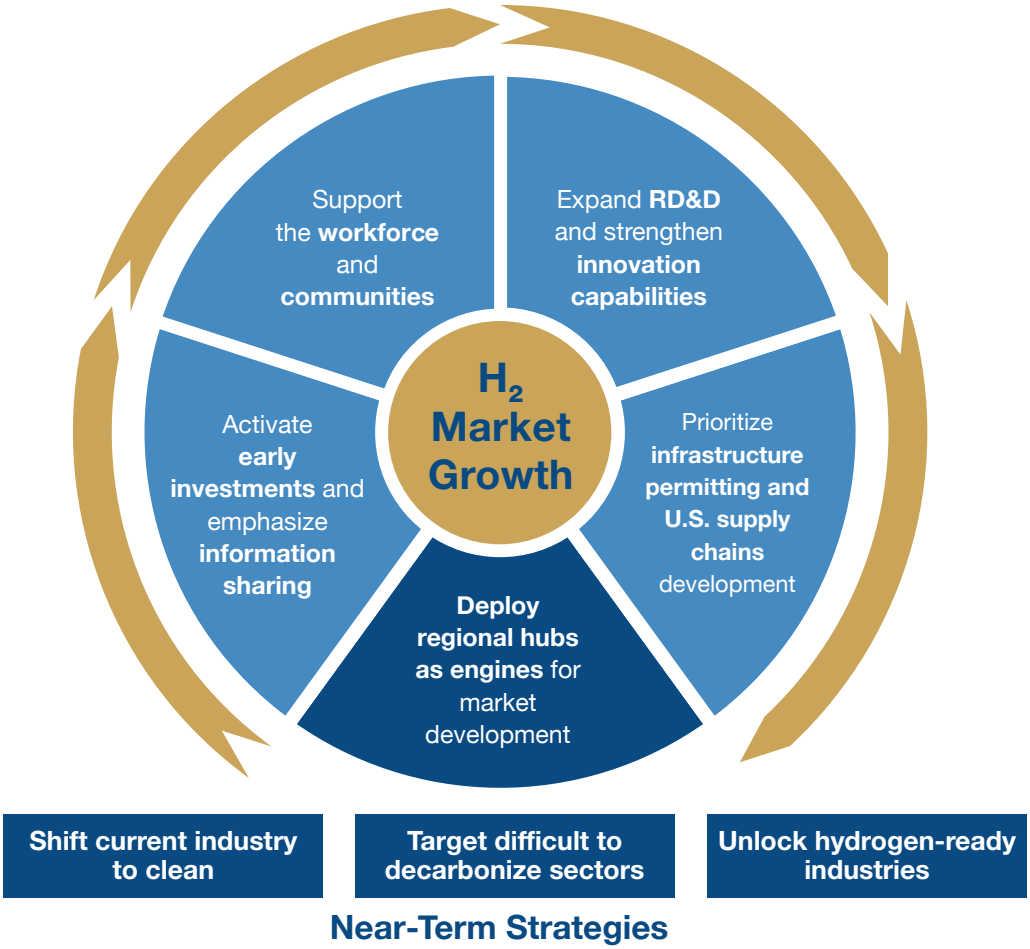
1. Deploy regional hubs as engines for market development

This study finds regional hubs can move investors effectively up the learning curve by encouraging testing multiple market applications. Regional hubs are one of the best methods for rapidly scaling demand, as they can allow multiple industries to coordinate closely, creating greater investment certainty for both producers and consumers. To ensure that regional hubs effectively engage a diverse group of offtakers, further de-risking clean hydrogen production projects, this study recommends that:

a. **Congress should significantly increase the funding for DOE's H2Hubs program** for additional hydrogen clusters throughout the

Figure ES3

Action Plan for U.S. Clean Hydrogen Market Formation

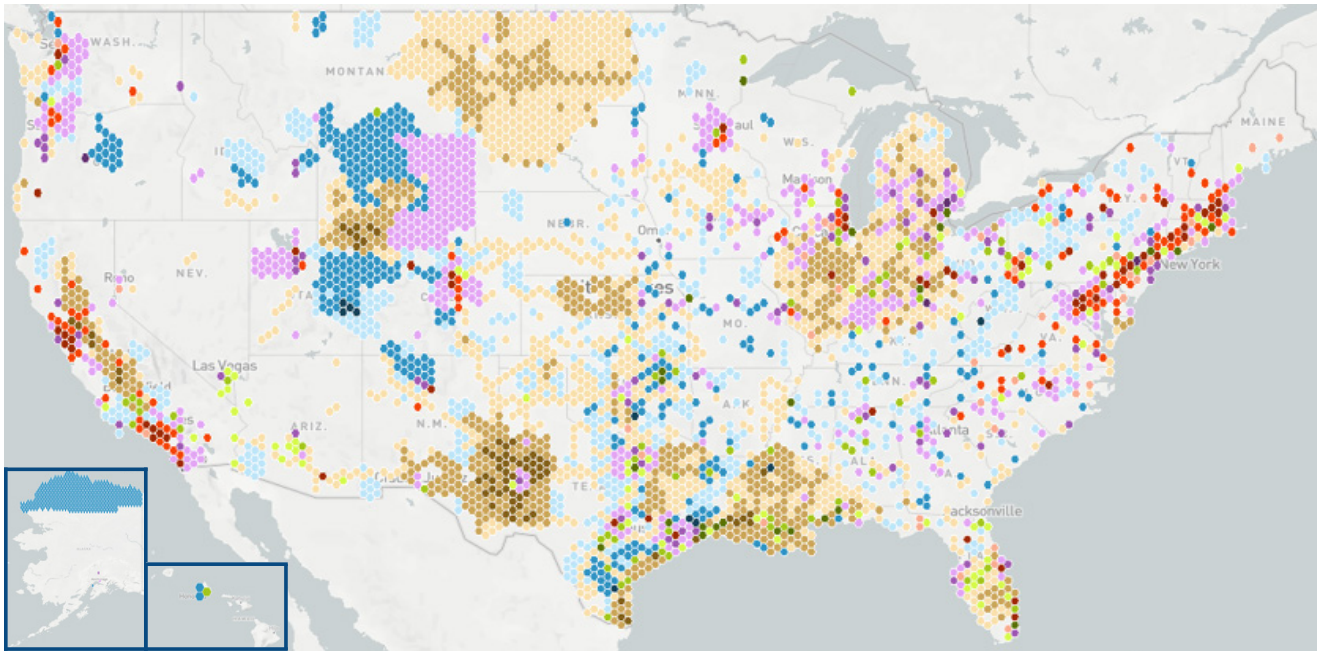


EFI's Action Plan for U.S. Clean Hydrogen Market Formation recommends using hubs as the foundation to stimulate clean hydrogen demand in the current hydrogen industry, difficult-to-decarbonize sectors, and hydrogen-ready industries. This Action Plan also highlights the five main objectives for market formation that clean hydrogen hubs can encourage through the development of Governance, Business, Infrastructure Development, Community and Workforce, and Innovation Design Plans that would have reinforcing benefits across the value chain.

country, focusing on projects that enable regional network expansion and building on the first wave of activities. DOE envisions enabling six to ten regional hubs. Already, DOE's H2Hubs program has given the go-ahead to 33 regional concept proposals to proceed to the FOA's full application.[7] EFI's analysis of clean hydrogen project announcements found nearly 400 distinct projects nationwide that could join a hub (Appendix B). EFI's HyTF, described in Chapter 1, also shows there is untapped hydrogen market development potential in most regions of the United States (Figure ES4) and increasing the support of the H2Hubs program—one of the only active programs targeting demand-side market activators—can accelerate the pace of market development.

b. **DOE and the H2Hubs should create robust information-sharing requirements for all hubs to access data and lessons learned on project financing and economics, operations and safety, and other performance measures.** A risk of the regional hub program is that each activity is isolated from others, limiting sharing lessons learned from business, technical, and operational activities. DOE should also take

Figure ES4
EFI's Hydrogen Transition Framework (HyTF)



Existing Resources	Enabling Resources	Demand	Interest	Capabilities
Good	Good	Good	Good	Good
Very good	Very good	Very good	Very good	Very good
Excellent	Excellent	Excellent	Excellent	Excellent

HyTF profiles the U.S. capabilities, resources, demand, and interests in clean hydrogen. Over 11,000 hexagonal areas (each 400 square miles) are evaluated by strength of each category; the strongest hexes for a given category are described on an interactive map via a dropdown box. The tool (not previewed here) also shows overlap of categories; areas with multiple categories are viewed as important indicators of potential viable hydrogen hubs.

an active role in sharing relevant insights with key regional actors, such as utility regulators and labor unions, to understand the opportunities and challenges as these stakeholders make decisions on local projects. Finally, each hub should ensure that its monitoring and reporting systems address other shared challenges of hydrogen market formation, namely, the impact of new hydrogen projects on water stress and gas-system leakage, and opportunities for advanced hydrogen storage methods.

c. **The Governance Plan for each regional hub should clearly define the relationship rules for hub participants and establish processes for new entrants,** informing industry's next steps for regional expansion. Building on the FOA's requirement for a Management Plan, the Governance Plan should coordinate activities across various hub projects, ensure requirements are met, and align near-term activities with the IIJA's project objectives to expand the national hydrogen network. Regional expansion will depend on clear rules for hub entry and exit, cost and revenue sharing, and ownership structures.

2. Activate early investments for market-ready applications

Historically, hydrogen has not been a notable share of U.S. federal energy research and development (R&D), and the recent policy focus on demonstration

and deployment may not build a long-term bridge over the technology "valley of death." Hydrogen R&D accounted for only 2.0 to 3.7 percent of total energy R&D over the last decade. While the new IRA incentives should lower clean hydrogen production costs, additional measures will likely be needed to ensure new projects are built. To promote early mover technologies and projects, supporting near-term market development, this study recommends that:

a. **The U.S. Internal Revenue Service (IRS) should develop a pragmatic, and timely, phased approach to issuing 45V guidance.** In November, the IRS requested comments from the public on the 45V credit implementation.[8] It will be important to the effectiveness of 45V that clear guidance is provided in a timely manner on key issues, including the scope of and process for managing the measurement, reporting and verification (MRV) of a project's life cycle emissions. Converging on these definitions can take time. A pragmatic approach can satisfy the IRA's objective to spur the development of clean hydrogen production, while also ensuring that early-mover projects receive the support they need to move the industry up the learning curve. The IRS should consider a phased approach to providing guidance that enables investors to start the project development process in the near term, but that also maintains flexibility to adjust requirements over time. Such an approach may require grandfathering in the early movers to the more stringent policies. For example, the IRS could initially require annual estimates of life cycle emissions—allowing producers to combine multiple energy input types—and phase to daily or hourly data over time. This approach could help multiple types of hydrogen producers (e.g., blue and green). Note that the estimated emissions from electricity used by an average blue hydrogen project is more than 25 percent of the project's total life cycle emissions.[9] Moreover, the IRS could also initially allow for the use of carbon offsets to help projects meet the life cycle emissions requirement with clear expectations that these will be phased out in future years.

b. **The federal government should develop and implement hydrogen procurement opportunities to help achieve its own decarbonization goals and provide a game-changing platform for new demand across regions of the United States.** In addition to economywide targets, President Biden has committed the U.S. to achieving net-zero federal operations by 2050. The federal government's emissions align with hydrogen use cases: 60 percent from on-site fuel use at facilities, 30 percent from transportation, two percent from industrial use and processes, and the remainder from fugitive emissions. By developing a federal commitment to fuel switching for up to 10 percent clean hydrogen, the government can reduce its annual emissions by over 1 Mt. This commitment could start as a hub project and expand into contract requirements (e.g., Utility Energy Service Contracts). Regions that can partner with a large federal facility (e.g., DOE lab, military base, etc.) may offer near-term opportunities. Another early mover opportunity could be a DOE-Department of Homeland Security Coast Guard project that demonstrates hydrogen fueling with associated port facility infrastructure.

c. **The Business Plan for each regional hub should include provisions to coordinate cost management, employ financing strategies, and facilitate the hub's growth over the longer term.** In addition to the FOA's recommended Financing Plan, the Business Plan should be forward looking, and clearly define how the new IRA incentives will be leveraged, including their expected impact on the project economics. It should also consider ways to use additional financing resources to support regional expansion.

3. Prioritize local/regional workforce development and community benefits

The transition to net-zero emissions will depend on an unprecedented transition of the U.S. workforce and strong alignment of projects with frontline and environmental justice communities. Developing clean hydrogen industries can leverage the skills and expertise of workers in vulnerable industries and regions during the clean energy transition. As described in Chapter 3, roughly 45 percent of the workforce in industries that are most at-risk during the clean energy transition are well suited for jobs in clean hydrogen. Meanwhile, environmental justice and frontline communities may be hesitant, and, in some cases, against the transition to clean hydrogen. To ensure the H2Hubs program creates efficient and effective collaboration between project developers and community and workforce groups, this study recommends that:

a. **Each hydrogen hub should establish a goal for improving the overall quality of life for frontline communities.** Regional hydrogen hubs can drive positive economic change in any community. They can create new jobs and platforms for engagement, while driving down the system-wide cost of regional decarbonization. Each regional hub should work with its local community to define ways they can support these stakeholders beyond decarbonization, including other energy cost, resilience, and economic needs.

b. **Regional hubs should incorporate and prioritize local economic and environmental safety in project selection and performance criteria.** While it is implied by DOE's FOA, regional hubs should explicitly dedicate resources to align safety requirements with frontline community needs—groups that are most impacted by safety and performance failures. This strategy is critical during the transition of localized hubs to broader regional markets. Regional hubs must demonstrate strong monitoring, coordination, and intervention to eliminate local air quality issues, such as the release of nitrogen oxide (NO_x).

c. **The Community and Workforce plan for each regional hub should enable local stakeholders to participate in standing engagements to maximize the opportunities for clear lines of communication.** It is important that labor and community groups are integrated from the start of the hub development process, as these groups are often under-resourced and will need support from project developers to convene and engage.

4. Expand R&D and strengthen innovation capabilities

As noted, hydrogen has not been a significant focus of federal U.S. energy and climate policy in the past. While some federal and state policies on hydrogen exist, their impact on clean hydrogen development has been minimal—there is essentially no clean hydrogen production today, except for a handful of small-scale pilot projects. Regional clean hydrogen hubs can demonstrate new technologies, policies, and business models, generating a wealth of knowledge on the cost, performance, and management of clean hydrogen projects. As such, this study recommends ways hubs can drive new research priorities for clean hydrogen and broader market formation:

a. **Congress, DOE, and the national laboratories should continue to develop cross-functional centers of innovation, focused on decarbonizing industrial clusters.** These centers should focus on industrial hydrogen clusters, systems integration analysis, understanding the technology and operational bottlenecks, and identifying opportunities to improve the current approaches. Because these facilities will take a longer-term view, they may complement recent policies, such as the IIJA's nearly $6B for industrial decarbonization demonstration and deployment projects.[10] The topics of investigation could include hydrogen safety, including solutions for advanced measurement, reporting, and verification of leaks from pipelines, projects, and throughout regional hubs. Developing advanced MRV also supports the U.S. Environmental Protection Agency's (EPA) proposed enhanced methane reduction efforts, aimed at lowering gas sector emissions by around 68 Mt per year.[11] A related topic for cross-functional analysis is technology and process solutions for controlling NO_x emissions during hydrogen combustion. These activities, for clean hydrogen, as well as other pathways, are likely to grow in importance due to their "economy of effort," where the economics of project studies, permitting, and construction can be more favorable due to co-location of facilities.[12]

b. **DOE should pursue new collaborations between U.S. and international clean hydrogen hubs,** to partner on sharing data related to hub development, operations, financing, and community impacts. Regional clean hydrogen hubs in Europe and Asia, for example, have experience demonstrating clean hydrogen projects across the value chain for over a year in some cases. These efforts could build on the H2 Twin Cities framework—a Clean Energy Ministerial initiative—which consists of self-started international hydrogen partnerships.[13] International engagements and collaborations that share lessons between these efforts could rapidly support U.S. regional hubs and other project development in different regions and create future opportunities for global hydrogen trade. The United States could also develop an international hub in collaboration with Canada, given Canada's federal clean hydrogen funding and targets (Appendix C), through the U.S.-Mexico-Canada Agreement (USMCA) free trade policy.

c. **Each regional hub should develop an Innovation Plan to ensure that technology turnover is managed and there are opportunities to share valuable lessons learned between regional hubs.** A key objective of the H2Hubs program is to move companies and regions up the clean hydrogen learning curve. This move will involve a process of learning between regional hubs and opportunities to pivot based on technical and operational feedback. DOE may consider using part of the H2Hub funds (e.g., the $1B to $2B in reserve) to support these activities.

5. Prioritize infratructure permitting and U.S. supply chains development

The United States maintains a relatively large hydrogen infrastructure, but new production facilities, delivery systems, and end use equipment will be needed to support regional clean hydrogen hubs. Building these hubs involves much complexity, as many will require other enabling infrastructures that face their own investment issues. Clean hydrogen systems are enabled by electricity and/or CO_2 infrastructure with their own siting, permitting, and operational challenges. This study recommends policies and strategies to enable near- and long-term clean hydrogen project builds:

a. **The Administration should work with Congress to develop a public-private partnership model for CO_2 storage management,** to avoid costly project uncertainty related to blue hydrogen, as well as other decarbonization technologies (e.g., direct air capture) that depend on CO_2 sequestration. CO_2 storage is a critical pathway for reaching economywide net-zero emissions. This partnership could establish a liability scheme for CO_2 storage, as detailed in EFI's report *CO2-Secure: A National Program to Deploy Carbon Removal at Gigaton Scale*, which is a critical pathway for reaching economywide net-zero emissions.[14] Blue hydrogen is one of the most scalable clean hydrogen production methods in the United States—due to the country's large endowment of low-cost natural gas and abundant geologic storage resources. Blue hydrogen's potential is being limited by a highly inefficient domestic CO_2 management regime.

b. **The Federal Energy Regulatory Commission (FERC) should begin the process of regulating the blending of hydrogen into interstate natural gas pipelines, an important step for hydrogen demonstrations that aligns with FERC authority.** FERC's mission includes establishing the rules and regulations for main components of electricity and natural gas markets. In the past, gas quality standards issues centered on pipeline safety and heat rates—both concerns for blending hydrogen into existing natural gas systems.[15]

c. **Each regional hub's Infrastructure Plan should ensure that permitting, partnerships with upstream energy providers, and frontline community requirements are met.** Hubs can ensure large-scale infrastructure is built in a coordinated way, minimizing the project footprint and overall project complexity. A track record of new infrastructure builds among H2Hubs participants can encourage new investors and market scaling.

d. **Regional hubs should develop a credit trading system** for managing hydrogen production and consumption that can be used to track hydrogen blends, sales within and between hubs, and engagements with non-hub members.

1 THE U.S. CLEAN HYDROGEN LANDSCAPE

Chapter Insights

Recent policy support is the most significant federal investment in hydrogen in U.S. history. The Infrastructure Investment and Jobs Act's (IIJA) $8B for regional clean hydrogen hubs can concurrently enable supply and demand, while the Inflation Reduction Act's (IRA) (e.g., hydrogen production tax credit) can significantly bring down the production cost.

Regional clean hydrogen hubs are ideal platforms for projects to coordinate and leverage IRA incentives. IRA incentives offer greater credit stacking flexibility for green hydrogen compared to other pathways. The IRA seeks to improve bankability through direct pay and third-party credit sales to attract investors.

EFI developed the Hydrogen Transition Framework (HyTF), a database and geographical display of relevant energy, economic, and policy information to inform hydrogen project development, regional hydrogen hubs, and broader network and market formation. HyTF can help investors, researchers, and policy makers make informed decision on how to build out a U.S. hydrogen market.

The United States is one of the world's largest hydrogen producers today. Currently, hydrogen is a niche industry compared to other energy commodities. Current production comes from steam methane reforming (SMR), a cost-effective, yet emissions-intensive process. Average life cycle emissions from SMR are 12 kilograms of carbon dioxide equivalent per kilogram of hydrogen (kg CO_2e/kg H_2) produced.

The definitions of "clean" hydrogen vary by policy. The IIJA defines clean as 2.0 kg CO_2e/kg H_2 at the site of production while the IRA uses less than 4.0 kg CO_2e/kg H_2 for life cycle emissions.

There is essentially no clean hydrogen production or use in the United States today. U.S. hydrogen research and development (R&D) investment has accounted for only 2.3 percent to 3.7 percent of total energy R&D over the last decade. This is important as new policy support is focused on technology demonstration and deployment, though U.S. Department of Energy (DOE) programs are making up lost ground.

EFI identified a nearly sevenfold increase in announced clean hydrogen activities from June 2021 to August 2022. Announced U.S. hydrogen projects represent at least 2.2 megaton (Mt) of clean hydrogen production if developed. Most projects geographically align with heavily industrialized U.S. regions.

Seventy percent of new clean hydrogen projects are relatively small green hydrogen projects (between 120 kilowatts [kW] to 120 megawatts [MW]), though blue hydrogen projects account for 95 percent of the announced expected production capacity. Scaling clean hydrogen depends on building new, enabling infrastructures, including electricity, natural gas, and CO_2 and H_2 storage facilities.

Globally, governments have committed around $450B in clean hydrogen funding, focusing heavily on geographic hub clusters. There are now clean hydrogen strategies being developed across nearly 40 countries, representing 65 million Mt of new clean hydrogen production, compared to 90 Mt from gray hydrogen today.

The science shows that reaching global net-zero emissions by 2050 is critical to avoiding the most dangerous impacts of climate change.[16] Reaching net-zero targets will require unprecedented investments and innovative solutions to reduce, and remove, greenhouse gas (GHG) emissions, while still maintaining vital energy services for homes, factories, and businesses across the country and world. Due to the relatively slow pace of technological change, the next decade will likely define U.S. options for reaching net-zero GHG emissions by midcentury. Clean hydrogen offers a unique pathway to economywide emissions reductions. It can be used by multiple sectors of the economy, including some of the most difficult to abate sectors and processes, decarbonizing the existing system and shaping the transition to an entirely new energy economy over the long-term.

> **Reaching global net-zero emissions by 2050 is critical to avoiding the most dangerous impacts of climate change.**

Recent U.S. policies show a nationwide commitment to shifting to new energy sources to put the United States on track to net-zero. In April 2021, President Biden pledged to reduce GHG emissions by 50 percent by 2030, relative to 2005 levels, and achieve net-zero emissions by midcentury.[17] Two major policies followed, the $1 trillion IIJA, also known as the Bipartisan Infrastructure Law (BIL), and the IRA. The IIJA provides $1 billion (B) for electrolysis research and development (R&D) and $8B for regional clean hydrogen hubs, while the IRA offers new tax credits for clean hydrogen production and a range of incentives across the hydrogen value chain. These policies, combined with 32 countries pledging more than $500B in policy support in recent years, are spurring notable interest in clean hydrogen. More details on these hydrogen trends are presented in Appendix B.

Why Hydrogen?

Periodically over the last half century, public- and private-sector leaders have considered the potential of hydrogen as an energy carrier, particularly for transportation and power systems. Interest in hydrogen typically coincided with energy security concerns. During periods of supply constraints in global oil and gas supplies, hydrogen is considered an exploitable domestic energy pathway. Starting in the 2010s, the United States' most recent energy boom eroded energy security concerns, and the interest in hydrogen waned. However, Russia's recent invasion of Ukraine contributed to the latest energy price shocks. The invasion has served as a reminder: hydrocarbons still account for roughly 79 percent of global energy consumption.[18] These renewed energy security concerns, combined with hydrogen's potential role in unlocking economywide deep decarbonization pathways, is creating significant interest in hydrogen across most regions of the world.

Hydrogen offers versatility to the decarbonization portfolio, as it can be produced in many ways, across multiple regions of the country, and many current and potential uses that could contribute to decarbonization exist. Hydrogen also supports investor scalability, enabling a broad range of investments (both small and large) to help firms quickly move up the learning curve. Hydrogen offers energy system flexibility during the transition to low carbon, decarbonizing the existing energy system while also providing breakthrough potential for becoming the backbone of a future energy economy. Hydrogen can be produced at an industrial scale without direct emissions. It is a highly storable resource that can be used directly for heat or chemical processes, or converted to hydrogen-based fuels, such as synthetic methane, ammonia, and methanol. These characteristics can help with rapid technology development and adoption of clean hydrogen compared to some alternatives (Table 1).

Table 1
Primary Applications of Hydrogen

Classification	Use Case	Fossil Fuel Displaced	Competing Clean Technologies
Fuel	**Electricity:** Combusted in turbines to produce electricity **Process Heating:** Used as heat source for high-temperature industrial applications **Transportation:** Used in a fuel cell to produce power for electric vehicles	Natural Gas, Coal, Petroleum	**Electricity:** Renewable Energy **Process Heating:** Direct Electrification **Transportation:** Direct Electrification, Biofuels
Specialty Chemical	**Refining:** Used as a feedstock to lower the sulfur content of fuels **Chemical Processes:** Used to create derivative industrial products and fuels such as ammonia, methanol, liquid organic hydrogen carriers (LOHCs), and synthetic fuels	Natural Gas, Petrochemicals	**Refining:** Synthetic fuels **Chemical Processes:** Biomass-derived Chemicals, Biological Pathways
Energy Storage Medium	**Grid Balancing:** Production of long-term energy storage from clean energy resources **Stationary Power:** Used as energy source for firm power, backup, and/or peaking capacity **Mobility Applications:** Used on and off road as a clean energy carrier for transport, either as hydrogen or other hydrogen carriers (e.g., ammonia, methanol)	Natural Gas, Coal, Petroleum	**Grid Balancing:** Long-Duration Batteries **Stationary Power:** Pumped Hydropower, Biomass, Nuclear **Mobility Applications:** Batteries, Biofuels

Hydrogen can function as a clean energy alternative for traditional fuel applications, chemical processes, and a medium for energy storage. These characteristics have application across the energy sector and can displace primary fossil fuels such as coal, petroleum, and natural gas.

The Current U.S. Hydrogen Industry

Hydrogen has been part of the U.S. economy for more than a century, albeit in limited applications and often with relatively high carbon intensity. Starting in the late 1800s, the early natural gas system delivered manufactured gas containing more than 30 percent hydrogen. The Island of Oahu, Hawaii has used a synthetic natural gas product that contains up to 15 percent hydrogen for decades, carried through a 1,100-mile pipeline network.[19]

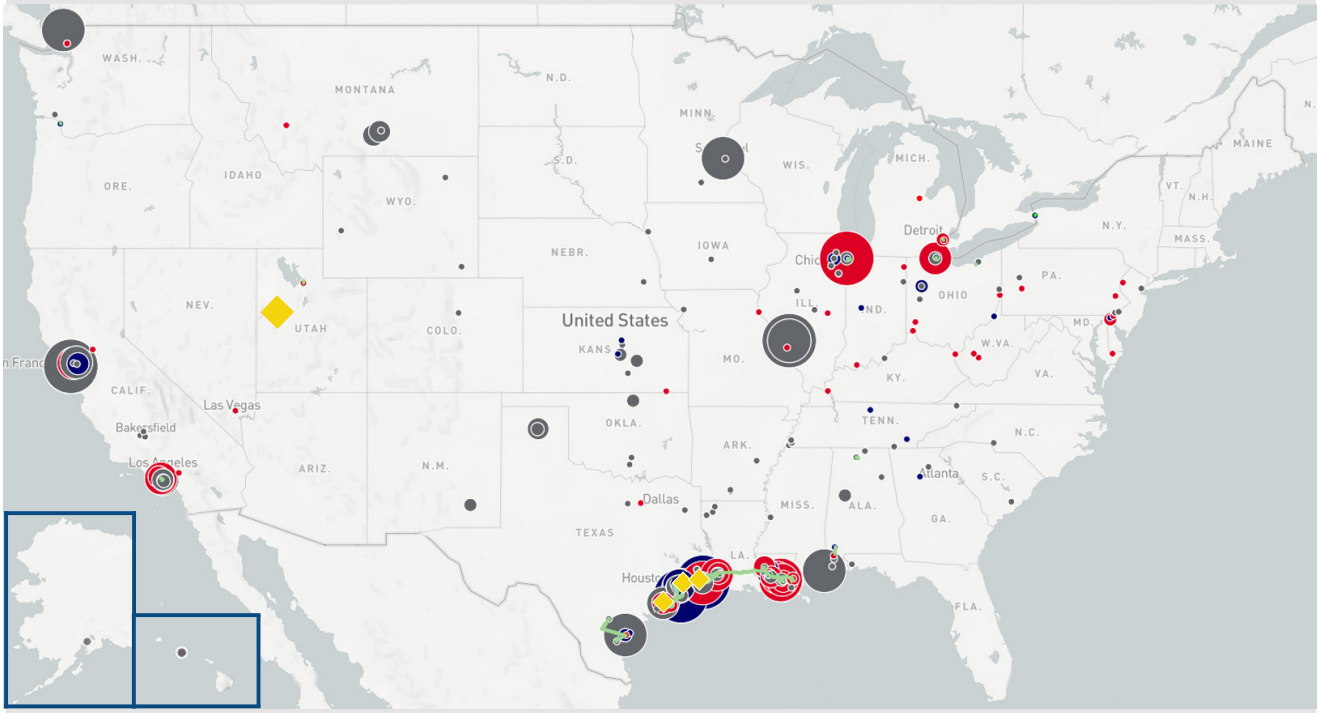
The U.S. maintains a robust hydrogen industry, though it is limited to a few sectors and regions.

In 2021, the United States produced roughly 11.4 million metric tons (Mt)[c] of hydrogen, more than 15 percent of the world's total.[20] This sum equates to roughly 1.30 quadrillion British thermal units (quad) on an energy basis, just over 1 percent of total U.S. energy production in 2021.[21] Another point of reference: the United States produced more than 30 quads of natural gas in 2021, or roughly 35 trillion cubic feet.[22] As of 2021, there were 257 dedicated hydrogen production facilities in the United States (Figure 1). There are 25 hydrogen pipelines in the U.S., collectively spanning approximately 1,600 miles.[23]

c This report uses SI units and prefixes throughout; "tons" (t) refers to metric tons unless otherwise specified. In a few instances figures will use non-SI units, which are noted.

Figure 1
Current U.S. Hydrogen Production by Producer Type

Overall United States



Tons of Hydrogen Capacity per Year

1-30K | 30–60K | 60-100K | 100-150K | 150-200K | >200K

Merchant Hydrogen from SMR | Merchant Byproduct Hydrogen | Captive Production | Hydrogen Underground Storage Facilities | Hydrogen Pipelines

The Los Angeles Area

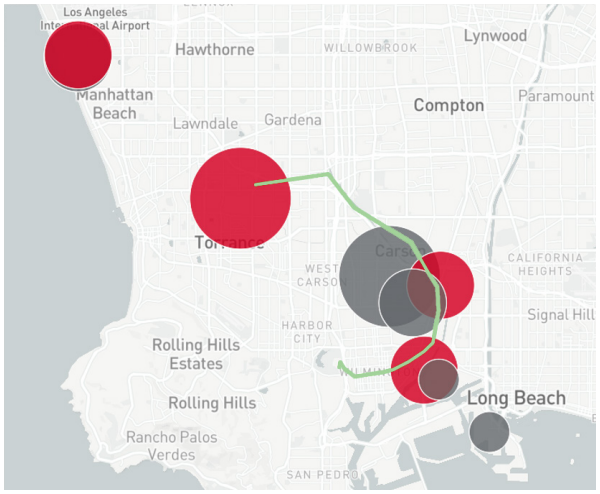
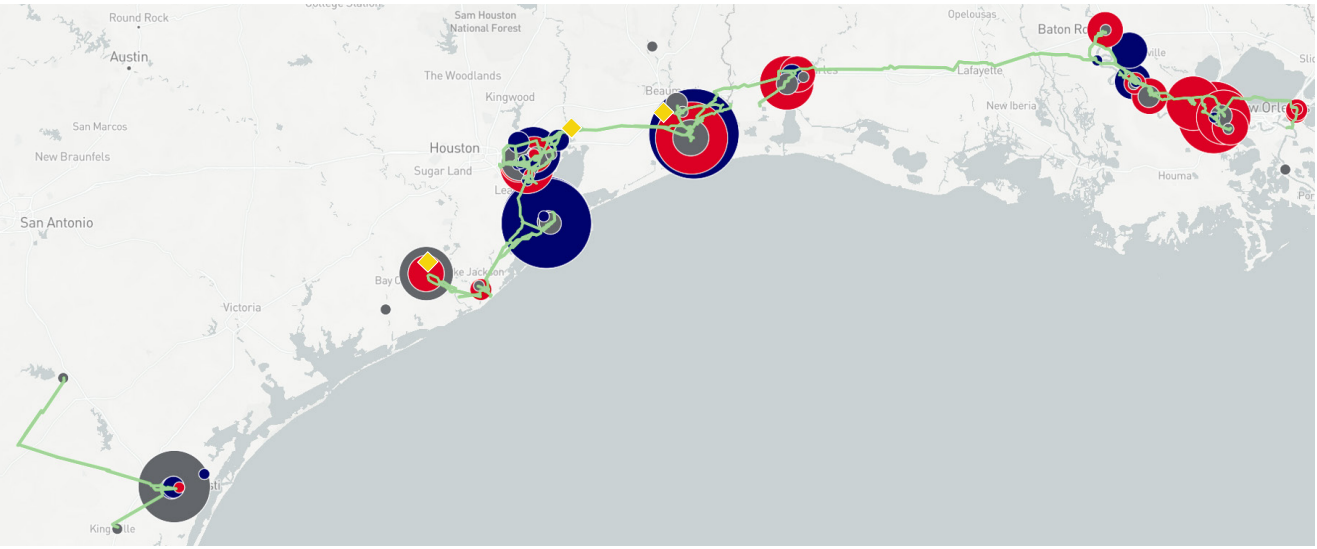
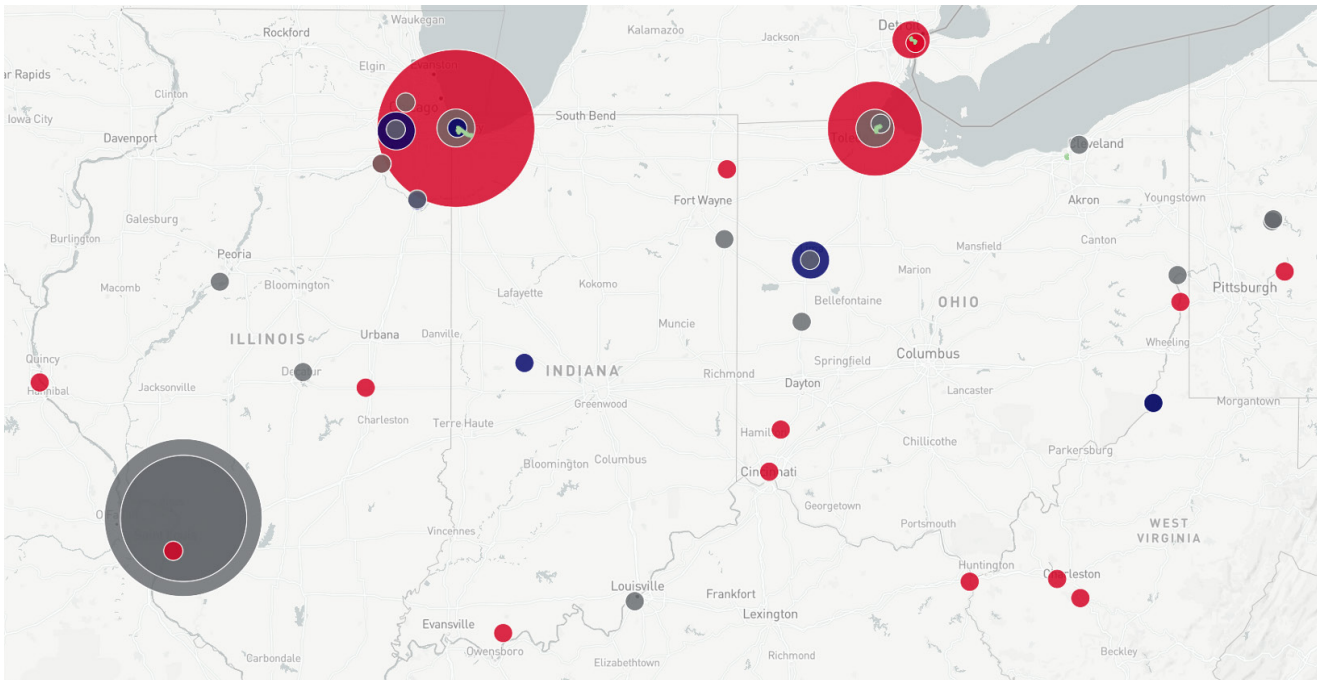


Figure 1 (cont.)

The Texas and Louisiana Gulf



The Industrial Midwest



Existing hydrogen production in the United States is largely located in the Gulf Coast, upper Midwest, and California and comes from captive production, or merchant production via steam methane reformation or as a by-product. The size of the circles represents these facilities' estimated hydrogen production in a year and are mapped alongside existing hydrogen pipelines and underground storage facilities. Data from: EIA, NREL and Nutrien, 2022.

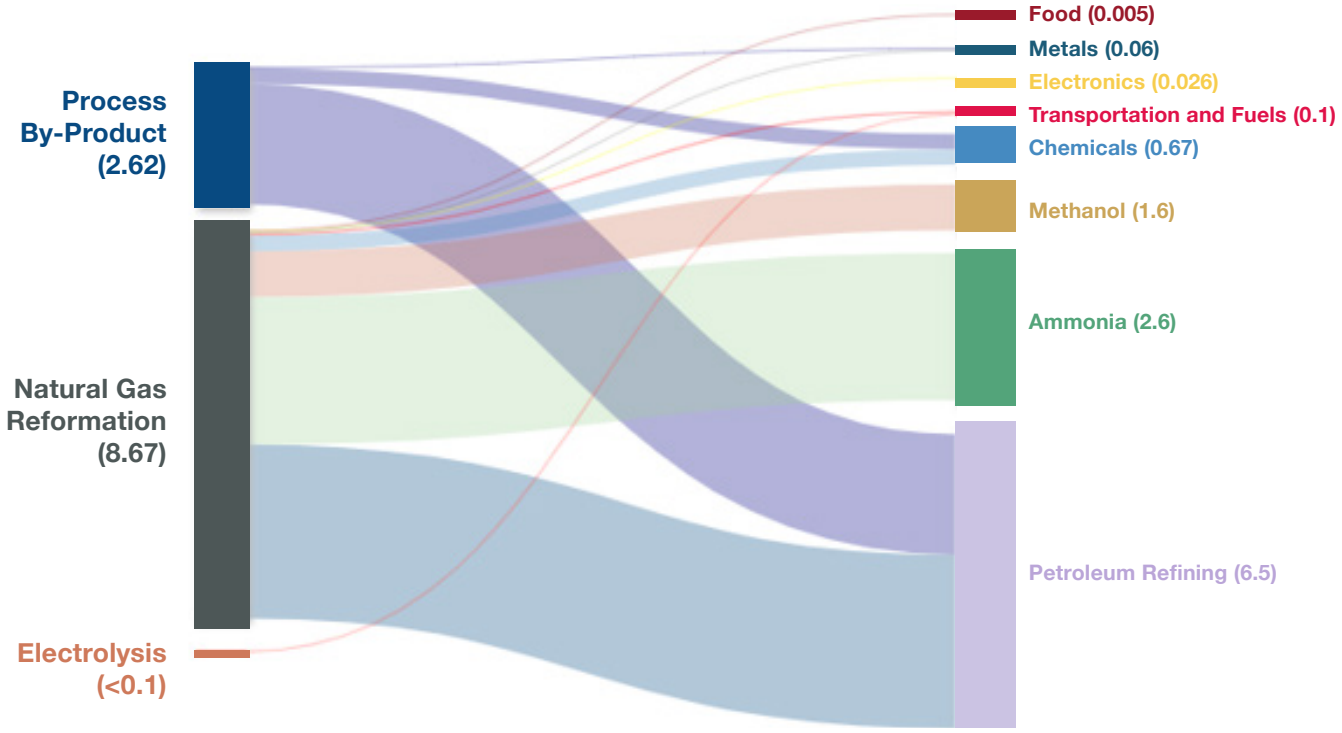
There are four underground hydrogen storage facilities that are in use or development across the United States — three of which are in the U.S. Gulf Coast.[24]

Hydrogen is primarily used today as a chemical feedstock for industrial applications. Most U.S. hydrogen production is via SMR, while around 20 percent is made as a by-product of other industrial facility operations (Figure 2).[25] Roughly half of the current U.S. hydrogen production comes from merchant plants and is sold to consumers through bilateral contracts, delivered by pipeline or truck, while the other half is produced and consumed at integrated facilities by the same entity.[26] For example, many refineries and ammonia production plants employ their own SMRs at their facilities to produce hydrogen for manufacturing final fuel products (see Appendix A for more details).

Ultimately, the formation of a clean hydrogen market will depend on the growth of hydrogen demand. Current U.S. hydrogen demand is highly concentrated in a few sectors and uses, as described in Box 1. For the merchant projects, while the bilateral contract model works effectively today, new models may need to emerge to enable expanded trade to serve growth in different sectors and regions. Also, increasing the number of market players will increase the competitiveness of hydrogen.

Figure 2

Sources of U.S. Hydrogen Supply and Demand Today (Mt) [27, 28, 29, 30]



This diagram showcases the existing sources of hydrogen supply and depicts how proportions of each contribute to existing sources of hydrogen demand. Data from: U.S. EPA, 2022; IHS Markit, 2022; Brown, 2016; FCHEA, 2020.

Box 1

Current U.S. Hydrogen Demand

Refining accounts for about 57 percent of U.S. hydrogen demand, making it the largest hydrogen-consuming industrial subsector.[31] Refineries use hydrogen primarily to remove sulfur from products (i.e., hydrotreating) and in the process of cracking heavy oil into gasoline and other lighter products (i.e., hydrocracking).[32] The amount of hydrogen used by U.S. refineries depends on the types of crude oil being processed, especially the API gravity (i.e., the relative weight of petroleum compared to water), and the types of products being produced. Hydrogen is also often a by-product of the refining process, especially during catalytic reforming, a chemical process that yields high-octane products.[33]

Ammonia production accounts for roughly 20 percent of U.S. hydrogen demand (Figure 2). Ammonia is primarily used for fertilizer production, supporting farming and other agricultural industries. Hydrogen is a primary feedstock for making ammonia; ammonia production facilities can have integrated hydrogen production (Appendix A). In 2021, the U.S. produced 17 Mt of ammonia, requiring 2.7 Mt of hydrogen, across 32 facilities.[34] The largest SMR in the United States is at an ammonia plant. Producing nearly 590,000 t of hydrogen per year, it is twice as large as the next largest hydrogen production facility.

Methanol production accounts for around 10 percent of U.S. hydrogen demand. Methanol is used as a feedstock to produce chemicals and products, such as plastics and fuels. The U.S. methanol industry, located primarily in the U.S. Gulf Coast, supports a relatively stable domestic market and a rapidly growing export market, primarily in Europe and Asia.[35] Similar to ammonia plants, U.S. methanol producers may have integrated SMRs that produce hydrogen. Methanol is produced by reforming natural gas, resulting in a synthetic gas that includes hydrogen, which is then synthesized into methanol.[36] In 2021, nine U.S. facilities made around 10 Mt of methanol and 1.6 Mt of hydrogen.[37] According to U.S. Energy Information Administration (EIA), "methanol plants are among the most natural gas-intensive industrial end users and require natural gas as a feedstock and for process heat."[38]

See Appendix A for more details on the current hydrogen industry.

Clean Hydrogen Trends

DOE issued a draft Clean Hydrogen Production Standard (CHPS) to begin to clarify how these policies align and should be interpreted by prospective investors.[39] According to a comprehensive study by the National Energy Technology Laboratory (NETL), the average life cycle emissions of a gray hydrogen production facility is 12 kg CO_2e/kg H_2 with nearly one-third of the total emissions coming from the upstream processes (Box 2).

The term "clean hydrogen" is often used without specific definition but refers to the carbon intensity of hydrogen, often focused on the emissions at the site of production or the total life cycle emissions.

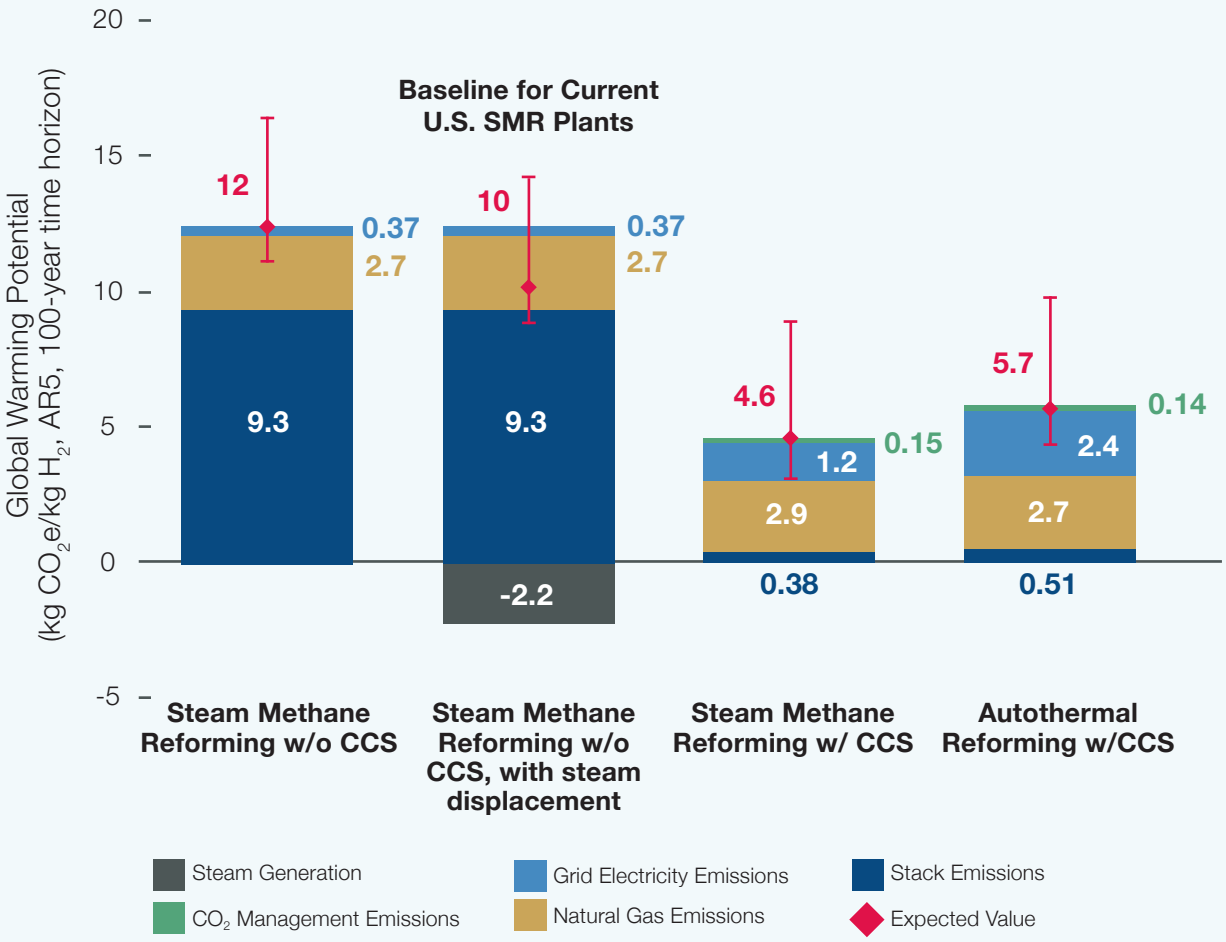
Box 2

Life Cycle Emissions of Current Gray Hydrogen Production

The average life cycle emissions of a current gray hydrogen production facility are 12 kg CO_2e/kg H_2, as shown in Figure 3.[40] Two-thirds of the emissions come from the reformation process. Nearly one-third comes from upstream natural gas emissions, while 3 percent comes from the electricity used to run the facility. The upstream emissions from natural gas and electricity production and delivery are often out of the control of the production facility. According to a 2022 study by NETL, adding carbon capture, with a 96.2 percent capture rate, to an existing SMR results in roughly 1.2 kg CO_2e/kg H_2 at the site of production.[41] However, the life cycle emissions that remain are 4.6 kg CO_2e/kg H_2—outside of the eligibility of the IRA's 45V hydrogen production tax credit (i.e., 4.0 kg CO_2e/kg H_2). Chapter 2 provides analysis of the impact of these policy designs and offers some recommendations to ensure they are driving U.S. clean hydrogen market formation.

Figure 3

Comparison of CO_2e Life Cycle Emissions for Fossil Fuel-Based Hydrogen Production Pathways[42]



The global warming potential of fossil fuel-based hydrogen production pathways is dramatically reduced with the addition of carbon capture and storage (CCS) across all pathways. However, on average these cases are still ineligible for the 45V hydrogen production tax credit because of the life cycle emissions requirements. Source: NETL, 2022.

Definitions are often articulated by specific policies. In the United States, for example, the IIJA set the clean hydrogen production target as 2 kg CO_2e/kg H_2 at the site of production. Meanwhile, the IRA provides production tax credits to projects with less than 4 kg CO_2e/kg H_2 based on life cycle emissions.

This Action Plan will use the term "clean hydrogen" generally unless otherwise noted by a specific policy definition. Appendix B provides greater detail on defining clean hydrogen and how the definition differs globally.

Based on the IIJA and IRA definitions, essentially zero percent of current U.S. hydrogen production would be considered clean.[43, 44] Despite over 4,000 t of annual electrolytic hydrogen production, most electrolyzers run on grid electricity, whose emissions intensity varies depending on power generation's profile.[45, 46] According to the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model, the emissions associated with producing a kilogram of electrolytic hydrogen in the U.S. are anywhere from 13 to 22 kg of GHGs, depending on the penetration of renewables in a region. [47] That amount is well above the IRA's 4 kg threshold.

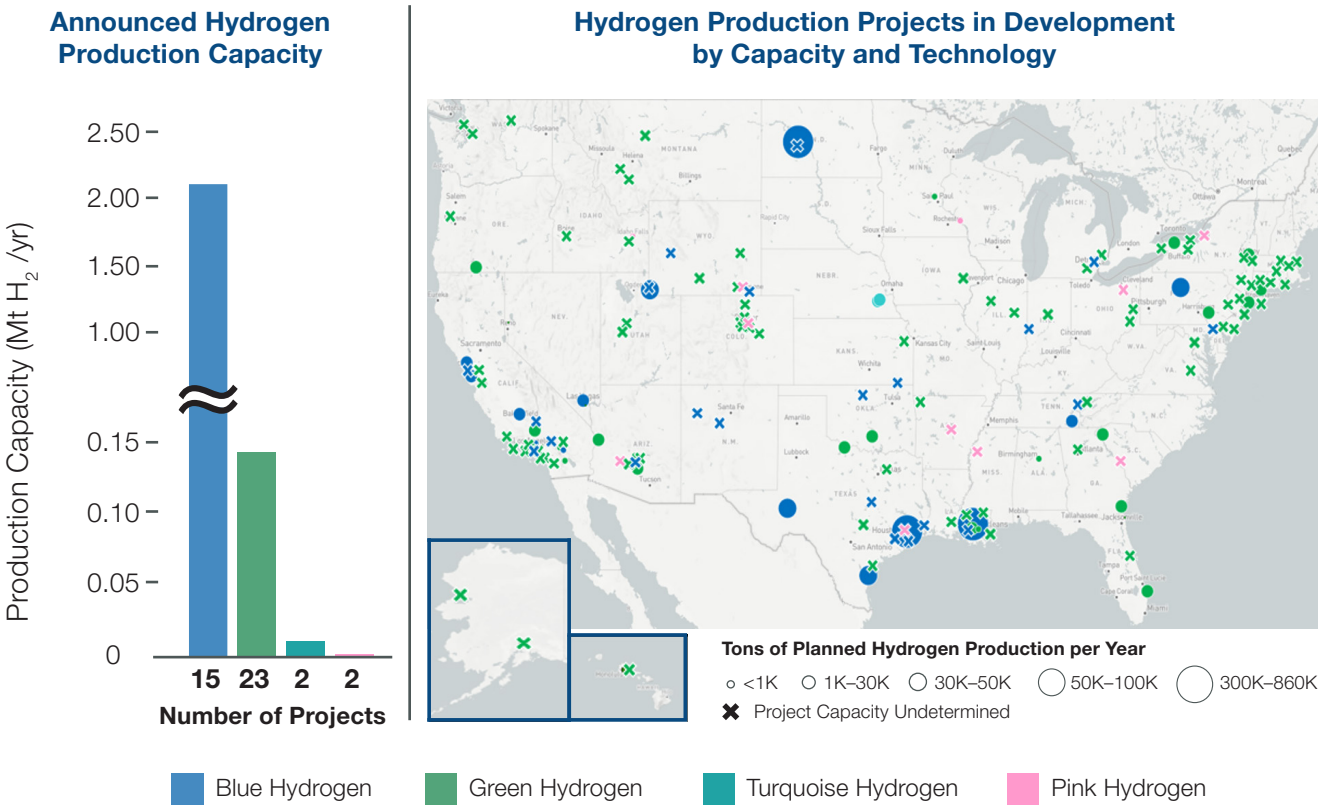
Such relatively low clean hydrogen production amount is driven by many factors. Hydrogen has been a relatively small focus of U.S. energy R&D efforts in the past, accounting for around 3 percent over the last decade (see Appendix B for details on DOE hydrogen R&D funding). However, there is a rapidly growing number of new clean hydrogen project announcements in the United States. As of August 2022, EFI has tracked 374 distinct clean hydrogen project announcements that cover many aspects of the value chain. Notably, since EFI began tracking projects in June 2021, the number of announced projects increased nearly sevenfold, with a major jump following the announcement of the IIJA's $8B regional clean hydrogen hub program. EFI began tracking publicly announced clean hydrogen projects in a previous study, *The Future of Clean Hydrogen in the United States: Views from Industry, Market Innovators, and Investors*, published in September 2021.[48]

A review of the clean hydrogen project announcements shows a strong investor preference for green hydrogen (i.e., produced with renewable energy via electrolysis) over other pathways. Such preference in part seems to be driven by the downward scalability of electrolyzers, giving firms the ability to make relatively small investments. Other technologies, like blue hydrogen are not scalable and require large capital investments (see Appendix A for a description of different hydrogen production pathways). As such, around 70 percent of recently announced projects involve green hydrogen, while only 20 percent are blue hydrogen. Even though this interest in green hydrogen may help with developing electrolysis-based technologies, it may not be immediately effective for scaling regional clean hydrogen markets. Despite representing a relatively small share of the total, blue hydrogen projects account for nearly 95 percent of the capacity of the announced projects (Figure 4).

Furthermore, over 40 percent of the announced clean hydrogen projects are considered R&D projects with no immediate commercial application. This finding supports a conclusion from EFI's *Views from Industry* report that investors today are trying to quickly move up the learning curve of hydrogen, as it is a relatively new technology for many industries. It also tracks recent global hydrogen project developments (Box 3). Meanwhile, roughly 20 percent of announced U.S. clean hydrogen projects are targeting on-road transportation applications, and nearly 20 percent are targeting using clean hydrogen for power generation. These areas of interest are likely due to the project developer's ability to access and test applications, rather than wait for entirely new technologies to become available. The remaining projects involve a broad range of potential end-use cases, including off-road mobility, process heating, pipeline blending, and others.

Figure 4

Announced Clean Hydrogen Project Activities



Over 2.2 Mt per year of clean hydrogen is expected from just 42 of the 177 announced production activities across the country (right). Most hydrogen production projects have not yet declared a capacity, but the scale and scope of certain undeclared projects suggests considerably more hydrogen will be added to the capacity already identified (left).

Box 3

Global Clean Hydrogen Trends

This analysis identified 33 countries with national hydrogen strategies or roadmaps with at least $450B in government funding support. If fully realized, these national strategies would produce roughly 54 Mt of new clean hydrogen supply by 2030 (Appendix C). According to the International Energy Agency (IEA), there are nearly 400 clean hydrogen projects under development globally, most of which are in very early stages of development.

A review of the existing national hydrogen strategies shows extensive focus on incentivizing regional hubs and green hydrogen production. Roughly three-quarters of these strategies include a "green" hydrogen production target and most focus heavily on regional hubs to drive market formation. Many include CO_2 intensity targets, technology production preferences (e.g., "green"), and clean hydrogen production volume targets.[49] The end-use sectors that feature the most in national hydrogen strategies are iron and steel production, chemical feedstock, and medium- and heavy- duty transportation.[50] There are, however, few end-use targets and they are relatively generic, long-term, or lack specific commitments.

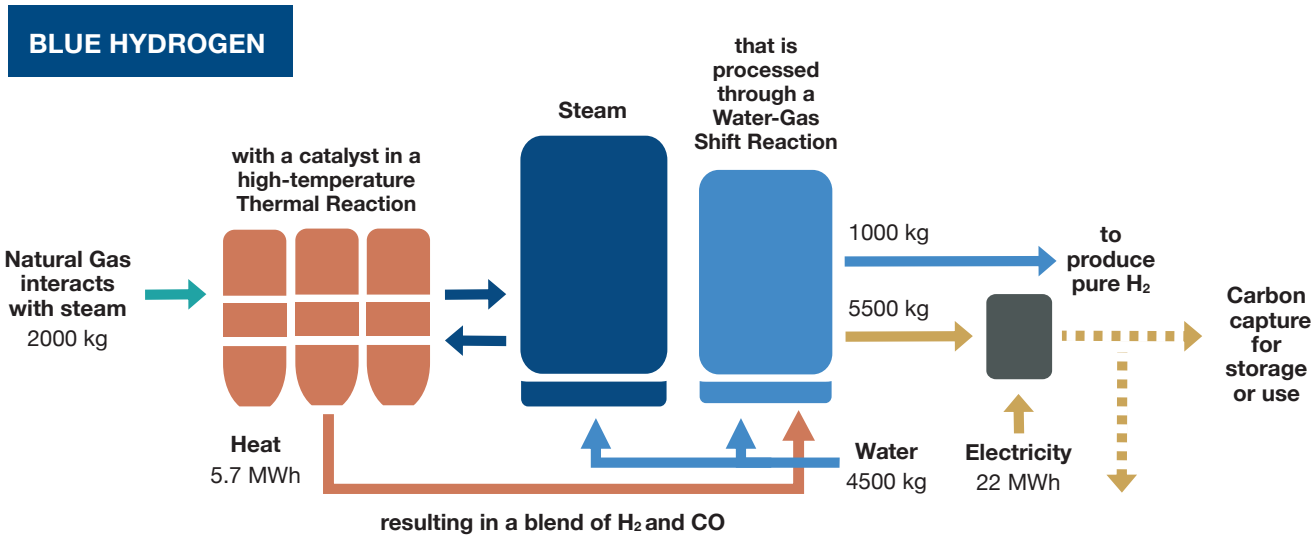
Hydrogen Production Technology Overview

Hydrogen can be produced from different processes, mostly from natural gas or from water using heat or electricity. Globally and in the United States, hydrogen production predominantly comes from SMR, which involves reacting steam and natural gas to produce hydrogen. This process currently dominates hydrogen production because of the relative abundance of low-cost natural gas and the energy (and cost) efficiency of splitting methane compared to water. As such, SMR is a relatively scalable, emissions-intensive, and low-cost production pathway. A large share of hydrogen production is located at or nearby large demand centers such as refineries, ammonia production facilities, and methanol plants. Less mature processes that produce hydrogen through biological processes are also being developed.[51]

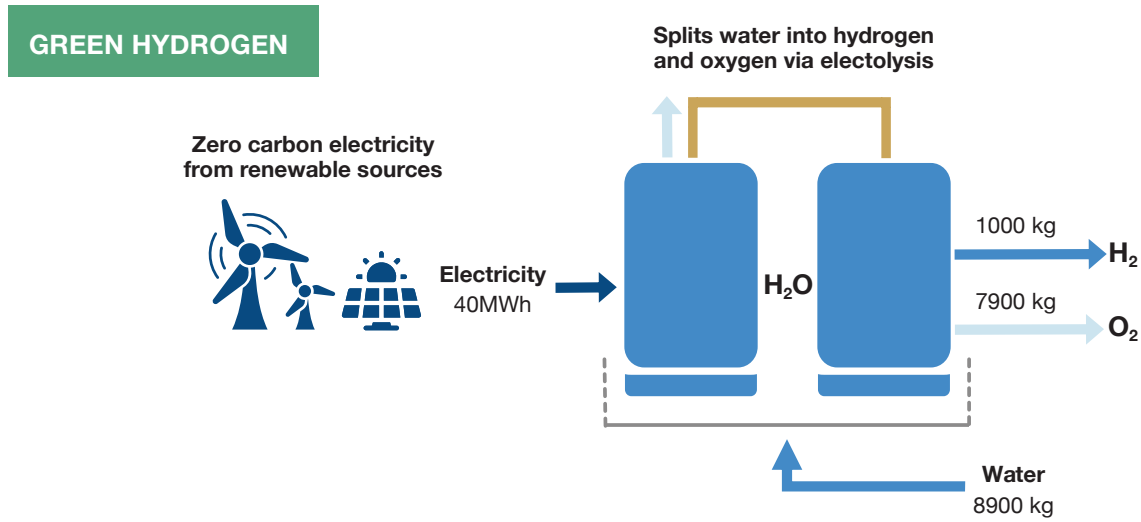
There are emerging production pathways that offer significant reductions in life cycle emissions intensity (Figure 5). The associated costs and emissions profiles vary by project and location, as energy inputs (and associated costs), capacity factors, and project design are the primary drivers of the cost of delivered hydrogen. The energy requirements shape the process and economics of each pathway. (Note that it requires less energy to split methane compared to water. See Appendix A for more details).

Figure 5

Select Clean Hydrogen Production Pathways and Resource Balances



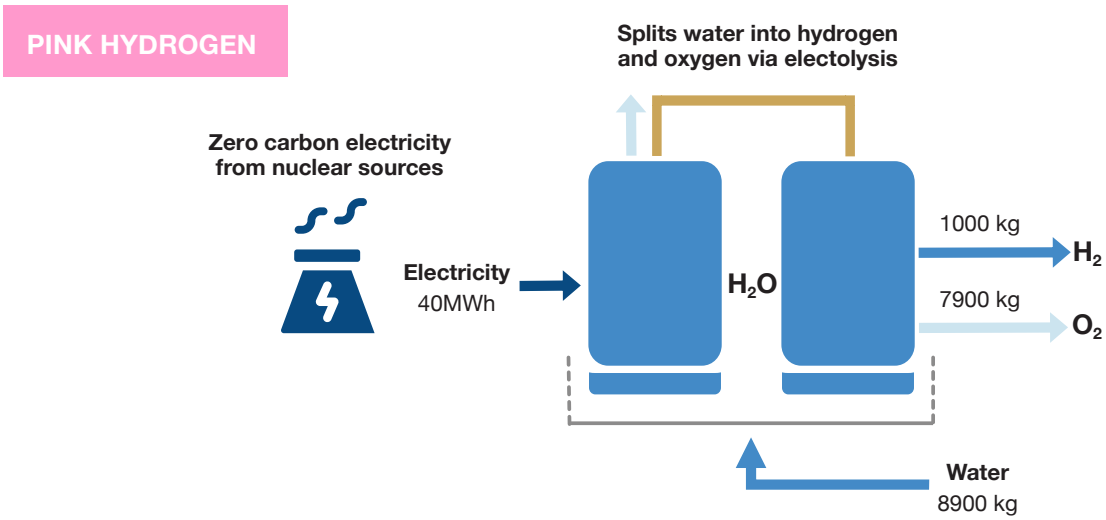
Blue hydrogen production follows the same process as gray hydrogen (i.e., SMR) to the production of pure hydrogen and CO_2. However, blue hydrogen adds a carbon capture unit to the process which requires electricity to facilitate the capture of the CO_2 for storage or utilization.



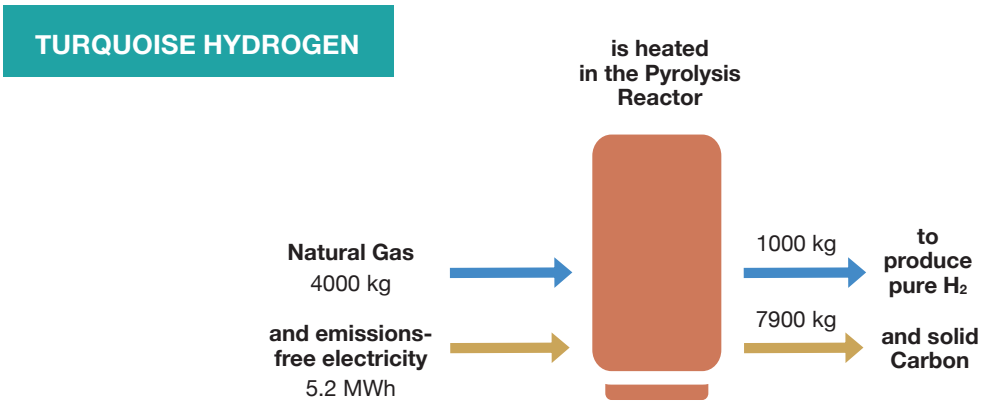
Green hydrogen is produced through the process of electrolysis, where zero-carbon electricity from renewable energy sources is used to split the component atoms of water molecules in an electrolyzer into pure hydrogen and oxygen gas. This process yields no greenhouse gas emissions.

Figure 5

Select Clean Hydrogen Production Pathways and Resource Balances (cont.)



Pink hydrogen is produced through the process of electrolysis, where zero-carbon electricity from a nuclear power plant is used to split the component atoms of water molecules in an electrolyzer into pure hydrogen and oxygen gas. This process yields no greenhouse gas emissions.



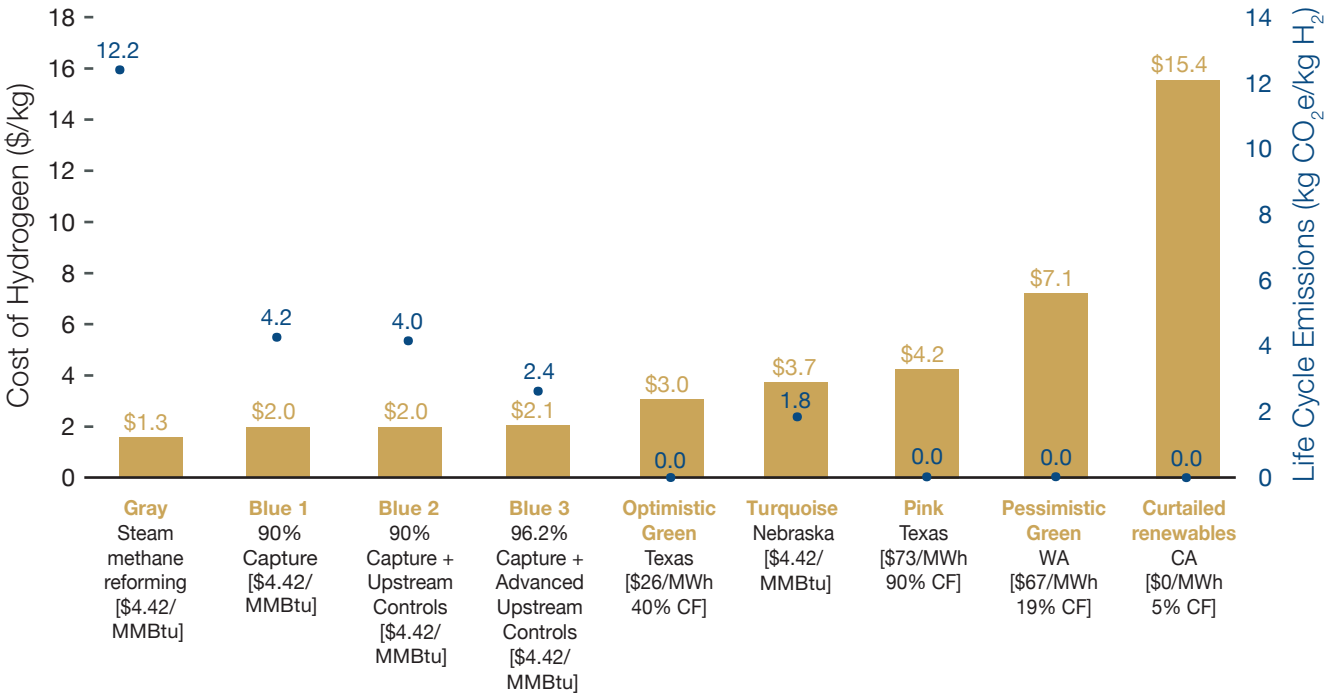
Turquoise hydrogen is produced through methane pyrolysis, which requires inputs of natural gas and low- to zero-emissions electricity. Pyrolysis uses these inputs to produce pure hydrogen gas and a solid carbon byproduct known as carbon black, as opposed to carbon emissions.

Figure 6 shows a breakdown of delivered hydrogen costs and associated emissions intensities of select hydrogen production projects. These scenarios are built using real-world data.[d] The life cycle GHG emissions for each pathway are based on GREET model assumptions, the framework being used by the IRA tax credit incentives.[52]

The analysis concludes that energy inputs drive hydrogen costs. In all cases, levelized costs increase as capacity factors decline due to the diminished productivity of the pathway, as described in Chapter 2. For example, the capacity factor for a large-scale green hydrogen project that runs on excess or "free" renewable electricity is very low, reflecting the limited availability of these resources and impacting the project's ability to recover capital costs, adding to the pathway's overall costs.

Figure 6

Cost Comparison of Major Clean Hydrogen Production Pathways



This graph shows the cost of hydrogen production from eight clean pathways compared to a conventional production pathway (i.e., gray). Blue hydrogen pathways require additional costs associated with natural gas and CO_2 transport and storage, while green and pink hydrogen pathway costs are dependent on electricity costs and capacity factors. The associated blue dots represent the life cycle greenhouse gas emissions for each pathway.

d This analysis employed the Sustainable Energy System Analysis Modelling Environment (SESAME) to simulate and analyze the data. See Appendix E for more details.

The United States Can Become a Clean Hydrogen Powerhouse

The United States is one of the world's most hydrogen-ready economies. On the supply side, according to one DOE study, the United States has the resource base to produce 1B metric tons of clean hydrogen—11 times greater than today's global production (90 Mt).[53, 54] On the demand side, hydrogen pairs well with existing U.S. industrial bases, workforce capabilities, and decarbonization needs. This study identifies nearly 800,000 workers across six industries that are vulnerable during the clean transition whose jobs and skills may be repurposed for a clean hydrogen economy (Appendix D).

> **The United States has the resource base to produce 1B metric tons of clean hydrogen—11 times greater than today's global production.**

Boundary conditions of the energy sector, however, make it historically slow to change. The energy industry is a multi-trillion dollar per year, highly capitalized, commodity business with robust supply chains, established customer bases, providing essential services at all levels of society. To rapidly scale clean hydrogen production and use from the current low levels of production and use will require leveraging a broad range of resources and capabilities, decarbonizing the existing system, while also enabling new applications with breakthrough potential.

The Hydrogen Transition Framework (HyTF)

To shape this policy study, EFI developed an analytical framework that includes relevant energy, economic, and policy information needed to inform hydrogen project development, regional hydrogen hubs, and broader network and market formation. The Hydrogen Transition Framework (HyTF)—pronounced "high-tiff"—is a database and geographical display of existing and potential U.S. clean hydrogen value chain components, hydrogen technologies, hydrogen-ready industries, and enabling infrastructures (Table 2). These attributes for market development may be hydrogen-specific (e.g., cheap renewable or natural gas resources that can be used to produce clean hydrogen) or hydrogen-adjacent (e.g., state policy that encourages hydrogen use).

Table 2
EFI's Hydrogen Transitions Framework (HyTF)

Resources	Interests	Capabilities	Demand
Natural conditions and established systems that could support a hydrogen economy	**Demonstrated direct or indirect support for hydrogen from firms or policies**	**Expertise and experience that can be utilized to innovate, educate, or provide necessary skills to the hydrogen economy**	**Current and potential end uses that will help drive the quantity of hydrogen supplied to the market domestically**
Existing • Fresh Water Access • Natural Gas Reservoirs • Hydrogen Pipelines • Salt Domes • Existing Hydrogen Production Capacity	**Private Sector** • Largest Investor-Owned Utilities • Other S&P 500 Companies	**Education Centers** • Universities by RD&D budget	**Near-Term Demand (Currently Commercialized)** • Refineries • Ammonia Plants • Methanol Plants • Limited Mobility Applications
Enabling • Saline Aquifers and Oil & Gas Reservoirs • CO_2 Pipelines • Natural gas pipelines • Roads, railways, waterways • Hydro, Solar, Wind, Geothermal, Biomass electricity generation installed capacity • Hydro, Solar, Wind, Geothermal, Biomass electricity generation potential • CO_2 Storage Potential	**Policy** • Favorable State Climate Policies/Plans	**Skilled Labor** • Bureau of Labor Statistics regions with strongest adjacent hydrogen jobs/skills • Technical and Community Colleges	**Medium-Term Demand (Commercialized 2025-2035)** • Data Centers • Steel Plants • Ports & Maritime Applications • Natural Gas Plants • Energy Storage Potential • Medium and Heavy Duty Mobility
	Public-Private Partnership • Government grants, direct payments, and loans for hydrogen technologies • Small Business Innovation Research Awards (SBIRs)	**Innovation Centers** • Patents for hydrogen technology • National Laboratories	**Long-Term Demand (Commercialized After 2035)** • Airports • Biofuels Production Potential • Cement Plants

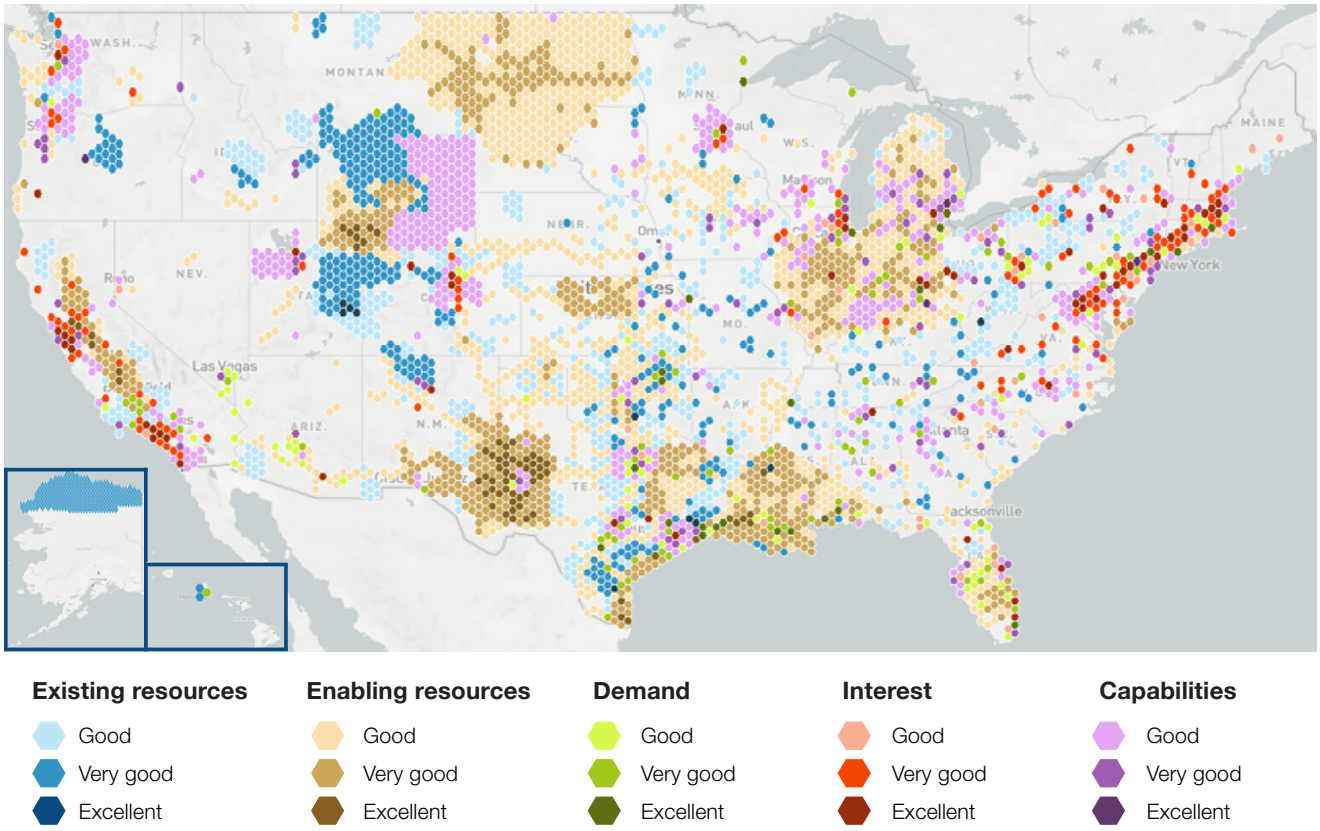
To assess the potential of clean hydrogen in the United States, EFI developed a tool for profiling the diverse array of potential energy resources, human capabilities, political and economic interests, and demand sources across the country. These distinct elements—ingredients with the potential to act as building blocks for regional hydrogen market formation—can be used by policymakers, private investors, and energy incumbents to evaluate regional opportunities to unlock clean hydrogen activities. These data are visualized in the maps below and can be used for reference.

HyTF is organized by Resources, Interests, Capabilities, and Demand. While these attributes vary across the country, most regions offer strong enabling environments for clean hydrogen activities (Figure 7). Certain regions are rich in all categories, offering strong clean hydrogen market development potential. For example, the U.S. Gulf Coast, California, and parts of the Midwest offer robust existing hydrogen resources (e.g., hydrogen pipelines) and enabling resources (e.g., solar and wind resources for green hydrogen production and CO_2 storage capabilities for blue hydrogen production). Other regions may offer distinct qualities for a certain project, regional hub, or support of an aspect of the value chain (e.g., manufacturing of electrolyzers). Building on these traditional project evaluation criteria, HyTF also shows that these regions have supportive policy environments (e.g., California's Low Carbon Fuels Standard [LCFS]), highly technical and equipped labor force, hydrogen patents, and large research universities and laboratories. Leveraging these information sources can inform new project partnerships, regional hub development, and regional expansion opportunities. Appendix D explains the technical components and additional details on HyTF.

On February 17, 2022, DOE released an interactive website called H2 Matchmaker to encourage data

Figure 7

Map of U.S. Hydrogen Resources, Capabilities, Interests, and Demand



HyTF profiles the U.S. capabilities, resources, demand, and interests in clean hydrogen. Over 11,000 hexagonal areas (each 400 square miles) are evaluated by strength of each category; the strongest hexes for a given category are described on an interactive map via a dropdown box. The tool (not previewed here) also shows overlap of categories; areas with multiple categories are viewed as important indicators of potential viable hydrogen hubs.

sharing and transparency among stakeholders interested in clean hydrogen development. This platform is designed to help establish new collaborations and partnerships—pivotal for developing the activity clustering to launch and develop regional clean hydrogen hubs. H2 Matchmaker fills a critical information gap in early market formation, especially as many new players enter this nascent market. HyTF is designed to help

EFI developed an analytical framework that includes relevant energy, economic, and policy information needed to inform hydrogen project development, regional hydrogen hubs, and broader network and market formation.

H2 Matchmaker users, policymakers, and other prospective investors analyze the resources at their disposal, cultivate new projects and partnerships, and ultimately drive more project development. Box 4 illustrates another application of HyTF, which is used to match the intersection of environmental justice and regional hydrogen opportunities in the United States, providing further insight into how best to build out a hydrogen industry in a just and equitable manner.

Box 4

The Intersection of Environmental Justice and Hydrogen Opportunities

In 2019, Cleveland, Ohio had the largest poverty rate of any major U.S. city in the country.[55] Job loss and health issues from the COVID-19 pandemic have only amplified concerns, especially for children and seniors. In addition, the highly industrial nature of the metro area, coupled with energy access and sustainability problems many households are burdened with, lead to severe environmental justice challenges. In multiple census blocks, asthma, diabetes, heart disease, and low life expectancy are all above the 99th percentile relative to the rest of the country. Relatedly, fine particulate matter (PM2.5) in the air in most blocks is above the 80th percentile, which can lead to those health issues. Legacy pollution issues are also pervasive, with proximity to hazardous waste facilities, Superfund sites, and Risk Management Plan facilities. Energy affordability can cripple households too, with some of the highest proportions in the country of income going to energy bills.[56]

Environmental justice concerns are in many ways tied to the opportunities identified in HyTF. Figure 8 provides an example overlay of HyTF and the Climate and Economic Justice Screening Tool (CEJST) in the Cleveland area.[e] Excellent Demand and Environmental Justice areas overlap, indicating that locations with potential strong demand for clean hydrogen, such as large industrial facilities, have been

e DOE's CEJST identifies census blocks with demographically poor and/or uneducated populations and assesses those against various environmental justice indicators including: climate change (e.g., agriculture loss); clean and affordable energy access (e.g., high particulate exposure); clean transit (e.g., traffic proximity metric); affordable and sustainable housing (e.g., lead painted houses); legacy pollution (e.g., high level of exposure to hazardous waste facilities); wastewater infrastructure (e.g., high level of wastewater discharge); health burdens (e.g., cancer risk); and workforce inequities (e.g., high unemployment).

Box 4 (cont.)

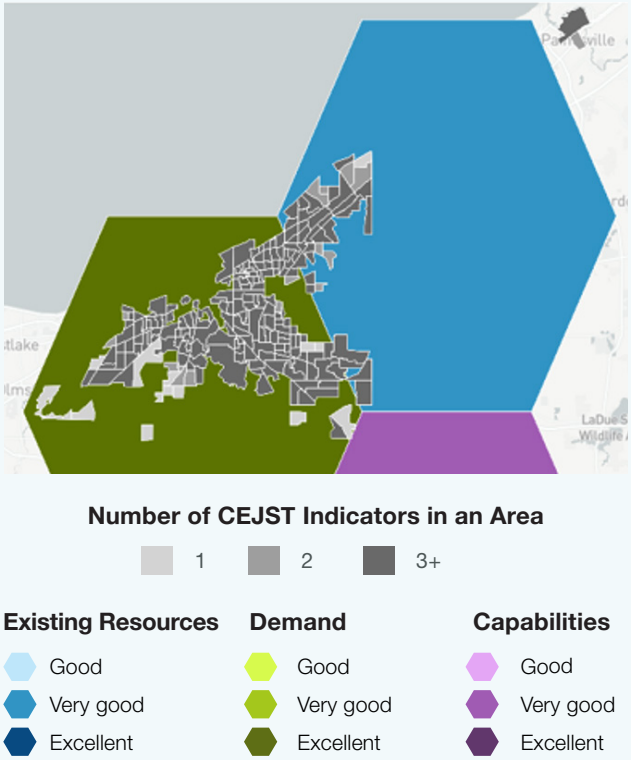
historically impacted by these same industries. Very Good Existing Resources, such as gas plants, natural gas pipelines, and major roads, shipping routes, and rail hubs, also intersect with Environmental Justice areas. Substituting hydrogen as a fuel source for power plants or steel plants is a viable opportunity for reduced overall emissions but must be weighed against the rise in nitrogen oxide (NO_x) pollution that could exacerbate health concerns. If pipelines are necessary to transport hydrogen, careful attention should be paid to minimizing leakage of warming gases, and pipeline siting should ideally not concentrate in communities already faced with environmental quality and socioeconomic problems.

Disadvantaged communities should receive some of the largest benefits from bringing a hydrogen economy to their backyard. Retraining programs at nearby community colleges, technical schools, or universities should be affordable and lead directly to related hydrogen-adjacent jobs in the workforce. Those jobs should be high paying and ideally unionized—which are, in fact, requirements for Regional Clean Hydrogen Hubs programs (H2Hubs) applicants, as well as for projects receiving the 45V hydrogen production tax credit. Energy bills should not rise as a result of introducing hydrogen as an energy carrier, and the business model for a hydrogen hub ideally should elucidate how it will bring energy costs down for lower-income families. Innovation at research institutions, such as Case Western Reserve University, should consider concerns in environmental justice communities (e.g., mitigating NO_x from combusting hydrogen).

By matching the opportunities found in HyTF with the challenges found in CEJST, developers, funders, and stakeholders alike can better understand the intersection between environmental justice and energy infrastructure, to ensure past mistakes (or intentions) are not recreated in the design phase of hydrogen hubs and other projects. They can also use HyTF to leverage the human capital at their disposal to ameliorate environmental injustices.

Figure 8

Climate and Economic Justice Screening Tool (CEJST) and HyTF — Cleveland Metropolitan Area Example



The overlay shows that there are both many opportunities for clean hydrogen growth and many environmental justice concerns in the region. The two can inform each other on key questions like where infrastructure is located, how research is conducted, and what environmental justice concerns can be addressed.

Regional Hydrogen Hubs can Jumpstart U.S. Hydrogen Market Development

The IIJA, which became law in August 2021, provides $8B for "at least" four regional clean hydrogen hubs, authorized through 2026.[57] In September 2022, DOE issued a Funding Opportunity Announcement (FOA) for the H2Hubs, clarifying that it envisions selecting six to ten regional hubs for a combined total of $6B to $7B in federal funding; DOE may issue a second round of funding for the remaining resources ($1B to $2B).[58]

Employing regional clean hydrogen hubs to rapidly support market development is based on tested economic frameworks for creating efficient and effective industrial activity through government-supported geographic clustering. Industrial parks, special economic zones, research hubs, and economic clusters are all examples of this approach.[59] As of August 2022, there are active regional clean hydrogen hubs in at least 21 countries. Each of these examples of "industrial policy" involves government-driven economic outcomes.

The industrial hub model can help stimulate demand by de-risking investments and allowing participants to pool resources, jointly manage costs, and coordinate infrastructure development. Regional clean hydrogen hubs, many of which would also be multi-state, can focus investment, policy and regulations, and R&D to develop new businesses and the associated infrastructure.[60] Hubs also provide an organizing principle for stakeholders to collectively leverage the broad climate policy support of the IRA (Figure 9), which could help firms rapidly scale, while jointly managing risk, pooling resources, and coordinating closely on project costs, permits and regulations, resource quantities, and business models. As hub members use and deploy technologies and infrastructure supported by IRA provisions, there is likely to be even greater focus from the energy and investment community on how to effectively scale regional hubs for broader market formation.

Regions with opportunities to leverage new policy resources could already see geographic clustering emerge. Comparing the existing U.S. Gulf Coast hydrogen industry with recently announced clean hydrogen projects shows that new activities are clustering around existing resources and infrastructures (Box 5).

Additional coordination and policy action is necessary to accelerate the rate of natural hub clustering in the timeframe needed to fully capture the funding opportunities in the IRA and IIJA. It will require additional coordination between regional hubs, DOE, and other stakeholders, who will have to create formal strategies for information sharing of data and lessons learned from hub performance, identifying barriers to project development (e.g., permitting), evaluating interdependencies involved with regional hub development (e.g., other infrastructure needs), and developing strategies for expanding hub regions.

Figure 9

The IRA Provides Unprecedented Support Across the Hydrogen Value Chain

Incentives for clean transportation

credit for:

- new/used hybrid and electric vehicles, commercial vehicles using clean fuel sources, including electricity and hydrogen;
- grants to replace existing heavy-duty vehicles with zero-emissions alternatives;
- extends credit for EV charging stations and hydrogen refueling

Incentives for clean electricity production

credit for:

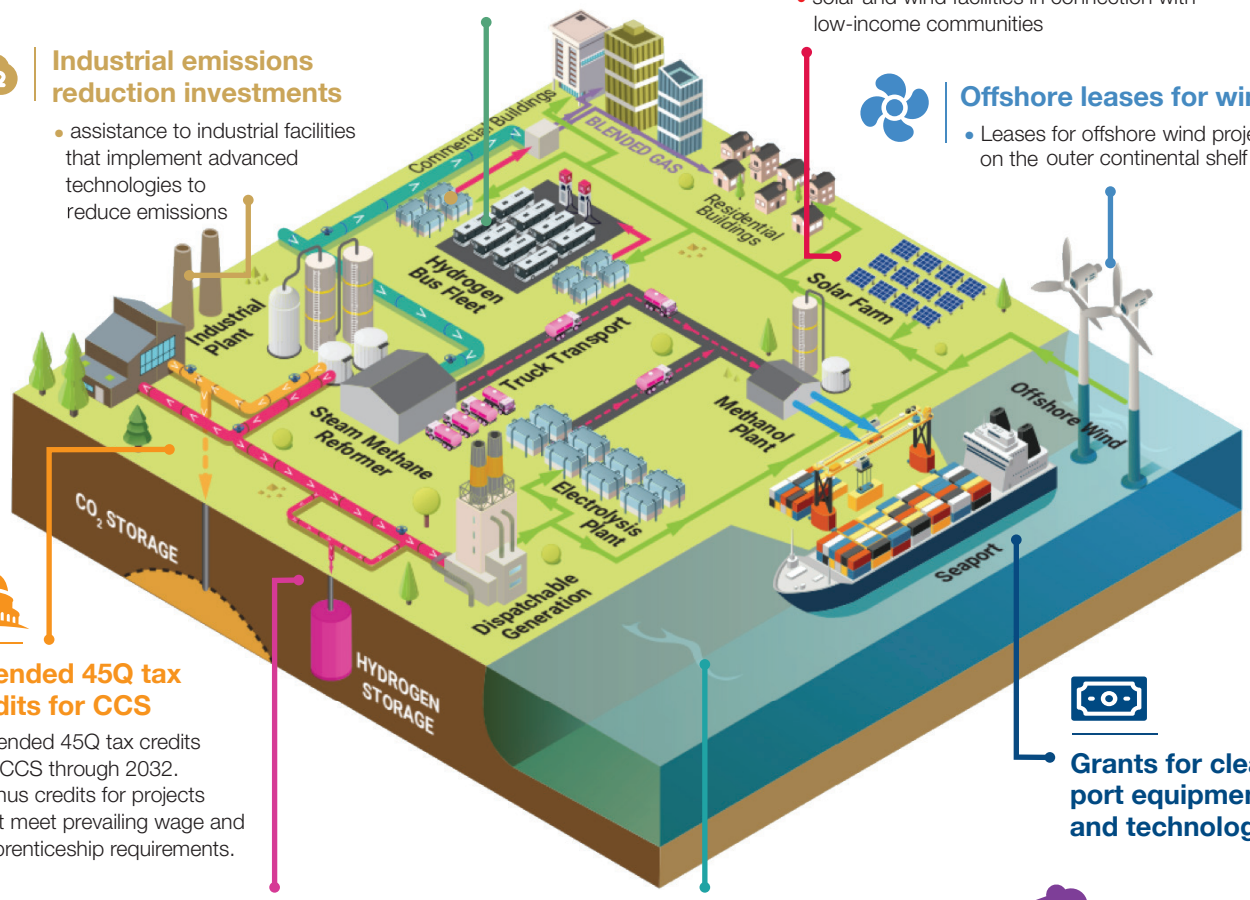
- investment and production of zero-emission electricity;
- electricity produced from renewable sources;
- clean energy technologies;
- solar and wind facilities in connection with low-income communities

Industrial emissions reduction investments

- assistance to industrial facilities that implement advanced technologies to reduce emissions

Offshore leases for wind

- Leases for offshore wind projects on the outer continental shelf



Extended 45Q tax credits for CCS

- extended 45Q tax credits for CCS through 2032. Bonus credits for projects that meet prevailing wage and apprenticeship requirements.

Grants for clean port equipment and technologies

New 45V tax credits for clean hydrogen production

- New 45V tax credits for clean hydrogen production that can reach a maximum value of \$3/kg H_2 produced for cleaner pathways (life cycle GHG emissions lower than 0.45 kg CO_2e/kg H_2) in projects built within a given period and that meet certain prevailing wage and apprenticeship requirements.
- Additional 10% credit if projects meet certain domestic content requirements and are located in an energy community.

New credits for clean manufacturing of energy equipment and upstream enablers

credit for:

- equipment for energy storage;
- grid modernization;
- clean vehicles, and manufacturing facilities designed to reduce emissions 20%;
- domestic production of solar, wind, and battery components

Methane emissions reduction program and investments

- fee on emitting facilities across O&G supply chain and funding for methane monitoring and mitigation

Hydrogen | Natural Gas | Electricity | Carbon Dioxide | Blended Power | Hydrogen/Ammonia

Tax incentives from the IRA span the entire hydrogen value chain and could benefit multiple actors participating in hydrogen hubs. As a result, these incentives could contribute to multiple pathways for different sectors to decarbonize production, transport, and end use applications.

Box 5

The U.S. Gulf Coast Shows the Promise of Industrial Clusters for Hydrogen

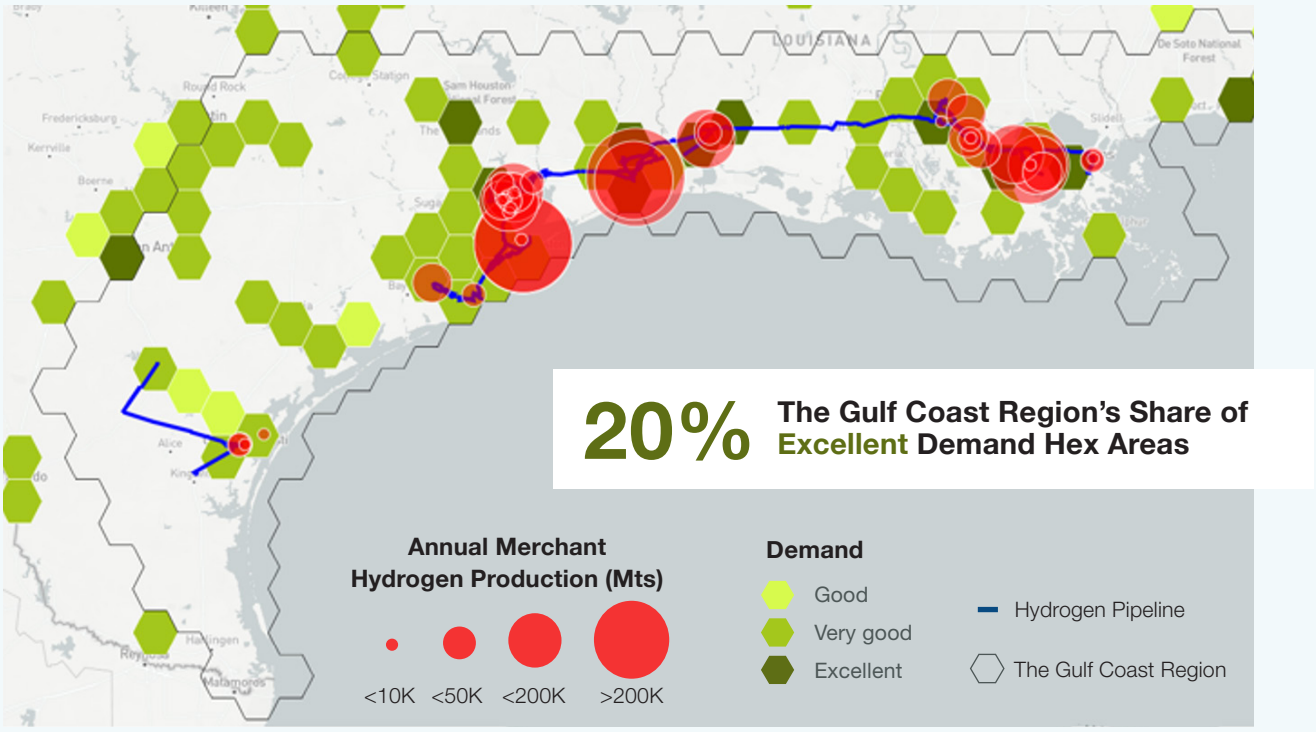
In June 2022, EFI hosted the workshop Building the U.S. Gulf Coast Clean Hydrogen Market, which brought together regional stakeholders to examine the opportunities and challenges of developing a clean hydrogen hub in the region.[61] Participants agreed the region's existing infrastructure, natural and human resources, and experience with hydrogen make it a prime location for a regional clean hydrogen hub. Nearly half of the U.S. hydrogen production today, and about a quarter of hydrogen demand, or 3 Mt H_2/yr, occurs in the Gulf Coast.

EFI used HyTF to analyze the potential for market growth in the Gulf Coast region. Figure 10 compares the region's existing hydrogen production and delivery facilities and potential future sources of demand.

The Gulf Coast region is home to nearly 60 hydrogen production facilities, nearly all of the country's 1,600 miles of hydrogen pipelines, and potential market enablers like 1,000 Gigaton (Gt) of CO_2 storage capacity and six of the 10 largest U.S. ports. The strong overlap of resources suggests that the existing hydrogen activities could be leveraged

Figure 10

Mapping HyTF Demand Elements to Existing Hydrogen Infrastructure in the Gulf Coast Region



The existing fossil fuel-based hydrogen production located in the Gulf Coast is closely co-located with the primary components of existing and potential clean hydrogen demand identified by HyTF, including existing use in refineries, ammonia plants, methanol plants, and potential use at ports, logistics centers, and for energy storage applications. The chart depicts the proportion of HyTF's hexagonal areas that encompass "Excellent" Demand in both the Gulf Coast region and the entire United States. The higher proportion of areas with these categories of Demand in the Gulf Coast indicates that this region already has densely located demand opportunities for clean hydrogen development.

Box 5 (cont.)

to drive new demand in the near-term in refining and ammonia production sectors as well as the handling equipment at ports and possibly energy storage for the electric grid. EFI is also tracking 28 announced new clean hydrogen projects that are similarly co-located with this infrastructure in the Gulf Coast region.

As identified in the workshop, these regional conditions exemplify how the Gulf Coast can be a major contributor to clean hydrogen demand creation. Given the industrial clustering already present in the Gulf Coast, harnessing this region's demand can help stimulate a clean transition in the existing industry and build up a broader market by de-risking investments across the growing clean hydrogen value chain.

2 PATHWAYS FOR ACCELERATING CLEAN HYDROGEN DEMAND

Chapter Insights

The IRA offers significant value for the development of U.S. clean hydrogen projects. The new 45V clean hydrogen production tax credit can reach $3.00/kg H_2—roughly double current gray hydrogen costs—if carbon-intensity, labor, and apprenticeship requirements are met.

IRA support can significantly reduce clean hydrogen production costs; additional policy measures can encourage the current hydrogen industry to switch to clean feedstocks, with emission reductions potential of around 50 Mt CO_2e per year. Additionally, the IRA can support expanding hydrogen's use in hydrogen-ready, difficult-to-decarbonize sectors, including steelmaking, blending, and long-duration storage. Adoption in these sectors would rapidly create a 4x growth in U.S. hydrogen demand, resulting in emissions reductions of at least 50 Mt CO_2e per year.

Recommendations for Accelerating Clean Hydrogen Demand

The Internal Revenue Service (IRS) should issue guidelines for how fossil-based hydrogen projects could be eligible for 45V credits, as a large portion of their life cycle emissions are not within their control. The design of the 45V credits favors certain pathways over others. Eligible projects may instead access the new 45Q tax credits for CO_2 storage ($85/t CO_2).

Congress should increase the funding for DOE's H2Hubs program for additional hydrogen clusters throughout the country, focusing on projects that enable regional network expansion that build on the first wave of projects. The IRA does not offer robust demand-side incentives that match the significant supply-side opportunities. Additional funding could create new collaborations between U.S. and international clean hydrogen hubs to partner on sharing data related to hub development, operations, financing, and community impacts.

The White House should develop new permitting strategies that enable regional clean hydrogen hubs infrastructure. This would demonstrate a national commitment to developing industrial low carbon clusters. Coordinating project permits through a single federal agency could accelerate timelines for completion, rapidly reduce emissions, and provide greater transparency and guidance for project developers.

The federal government should develop a credit trading system for managing hydrogen production and consumption that can track hydrogen blends, create a mechanism for credit trading, and foster economic incentive for industrial customers looking to decarbonize. The government should work with hubs to ensure there is transparency and public access to relevant data.

The Administration should work with Congress to develop a public-private partnership model for CO_2 storage management to effectively prioritize infrastructure permitting and supply chain development. This structure would help to avoid costly project uncertainty related to blue hydrogen, as well as other decarbonization technologies (e.g., direct air capture) that depend on CO_2 sequestration.

Maximizing the IRA Policy Incentives

The IRA represents the most significant policy support for hydrogen in U.S. history. It is essential that these tax credits are maximized to increase clean hydrogen's cost competitiveness as a clean fuel to support market development. While there are some state and federal policies supporting hydrogen, such as DOE grants for zero-emissions vehicle infrastructure and California's LCFS, hydrogen remains relatively uncompetitive in most markets. For example, despite the hydrogen pathway in the LCFS, there are fewer than 70 hydrogen fueling stations in the country, mostly located in California,[f] and around 14,000 fuel cell vehicles in the United States.[62,63] Alternatively, there are more than 1 million electric vehicles (EVs) and nearly 50,000 EV charging stations in the country.[64,65]

The IRA's new clean hydrogen production tax credit (45V), the extension and expansion of the 45Q carbon sequestration credit, additional flexibility for clean electricity tax credits, as well as key enabling policies—such as the support for domestic manufacturing and clean energy storage—all provide new opportunities to build out the U.S. hydrogen value chain. To understand how the IRA may impact market development, it is important to analyze the opportunities and tradeoffs of the major IRA incentives (i.e., 45Q and 45V), how they may impact the overall cost of emissions mitigation, and how the tax credits may influence investor preferences.

f In the United States, California is home to all but one hydrogen refueling station, which is located in Hawaii.

Comparing 45V and 45Q Credits

The IRA's major clean hydrogen production incentives include the 45V clean hydrogen production tax credit and the expanded 45Q credits for geologic sequestration. IRA provisions do not allow a project to combine the two credits. Multiple factors will shape an investor's decision to choose one incentive over another.

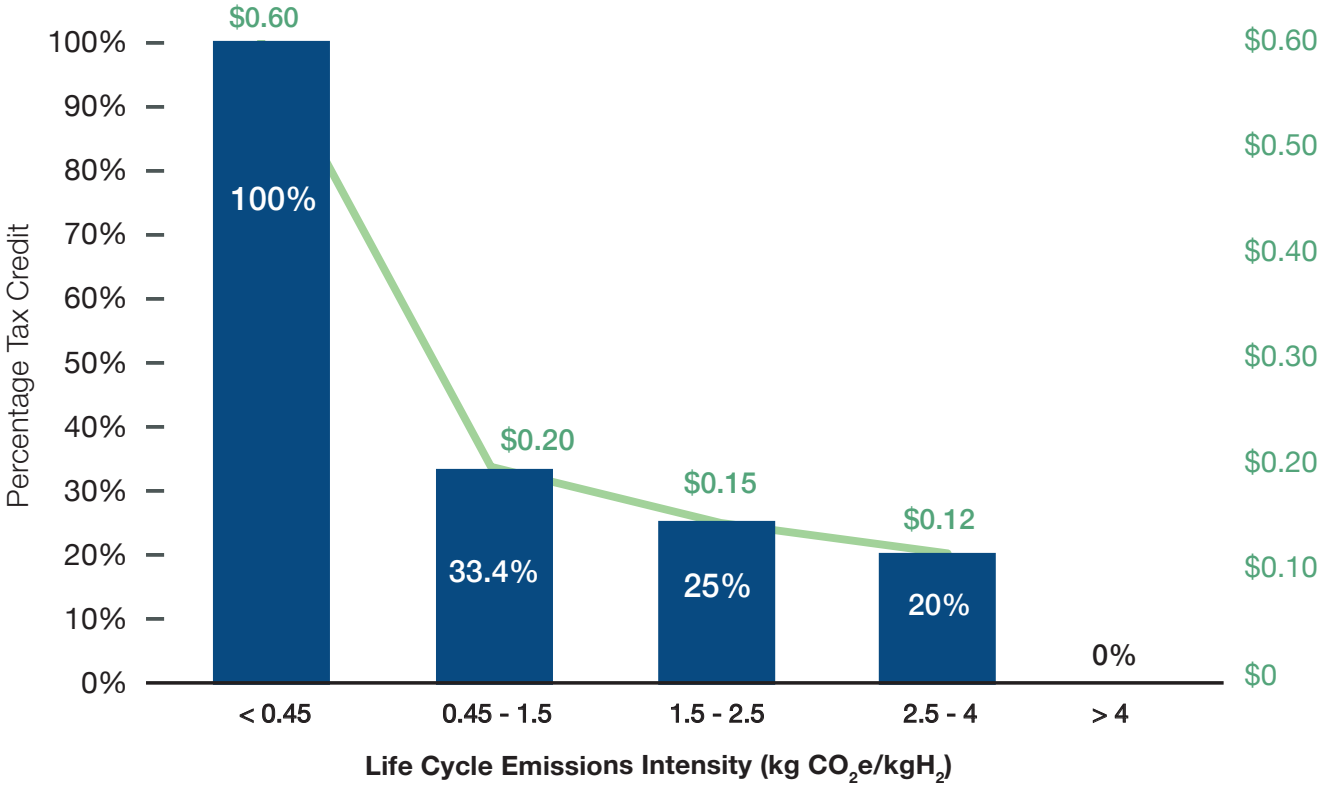
As one factor, a project's life cycle emissions directly impact the size of the incentive. For example, the 45V incentive increases with life cycle emissions intensity levels, starting at \$0.12/kg H_2 for projects that reach 4.0 kg CO_2e/kg H_2 up to \$0.60/kg H_2 for projects that reach 0.45 kg CO_2e/kg H_2 target (Figure 11). For 45Q, the credit was increased to \$85/t CO_2 captured from a point source and permanently sequestered. IRA 45Q credits are not dependent on life cycle emissions intensity.

As another factor, the costs of capital and operational expenditures are different across production pathways, which can impact a project's ability to attract financing. Third, the availability of infrastructure to support either blue (e.g., geologic storage) or green (e.g., electric grid access) may be region-specific.

Finally, the local energy input costs, which represent most costs for natural gas- and electricity- driven production pathways, vary across regions and will be major factors in project economics. These factors, among others, must be weighed before comparing the values of the 45V and 45Q credits.

Figure 11

45V Hydrogen Production Tax Credits by Hydrogen Life Cycle Emissions Intensity



This figure illustrates the life cycle emissions intensity required to receive higher percentages of the 45V hydrogen production tax credit. The credit begins at \$0.12/kg H_2 with a life cycle greenhouse gas emissions intensity between 2.5 and 4.0 kg CO_2e/kg H_2, increasing to \$0.60/kg H_2 for hydrogen that is lower than 0.45 kg CO_2e/kg H_2.

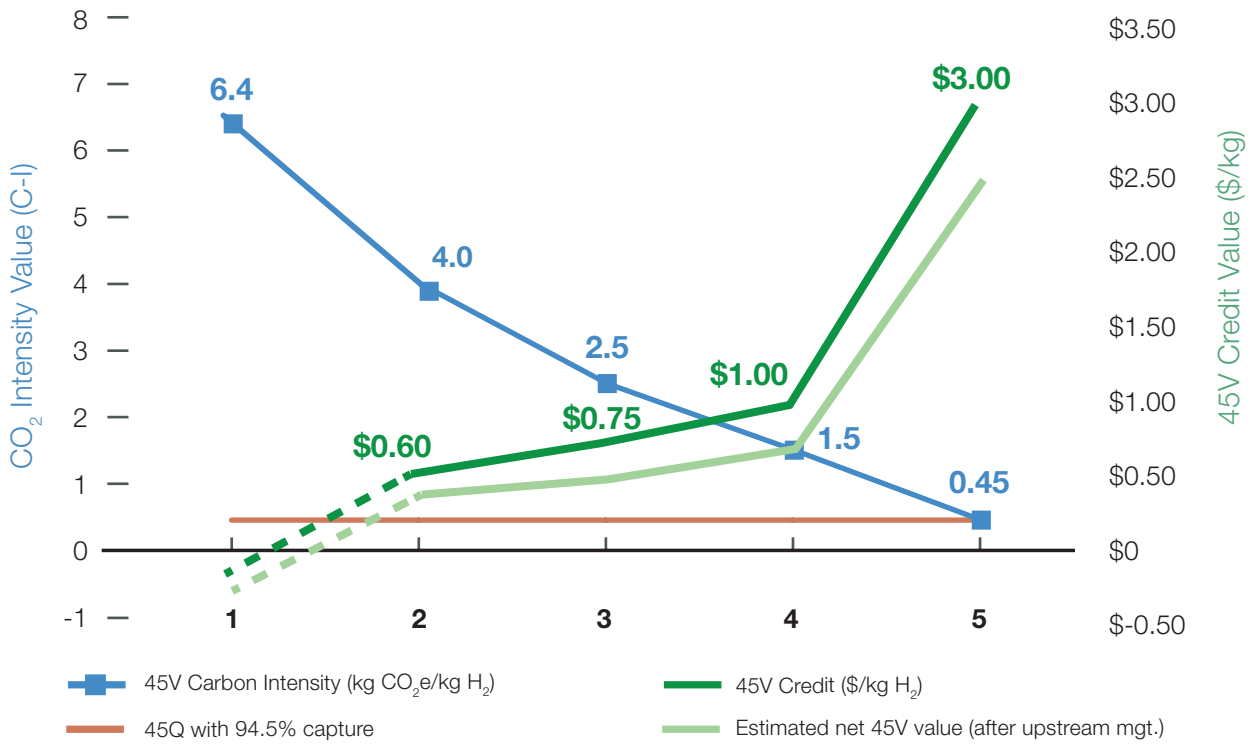
Blue hydrogen projects may not be eligible for 45V credits without addressing upstream electricity and natural gas emissions. As noted in Chapter 1, two thirds of the emissions in an average SMR facility come from reforming, while one third comes from the upstream natural gas emissions, and 3 percent comes from the electricity used to run the facility. Adding carbon capture to an SMR with a 96.2 percent capture rate results in life cycle emissions of 4.6 kg CO_2e/kg H_2. The low end of the IRA credits begins for projects with life cycle emissions of at least 4.0 kg CO_2e/kg H_2. Blue hydrogen projects seeking either 45V or 45Q must cover the costs of CO_2 capture.

Additionally, unless they are in favorable locations with better than average upstream emissions, projects seeking 45V that have upstream emissions must bear additional costs to procure clean electricity, while ensuring that the natural gas delivery system is effectively managing leaks.[66]

The actual costs for addressing these upstream emissions will be driven by local energy costs. This analysis assumes additional costs to cover the life cycle emissions are \$0.10/kg H_2 at the low end (i.e., to reach 4.0 kg CO_2e/kg H_2) and \$0.50/kg H_2 at the high end (i.e., to reach 0.45 kg CO_2e/kg H_2). These assumptions are based on average U.S. energy costs, accounting for upstream natural gas mitigation and to procure clean electricity to reduce life cycle emissions. Figure 12 shows different scenarios—from left to right—for a project developer choosing between 45V and 45Q. The 45Q tax credit (\$0.26/t H_2) offers a

Figure 12

Comparing the Value of 45V and 45Q Credits



Different scenarios are depicted in this figure for a project developer choosing between 45V and 45Q for clean hydrogen production projects. The 45V value is depicted by the dark green line in dollars per kg at different CO_2 intensity levels indicated by the blue line. The light green line is an EFI estimate of the net value of the 45V credit after including marginal upstream emissions reduction costs. The red line is the value of the 45Q credit (\$/kg) for a blue hydrogen project with a ~95 percent capture rate. In scenario one, a project with life cycle emissions of 6.4 kg CO_2e/kg H_2 is ineligible for 45V but may collect 45Q.

significant benefit from many blue hydrogen projects that cannot procure clean upstream energy or that may find the risk of compliance to be too high.

DOE's CHPS shows that certain fossil-based production pathways will need to address upstream emissions to qualify for 45V. Issued in September 2022, CHPS's draft guidance stated: "fossil fuel systems that employ high rates of carbon capture… are generally expected to be capable of achieving 4.0 kg CO_2e/kg H_2 on a life cycle basis using technologies that are commercially deployable today." As an example, CHPS notes: "a steam methane reformer with ~95 percent carbon capture and storage (CCS) could achieve ~4.0 kg CO_2e/kg H_2 life cycle emissions by using electricity that represents the average U.S. grid mix and ensuring that upstream methane emissions do not exceed 1 percent."[67] According to the U.S. Environmental Protection Agency (EPA)—a primary input into GREET calculations—the average U.S. natural gas system released 165 Mt CO_2e of methane in 2021, with a leak rate (percent of total sales) of 2 percent.[68] Meanwhile, according to DOE, the U.S. natural gas system leakage rates range between 0.7 percent and 3 percent.[69] To be 45V eligible, these projects must employ very high levels of carbon capture and be measurably better than national averages in terms of upstream emissions or they must seek to mitigate these emissions.

There are recent policy efforts to reduce upstream methane system emissions. While these policies can substantially lower the life cycle emissions of the natural gas network (by more than 80 percent), increasing the 45V credit value for blue hydrogen producers, they will not help gas-based hydrogen production pathways access the high end of the 45V credit ($3/kg H_2). The IRA's Methane Emissions Reduction Program and Fee amends the Clean Air Act to charge oil and gas facilities that report emissions of more than 25,000 t CO_2e per year. The charge starts at $36/t CO_2e in 2024, moves to $48 in 2025, and $60 from 2026 to 2035. To avoid the charge, gas producers must reduce methane leaks to 0.2 percent, transmission and storage must reduce to 0.11 percent, and non-production gas systems must limit leaks to 0.05 percent of total U.S. gas sales. This policy does not cover distribution entities, which account for roughly 15 percent of the gas sector's emissions. If every covered entity were to comply with these levels—and assuming an average current gas system leak rate of between 2 percent to 3 percent—the gas system emissions would decline by roughly 80 percent, resulting in a new system-wide leak rate between 0.45 percent to 0.7 percent. For context, a blue hydrogen project with 96.2 percent capture and an average upstream leak rate of 0.7 percent is eligible for the $0.75/kg H_2 IRA credit.

Another recent policy proposal came from the EPA in November 2022 to enhance methane regulations for new and existing facilities.[70] These new standards would reduce leaks, deploy more measurement, reporting and verification (MRV) technologies, and eliminate a total of 810 Mt CO_2e between 2023 and 2035 (67.5 Mt CO_2e per year). On an annual basis, this policy would reduce the U.S. gas system leak rate to around 0.6 percent.

There are important questions about how these policies would interact. The IRA's Methane Fee may force entities to pay the fee in the early years while they develop pathways for compliance before the penalties increase significantly. Meanwhile, the exact timing and future of the EPA proposal is uncertain. The impact on blue hydrogen may be notable though the credit value is still less than that for green hydrogen projects. The stack emissions for a blue hydrogen facility with 96.5 percent capture are 1.45 kg CO_2e/kg H_2, while the high end of the 45V credit requires emissions below 0.45 kg CO_2e/kg H_2.

IRA's Impact on Delivered Hydrogen Cost by Project Types

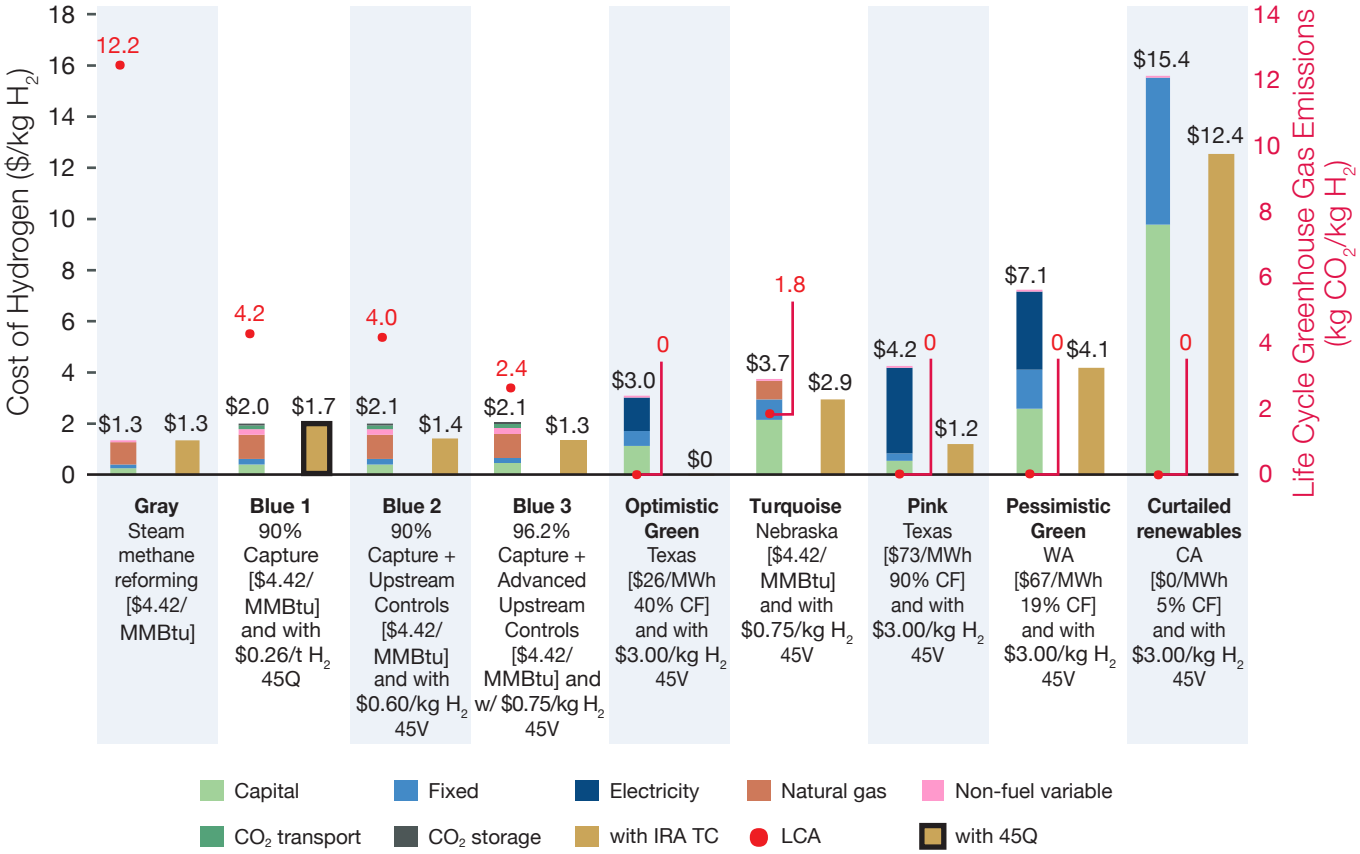
The impact of the IRA's 45V and 45Q incentives will be different across project types, energy costs, and capacity factors. Using the Sustainable Energy

System Analysis Modelling Environment (SESAME), which performs techno-economic analysis of various energy systems, nine hydrogen production projects were analyzed. The project scenarios were designed to reflect realistic market conditions for a select number of production pathways. Figure 13 shows the average hydrogen production cost for each scenario, the estimated life cycle emissions, and a comparison of the cost of delivered hydrogen including the relevant IRA incentives.

The "gray" project is a new build steam methane reformer that runs on $4.42 per million British thermal units (MMBtu) natural gas, with life cycle emissions of 12.2 kg CO_2e/kg H_2, resulting in delivered hydrogen costs around $1.30/kg H_2.[71] Three blue hydrogen project scenarios were designed to reflect different CO_2 capture rates, ranging from 90 percent to 96.2 percent, and a range of upstream emissions mitigation measures. "Blue 1" is an SMR with 90 percent CO_2 capture rates, resulting in life cycle emissions of 4.2 kg CO_2e/kg H_2, and a delivered hydrogen cost of $2/kg H_2. After leveraging the new 45Q credit ($85/t CO_2), the cost of delivered hydrogen is nearly $1.70/kg H_2. In this scenario, "Blue 1" is ineligible for 45V based on its life cycle emissions. "Blue 2" uses the same SMR and CCS with 90 percent capture as "Blue 1" but it includes additional upstream emissions controls (at

Figure 13

Cost Comparison of Select Hydrogen Production Pathways and with IRA Incentives



This graph shows the cost of hydrogen production from seven clean pathways compared to a conventional production pathway (i.e., gray). The left bar in each pathway shows the specific cost components. The associated red dots represent the life cycle greenhouse gas emissions with that pathway, based on GREET model assumptions. The right bar in each pathway shows the total production costs with the IRA hydrogen production tax credits. The right bar outlined in red for "Blue H_2" denotes the price if the blue hydrogen plant seeks the 45Q carbon capture and storage credit. Note that each production pathway represents only one potential clean hydrogen plant based on the criteria specified.

a cost of \$0.10/kg H_2), making it eligible for the low end of the 45V credit (\$0.60/kg H_2), and resulting in a delivered cost of \$1.40/kg H_2. For "Blue 3," it is assumed the project has very low life cycle emissions. It has a 0.7 percent leak rate, driven by its location with greater than U.S. average upstream emissions, combined with advanced upstream emissions controls (\$0.10/kg H_2), helping the project access the next level of the 45V credit (\$0.75/kg H_2). The result is hydrogen costs of \$1.30/kg H_2.

The "optimistic green" scenario involves purchasing utility-scale solar and wind at \$26 per megawatt-hour (MWh) to run an electrolyzer at 45 percent capacity. These variables are shaped by real-world data in West Texas. Delivered hydrogen costs for the project are around \$3/kg H_2. This project is eligible for the full 45V credit (\$3/kg H_2), if it also meets the prevailing wage and apprenticeship requirements, resulting in delivered hydrogen costs of \$0/kg H_2. The "pessimistic green" scenario involves lower capacity factors (19 percent) and higher electricity costs (\$67/MWh), resulting in delivered hydrogen costs of \$7.10/kg H_2. After capturing the \$3/kg H_2 45V credit, the costs fall to \$4.10/kg H_2. A "curtailed renewables" scenario is provided, showing the negative impact on delivered hydrogen costs of running electrolyzers with very low-capacity factors (5 percent).

The impact of the IRA's 45V and 45Q incentives will be different across project types, energy costs, and capacity factors.

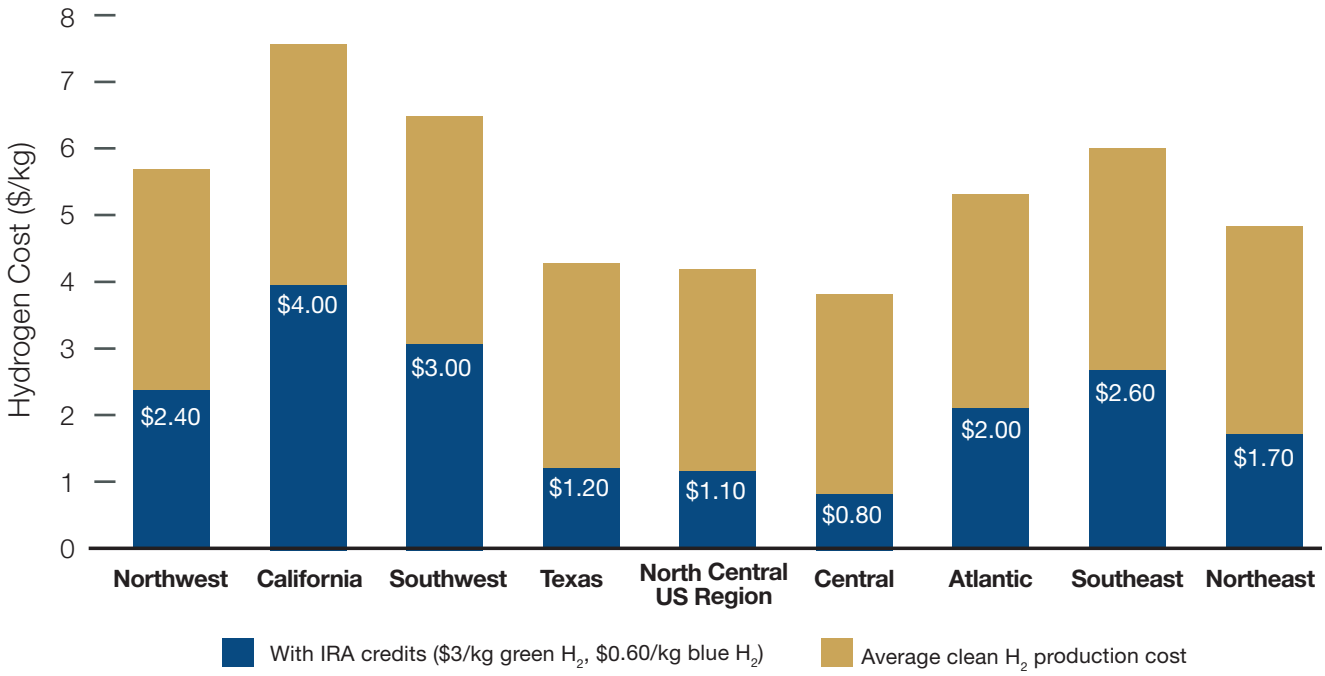
The "turquoise" project scenario involves large-scale thermal pyrolysis, using energy data assumptions in Nebraska. Relatively high capital costs reflect the newness of the technology. While the natural-gas intensive process results in no stack emissions, life cycle emissions from upstream natural gas and electricity must be considered. This project can deliver \$3.70/kg H_2, which falls to \$2.90/kg H_2 after \$0.75/kg H_2 45V. Finally, the "pink" hydrogen project scenario leverages relatively high-capacity factors (90 percent) for the electrolyzer, with industrial electricity costs in Texas (\$73/MWh). This project is eligible for the \$3/kg H_2 production tax credit (PTC).

IRA's Cost Impact by U.S. Region

Another way to assess the IRA's impact on clean hydrogen costs is by analyzing average energy cost data at a regional level. Using SESAME to simulate and analyze the data, regional clean hydrogen supply profiles were built based on average costs of natural gas, wind, and solar resources.[72] To simplify the analysis, a supply curve was built for each region, shaped by the cost of local resources, assuming each region must produce 1 Mt of clean hydrogen. While blue hydrogen is on the low end of the cost curve for most regions, the projects were constrained in regions without CO_2 storage resources. With these parameters, the model deployed the most cost-effective mix of clean hydrogen supply, resulting in average costs ranging from around \$4/kg H_2 to \$7/kg H_2. Regions with abundant CO_2 infrastructure and storage and robust, low-cost wind resources, have the lowest clean hydrogen costs (Figure 14). The IRA incentives were applied to the regional cost curves. The regions with the greatest impact have significant renewable resources, due to the value of 45V. See Appendix E for additional details.

Figure 14

Clean Hydrogen Production Costs by Region with IRA 45V Tax Credit



This figure compares regional hydrogen production prices based on energy input costs, CO_2 storage, and clean energy resource availability and how those impact eligibility for the 45V hydrogen PTC. Regions with abundant CO_2 infrastructure and renewable resources overall have the lowest clean hydrogen production costs as a result of the PTC.

Decarbonizing the Hydrogen Industry

The existing hydrogen industry—refineries, methanol plants, and ammonia production facilities—offer near-term opportunities to rapidly reduce difficult-to-decarbonize U.S. industrial emissions. The industry has the experience, captive demand, and substantial interest in switching to a clean hydrogen supply due to the need to reduce its emissions. This "no regrets" strategy can rapidly kick-start demand in diverse regions of the country, including many fossil-dependent economies. It is important to note that DOE's National Hydrogen Strategy and Roadmap also considers refining and ammonia production as near-term candidates for decarbonization.[73]

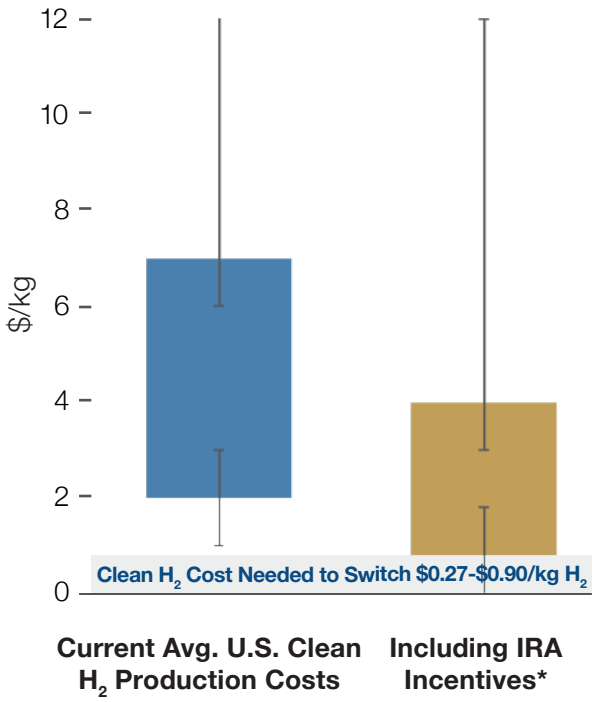
The IRA can reduce clean hydrogen costs to between \$0.80/kg H_2 and \$4/kg H_2. However, switching the existing consumers to clean hydrogen will require new contracts, new infrastructure, and strong alignment among producers and consumers. According to a techno-economic analysis performed by SESAME, to compete with existing merchant plants, clean hydrogen costs need to be between \$0.27 to \$0.90 depending on the end use sector (Figure 15) (Appendix E).

Steam Methane Reforming Facilities

The top 30 SMR facilities account for roughly half of total U.S. capacity; they are also responsible for 70 Mt CO_2e of emissions per year (Figure 16).[74,75] While about half are part of an integrated system (e.g., SMR with ammonia production), the others are merchant producers that sell mostly to refineries. Targeting the merchant plants offers significant emissions reduction potential. The net emissions impact of switching to a clean hydrogen feedstock would depend on the life cycle emissions of the alternative. One low end estimate of switching to hydrogen with 4.2 kg CO_2e/kg H_2 would have an emissions reduction potential of around 50 Mt CO_2e.[76] Cleaner hydrogen feedstocks could have even greater impact on U.S. industrial emissions.

Figure 15

Average U.S. Clean H_2 Production Costs with IRA and Cost Ranges Needed to Switch for Steelmaking, Refining, and Ammonia and Methanol Production



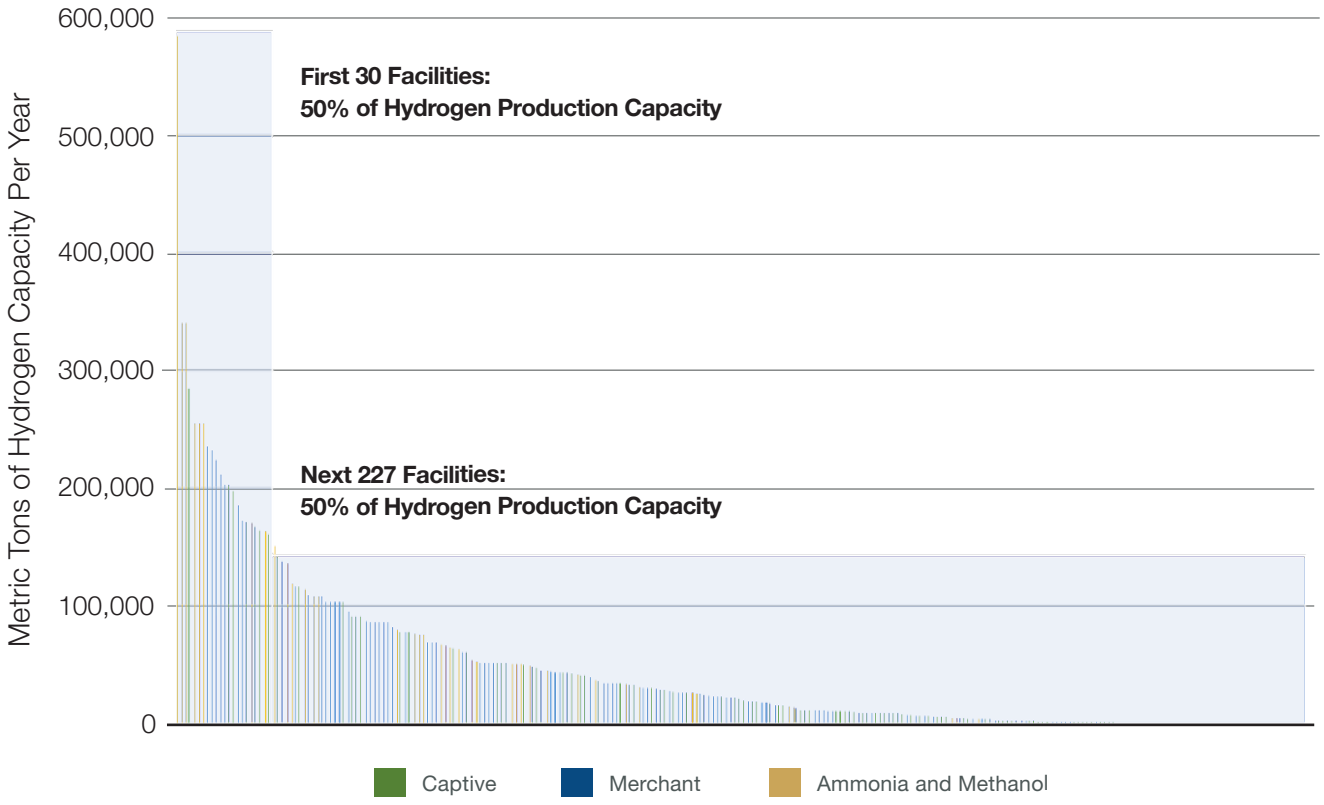
Steel (\$0.90/kg H_2), Ammonia (\$0.80/kg H_2), Refining (\$0.50/kg H_2), Methanol (\$0.27/kg H_2)

*IRA Incentives: \$3/kg green H_2, \$0.60/kg blue H_2

EFI estimated the cost of clean H_2 production today for nine separate U.S. regions based on regional energy input costs and availability (i.e., for intermittent renewable resources). A supply profile for each region was developed, and the cost was estimated. The impact of the IRA incentives was analyzed based on the regional resources and an estimated life cycle accounting for each pathway. In the gray box, EFI estimated the cost of clean hydrogen needed to reach cost parity with existing sources for select end-users, including refining, ammonia, methanol, and steel. Some of these sectors represent the most "clean hydrogen ready" based on their current use of hydrogen.

Figure 16

U.S. Hydrogen Production Facilities by Capacity[77]



Hydrogen production facilities in the United States produce hydrogen for captive use, merchant sale, or for use in ammonia and methanol production. Of these 257 facilities, the 30 largest plants make up half of all production capacity in the country and have a significant impact on U.S. industrial emissions. Data from: PNNL and Nutrien, 2016.

Refining

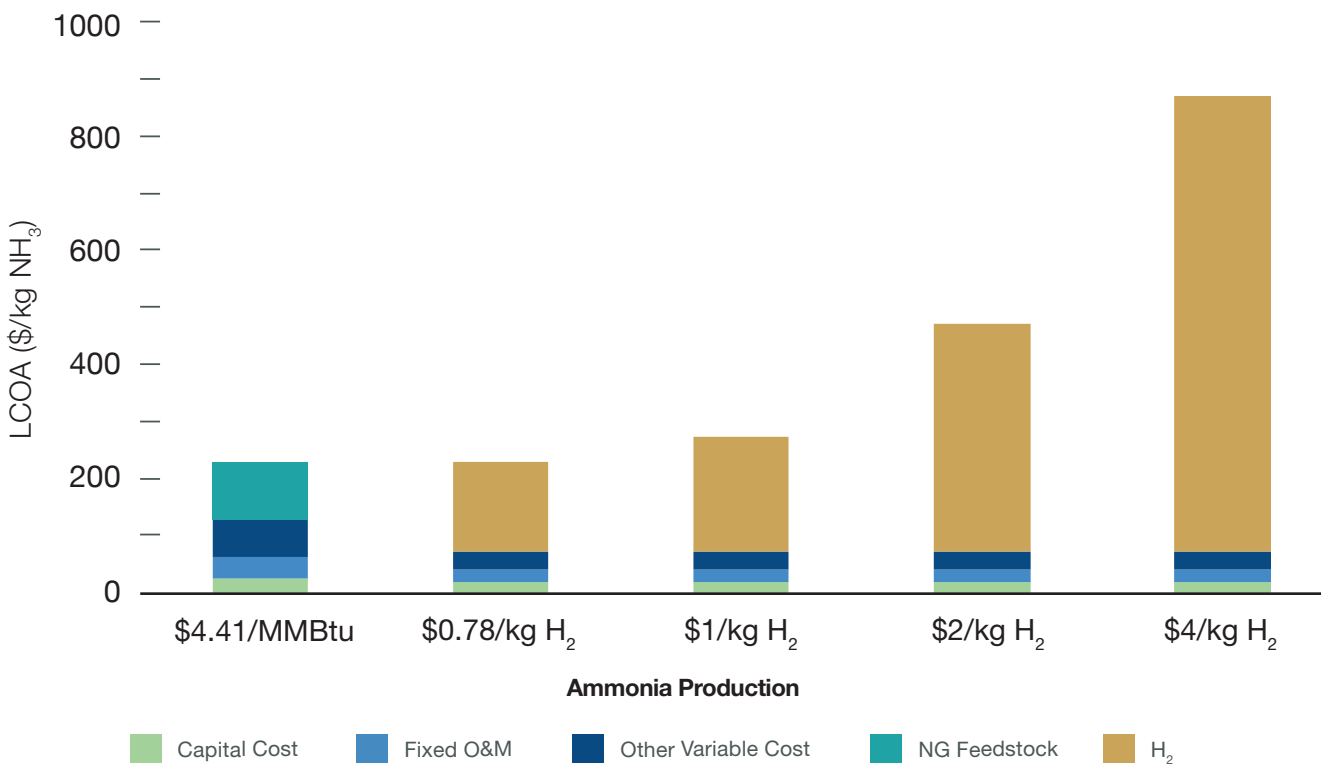
Decarbonizing hydrogen for U.S. refining generally involves either deploying CCS at on-site SMR plants or switching to low-carbon hydrogen supply from merchant producers. According to SESAME, the delivered cost of clean hydrogen will need to be around \$0.50/kg H_2 to be cost competitive with \$4.41/MMBtu natural gas. In this range, refiners should consider switching to clean hydrogen from merchant providers. It may be challenging for refiners to deploy CCS at their existing facilities and capture the 45V credit, as the level of CCS increases, the facility will demand more natural gas for processing, negatively impacting the life cycle emissions. See Appendix A for details on the carbon intensity of refinery configuration.

Ammonia

Ammonia, which is used primarily for fertilizer production, has extensive infrastructure (e.g., pipelines, rail) and uses SMRs and methanation to first produce hydrogen and then produce ammonia. In most cases, the ammonia uses an integrated hydrogen production process. SESAME analysis shows that to keep ammonia prices flat—avoiding charging customers higher prices—ammonia producers would need to switch to a clean hydrogen production process that is around \$0.78/kg H_2 (Figure 17). In certain scenarios, the IRA can create cost parity for the production of clean ammonia.

Figure 17

Scenarios of Cost Competitiveness of Clean Hydrogen in Ammonia Production



This figure shows the levelized cost of ammonia for conventional and low-carbon hydrogen-supplied options. Parity with the conventional option is achieved at $0.78/kg hydrogen price.

Shifting a relatively small number of ammonia plants to clean hydrogen could have a significant impact on emissions. Of the 30 largest hydrogen production facilities, there are six ammonia plants that account for over 1.3 Mt of hydrogen production per year. Retrofitting the facilities with SMRs or switching to merchant-delivered clean hydrogen could lead to a reduction of life cycle emissions of between 12 and 16 Mt CO_2e per year. The largest hydrogen-producing facility in the United States is an ammonia plant. At nearly 0.6 Mt H_2/yr, it is twice as large as the next largest hydrogen production facility (Box 6). Adding 90 percent carbon capture could lead to life cycle emissions reductions of roughly 5.0 Mt CO_2e. Decarbonizing all 32 operational ammonia plants would create 2.6 Mt of clean hydrogen and lead to more than 24 Mt CO_2e of emissions reductions.

Methanol

Methanol is used as a feedstock to produce chemicals and products like plastics and fuels. Methanol plants are among the most natural gas-intensive industrial facilities, requiring natural gas as a feedstock and for process heat. Replacing hydrogen with a clean feedstock (e.g., adding CO_2 capture to the SMR) is relatively straightforward. However, natural gas is significantly cheaper than hydrogen on a calorific basis, making its replacement as a heat source more challenging. Because methanol production uses carbon monoxide (CO) created during combustion, replacing natural gas with hydrogen for process heat requires the purchase of CO from a separate source at an additional cost. As such, fully replacing natural gas with clean hydrogen in methanol production

Box 6

CF Industries' Clean Hydrogen Ventures in Louisiana

In Donaldsonville, Louisiana, a single chemical manufacturing facility produces nearly 0.6 Mt H_2/yr—five percent of all hydrogen production in the United States. This CF Industries' facility is the largest ammonia producer in the world, including six large-scale ammonia plants in addition to four nitric acid plants, five urea production facilities, three urea ammonium nitrate plants, and a diesel exhaust fluid plant. The facility supplies nearly 4 Mt of ammonia to nearly every continent, making up around half of CF Industries' entire ammonia capacity. Around 400 full-time employees operate the 1,400-acre facility.[78]

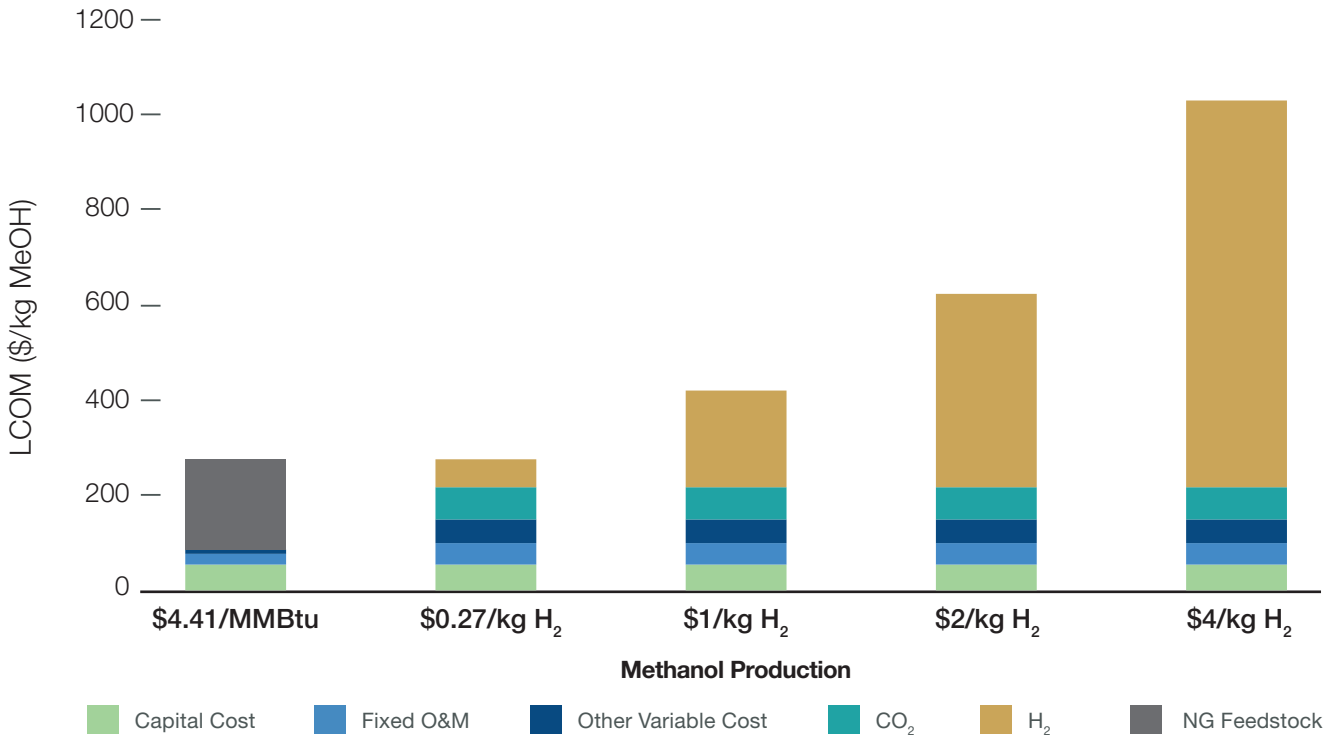
Hydrogen production accounts for most emissions in ammonia making. CF Industries is trying to reduce emissions through several clean hydrogen projects. The first project involves an engineering and procurement contract with the company thyssenkrupp for a 20 MW alkaline electrolyzer that will produce enough hydrogen for 20,000 t of green ammonia at the Donaldsonville facility.[79] The electricity will be sourced from renewable sources. Once completed, expected in 2023, it will be the largest green hydrogen producer in the United States.

CF Industries also announced a $200MM CO_2 capture project at the same facility. When complete, the capture units should help sequester up to 2 Mt of CO_2e, annually. In addition to 20,000 t of "green" ammonia, another 1.7 Mt of "blue" ammonia may soon be ready for consumption as well. CF Industries is also considering a separate "blue" ammonia manufacturing facility in Ascension Parish, LA. This $2B project, a partnership with Mitsui & Company, is currently in the Front-End Engineering Design (FEED) study evaluation phase and would be sited a short distance from a $4.5B blue hydrogen facility already being built by Air Products.[80,81]

is relatively challenging compared to other current hydrogen applications. Levelized costs for methanol plants to switch to clean hydrogen are shown in Figure 18. While the IRA could drive down the average costs of clean hydrogen to between \$0.80/kg H_2 and \$4/kg H_2, the cost parity for clean hydrogen with conventional sources in methanol production is around \$0.27/kg H_2.

Figure 18

Scenarios of Cost Competitiveness of Clean Hydrogen in Methanol Production



This figure shows the levelized cost of methanol for conventional and low carbon hydrogen supplied options. Parity with the conventional option is achieved at \$0.27/kg H_2. Methanol production cost is estimated at \$230/kg methanol.

Expanding Hydrogen's Use in New Industries

Around 40 percent of U.S. emissions are considered difficult-to-decarbonize due to the lack of clean alternatives or the complex operations and value chains that make decarbonization impractical.[g] According to DOE, four of these sectors can switch to clean hydrogen today for some portion of their market needs, including steelmaking, natural gas blending for industrial customers, and long-duration energy storage.[82] These sectors are considered "hydrogen ready" for purposes of this analysis.

Expanding hydrogen's use in hydrogen-ready, difficult-to-decarbonize sectors could rapidly lead to 4x growth in U.S. hydrogen demand and, in the near-term, reducing emissions by at least 50 Mt CO_2e. Targeting the hydrogen-ready, difficult-to-decarbonize

g "Difficult to decarbonize" sectors were determined based on 2020 emissions data from the EPA GHG Reporting Program encompassing stationary combustion from electricity and industrial applications, on- and off-road mobile combustion, and industrial process and product use emissions.

sectors also shows considerable near-term potential for market growth.

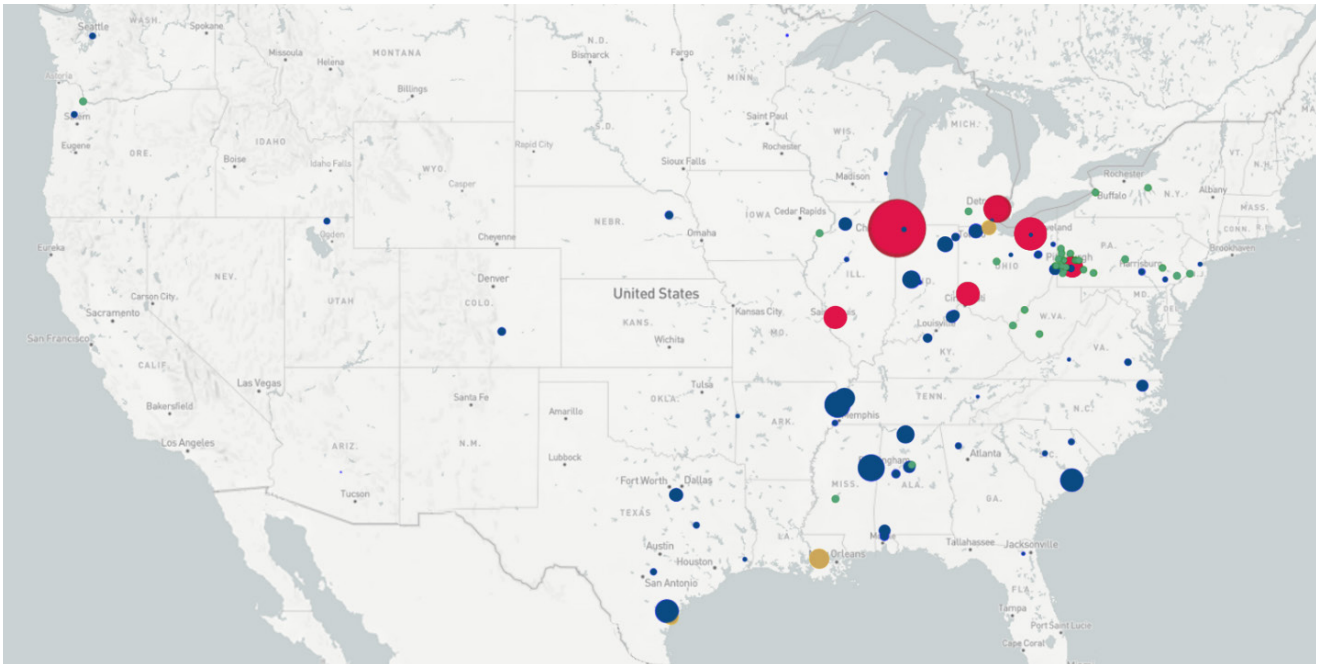
Steelmaking

There are more than 70 steel plants in 29 states across the United States (Figure 19). Nearly every clean energy technology is made of, and depends on steel, including solar panels, nuclear power plants, and windmills. U.S. steelmaking accounts for roughly 67 Mt CO_2e.[83] At the same time, the U.S. steel industry has made a commitment to reach net-zero emissions by midcentury.[84]

There are two primary steelmaking methods: Basic Oxygen Furnace (BOF) uses a blast furnace to produce "pig" iron. Direct Reduction Iron (DRI) uses natural gas to remove oxygen from iron ore, producing briquettes, that are then put in an electric arc furnace (EAF) to produce crude steel. In the United States, there are approximately 64 DRI/EAF plants and just nine BOF facilities. A variety of specialty steel mills are located across the country for rolling, extrusion, press braking, stamping, forging, and casting of crude steel. Some of these facilities already use hydrogen in small quantities for production and fabrication. There are also a growing number of DRI/EAF plants in construction or development that will add millions of metric tons of crude steel capacity to the U.S. portfolio, such as two major facilities in Kansas.[85]

Figure 19

Major Steel Production Facilities in the United States by Production Equipment and Capacity[90]



Electric Arc Furnace
Blast Oxygen Furnace
Direct Reduction of Iron
Misc. Steel Production Facilities*

Nominal Steel Production Capacity (Thousand Tons Per Annum)*

50 — 8,000

Does not include misc. steel facilities

This map shows existing steel production facilities in the United States by capacity and production pathway, including electric arc furnace, blast oxygen furnace, and direct reduction of iron. There are also many miscellaneous facilities focused on specialty applications. Across all methods and applications, clean hydrogen could be used to help decarbonize steel operations. Data from: Global Energy Monitor, 2022.

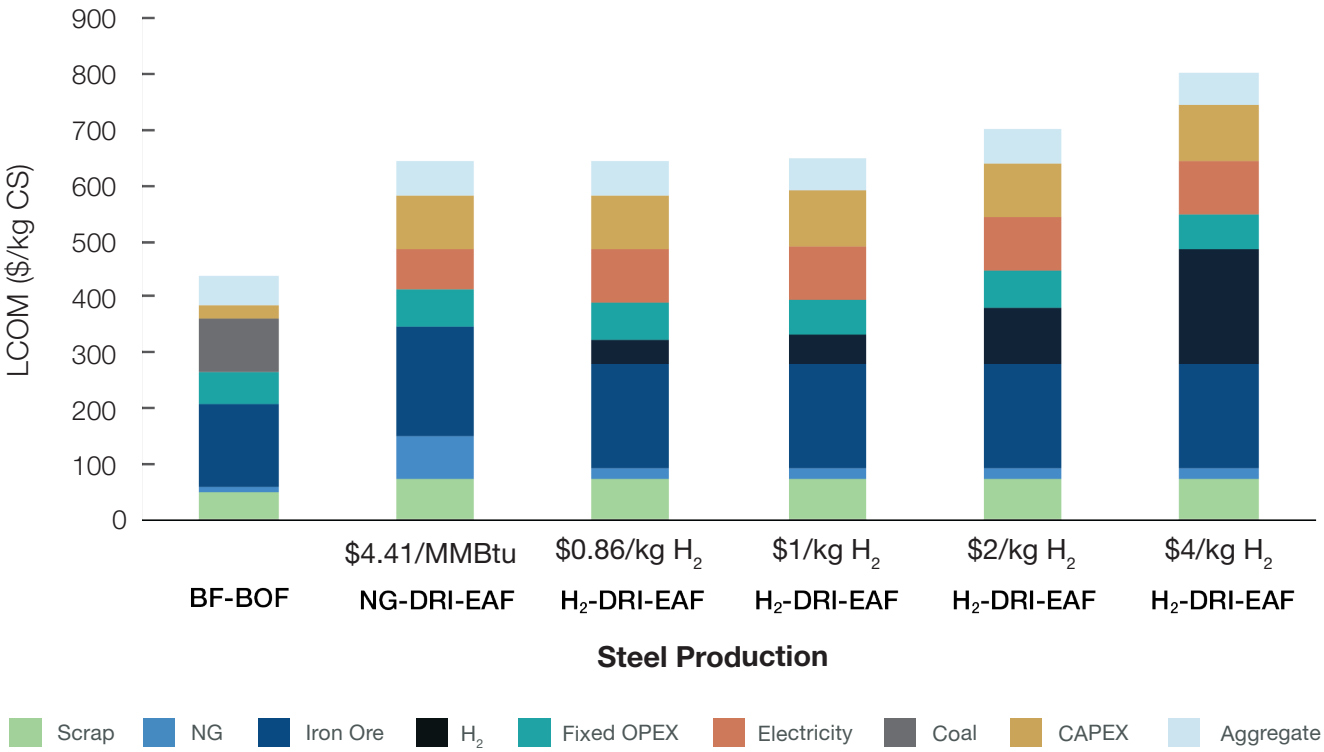
The U.S. steel industry is already considering options for transitioning to hydrogen. A DRI factory in Toledo, Ohio, Cleveland-Cliffs, is one of the largest suppliers to the U.S. automotive industry. According to the firm's CEO, it is relatively straightforward to switch to a 30 percent hydrogen blend today and a 70 percent blend could be achieved with limited modifications.[86] A 2020 DOE report noted that the "DRI process can use mixtures of hydrogen…up to 100 percent." Another study finds that a 30 percent (by energy) mix of hydrogen with natural gas is feasible without altering the production process.[87]

IRA's impact: Hydrogen is suited to decarbonize steelmaking as it can be used for both heat and as a chemical catalyst. Switching to hydrogen use for steelmaking can help address an emissions-intensive sector, expand the U.S. hydrogen supply chain in key regions, and create a strong demand signal for investors. Cost competitive hydrogen can lead to an overall emissions reduction of DRI/EAF by up to 30 percent.[88] No feasible option exists, however, for clean hydrogen to be competitive with BOF—even if the cost of hydrogen is \$0/kg H_2.

The IRA creates a promising path to switching to clean hydrogen in U.S. steelmaking, either as a blend in natural gas or as a direct replacement for natural gas for fuel combustion. It could make some clean hydrogen projects cost competitive for meeting the current needs of the steel industry. Clean hydrogen reaches cost parity with current hydrogen supplies around \$0.86/kg H_2 for DRI/EAF facilities. The levelized costs for steel plants to switch to clean hydrogen are seen in Figure 20. DOE's Hydrogen Roadmap includes steel in a second wave of hydrogen development, after 2030.[89]

Figure 20

Scenarios of Cost Competitiveness of Clean Hydrogen in U.S. Steel Production



This figure shows the levelized cost of crude steel for Blast Furnace-Basic Oxygen Furnace, Natural gas Direct Reduced Iron – Electric Arc Furnace (DRI-EAF) and Hydrogen DRI-EAF. Parity with conventional option is achieved at \$0.86/kg H_2. Even with \$0/kg H_2, current BF-BOF cost cannot be matched.

Hydrogen Blending in Natural Gas Pipelines

The existing U.S. natural gas system is one of the largest energy infrastructures in the world.[91] In 2021, the system delivered 32 percent of total U.S. energy consumption through three million miles of pipeline, 400 underground storage facilities, and 1,400 compressor stations.[92] It is operated by more than 200 private firms serving 77 million customers. Seventy percent of the mileage of the natural gas transmission system is classified as interstate pipeline, and most operators are subject to U.S. federal regulation.

Natural gas pipelines in the U.S. vary by type, size, capacity, length, and materials. Some run through regions that experience dramatic temperature changes; each line is operated under specific pressures to manage flows. Blending hydrogen into natural gas systems is not new. The U.S. natural gas system delivered manufactured gas containing more than 30 percent hydrogen until the 1950s.[93] The Island of Oahu, Hawaii has been using a synthetic natural gas product for decades that contains up to 15 percent hydrogen, carried through a 1,100-mile pipeline network.[94]

Targeting industrial clusters for hydrogen blending in gas pipelines can address the emissions reduction needs of difficult-to-decarbonize sectors, while tapping into captive demand. DOE estimates that 16 Mt of new hydrogen demand potential exists for natural gas blending in pipelines, assuming there is a large enough spread between industrial gas and hydrogen prices.[95] It is important to note that due to hydrogen's low energy density per volume, there is not a one-to-one ratio from an emissions reduction perspective from blending.[96] When a 20 percent hydrogen blend is burned, the avoided greenhouse gas emissions—from the displaced natural gas—is between 5 percent to 7 percent.[97] While the scalability of this pathway may be limited by technical blend rates, tapping into this new market still represents a significant scale of emissions reduction potential of 20 Mt CO_2e to 30 Mt CO_2e per year. Furthermore, it could play a key role in immediately jumpstarting new demand in sectors that are unfamiliar with hydrogen.

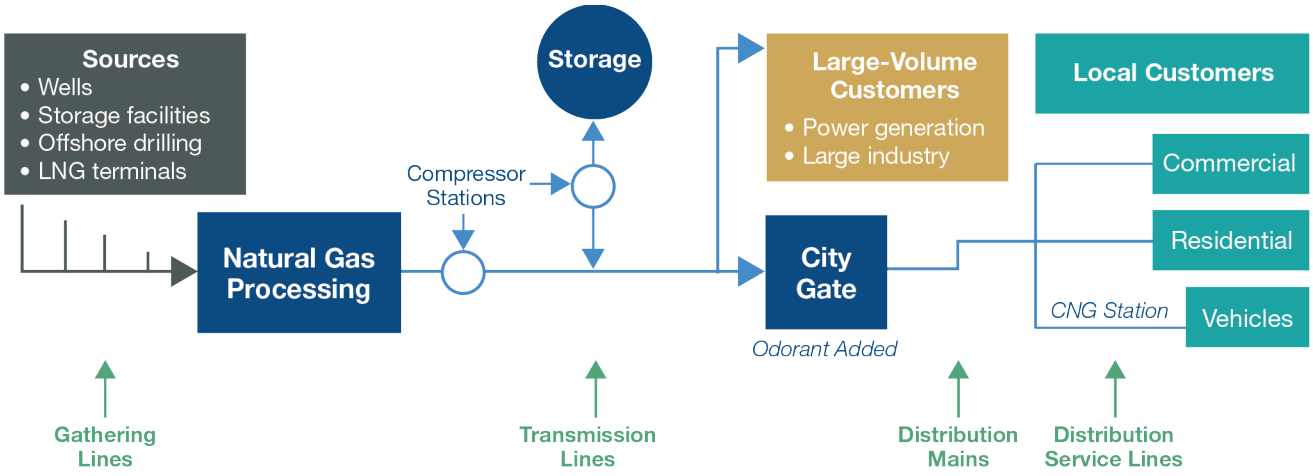
IRA's impact: Industrial customers accounted for one-third of U.S. natural gas demand in 2021. The most frequent uses of natural gas by the industrial sector are for process heat, a feedstock to produce chemicals, fertilizer, and hydrogen, and lease and plant fuel.[98] Many industrial customers are served by dedicated, large-diameter pipelines (Figure 21). Blending up to 20 percent hydrogen by volume into pipelines that feed industrial customers can support difficult-to-abate emissions, while accessing creditworthy offtakers to help finance clean hydrogen production projects and support the development of the supply-side market. Although DOE's hydrogen roadmap only includes hydrogen blending with natural gas in a third wave of development (after 2040), it also notes that blending applications can start during the first wave (until 2030) as long as costs decline considerably.[99]

Reports show that blend concentrations vary significantly by system design, operational profiles,

Industrial customers accounted for one-third of U.S. natural gas demand in 2021. The most frequent uses of natural gas by the industrial sector are for process heat, a feedstock to produce chemicals, fertilizer, and hydrogen, and lease and plant fuel.

Figure 21

Natural Gas Supply Chain and Transmission Spurs to Industrials[100]



This figure diagrams the current natural gas supply chain, composed of gathering lines, transmission lines, distribution mains, and distribution service lines. The yellow box denotes the dedicated, large-diameter transmission pipelines which service many of the industrial customers that could benefit from clean hydrogen for decarbonization. Source: NREL, 2013.

and product compositions.[101] Hydrogen can degrade certain steel pipes and is much more mobile than methane, which can increase safety and operational risks at higher blend rates.[102] Enhanced pipeline integrity management and monitoring systems are needed to assess the operational integrity and performance of blending infrastructure.

The benefits of hydrogen blending could be significant to hydrogen market development. This pathway also may reduce the need for new hydrogen infrastructure in early market development stages, while accessing difficult-to-decarbonize industrial sectors. This approach will require evaluating the readiness of each segment of the natural gas system, which could be both time-consuming and costly. Current strategies using blending of hydrogen in natural gas to create demand for hydrogen are already in place in the Netherlands, Japan, and Australia.[103]

Long-Duration Energy Storage and Load Following

There are multiple hydrogen applications in the electricity sector. Hydrogen can be used to power turbines, and many existing turbines can handle a mix of natural gas and hydrogen. To handle pure hydrogen, however, injection systems and combustion chambers need modifications.

Several utilities in the United States are experimenting with hydrogen blends in natural gas turbines and intend to completely transition to 100 percent clean hydrogen-fueled turbines by 2050.[104] For example, in 2020 the Long Ridge Energy Terminal in Ohio announced the transition of its 485 MW gas-fired power plant to a GE turbine that can burn hydrogen-blended gas streams up to 20 percent, and has already demonstrated functionality with hydrogen blends at five percent.[105] Also, the Intermountain Power Agency plant in Utah plans to convert its Siemens power turbines from 30 percent blends initially to 100 percent hydrogen by 2046.[106]

While most existing natural gas combined cycle (NGCC) turbines today can blend hydrogen up to about 5 percent, there are new turbines on the market that can burn anywhere from 15 percent to 100 percent hydrogen and that employ a whole new category of technologies.[107] Hydrogen, however, is currently not considered a "drop-in" fuel for most natural gas-fired turbines because higher-percentage blends require extensive plant modifications, such as alterations to fuel handling systems, valves, piping, and combustion hardware to reduce pollutant emissions, improve operability, and reduce long-term costs.[108] Plant operators need to consider differences in combustion properties between natural gas and hydrogen, impacts on the combustion systems, and changes to the energy balance of the plant to handle greater quantities of hydrogen.[109,110]

Clean firm power will continue to grow in importance to the electric grid in view of the buildout of intermittent renewable resources. Renewable energy sources, including wind, solar, and—now as droughts and glacier melts increase—hydropower, are indispensable for achieving U.S. decarbonization goals. However, their increased penetration creates challenges for the grid due to their intermittency and the duration limitations of current storage technologies. The changing dynamics of the system increase the need for a clean, on-demand backup source of electricity.

Natural gas fired generation provides electricity balancing to ensure reliable operations when the variable renewable resources are unavailable for minutes, hours, days, or, in some cases, weeks. One study developed in partnership between EFI and E3, found that to successfully decarbonize New England's electricity system, as much as 46 gigawatts (GW) of firm generation capacity will be needed to ensure resource adequacy—roughly the size of the renewables buildout.[111] This study also showed in certain decarbonization scenarios the firm capacity is infrequently used, though it is important for ensuring grid integrity during critical time periods. The emissions from current load following electricity resources, however, can account for up to 30 percent of the Scope 1 emissions from the power sector.[112] Box 7 provides greater detail on modeling an electric grid using hydrogen to balance load.

IRA's impact: Electricity is a highly regulated sector. Prices are driven by market rules and the cost of generation and the grid. While most electricity markets do not explicitly value long-duration energy storage, studies show that these systems could add much flexibility to the grid. The IRA incentives will likely make some clean hydrogen storage projects cost competitive with other long-duration energy storage technologies. Energy storage costs for clean hydrogen, including the 45V incentive (i.e., \$3/kg H_2), and other prominent storage technologies are shown in Figure 23. DOE's National Clean Hydrogen Strategy and Roadmap includes energy storage in the second wave of hydrogen development (after 2030).[113]

Hydrogen can also support the electric grid through fuel cells. Hydrogen fuel cells are significantly more efficient than conventional gas plants. The National Renewable Energy Laboratory (NREL) has been working on fuel cells for power generation and, according to its website, "will soon have a new research capability to demonstrate large-scale power production using hydrogen fuel cells in an integrated energy system. NREL is collaborating with Toyota Motor North America through a cooperative research and development agreement to build, install, and evaluate a 1 MW proton exchange membrane fuel cell power generation system at NREL's Flatirons Campus. This three-year, \$6.5 million project is funded in part by DOE's Hydrogen and Fuel Cell Technologies Office in the Office of Energy Efficiency and Renewable Energy and supports DOE's H2@Scale vision for clean hydrogen use across multiple applications and economic sectors."[114] The size of this project is, however, only one MW; fuel cells are currently more suitable

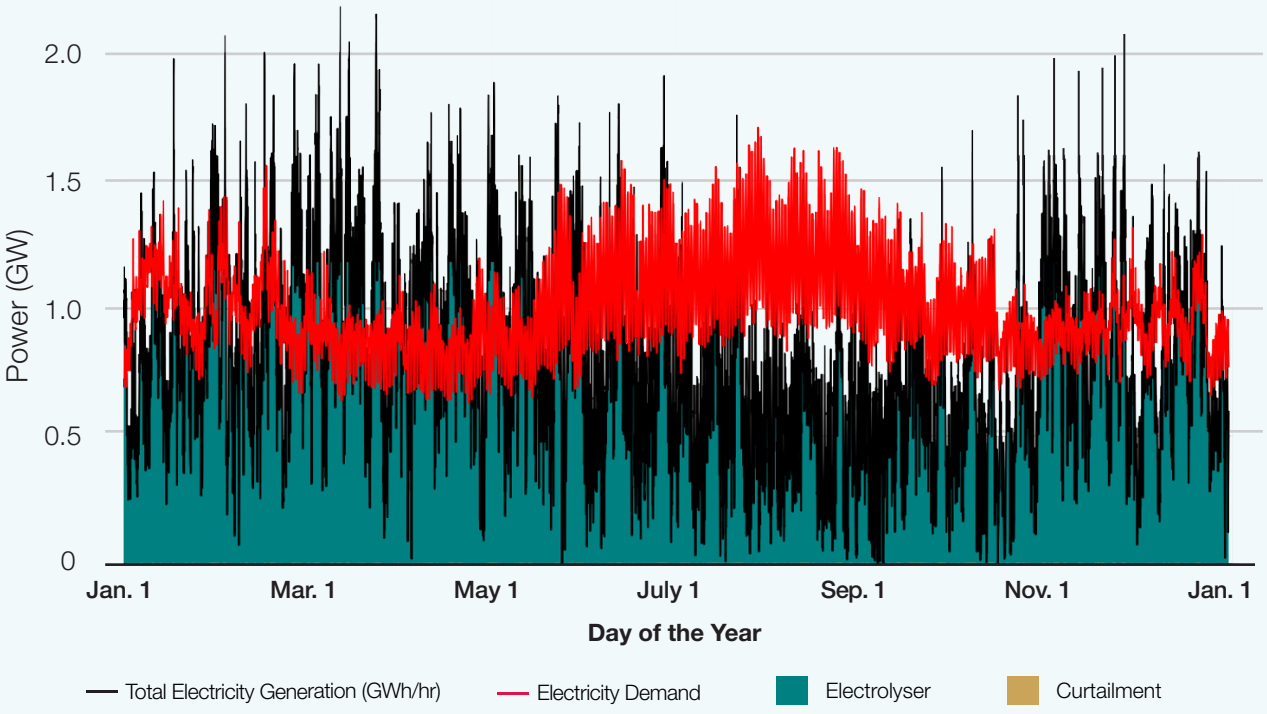
Box 7

Reviewing the Technical Feasibility of a Hydrogen-Supported Electric Grid

System modeling demonstrates that hydrogen can be integrated into electric grid operations for energy storage and load following. During periods of peak renewable generation, any supply that exceeds demand can be used to run an electrolyzer facility to produce green hydrogen, which can be sent to storage. To balance the grid when demand exceeds generation, a grid operator can call on stored hydrogen to produce clean electricity.

A detailed examination of one region, the U.S. Southeast, shows the technical feasibility of operating a system with hydrogen balancing using real energy data. In this scenario, the U.S. Southeast can produce enough hydrogen (~1 Mt H_2) during off-peak hours to manage the intermittency of renewable resources. Required is a hydrogen system buildout of 5.4 GW of electrolyzer capacity, 2,300 GWh of hydrogen storage capacity, and 23.5 GW of dedicated electricity generation (60 percent wind, 40 percent solar). The hourly operation of the U.S. Southeast, integrated with hydrogen, over the course of one year is shown in Figure 22. Between March-August, there is enough surplus renewables generation to produce the quantities of hydrogen needed to cover the winter months when electricity demand exceeds renewables production.

Figure 22
Southeast U.S. Hydrogen Production



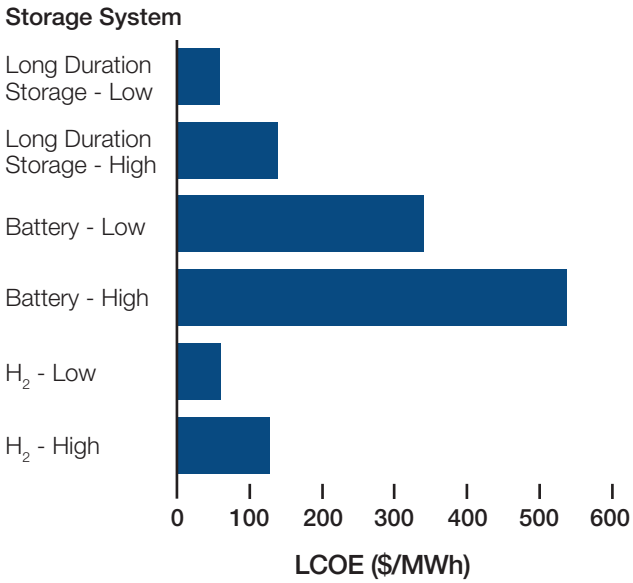
This figure depicts a theoretical scenario using hydrogen storage and power production for grid balancing in the U.S. Southeast over one year. The components shown here are electricity demand (red line), electricity generation (black line), and electrolyzer operation to produce hydrogen (green bars). Using real electricity cost, load profiles, and resource availability data for the U.S. southeast, this scenario assumes a mix of 65 percent wind and 35 percent solar.

for small-scale applications, such as providing backup power to a home or office facility.

When considering the fuel properties and the combustion system, the major challenge to scaling up is how to guarantee low NO_x emissions in systems that can use a range of fuel compositions, including pure hydrogen. This point is most relevant for power generation, as the air quality challenges increase as the amount of hydrogen burned grows. Today, existing "diffusion combustors" can operate on high hydrogen content-fuels and have high fuel flexibility (i.e., can use a range of hydrogen and natural gas blending levels, or pure hydrogen), but these systems result in high NO_x emissions and subsequently require high levels of water or steam injection to comply with emissions standards. Conversely, "lean, premixed combustors" can produce compliant emissions without water or steam by avoiding the high temperatures used in diffusion combustors that ultimately contribute to NO_x emissions. However, these premixed systems face operability concerns when using hydrogen blends.[115]

Figure 23

Levelized Cost of Energy Storage for Clean Hydrogen with 45V and Alternatives



The levelized cost of energy storage for hydrogen is calculated based on an electricity cost of $30/MWh, availability of solar electricity ~33 percent, and electrolyzer CAPEX of $800/kilowatts (kW) to $1300/kW. Cost of batteries is calculated using Li-ion batteries (high-cost case) with 92 percent round-trip efficiency and $277/kWh storage capital cost. For the low-cost case, redox flow batteries with 88 percent round-trip efficiency were used with a $171/kWh storage capital cost. The long duration storage low and high are based on estimates of pumped hydropower.

Recommended Policies to Drive Demand

Congress should significantly increase the funding for the regional clean hydrogen hub program, unlocking additional potential of these industrial clusters to jumpstart hydrogen demand. As noted, the IIJA provides $8B for the regional clean hydrogen hub program, which intends to develop six to 10 hubs.[116] As EFI's HyTF shows, there is untapped hydrogen potential in most U.S. regions and increasing the support of this program can accelerate the pace of market development. Funding another tranche of hubs would allow DOE the flexibility to leverage the lessons learned from the first group to improve its effectiveness.

DOE should focus its subsequent efforts on regional expansion, connective infrastructure, and the main enablers for broader market formation. This additional funding, for example, could facilitate regional hubs to demonstrate valuable hydrogen market enablers, such as supply chains, manufacturing of hydrogen-ready products, and transportation and storage infrastructure. There are regions that may not offer robust hydrogen supply resources but could support the domestic hydrogen value chain and critical operational functions of the market. These new regional hydrogen hubs could also establish linkages between different hub locations to support broader market formation.

Additional funding for this program could ensure strong alignment between domestic and international clean hydrogen hubs by sharing lessons learned and aligning approaches to determining the appropriate measures for carbon intensity, performance, and cost management. Opportunities to ship hydrogen, or hydrogen carriers, between international hubs could also demonstrate a critical area of need.

The Internal Revenue Service (IRS) should work with DOE and EPA to develop a pragmatic, and timely, phased approach to issuing 45V guidance. The most important aspect of initial IRS guidance will be the MRV of a project's life cycle emissions because the 45V credits are based on the full scope of a project's emissions. However, the tax credit's structure does not prescribe the temporal element of the life cycle emissions calculations. Initially, projects should be allowed to calculate emissions on an annual basis and be given the expectation that daily, and possibly, hourly units of measurement will be required in the future. This aspect is important for multiple production types that run on—at least partially—electricity from the grid. According to one DOE study, emissions from the electric grid can account for more than one-quarter of the life cycle emissions for a blue hydrogen project.[117] This is because steam methane reformers and carbon capture systems all require electricity. Green hydrogen projects that run on energy from the grid will be subject to the emissions intensity of the region's generating fleet. The IRS may also consider allowing producers to access predetermined offsets and clean energy purchases (e.g., renewable energy credits) to meet the carbon-intensity standards in the initial phase. A phased approach that enables investors to start the project development process in the near-term, but that also maintains flexibility to adjust key requirements over time, will be critical for activating early-mover investors.

The Federal Energy Regulatory Commission's (FERC) mission includes establishing the rules and regulations for key components of electricity and natural gas markets. Blending hydrogen into natural gas systems should be subjected to FERC's regulation of interstate natural gas systems in markets.

FERC should begin the process of regulating the blending of hydrogen into interstate natural gas pipelines. There is likely to be ongoing debate on what standards are needed for hydrogen blends. Pipeline operators who seek to blend hydrogen into their system will likely need to update the gas quality standards used to create FERC-approved tariffs.[118]

FERC's mission is, in part, to ensure that interstate pipelines deliver quality products that meet customer's needs. In the past, gas quality standards issues have centered on pipeline safety and heat rates—both concerns for blending hydrogen into existing natural gas systems.[119] FERC should begin proceedings to discuss the appropriate product standards for hydrogen to be blended into existing interstate natural gas pipelines.

The White House should develop new permitting strategies that enable regional clean hydrogen hubs infrastructure. Building on the recommendations from Senator Manchin's federal permitting reform strategy, released on September 21, 2022, the White House should designate hydrogen hubs as high-priority energy infrastructure projects.[120] This designation would demonstrate a national commitment to developing these industrial clusters.

In addition, identifying a lead agency to coordinate hydrogen hub permits is also recommended. As discussed later in Box 10, permitting clean hydrogen infrastructure is subject to complex regulations at the state and federal levels. This analysis finds, for example, that each hydrogen pipeline is subject to four fundamental federal and state permits and at least eight permits that are project-specific. Coordinating project permits, especially for the regional hubs, through a single federal agency could accelerate timelines for completion (and achieve much needed emissions reductions) as well as provide additional transparency and guidance for project developers.

The Administration should work with Congress to develop a public-private-partnership program for CO_2 storage management. One of the biggest challenges to CCS projects is the high coordination costs of developing the capture technology, CO_2 transportation, and geologic storage facilities. Each aspect of the CCS value chain is subject to its own financing, permitting, and operational requirements that often lead to unacceptably high risk for developers. For example, capture facilities are eligible to receive the 45Q tax credit (a tax code program), though they cannot receive the credit until after the CO_2 has been permanently stored or adequately managed under IRS guidance.[121]

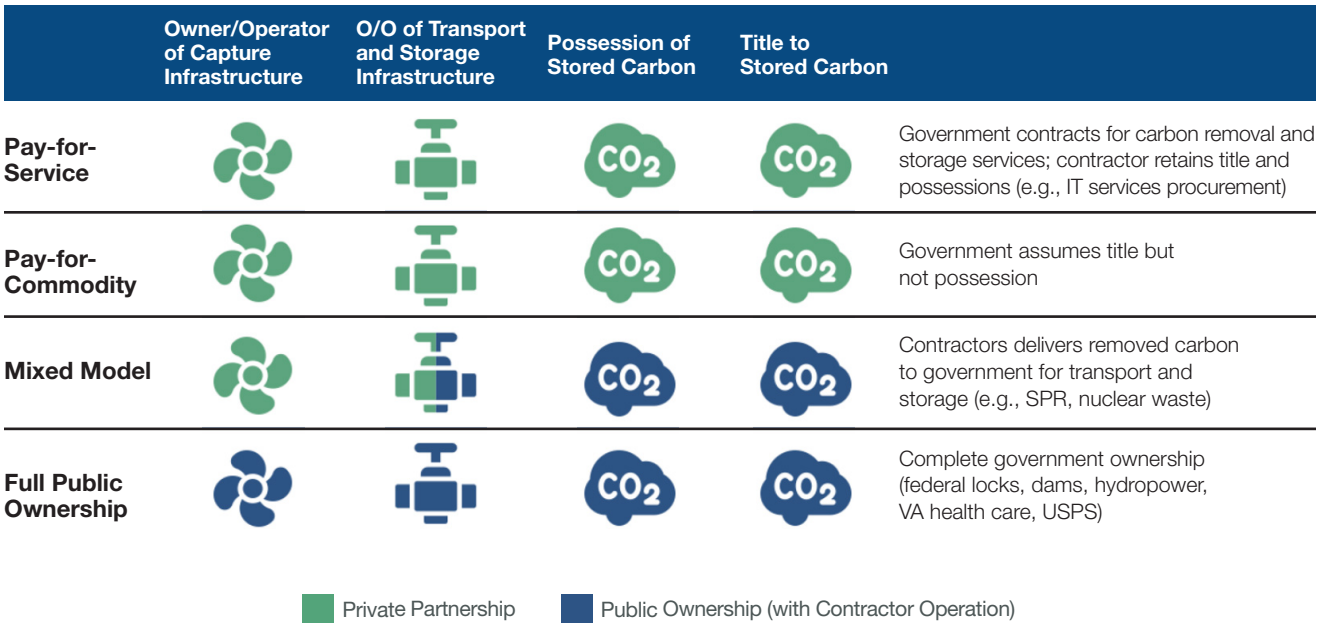
While the federal government has a long history of supporting CO_2 storage R&D (e.g., regional carbon sequestration partnerships), the private sector is developing most of the new CO_2 transport and storage projects.[122] The United States is estimated to have 3,000 miles of CO_2 pipelines, and firms have injected nearly 1,000 Mt CO_2, into the subsurface, with a current injection rate of 60 Mt CO_2/yr.

The federal government could develop public-private-partnerships (PPPs) to support targeted CO_2 storage projects designed to reduce the coordination challenges, by, for example, treating CO_2 management as an essential public service, like water supply, sewage, electricity, and telecommunications. These services may be managed by different structures with some form of government involvement and regulation. There are many associated scenarios to consider, including the ownership and operational structure, sources of financing, management of liability, and project permitting and siting. Figure 24 shows four possible ownership and management structures that highlight some of these design options. In December 2022, EFI released *CO2-Secure: A National Program to Deploy Carbon Removal at Gigaton Scale*, which details these structures and proposes the development of a direct federal investment program in CO_2 removal from the atmosphere and the oceans at gigaton scale by midcentury.

Federal procurement mechanisms can create new demand and help build out the U.S. hydrogen supply chain. President Biden's Federal Sustainability Plan outlines the pathways for net-zero federal operations by 2050. This plan focuses on the transition of federal infrastructure, e.g., zero-emission vehicles, buildings, carbon-free

Figure 24

Ownership and Management Design Options for a Large-Scale CCS Project[123]



If the government were to develop a public-private partnership for large-scale CO_2 management, there are four potential models ranging from full private ownership to full public ownership of the resource. This partnership scheme would focus on a handful of target CO_2 management projects and treat the management as an essential public service. Source: EFI, 2022.

electricity, and requires agencies to set goals to reduce GHG emissions.[124]

According to the Federal Energy Management Program (FEMP), federal agencies used 852 trillion (T) Btu of delivered electric and thermal energy in 2021.[125] In this context, such a plan would create many opportunities to expand the federal government's direct use of hydrogen to help support the decarbonization of its on-site fuel consumption, heavy-duty vehicles, and manufacturing and industrial process emissions (Table 3).

Given the extent of federal energy consumption, the direct use of clean hydrogen across the federal government would not only help achieve decarbonization goals, but it would also provide a major platform to stimulate early clean hydrogen market demand across the United States. For example, additional appropriations could facilitate relationships between DOE and other government agencies to transition fleets of marine vehicles away from diesel or fuel oil, as in a hub agreement between DOE and the Department of Homeland Security to reduce U.S. Coast Guard emissions. The Coast Guard has operations throughout much of the western hemisphere divided across 37 sectors.[126] The Houston-Galveston and New Orleans sectors in the Gulf have an abundance of Coast Guard activity and are heavily connected to thousands of miles of ammonia pipelines and waterways, and at least 17 major ammonia plants in the Midwest. Leveraging the existing infrastructure and ammonia plants already in place would serve as an opportunity to secure a domestic fuel source (at an established cost backstopped by the U.S. government), bridge different hubs with viable offtakers able to transport ammonia as needed, and eliminate emissions of hundreds of regularly operating marine vehicles.

Table 3

2021 Scope 1 GHG Emissions for the Federal Government (in t CO_2e)[127]

Greenhouse Gas Inventory: Government Totals	FY 2021		
Scope and Category	**GHG Emissions from Standard Operations (t CO_2e)**	**GHG Emissions from Non-Standard Operations (Military Operations, Law Enforcement, and Other) (t CO_2e)**	**Total Quantity Emitted Biogenic (t CO_2e)**
Scope 1: On-Site Fuel Consumption at Federal Facilities	**8,615,949.90**	**6,758.40**	**230,974.80**
Scope 1: Mobile Emissions—Vehicles, Aircraft, Ships, and Equipment	**1,323,031**	**32,340,969.10**	**8,292.50**
Scope 1: Mobile Emissions—Passenger Fleet Vehicles	**2,677,849.80**	**551,064.10**	**46, 953.60**
Scope 1: Fugitive Emissions—Fugitive Fluorinated Gases and Other Fugitive Emissions	687,582.70	327,463.60	
Scope 1: Fugitive Emissions—On-site Landfills and Municipal Solid Waste Facilities	8,840.80		1,540.40
Scope 1: On-Site Fuel Consumption at Federal Facilities	292,996.90		74,962.40
Scope 1: Manufacturing and Industrial Process Emissions	**186,792.50**	**0.0**	
Subtotal Scope 1	**13,793,043.50**	**33,226,255.30**	**362,723.70**

This table includes the Scope 1 GHG emissions from federal government operations during FY21. Scope 1 refers to on-site fuel consumption at federal facilities, mobile emissions from federal vehicles, fugitive emissions, and process emissions from federal manufacturing and industry. These emissions are categorized under standard operations, non-standard operations related to military and law enforcement operations, and biogenic emissions. The categories highlighted in bold are those with the greatest potential for the direct use of hydrogen to support federal decarbonization efforts. Source: DOE, 2021.

In addition to direct use by the federal government, FEMP could use its federal procurement system to encourage greater hydrogen use by its support contractors. FEMP's Energy Savings Performance Contracts (ESPC) tool could help enable such action.

An ESPC is a partnership between a federal agency and an energy service company (ESCO) that allows federal agencies to procure energy savings and improvements with no upfront capital costs or Congressional appropriations.[128] Although ESPCs focus primarily on energy conservation measures, a similar contract structure could be used for the adoption of clean energy, including clean hydrogen, with the goal of achieving energy savings that lead to GHG emissions reductions.

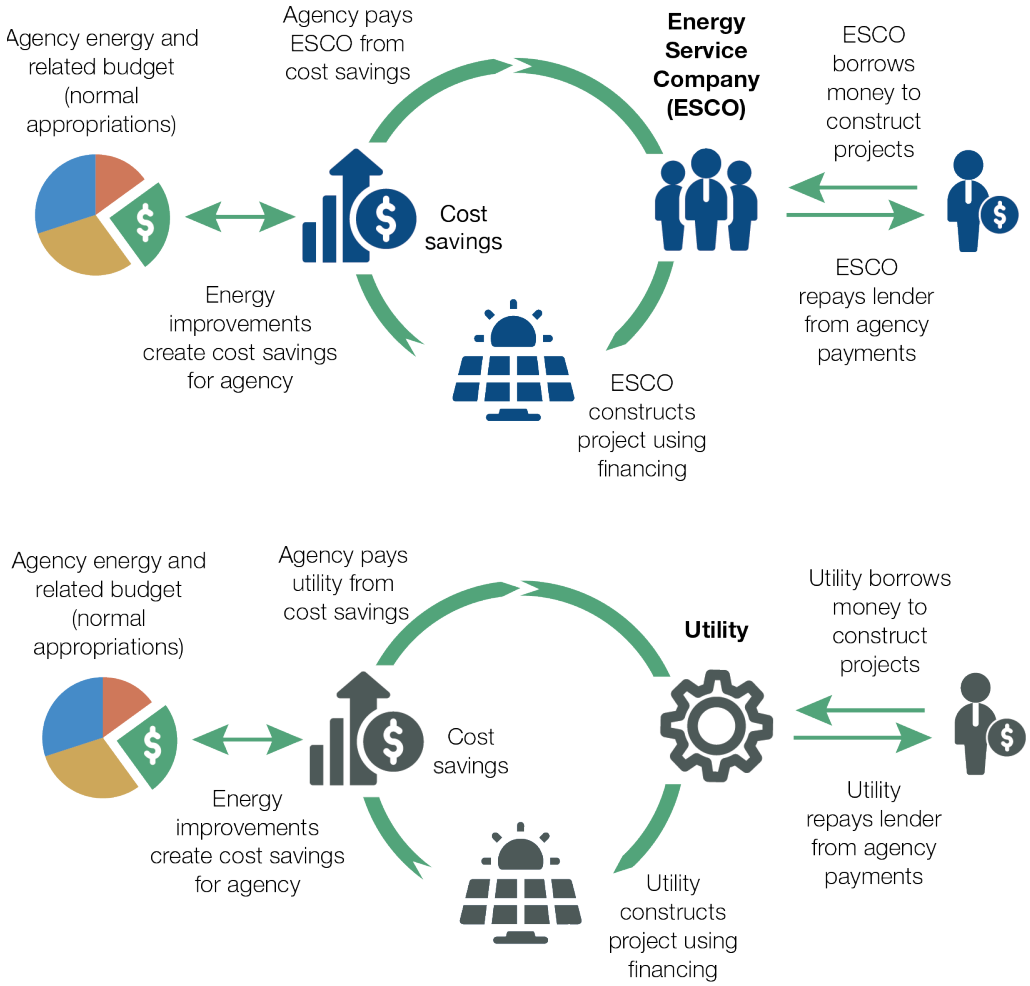
FEMP also facilitates utility energy service contracts (UESC) that are similar in structure to ESPCs and provide a streamlined approach for federal agencies

to receive energy management services from local utilities, including system retrofits and renewable energy systems (Figure 25).[129] Congress should consider expanding both federal procurement structures to encourage the use of and demand for clean hydrogen, or use them as models for a new procurement system for clean hydrogen applications specifically.

Another potential model for the federal clean hydrogen procurement is the Technology Modernization Fund (TMF), a funding model for federal technology modernization projects administered by the U.S. Office of Management and Budget and the General Services Administration. The proposal process involves two phases of project review by the TMF Board and funds are distributed incrementally based on performance and milestones agreed to in the proposal. The board reviews projects quarterly and can provide technical support for projects. Additionally, agencies with TMF projects make repayments to the fund based on the terms of the

Figure 25

ESPC and UESC Contract Structure Diagrams[130, 131]



The contract structures for ESPCs (left) and UESCs (right) are nearly identical, differing mainly based on the type of firm partnering with the government for federal procurement (energy service companies and utilities, respectively). In both cases, federal agencies are able to procure energy services with no upfront capital costs and ESCOs and utilities are able to have a guaranteed buyer in the federal government which increases investment certainty. Adapted from DOE, 2022.

project agreement.[132] This federal fund structure could be useful for clean hydrogen demand creation, as it provides agencies with flexibility to invest in new modernization projects while generating savings to the agency that will ultimately replenish the fund for future projects.[133]

DOE and the national laboratories, supported by congressional authorization and funding, should develop cross-functional centers of innovation focused on industrial decarbonization clusters. As noted in this analysis, industrial clusters can be critical for enabling decarbonization and are one of the best near-term options for de-risking new sources of demand. These activities, for clean hydrogen, as well as other pathways, are likely to grow in significance due to their "economy of effort," where the economics of project design studies, permitting, and construction are favorably supported by the co-location of hydrogen production and consumption.[134]

Despite limited historic federal investment in hydrogen R&D, there is a renewed focus on investing in clean hydrogen production technologies; the IIJA's $1B for electrolyzer R&D offers an example.[135] There, however, must also be a similar focus on R&D for industrial hydrogen clusters, systems integration analysis, understanding the technology, business, and operational bottlenecks, and identifying opportunities to improve the current approaches. The topics of investigation could include hydrogen safety, including solutions for advanced MRV of leaks from pipelines, projects, and throughout regional hubs. As noted in previous chapters, data collection and information sharing are core pillars of a successful hub, yet industry practices to date are unrefined, error-prone, and expensive.

A related topic for cross-functional analysis is technology and process solutions for controlling NO_x emissions during hydrogen combustion. An example is found in the National Infrastructure Simulation and Analysis Center (NISAC), a collaboration between Los Alamos National Laboratory and Sandia National Laboratories. NISAC provides analytical support to a range of federal agencies and other stakeholders on the challenges posed by the interdependencies of critical infrastructure. This multidisciplinary approach by NISAC helps industry players understand the risks of physical and cyber energy systems, for example. A similar structure could be developed to support similar needs for controlling NO_x emissions. This recommendation for an NISAC-like structure aligns with DOE's Industrial Decarbonization Roadmap, which describes the need to prioritize these sectors, improve the tools for assessing the opportunities to lower emissions, and the need to integrate new technologies into process systems to reduce energy and emissions.[136]

A credit trading system, similar to renewable energy certifications (REC), could be used to help manage receipts and create new investment in hydrogen blending. According to the EPA, a REC is a market-based instrument representing the property rights to the clean attributes of renewable electricity generation.[137] RECs are issued for each MWh of electricity generation; a similar credit trading system could apply to natural gas with a specific blend content of clean hydrogen.

Many large industrial customers currently receive natural gas via dedicated pipelines. There could be a substantial benefit to employing a system for managing hydrogen blending from source to end use. To support new investments in clean hydrogen, regulatory design for hydrogen blending could issue credits similar to an REC to help track the products and create a mechanism for the trading of credits. This approach would be especially beneficial to industrial customers and could help create economic incentives for: 1) using curtailed renewables for hydrogen production; 2) improving the carbon-intensity of the natural gas grid; and 3) encouraging the output from existing renewable energy facilities.

According to DOE, understanding the techno-economic potential and spatial logistics associated with this type of energy storage and hydrogen delivery system would require additional analysis.[138] Guarantees of origin programs are being explored in Europe and other countries to facilitate the emerging clean hydrogen market. These schemes enable customers to determine the source, and emissions content, of the hydrogen they purchase.[139]

3 INDUSTRIAL STRATEGIES FOR HYDROGEN MARKET FORMATION

Chapter Insights

Meeting the economic and decarbonization objectives of the IIJA's regional clean hydrogen hubs program will require coordinated planning.

The transition to net-zero emissions will also depend on an unprecedented transition of the U.S. workforce. Nearly half of workers in industries vulnerable to the clean transition, e.g., coal mining, oil and gas extraction, petroleum, have skills that could support a clean hydrogen economy.

Using HyTF in case studies based on EFI's regional hydrogen workshops, the tool suggests there are unique opportunities for each region. In the Carolinas, there is significant buy-in from industry leaders and existing hydrogen expertise to support demand from "bankable" offtakers utilizing the region's extensive infrastructure. HyTF shows that the Ohio River Valley's vulnerable communities geographically overlap with existing labor capabilities and heavy industry that could support hydrogen development. HyTF also identifies the significant existing industrial clustering in the Gulf Coast that could immediately jumpstart a shift to clean hydrogen use.

Recommendations for Hub Design

EFI has developed Industrial Strategies, based on tested economic frameworks to guide regional hub development in key five areas. These include the following recommendations:

The Governance Plan should ensure all hub participants are aligned and that the project meets IIJA's objectives, including driving market growth. Each hub will need a strategy for engaging federal and state regulators, especially for electric utilities.

The Business Plan should guide the management of the initial capital investment and attract new resources. A regional hub will likely involve multiple projects, with their own costs and revenues that must be managed effectively. How each hub will expand should also be integrated into the planning.

The Infrastructure Plan should help stakeholders coordinate system builds, permitting, and integration with new markets. This plan could include engaging upstream energy providers, especially for monitoring life cycle emissions; and local communities that may be impacted by project development.

The Workforce and Community Engagement Plan should align the hub with frontline community issues and ensure these critical stakeholders are engaged early and often. This should include opportunities for hubs to support community-specific needs beyond decarbonization, such as air quality, employment, and energy resilience.

The Innovation Plan should anticipate technology turnover and innovation, share insights across stakeholders within and between hubs. These plans should also seek to address some of the key research issues that the regional hubs aim to demonstrate, such as managing life cycle water consumption.

Overview of U.S. Regional Clean Hydrogen Hubs

The IIJA created the H2Hubs Program to address multiple challenges facing hydrogen technology and market development. Currently, there is a large U.S. hydrogen industry but there is no liquid market, i.e., one with many available buyers and sellers, and extremely little clean hydrogen production or use. To address these challenges, the IIJA calls for each H2Hub to establish "a network of clean hydrogen producers, potential clean hydrogen consumers, and connective infrastructure located in close proximity."[140]

The IIJA also funded the Office of Clean Energy Demonstrations (OCED) at DOE to administer over $20B in funding for projects, including the regional clean hydrogen hubs.[141] The OCED essentially serves as a management coordinator to help implement these projects, releasing a Request for Information (RFI), a Notice of Intent (NOI), and an FOA, which opened applications for funding in September 2022.[142] Concept papers were due in November 2022 and the deadline for full application is April 2023.[143] As of January 2023, DOE's H2Hubs program has encouraged 33 out of the 79 regional concept paper proposals to proceed to the FOA's full application.[144]

The release of the OCED's FOA in September 2022 for the H2Hubs program provided both the kickoff for applications for H2Hubs, as well as a high-level draft plan for its current vision to meet the H2Hubs program requirements; this plan includes a multi-phased approach over several years (Figure 26). Concept papers that describe the project scope include development, finance, community and labor engagement plans and timelines, as well as show how hubs will contribute to broader market formation and the achievement of decarbonization goals; these papers were due in November 2022. Full applications are expected in April 2023 and awards will be announced in Fall 2023.[145] DOE expects to select 6 to 10 hub proposals for advancement past the first phase of concept planning.

Figure 26

Summary of Activities and Outcomes in Each Phase of H2Hub Projects[146]

APPLICATION ➤ PHASE 1: DETAILED PLAN ➤ PHASE 2: DEVELOP, PERMIT, FINANCE ➤ PHASE 3: INSTALL, INTEGRATE, CONSTRUCT ➤ PHASE 4: RAMP-UP, OPERATE

Initial Application — Go/No Go Decisions

$0.4B - $1.25B Total DOE Funding; Non-Federal Cost Share ≥ 50%

		Pre-DOE Funding	Up to $20M DOE Funding, ~12-18 Months	Up to 15% of Total DOE Funding, ~2-3 Years	DOE Funding to Be Negotiated, ~2-4 Years	DOE Funding to Be Negotiated, 2-4 Years
Technical Volume	**Business Development and Management**	• H2Hub Summary • Business Plan (BP), including preliminary site selection • Management Plan (MP) • Financial Plan (FP)	• Market, feedstock, and offtake letters of commitment • Final site selection • Financial model • Updated BP, MP, FP	• Teaming, offtake, and feedstock agreements • Site access secured • Confirmed project financing • Updated BP, MP, FP • Labor agreements	• Regular progress/ status reporting for all agreements • Regular financial status reports • Other reporting per terms & conditions (T/Cs) • Updated BP, MP, FP covering Phases 3-4	• Financial model updated with offtake and production data • Revised growth plan and projections • Updated BP, MP, FP covering ramp-up and steady state operations
Technical Volume	**Engineering, Procurement, Construction, and Operations**	• Engineering concepts (~5%) • Technology Readiness Level (TRL) descriptions • Integrated Project Schedule (IPS): Full Project - L1; Phase 1-2 • Class 4 Total Project Cost (TPC) estimate • Operating and disposition concepts	• Engineering & Design concepts (~30%) and related documents • Performance model • TRL analysis and uncertainties • IPS: Full Project - L2; Phase 2-L3 • Class 3 TPC estimate	• Engineering & Design concepts (~90%) and related documents • TRL updates • IPS: Full Project - L3 • Class 1 TPC estimate • Standard project management tool in use • Updated Operating Plan • Updated Disposition and Decommissioning (D&D) Plan	• Progress execution reporting • Integrated project completion testing	• Regular operations status reporting • Performance ramp verification and validation (V&V) • Validated performance model • Final TPC accounting
Technical Volume	**Safety, Security, and Regulatory Requirements**	• Safety history/culture description • Permitting workflow overview • Environmental Considerations Summary	• Initial Safety Plans (hydrogen and site; 30% design) • Cybersecurity Plan • Environmental Information Volume	• Execution-ready Safety Plans (hydrogen and site; 90% design) • Final Cybersecurity Plan • Permits in place for construction • Complete environmental reviews/assessments	• Status reporting on required permits and environmental • Safety and security incident reporting and audits • Permits for operations	• Ongoing permit, safety, and security reporting
Technical Volume	**Risk Analysis and Mitigation**	• Risk Management Plan (RMP) • Risk Register	• RMP, Risk Register updates	• Quantitative risk analysis • RMP, Risk Register updates	• RMP, Risk Register updates • Periodic quantitative updates	• Tech risk updated for operations • Ongoing risk reporting
Technical Volume	**Technical Data and Analysis**	• Preliminary Techno-economic Analysis (TEA) • Preliminary Life Cycle Analysis (LCA)	• Updated TEA • Updated LCA	• Mature LCA • Mature TEA with risk analysis • Technical Verification & Validation (V&V) Plan	• Periodic TEA and LCA updates • V&V data collection and analysis	• LCA and TEA incorporating operational data • Ongoing data collection and dissemination
Community Benefits Plan (CBP)	**Community Benefits: Job Quality and Equity**	• Initial plan, including: • Community and labor Engagement • Investing in the American Workforce • Justice40 Initiative • Diversity, Equity, Inclusion, and Accessibility (DEIA)	• Implement Phase 1 scope of CBP • Update CBP for future phases based on activities and lessons learned, including documentation of stakeholder engagement status, workforce development, Justice40 implementation, and documentation of extent of community consent	• Implement Phase 2 scope of CBP • Measure and report on all CBP metrics • Update CBP for future phases based on activities and lessons learned	• Implement Phase 3 scope of CBP • Measure and report on all CBP metrics • Update CBP for future phases based on activities and lessons learned	• Implement Phase 4 scope of CBP • Measure and report on all CBP metrics • Final reporting including accomplishments, findings, and plans for steady state operations

Each H2Hub proposal will entail a detailed application that requires plans for business development, operations, safety, risk analysis, data analysis, and community benefits. If chosen, H2Hubs would be required to maintain a multi-phase project timeline that institutes activities and deliverables from the planning phase through permitting and finance, installation and construction, and eventual operation. The intention is for execution of these plans to take place on an 8-year to 12-year timeframe. Adapted from: DOE, 2022.

The FOA established several requirements for successful applications. Hubs must demonstrate deployment of regional hydrogen infrastructure, reduce greenhouse gases and criteria pollutant emissions across the full project life cycle, produce at least 50 t to 100 t of clean hydrogen per day, and ensure a balance between clean hydrogen production and consumption. The FOA also states that these targets will help DOE achieve its "Hydrogen Shot" goal. Moreover, projects that source domestic resources and components will be considered favorably. Applications must also include a risk mitigation strategy that encompasses technical, construction, regulatory, permitting, safety, scale-up and infrastructure integration risks and describe whether the proposed technologies and systems are commercially viable. Projects that successfully demonstrate financial, and market viability beyond DOE funding, including non-federal cost share sources, and leverage available regional resources are preferred. An adequate business plan, which details revenue sources (financing, acquisition strategies, power purchase agreements, feedstock supply, offtake agreements) and costs, must also be included in applications.

In addition, a workplan that details the project timeline and schedule, metrics, and Go/No-Go criteria is required. DOE also requires a Community Benefits Plan that describes how local communities and workforce will be supported. Hubs must show potential to create high quality jobs and attract, train, and retain skilled workers, as well as "ability to support the overall goal of the Justice40 Initiative that 40 percent of the benefits of the overall investments flow to disadvantaged communities."[147] The degree that H2Hubs can leverage technological diversity, optimize available DOE funding, involve industry and community, among others, are also sought in successful hub applications. When a hub is selected and operational, it "will be required to collect and submit hydrogen-specific safety related data (e.g., component failure) during the period of DOE project funding."[148]

Recommended Industrial Strategies for Regional Clean Hydrogen Hubs

Meeting the economic and decarbonization objectives of the regional clean hydrogen hubs will require careful public-private coordination. Tested economic frameworks exist for creating efficient and effective industrial activity through government supported geographic clustering. Active regional clean hydrogen hubs exist in around 20 countries (Box 8), and industrial parks, special economic zones, research hubs, and economic clusters, are all examples of this approach.[149] Each of these examples of "industrial policy" involves government-driven economic outcomes. Applied to hydrogen, the industrial hub model can help stimulate market demand by de-risking investments and allowing participants to pool resources, jointly manage costs, and coordinate infrastructure development. Congress and DOE, through its RFI, NOI, and FOA provided clear technical, performance and managerial requirements for each hub.

Due to the nascency of clean hydrogen and the overall complexity of building and operating regional hydrogen hubs, however, there are five Industrial Strategies that could help guide the development of these regional clean hydrogen ecosystems for hub Governance, Financing, Infrastructure, Workforce and Community Engagement, and Innovation (Figure 27).

Figure 27
EFI's Regional Hub Design Strategy

EFI's Regional Hub Design Strategy includes five Plans that focus on governance, business, infrastructure development, community and workforce, and innovation priorities that will guide development beyond the current policy requirements. These Design Plans align with the five objectives of the Hydrogen Demand Action Plan to foster hub development and broader clean hydrogen market formation.

Governance Plan

DOE's H2Hubs are expected to leverage the expertise of several project partners.[150] Building successful regional clean hydrogen hubs will depend on strong governance. Each hub should be developed by a consortium that leverages existing resources, infrastructure, and market opportunities to demonstrate a network of clean hydrogen supply, demand, and connective infrastructure.[151] This consortium will involve multiple projects across multiple sectors and may involve multiple states; this combination will create complex development issues. Ensuring that the H2Hubs meet their targets for hydrogen production emissions-intensity, job creation, and new investment will depend on close coordination between all relevant participants, focusing on project planning and execution, community engagement, and growth.

Experience suggests that consortia that have been implemented thus far are considered a best practice among hydrogen hub developers. For example, according to the Hydrogen Valleys report, which

compiled data on hydrogen hub development around the world, most industrial hubs have more than 10 stakeholders from across the value chain of the hub in question (from production to end-use), while 40 percent have more than 15 stakeholders.[152]

A regional clean hydrogen hub may require the development of new energy infrastructures, such as carbon capture and storage and zero carbon electricity, and hydrogen. Each of these value chains involves upstream, midstream (albeit limited), and downstream components that support each hub. Transforming these often-disparate systems into a coordinated hub will depend on close coordination and planning by hub governance and operations. DOE requires H2Hub teams to be led by "a single entity (prime applicant) and envisions that each H2Hub will likely include multiple partners." It asks that applicants describe "management and operations strategies to be employed in executing on the H2Hub activities" and should further ask applicants to detail how this entity would be responsible for developing and executing project plans.[153]

Each regional hub should appoint a single governing entity to act as the development corporation, ensuring that all aspects of the project are coordinated and aligned with national policy goals, activities, and targets (Box 8). By designating (or developing) a single governing entity, the participating companies can closely coordinate, administer, and develop these multi-faceted projects. More than 70 percent of hydrogen hubs globally have a dedicated governance mechanism in place, established during the project's planning stage, and one third have a single governing entity to manage the project.[154] Hydrogen hubs around the world report that the official legal structure, clear rules, and delegation of responsibilities facilitated by a single governing entity positively contribute to their competitiveness.[155]

Box 8

Regional Industrial Hub Examples

Internationally, there are around 20 government-led efforts in many regions of the world to accelerate hydrogen market development through industrial clusters. A number of them include hydrogen in their government-supported industrial policy strategies. In the United Kingdom (UK), for example, the "UK Hydrogen Strategy" (2021) set funding and performance targets for hydrogen production and consumption and identified regional hubs as critical for "exploring investment signals and necessary amendments to legislation, regulatory frameworks and potential access to financing for hydrogen network projects in the early 2020s and the 2030s."[156] According to the strategy document: "Government action will be required to put in place a wider policy framework…and to work through key issues such as policy governance."

In 2020, the UK Research and Innovation (UKRI) announced the winners of the second phase of the Industrial Strategy Challenge Fund competition. UKRI awarded roughly $8.0 million across six projects aimed at demonstrating new approaches to decarbonizing industrial hubs. Each winning project is asked to bring together industry and government in each region to "devise a route to net zero emissions."[157] Each project involves a governing lead that must ensure the participants meet their goals to provide insights on industrial decarbonization strategies that can be scalable and replicable across the UK. The participants include a combination of consultancies, development companies, local authorities, partnerships, and consortiums.

The governing entity could help ensure that fundamental technical requirements are met, including hydrogen production volumes and carbon intensity metrics. The participating companies, working through the governing entity, could establish the project scope and development plans, setting clear by-laws for its functioning. A governing entity could also be a single point of contact and coordination for interactions with governments, local and regional stakeholders, and labor and community groups. It could coordinate activities for land development, infrastructure, facilities, utilities, and other key enablers, as well as the permitting and regulations needed to develop each stage of the regional hub. The governing entity could also lead the marketing activities to attract investors.

Importantly, one of the main responsibilities of the governing entity would be managing the MRV scheme for the hub. A robust MRV program could help address leaks and operational setbacks as soon as they occur. Long term, this MRV program will be critical for ensuring safe operation of the hydrogen ecosystem. Data would be shared within the hub, with the relevant government agencies, and could be distributed to other regional hubs for situational awareness and lessons learned.

The energy sector is highly regulated, especially in the electric utility sector—a critical sector for meeting the U.S. Nationally Determined Contribution (NDC) targets, which include a carbon-free electric grid by 2035. [158] Utilities will also be major players in regional hydrogen hubs both as direct participants and as upstream energy suppliers. Many utilities are regulated by state-level authorities that must approve the primary planning and operational strategies, including the transition to clean generation. In many cases, regulators will need to approve of, and be aligned with, utility participation in regional hubs. Each regional hub should work with DOE and relevant regulatory agencies, e.g., the EPA, state public utility commissions, and others, to ensure that policymakers and regulators are aligned with the existing and future hub plans. A coalition of federal agencies, working with energy sector regulators, could help improve the communication, coordination, and alignment of the regulators with the strategic objectives of the regional hub programs. Such alignment will likely help accelerate and enable regional hub development.

In addition to project coordination, the governing entity will need to drive market development and growth. The IIJA is clear that H2Hubs will be essential for

forming the "foundation of a national clean hydrogen network."[159] Developing strong PPPs, engagements with local and regional communities, and a plan for building a hydrogen-ready workforce will be critical components of the growth strategy.

The governing entity should also develop strategies for new firms to enter and exit the hub, ensuring that regional expansion is compatible with technical performance requirements. Finally, the governing entity can help manage data creation, standardization, and sharing within the hub (and possibly with DOE and other regional hubs). This approach will be important for encouraging new investment.

In Europe, New Energy Coalition coordinates the HEAVENN hydrogen hub project. Best practices and lessons learned from the hub are being collected and translated into a model that will inform the creation of other projects (replications are expected to take place in Denmark, Aragon, in Spain, Orkney, in the U.K., Northwest Germany, and Ireland). These replications could help leverage international cooperation to increase market size and create economies of scale, thus facilitating access to investment capital and de-risking investment throughout the European Union (EU) and beyond.[160]

Business Plan

Regional clean hydrogen hubs must develop a unified project business plan, a DOE requirement for H2Hubs applicants. Besides DOE's FOA that asks for detailed revenue sources and costs, contracts, permits, and agreements, the rationale for site selection, market and commercial feasibility analyses, and a growth plan, the business plan should also include managing the initial capital investment from the DOE H2Hubs program, which offers substantial funding of $8B total for at least four hubs, with up to 50 percent cost share with non-federal entities such as state or local governments, or other third-party financing. Consideration for project selection should also include the rules for managing cost and revenues of the hub and its component projects.

Each hub will also need a plan for attracting additional capital from private and public sources. According to DOE's NOI, "each H2Hub will demonstrate…a plan to be financially viable after the DOE funding has ended."[161] Hub developers around the world have stated that one of the main hurdles that projects have to overcome is developing a successful business plan, with a sound project concept as its foundation that covers the entire hub value chain and technology choices, as well as a detailed assessment of the project's capital and operating costs, expected revenues and funding needs, and the hub's competitiveness compared to alternative solutions.[162]

The business plan should also include strategies for leveraging additional government support. As noted, the IRA provides new incentives across the hydrogen value chain, including a hydrogen PTC, extended 45Q tax credits, support for new clean electricity generation projects, incentives for zero-carbon vehicles (including hydrogen), and many other provisions that could be leveraged by a regional clean hydrogen hub. There are also state-level incentives, such as the California LCFS, for which a hub may be eligible. A coordinated approach to stacking government policy support, where possible, will likely be critical to ensuring the long-term success of a regional hub. Around 90 percent of hydrogen hubs around the globe still rely, in part, on public funding, which is seen as essential to close investment gaps during the project's financing phase.[163]

H2Hubs are expected to provide letters of commitment or term sheets (including power purchase agreements) for prospective feedstocks and other suppliers, and prospective customers/offtakers (the latter, if available).[164] As such, the business plan for a regional hydrogen hub will need to manage costs and revenues across stakeholders. As noted, a regional hydrogen hub will likely include multiple projects, each with capital and operating costs and revenue streams. The business plan will need to allocate costs, revenues, and various policy incentives across stakeholders. One source of revenue, for example, may be hydrogen sales to an industrial facility that is a hub member. Those

revenues may be reinvested into the hub. Meanwhile, in the same hub, hydrogen blended into a natural gas pipeline may collect revenues from customers outside of the hub corporation. It will be up to the members, working through the governing entity, to develop cost and revenue strategies. A combination of these different business models to leverage additional revenue streams and clear contractual relationships between the hub and its customers (e.g., hydrogen purchase agreements) will contribute to the financial sustainability and de-risking of the entire hub project.[165]

Important business plan considerations exist for each hub's growth strategy. Because one of the goals of the IIJA funding is for hubs to form the foundation of a national clean hydrogen network, it is necessary that the business plan includes a growth strategy. DOE's H2Hubs FOA explicitly calls for a growth plan for expanding the proposed hub beyond the award performance period.[166] A growth strategy may involve how the hub takes on new investments and stakeholders, while meeting the IIJA's technical requirements; managing the regional stakeholders; and sharing costs and revenues within the hub.

Access to outside finance can, however, be challenging for large capital-expenditure requirements, especially those with uncertain demand, like hydrogen. Securing funding, either private equity funding through the participating private stakeholders in the project or through debt, is seen as a key element to guarantee the growth of hydrogen hubs. [167] A business plan must consider these and other avenues for enabling sufficiently large, consistent, and durable financing to pay down all capital and provide a fair return on top of the cost of ongoing operations. DOE expects applicants to detail such information in the hub's financial plan.[168]

According to hub developers around the world, a key lesson for emerging hubs is to "build a growing network along the value chain very early on and to keep investing in the collaboration of stakeholders."[169] Regional hubs should work closely with existing infrastructure owners on business opportunities and impacts. For example, the Port of Los Angeles has partnered with Shell Oil Products USA to build and operate two large capacity hydrogen fueling stations in Wilmington and Ontario, forming a hydrogen network infrastructure in Southern California.[170] To expand this network, the Port of Los Angeles could partner with HyDeal LA to secure upstream production of green hydrogen and midstream transport to port fueling facilities.[171]

DOE also expects H2Hubs to leverage existing regional infrastructure.[172] Several entities offer examples of bringing infrastructure providers into the hub consortium to enable and promote both efficacy and accountability. In the UK, several companies participate in the HyNet North West hub consortium and together develop its supply chain. Vertex Hydrogen produces clean hydrogen with natural gas and fuel gases from the Essar Oil refinery.[173] Cadent Gas, which operates and maintains the largest natural gas distribution network in the UK, is developing hydrogen pipelines that will connect hydrogen production with end-users. Eni Energy will capture, transport, and store the hub's emissions in the company's local depleted fields.[174] Hanson UK, part of HeidelbergCement Group, CF Fertilisers UK, INOVYN Chemicals and the University of Chester, complete the consortium, which is led by Progressive Energy.[175]

Infrastructure Development Plan

As noted, infrastructure development will be a core responsibility of DOE-supported regional hydrogen hubs. Building infrastructure to support hydrogen and other decarbonization pathways will be critical. For clean hydrogen, infrastructure could include the production facilities, transportation modes (i.e., pipelines, tanker trucks), storage facilities (i.e., above and below ground), and fueling stations, as well as the critical enabling infrastructure, such as clean electricity production and delivery systems, CO_2 pipelines and geologic storage capabilities, and hydrogen-ready end-user facilities. Box 9 summarizes an EFI case study of the hydrogen market development potential in the Carolinas region.

Box 9

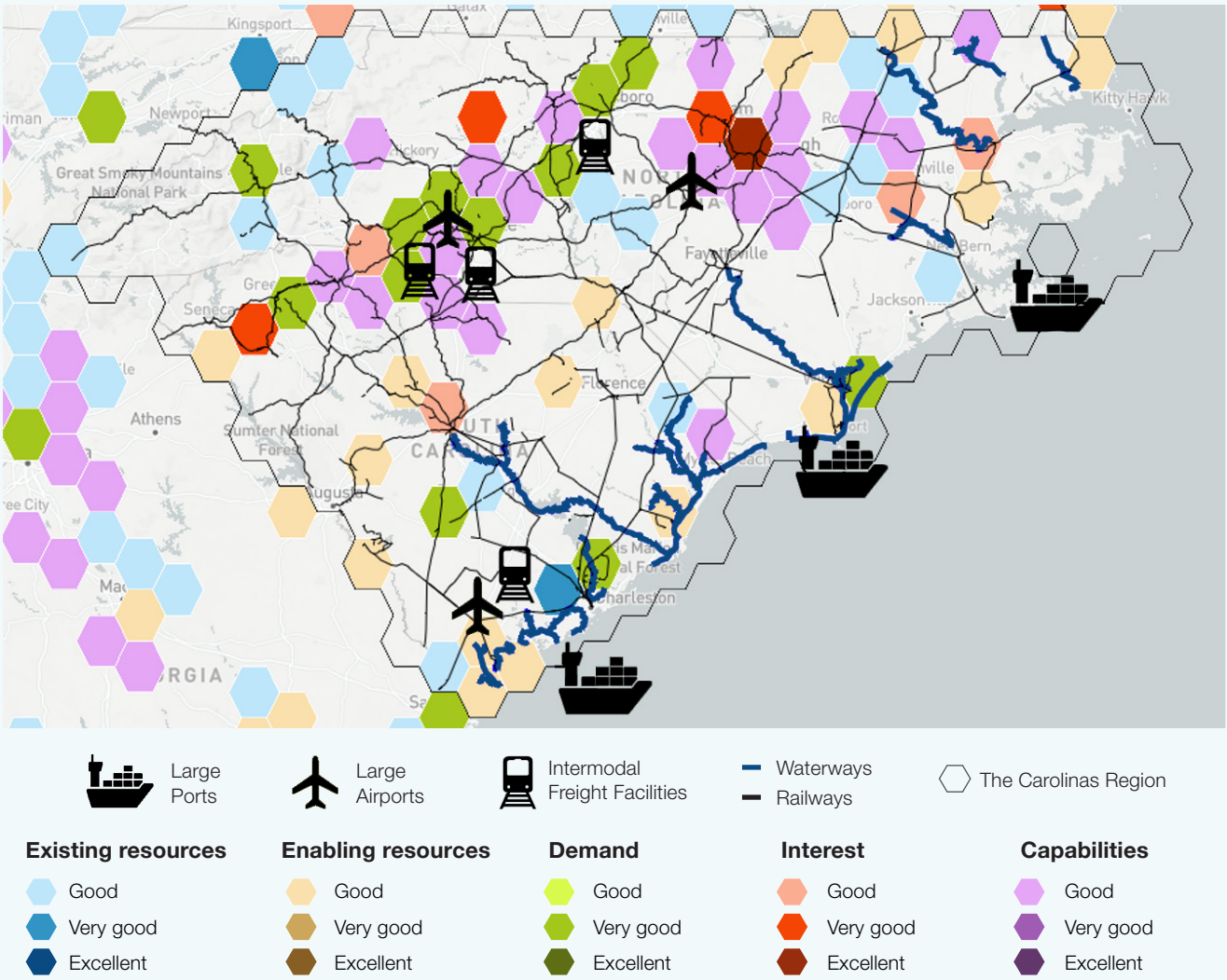
Using HyTF to Assess Hydrogen Infrastructure Development in the Carolinas

In October 2021, EFI held a public workshop on The Potential for Clean Hydrogen in the Carolinas, aimed at identifying the opportunities for a clean hydrogen hub in the region.[176] The event included leaders from energy, hydrogen, and manufacturing, discussing the region's potential hydrogen resources and capabilities. This discussion demonstrated the region's alignment of industry leaders in key sectors on the needs for hydrogen market formation: incentivize demand for bankable offtakers, including utilities.

EFI's HyTF shows the region's potential resources and capabilities for hydrogen, including its extensive network of infrastructure that may support hydrogen delivery and export (Figure 28). These include ports, railroads, and

Figure 28

HyTF Elements in the Carolinas and Surrounding Regions and Announced Clean Hydrogen Projects



Despite interspersed clean hydrogen resources, paired with limited hydrogen use to date, HyTF highlights where the opportunities for hydrogen demand penetration exist and the human capital that could catalyze such uptake in the near future. By pairing HyTF with the logistics and transportation infrastructure in the states, the figure shows how resources and demand can fit together.

Box 9 (cont.)

airports. Additionally, the region's robust wind and solar resource potential, its nuclear energy capacity (i.e., 11 plants), and its hydrogen expertise—at Savannah River National Laboratory and research universities—can be critical components for building out the region's clean hydrogen value chain.

HyTF shows that near-term demand potential in the region aligns with its strong logistics and transportation infrastructure. There are opportunities to use hydrogen for energy storage, back-up generation at data centers, port handling equipment, and fuel cell vehicles in long-haul transportation and logistics applications. Hydrogen is also being considered by the region's utilities for direct use in electric turbines for power generation and for blending into natural gas pipelines. Meanwhile, these sectors offer an existing labor force with a high proportion of workers in hydrogen-adjacent sectors such as engineering, logistics, and fabrication.[177]

The Carolinas region includes a variety of companies and organizations that have received DOE grants, patents, or Small Business Innovation Rewards (SBIRs) for innovative work on hydrogen technologies. These organizations can offer important capabilities for building a hydrogen network. Meanwhile, the large energy incumbents are also exploring new hydrogen research efforts. For example, Duke Energy, DOE, and Siemens Energy are collaborating at Clemson University in South Carolina to study hydrogen for energy storage and production.[178]

By design, regional clean hydrogen hubs will involve a broad constellation of projects and activities. Many of these will require permits and, in some cases, environmental impact statements, before they can proceed. Box 10 displays an example of the multiple permitting dependencies of developing a clean hydrogen pipeline in the U.S. Gulf.

The uncertainty of the associated timelines and project costs could negatively affect the investment rationale of regional clean hydrogen hubs. To mitigate this concern, applications for H2Hubs are required, in a permitting workflow overview, to identify relevant and applicable federal, state, and local codes, regulations, and permitting requirements that are likely to affect or prescribe project siting, construction, implementation, and operation of the hub.[179] To further enhance investment certainty, a Presidential Executive Order could establish a federal permitting coordinator within the White House Office of Environmental Policy to support an efficient, transparent, and thorough review process for regional clean hydrogen hub project permitting. The Office of Environmental Policy should be empowered to set clear permitting review timelines and progress reports from the relevant permitting agencies. The coordinator could also undertake an analysis of all legal opportunities to coordinate and prioritize the permitting of H2Hub infrastructure projects. While environmental protections should not be compromised, procedures could be established that acknowledge clean-energy priorities and expedite reviews.

Regional hubs should also closely coordinate major challenges of building clean hydrogen and its enabling infrastructure with main stakeholders. They could drive the process for integrating multiple stakeholders across multiple sectors, coordinating the process to overcome many of the infrastructure development and co-dependence challenges. Uncertain permitting timelines, various regulatory jurisdictions, inadequate policy guidance, and lack of public awareness and support are a few of the challenges that make it difficult to build infrastructure in the United States.[180] There are also co-dependence issues related to aligning the market players, financing, permits, and regulations that add complexity to infrastructure projects.

These hurdles have occurred—and have been overcome—in hydrogen hub development around the world.[181] Many of these hydrogen hubs require close coordination among stakeholders, as well as strong governance mechanisms, to guarantee that roles and responsibilities align and materialize in all stages of infrastructure development.[182] This experience and model should be replicated in H2Hubs projects.

Regional hubs could also develop partnerships with upstream energy providers to monitor and control life cycle emissions. A primary goal of developing regional hubs is to support significant emissions reductions, especially from difficult-to-decarbonize sectors. As required in the IIJA, hubs must aid achievement of scope 1 emissions reduction, that is, from hydrogen production. To foster further reduction, the scope 2 and 3 emissions from hydrogen hubs must also be addressed to ensure they fully support a net-zero future while informing methodologies that might be used for other projects and economic sectors to reduce embodied emissions.

H2Hubs must "demonstrably aid achievement of, but do not necessarily need to meet, the clean hydrogen production standard," which combines the IIJA specific carbon intensity targets for hydrogen production and the IRA's life cycle emissions targets. Each regional infrastructure hub should include energy service providers—that may or may not be direct participants in the hub—as part of the project development, focusing on ways to mitigate upstream emissions. This type of partnership can also support regional expansion of the hydrogen hub network, supporting the IIJA's goal of broader hydrogen market formation. The associated project costs of implementing emissions reduction technologies could be socialized across the hub members.

While there is plenty of debate around which technologies are best to monitor upstream emissions, there are widely accepted best practices, including: 1) deploying air-borne equipment for scanning gas infrastructure, targeting leaks, and quantifying emissions rates; 2) utilizing automated sensors for continuous monitoring of leak-prone nodes to determine the type, size, and plume direction; and 3) monitoring the health of the surrounding environment.[183] DOE lists some additional best practices to mitigate upstream emissions: "siting the H2Hubs (hydrogen production sites) near the point of natural gas recovery to mitigate gas transmission; sourcing natural gas from regions of the country with low fugitive emissions; and designing high efficiency systems that minimize the use of natural gas."[184]

Infrastructure planning should actively involve frontline community groups in decision-making. Frontline communities have been historically excluded from decision-making that directly impacts their lives and exposes them to risks. This procedural exclusion has led to the disproportionate siting of hazardous waste facilities, refineries, and other heavy industry in low-income, minority communities. Inclusion of frontline communities has been shown to produce more sustainable outcomes and increases the likelihood of obtaining a social license to operate. For example, from sustainability lessons learned from shale development in the United States, Castro-Alvarez et al. identified community engagement as an essential aspect of sustainable infrastructure development.[185] To achieve procedural equity (justice), frontline communities need to be included early and often in all stages of the decision-making process. Further, they should be given decision-making authority in some key areas, not simply provided with a platform for sharing concerns. Successful H2Hubs applications should include explicit support from communities and workforce through letters of recommendations and formal partnership agreements.[186]

An essential requirement for successful community engagement is the ability to publicly disclose all relevant baseline data before hub activities start. Other actions that hub leadership should undertake to engage frontline communities include: designate a period for information sharing, including holding meetings where operators and experts highlight potential quality of life impacts in areas with hub development; ensure the public has a chance to be involved in shaping plans through a mixture of participation channels (e.g., online, written, face-to-face meetings); and promote community involvement once project development starts, including the management of community benefits by local people.[187]

Box 10

Case Study Permitting Hydrogen Pipeline in U.S. Gulf Coast

This case study assesses the legal and regulatory implications for constructing a new, dedicated interstate hydrogen pipeline in Texas. Transporting hydrogen via dedicated pipelines is overseen by several federal agencies and a patchwork of federal statutes and regulations. At the local level, more entities get into the mix.[h]

The federal government regulates the economics and safety and security of hydrogen pipelines. Its role in siting and certification are focused on environmental regulations, such as the Endangered Species Act and the Clean Water Act that may be implicated depending on the location of the project. The Surface Transportation Board (STB), part of the Department of Transportation (DOT), regulates the rates, terms of service, and practices of interstate hydrogen pipeline carriers are just, reasonable, and nondiscriminatory.[i] The Transportation Security Administration (TSA) serves as the lead federal agency for transportation security which includes the transportation of hazardous materials such as hydrogen via pipeline. The Pipeline and Hazardous Materials Safety Administration (PHMSA), another agency within DOT, administers a national safety program for natural gas and hazardous liquid pipeline transportation, liquefied natural gas facilities, and underground natural gas storage facilities.[188] In this case study, the Texas hydrogen pipeline would ultimately be inspected by PHMSA's Office of Pipeline Safety, which is tasked with enforcing PHMSA's safety standards after a pipeline has been constructed.

Figure 29

Regulatory Jurisdictions over Hydrogen Pipeline Permitting in the Gulf Coast

	Federal	State
Fundamental	• Surface Transportation Board (STB/DOT): regulates the economic aspects of interstate hydrogen pipelines • DHS and TSA/PHMSA: regulate hydrogen pipeline safety	• Texas and state laws of any neighboring jurisdictions that the pipeline passes through: regulate pipeline siting, location, and certification • Texas Railroad Commission: pipeline compliance regulation
Situational	The following laws/agencies may be implicated: • Endangered Species Act • The National Historic Preservation Act • The Coastal Zone Management Act • The Clean Water Act • Permits from the U.S. Army Corps of Engineers • Federal Highway Administration	The following agencies may be implicated: • Texas Commission on Environmental Quality (TCEQ) • Texas Parks and Wildlife Department (TPWD)

Pipeline permitting in the Gulf Coast region must go through a matrix of federal and state regulations involving multiple agencies at both levels. Fundamental regulations are those which must be handled at the federal and state levels in order to properly permit a hydrogen pipeline. Situational regulations will only apply based on the particular circumstances or characteristics of individual projects, often times as a result of geographic and environmental considerations.

h This case study was developed in collaboration with Dentons US LLP.

i STB-regulated pipelines generally carry five commodities: anhydrous ammonia, carbon dioxide, coal slurry, phosphate slurry, and hydrogen.

Box 10 (cont.)

Federal law does not imbue any agency with siting authority over interstate hydrogen pipelines. To construct an interstate hydrogen pipeline, developers must secure siting approvals from each of the states in which the pipeline would be situated. In this example, the siting of a hydrogen pipeline in Texas would be governed by Texas law, as well as state law of any other jurisdictions that the pipeline passes through (Figure 29). In Texas, hydrogen pipelines are considered common carriers that must comply with regulations promulgated by the Texas Railroad Commission.[j] Building a hydrogen pipeline may require certain air permits from the Texas Commission on Environmental Quality (TCEQ).[189] These pipelines may also require permits for the discharge of pipeline wastewater, also authorized by the TCEQ. The Texas Parks and Wildlife Department (TPWD) is also required to review pipeline projects in Texas, including hydrogen projects, to protect fish and wildlife. The TPWD analysis further informs any environmental analysis required under federal or state law.

Statutory and Regulatory Gaps in Hydrogen Pipeline Regulation

The regulatory architecture for hydrogen infrastructure will evolve as new hydrogen projects take shape across the country. Currently, neither federal nor state law distinguishes between hydrogen pathways. As lawmakers implement new measures to combat climate change, federal and state law will likely develop more detailed classification systems to identify hydrogen based on its environmental attributes. Different regulations may favor green and blue hydrogen production over gray hydrogen, and some jurisdictions may drive the industry entirely to green hydrogen.

Hydrogen infrastructure will also require specific codes and standards to manage the safe production, transportation, and distribution of hydrogen. Dedicated hydrogen pipelines must be built to withstand hydrogen embrittlement. Hydrogen pipeline maintenance programs also must account for the fact that hydrogen is a highly flammable gas. Protocols and safety systems will have to be developed to protect pipeline workers as well as the communities that hydrogen pipelines traverse.

FERC's role in regulating hydrogen pipelines may also change. The economic regulatory system that FERC has erected to ensure just and reasonable rates and nondiscriminatory service for transporting natural gas via pipeline could be readily adapted to incorporate hydrogen pipelines. However, expanding FERC's responsibilities to include hydrogen would likely require new legislation from Congress. Hydrogen blending also raises questions about FERC's authority. Pipelines that transport hydrogen blended with natural gas are presumably within FERC's purview, but it is unclear the extent to which the hydrogen-natural gas blend can be primarily hydrogen. Furthermore, as FERC adopts new regulations that examine downstream greenhouse gas emissions related to the transmission of natural gas in pipelines, FERC would also have to consider whether the environmental effects related to hydrogen usage factor into its analyses. As federal law and agencies are adapted to regulate the hydrogen industry, state law is expected to follow suit and adopt similar modifications at the local level.

j TEX. NAT. RES CODE ANN. § 111.002 (2008): A person is a common carrier subject to the provisions of this chapter if it: owns, operates, or manages, wholly or partially, pipelines for the transportation of carbon dioxide or hydrogen in whatever form to or for the public for hire, but only if such person files with the commission a written acceptance of the provisions of this chapter expressly agreeing that, in consideration of the rights acquired, it becomes a common carrier subject to the duties and obligations conferred or imposed by this chapter.

Community and Workforce Plan

Each regional hub should develop a Community and Workforce Plan that builds on the guidance of the H2Hubs FOA. The DOE FOA focuses on high-level goals, such as "invest in America's workforce" and "advance diversity, equity, inclusion, and accessibility" and encourages certain practices, including submitting letters of support from regional community and labor groups. The H2Hubs FOA also offers some general direction to hub applicants, calling for a Community Benefits Plan, focused on job quality and equity requirements.[190] Each hub should implement a Community and Workforce Plan that also involves long-term planning for both the hydrogen hub and broader hydrogen market formation. Box 11 is a case study exploring how HyTF can identify workforce transition opportunities for regions heavily dependent on fossil fuel jobs, such as the Ohio River Valley.

Hydrogen hubs should develop a goal for improving the overall quality of life for frontline communities. Importantly, regional hubs should align with frontline community principles and definitions of environmental justice. Environmental justice is manifest in several ways: distributive justice in the location of environmental burdens; procedural justice in the processes that are used for decision-making; and corrective justice in how past wrongdoings are ameliorated. Each community will have a particular approach to environmental justice, including which

components of justice they are concerned with and the metrics by which they measure them.

Such community alignment is critical to project success, as evidenced by the Norton wind project in South Yorkshire, where there was a broad spectrum of opinions on whether the project was implemented in a procedurally just manner. The project leaders were committed to ensuring the project was democratic, using a community-wide poll that enabled residents to vote on whether the project should proceed. Local opinions, however, were quite mixed and some residents felt strongly that the process had been unfair and had failed to sufficiently involve local people. These differences in expectations were reinforced by contrasting experiences of the implementation process. Clearly defining expectations and goals with all relevant stakeholders is critical to achieving justice in future hub development.[191]

Box 11

Analyzing the Potential for Clean Hydrogen in the Ohio River Valley

In September 2021, EFI hosted the workshop Ohio River Valley Hydrogen and CCS Hub Market Formation to examine the key characteristics for hydrogen market formation in the region.[192] The major takeaway from the workshop was that a hydrogen hub could bring economic potential to a region heavily dependent on fossil fuels. Importantly, to enable the job growth needed by the clean transition, it is critical to support decarbonization pathways, such as hydrogen, that leverage numerous vulnerable workers. According to DOE, clean hydrogen depends on most of the same skillsets found in U.S. industrial and fossil-fuel sectors that are vulnerable to the clean energy transition.[193] The Ohio River Valley (Ohio, Pennsylvania, and West Virginia) supports a large share of U.S. heavy industry, including 22 percent of U.S.

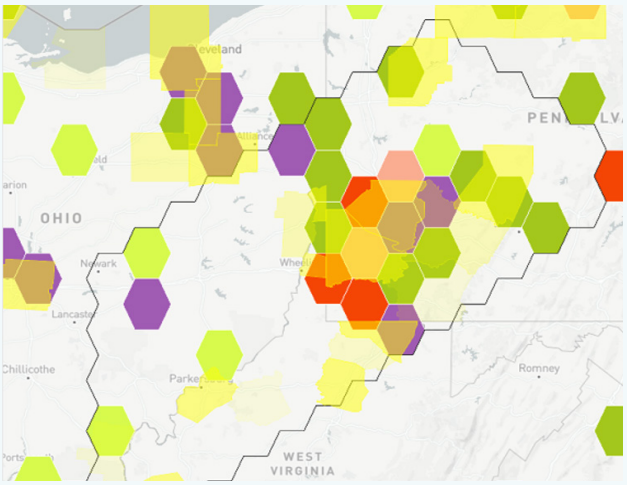
Box 11 (cont.)

steel production, and almost $120B worth of U.S. manufacturing sectors that depend on these vulnerable occupations and could use hydrogen in the near future.[194,195]

Results from EFI's HyTF shows important geographic overlap between the Ohio River Valley's fossil dependent communities (shown as yellow swaths)—defined as census tracts with 1,000+ coal, petroleum, or gas jobs—and the region's industries and jobs that could be leveraged in a transition to hydrogen (included in the "Capabilities" and "Interests" categories) (Figure 30). The region maintains a relatively high proportion of engineers, machine operators, fabricators, power operators, construction workers, electrical workers, financial experts, and industrial operators—all skillsets DOE defined as critical for a hydrogen economy.[196] Also, dozens of universities, technical schools, and community colleges produce tens of thousands of highly skilled graduates every year. Three R1 universities, Carnegie Melon University, University of Pittsburgh, and West Virginia University, offer suitable testbeds for innovation, as science and technology research funds amounted to over $1.5B between the schools in 2021. In parallel, the region has a fair amount of private hydrogen interest as well, including utility activity, several S&P 500 companies, and a handful of small businesses working on advancing hydrogen technologies.

Figure 30

Hydrogen Opportunities in Fossil Fuel-Dependent Communities



>1,000 Fossil Industry Jobs

The Ohio River Valley Region

Demand	Interest	Capabilities
Good	Good	Good
Very good	Very good	Very good
Excellent	Excellent	Excellent

Regions with hydrogen opportunities as defined in HyTF are often co-located with communities that are heavily reliant on the fossil fuel industry. The Gulf, Southern California, West Texas, and Wyoming, for example, all have thousands of jobs in at-risk sectors facing the energy transition. Hydrogen hubs could ameliorate some of the energy transition challenges, due to highly transferable skills found in the fossil energy sector.

Overlaying potential new sources of demand in the region shows important regional clustering that could be used to drive successful regional hubs and market expansion opportunities. HyTF identified several areas in the region where demand potential is strong, including seasonal grid energy storage, on-road medium and heavy-duty vehicle fueling, and fuel-switching at natural gas and steelmaking facilities. Leveraging the innovation at schools and businesses investing in clean hydrogen may drive down costs of new energy technologies along the value chain, while a knowledgeable labor force will benefit from preserved at-risk jobs or new jobs that require minimal retraining.

Regional hubs should support community-specific needs beyond decarbonization. The H2Hubs FOA explicitly requires this expansive approach.[197] In particular, regional hubs should prioritize local economic and environmental safety in project selection and performance criteria. As noted, hydrogen infrastructure projects must benefit frontline communities and address their particular concerns around climate resiliency, workforce transition, emergency preparation, and energy priorities such as local energy production and storage, among others. Hubs can support local communities in reaching their climate, energy, and economic goals. For example, frontline communities on the Gulf Coast are heavily impacted by coastal erosion and are increasingly vulnerable to floods as hurricanes worsen.[198] In this region, emergency preparedness is key, including energy storage and rapid energy deployment.

In this regard, hydrogen fuel cells could provide an energy storage medium to be used in emergency situations. Such local power storage capabilities could provide frontline communities with quick and reliable backup power on demand, which would run much cleaner than diesel generators. Additionally, hydrogen could also be used to fuel vehicles needed for evacuation and emergency rescue such as buses or boats as well as for hospitals, police and fire stations, gas stations, data centers, and more. There are many examples of this benefit.

After Superstorm Sandy decimated parts of the Caribbean and East Coast, fuel cells provided emergency backup power to at least 100 telecommunications towers in both the Bahamas and the Northeast United States. During Hurricane Irene in 2011, ReliOn fuel cells kicked on at 56 Sprint cell towers, and Doosan fuel cells provided power at both a storm shelter at South Windsor High School and a Whole Foods store in Connecticut. During the aftermath of Hurricane Katrina, generators failed or ran out of fuel at four hospitals, necessitating extraordinarily difficult evacuation efforts via boat and helicopter.[199]

These examples underscore the critical role of fuel cells in emergency preparedness. Hub development should be used to uplift the local/regional economy, including vulnerable and historically marginalized communities, supporting them in achieving their energy goals and keeping them safe by increasing climate resiliency.

According to the FOA, H2Hubs with end-uses that involve the combustion of clean hydrogen should also provide NO_x emissions estimates.[200] As noted, combustion of hydrogen can create NO_x, a family of poisonous, highly reactive, indirect greenhouse gases that form when fuel is burned at high temperatures.[201] NO_x damages heart and respiratory function, impairs lung development in children, and leads to higher rates of emergency room visits and premature death.[202, 203] Higher concentrations of H_2 result in higher amounts of NO_x being released during combustion. Regional hubs should provide strong monitoring, coordination, and intervention to address and eliminate local NO_x issues. Monitoring, coordination, and intervention is especially important when hydrogen is used in homes and industrial facilities and where there have been historic energy injustices. Any hydrogen combustion applications will require optimization of burner technology and more stringent emissions standards to minimize air quality impacts from a growth in hydrogen use. [204] After-treatment and removal of NO_x is possible, but such an approach reduces output and performance in appliances.

Hubs need to prioritize safety throughout the hydrogen value chain. The H2Hubs FOA requires that a Safety Program be developed to create a "safety culture" for the hydrogen and non-hydrogen aspects of the ecosystem. As the FOA indicates, regional hubs should dedicate resources to align safety requirements with frontline community needs. It is especially important to do so during the transition of localized hubs to broader regional markets. Some communities view hydrogen as an unsafe fuel source, as it can ignite more easily than natural gas and its flame is nearly invisible. [205] Hydrogen can also cause pipeline embrittlement, which presents problems for transporting hydrogen through the existing natural gas transmission network.[206] Hydrogen's low molar mass allows it to permeate through polyethylene (PE) pipes, which could risk gas buildup in confined spaces and increase the risk of explosion.[207] The risk of leaks and

explosions would more acutely affect urban centers of larger population density, which could also have a disproportionate impact on vulnerable communities.

Hydrogen, however, is non-toxic, lightweight, and dissipates faster than gasoline vapor or natural gas when released, making it generally safer in the case of a leak.[208] One solution would be to ensure that the hydrogen value chain is fitted with sensors, leak detection, and other safety infrastructure to measure leaked hydrogen on a parts-per-billion scale. Significant expansion is needed to deploy these technologies at the scale of commercial production required to cover this application scenario.[209] The continued development of sensor technologies and compatible pipeline materials is critical to ensure safety for frontline communities near hydrogen infrastructure.

Innovation Plan

The regional clean hydrogen hubs are designed to demonstrate clean hydrogen across the value chain. Each project within a hub will need to monitor progress and share insights across stakeholders and with the government to drive new insights and shape new R&D needs. It will be critical that such monitoring and insight sharing occurs for the IIJA's performance targets, i.e., carbon intensity, production volumes, and utility across the hydrogen value chain, and for the other design plans that are crucial to the success of each regional hub.

Each hub should also take a transparent approach to data sharing between regional hubs. The insights and lessons learned from each regional hub on performance targets will be critical for other regional hubs. This will be especially important as each regional hydrogen hub will be on its own timetable, and each will be subject to its own regulatory environment, have its own system configuration, and include a particular group of suppliers and customers. Sharing information both within the hub, i.e., from hub governing entity to all stakeholders, and outside the hub with the government and other hubs, is considered a best development practice among hubs worldwide. [210] DOE also plans to compile H2Hubs data for the purpose of informing future private sector investment decisions.[211]

DOE should develop a program for global information sharing between clean hydrogen hubs. As previously mentioned, there are nearly 40 countries with national hydrogen strategies in development. Many of these strategies offer specific production, consumption, and funding targets. With this level of new investment—more than $330B globally—it is important that new hydrogen projects are aligned in terms of safety codes and standards, regulations, hydrogen product composition, transparent cost and revenue models, and carbon-intensity measures and standards. There are already clean hydrogen hubs in active development in the United Kingdom, China, Chile, Australia, Japan, and South Korea. The U.S. State Department and DOE should leverage their international convening powers to encourage information sharing and formal cooperation between U.S. regional clean hydrogen hubs and relevant international activities.

Each regional hub should plan to use new technologies as they become available. As first-movers in demonstrating clean hydrogen at-scale across the value chain, each regional hub will identify technology and financing challenges that must be addressed for the sake of broader clean hydrogen market formation. Challenges may include region-specific characteristics, e.g., weather patterns, water access;, technology optimizations, including size and components; system optimization, e.g., configurations; and cross-cutting issues, such as water use metrics (Box 12); CO_2 intensity levels at each stage of the life cycle; overall impact on decarbonization; and techno-economic details of H_2 transportation such as compression pathways and modes of delivery; and a range of other issues.

An innovation plan that involves public-private cooperation should also help ensure the R&D community is investigating the lessons learned from the regional hubs, while making clear that the hubs are platforms for scaling new technologies as they become available. Several hydrogen hubs around the world involve research institutions in hub consortiums, including academic institutions, research centers, etc., a clear indication of the value of the relationship between hubs and the R&D community.[212]

Box 12

Clean Hydrogen Research Needs: Managing Water Use for Hydrogen Production

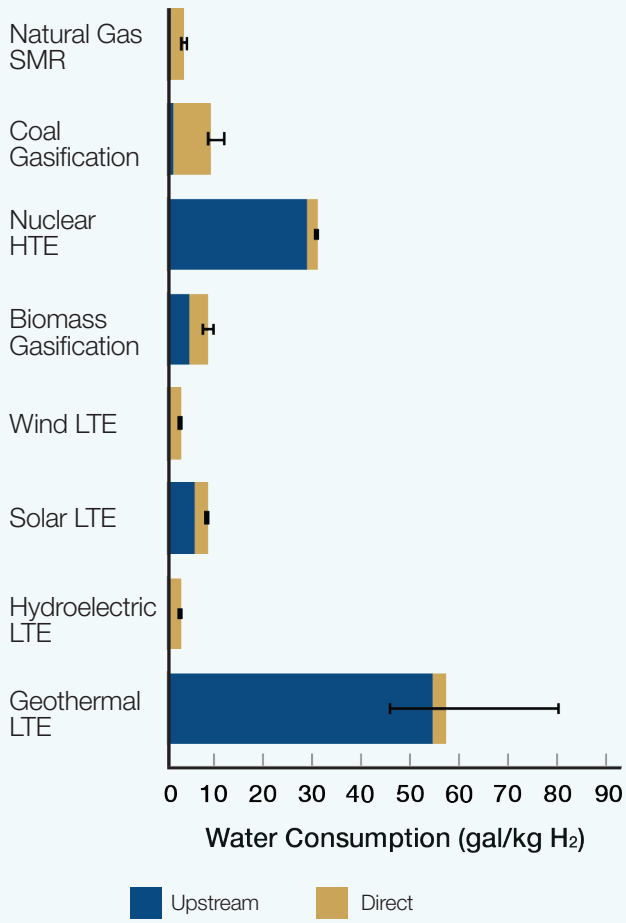
Continuing the study of the water intensity of hydrogen production is critical for enabling a growing hydrogen market. There are two important dimensions: the water scarcity of each region and the water consumption needs for each hydrogen production pathway.

According to DOE's water supply chain analysis, there are varying water stress conditions across regions of the United States. Areas of the southwest, for example, have the highest risk of water security issues in the country, followed by counties in California, Idaho, the Dakotas, and the Great Plains.[213] When factoring in the risk of increased hydrogen production, it will be important to consider any water-intense processes, such as oil and gas extraction and refining, that may ultimately be displaced by hydrogen. According to one study, the petroleum sector is one of the largest water consumers in the world.[214]

Figure 31 shows DOE's life cycle water consumption factors for select hydrogen production technologies, which includes the site of production and the upstream resource recovery or extraction.[215] Life cycle emissions factors are based on the GREET model. Nuclear high temperature electrolysis (HTE) and geothermal have the highest total water needs, mostly due to the upstream water consumption. Total nuclear water use includes the resources required for running the facility, operating the electrolyzer, and for uranium mining, transportation, and enrichment while geothermal includes the feedstock production. Total water use for the SMR-based pathway is 3.41 gal/kg H_2 (2.76 direct, 0.65 upstream), compared to the green hydrogen pathways which vary from 2.92 to 8.46 gal/kg H_2, with the largest variance in assumptions about the upstream water needs.

Figure 31

Life Cycle Water Consumption Factors for Select Hydrogen Production Pathways[216]



Life cycle water consumption includes both upstream water requirements and direct water requirements for each hydrogen production pathway. Note: HTE = High Temperature Electrolysis; LTE = Low Temperature Electrolysis. Adapted from: NREL, 2020.

The impact of water stress on local communities is essential to consider when determining a strategy for building out hydrogen infrastructure. The diversion of water to electrolysis or other forms of hydrogen production could exacerbate existing social and environmental injustices in communities that already lack adequate access to safe drinking water. These increasing water needs would also need to compete with a variety of sectors such as agriculture, power, and drinking water.

A hydrogen innovation plan should encourage new stakeholders to join the regional hub projects, while also facilitating broader regional expansion of hubs. DOE's FOA describes the need for funded projects to track several outcomes and outputs related to the performance of each hub, including: energy and environmental justice; consent-based siting; labor and community engagement; diversity, equity, inclusion and access; job quality, labor standards, workforce development; emissions intensity, including non-GHG air quality data; and the magnitude of hydrogen production, transportation, and use.[217] Each hub should release, on a regular basis, the non-proprietary performance data to the public. Similar to the business growth plan that H2Hubs applicants must submit, an innovation plan that shows progress can help attract investors, researchers, and community groups, as well as evaluate engagement strategies and facilitate new research that could benefit the regional hub projects. DOE should manage this data-sharing platform, ensuring up-to-date and accurate public knowledge of the returns on investment from the hydrogen hubs funding.

Some global initiatives with similar requirements or goals have been implemented, with lessons learned for hub and hydrogen market development. The detail of information being shared, however, varies. For instance, "Hydrogen Territories Platform" is an interregional initiative aimed at replicating the BIG HIT hydrogen hub concept in other localities;[218] "The Hydrogen Hub" brings together stakeholders to drive investment in hydrogen and fuel cell technology in the UK;[219] the "Hydrogen Valley Platform" is a joint initiative by the Fuel Cells and Hydrogen Joint Undertaking and Mission Innovation that showcases hydrogen flagship projects around the world for project developers.[220] DOE can build up from such initiatives and customize functionality according to the U.S. characteristics.

CONCLUSION

The U.S. Hydrogen Demand Action Plan finds that the United States maintains significant resources, both natural and manmade, across many regions of the country to rapidly drive hydrogen market formation. Hydrogen offers the energy system unique versatility, flexibility, and scalability to rapidly decarbonize existing infrastructure and transition to new clean energy pathways at scale. This is important as the timetable for developing and deploying new business models, technologies, and policies for reaching economywide net zero emissions by midcentury requires an immediate nationwide commitment.

This study focuses on how to implement recent federal policy most effectively, while capitalizing on the growing private investment into new clean hydrogen production projects. There will be a cost gap between the supply side incentives of the IRA and the conditions needed to accelerate demand in most commercial use cases, critical for market formation. This gap is mostly due to the lack of federal R&D in clean hydrogen—and therefore slow progress in advanced stage demonstration and deployment—during previous decades.

This study recommends additional policy and regulatory actions to accelerate hydrogen's use across a range of regions and sectors, especially by leveraging regional hydrogen hubs as growth engines. Additional policy measures that target hydrogen-ready applications in difficult to decarbonize sectors can effectively use hydrogen's unique attributes, while re-investing in America's workforce, and rapidly driving U.S. market formation.

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