U.S. DEPARTMENT OF ENERGY

DOE National Clean Hydrogen Strategy and Roadmap

Draft - September 2022

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Executive Summary

This is an unprecedented time in history for hydrogen with interest being amplified worldwide due to its potential to address the climate crisis as well as energy security and resiliency. Though there are significant challenges, zero and low-carbon hydrogen can be a key part of a comprehensive portfolio of solutions to achieve a sustainable and equitable clean energy future. And the United States is stepping up to accelerate progress through unprecedented investments in clean energy.

In November 2021, Congress passed, and President Joseph R. Biden, Jr. signed the Infrastructure Investment and Jobs Act (Public Law 117-58), also known as the Bipartisan Infrastructure Law (BIL). This historic, once-in-a-generation legislation authorizes and appropriates $62 billion for the U.S. Department of Energy (DOE), including **$9.5 billion for clean hydrogen.** Furthermore, in August 2022, the President signed the Inflation Reduction Act (IRA) into law (Public Law 117-169), which provides additional policies and incentives for hydrogen including a production tax credit which will further boost a U.S. market for clean hydrogen.

This draft report sets forth the **"DOE National Clean Hydrogen Strategy and Roadmap."** DOE will elicit stakeholder feedback through opportunities, such as workshops and listening sessions, and use this feedback to finalize the report and then develop updates as required by the BIL.

It provides a snapshot of hydrogen production, transport, storage, and use in the United States today and **the opportunity** that clean hydrogen could provide in contributing to national goals across sectors. Pathways for clean hydrogen to decarbonize applications are informed by demand scenarios for 2030, 2040, and 2050 – **with strategic opportunities for 10 million metric tonnes (MMT) of clean hydrogen annually by 2030, 20 MMT annually by 2040, and 50 MMT annually by 2050.** Using clean hydrogen can reduce U.S. emission approximately 10 percent by 2050 relative to 2005,[1] consistent with the U.S. Long-Term climate strategy.[2] These scenarios are based on achieving cost competitiveness to enable demand in specific sectors and where there are fewer alternatives, such as direct electrification or the use of biofuels. As technologies and markets develop, more detailed analyses will be forthcoming in the required updates to this document, including the optimal use of hydrogen in key sectors, avoiding stranded assets by creating demand certainty, and prioritizing energy and environmental justice.

The foundation of this draft roadmap is based on **prioritizing three key strategies** to ensure that clean hydrogen is developed and adopted as an effective decarbonization tool and for **maximum benefits** for the United States. DOE will:

(1) **Target strategic, high-impact uses for clean hydrogen.** This will ensure that clean hydrogen will be utilized in the highest value applications, where limited deep decarbonization alternatives exist. Specific markets include the industrial sector, heavy-duty transportation, and long-duration energy storage to enable a clean grid. Long-term opportunities include the potential for exporting clean hydrogen or hydrogen carriers and enabling energy security for our allies.

(2) **Reduce the cost of clean hydrogen.** The Hydrogen Energy Earthshot (Hydrogen Shot) launched in 2021 will catalyze both innovation and scale, stimulating private sector investments, spurring development across the hydrogen supply chain, and dramatically reducing the cost of clean hydrogen. Efforts will also address critical material and supply chain vulnerabilities and design for efficiency, durability, and recyclability.

(3) **Focus on regional networks.** This includes regional clean hydrogen hubs to enable large-scale clean hydrogen production and end-use in proximity, enabling critical mass infrastructure, driving scale, and facilitating market lift off while leveraging place-based opportunities for equity, inclusion, and sustainability. Priorities will include near term impact, creating jobs - including good paying union jobs - and jumpstarting domestic manufacturing and private sector investment.

To implement these strategies, DOE will work with other agencies, as well as with industry, academia, national laboratories, local and Tribal communities, the environmental and justice communities, and numerous stakeholder groups to accelerate progress and market lift off. **Effective collaboration and coordination** are cornerstones in all of DOE. As provided in this draft roadmap, concrete targets, market-driven metrics, and tangible actions will accelerate hydrogen's progress. DOE will continuously track, adjust, and refine its plans. Prioritizing stakeholder engagement will be key to address potential environmental concerns and ensuring equity and justice for overburdened, underserved, and underrepresented individuals and communities. DOE's focus on achieving the goals set forth in this strategy aim to deliver the maximum benefits of clean hydrogen to the American people and the global community.

Legislative Language

This draft report responds to the legislative language set forth in section 40314 of the Infrastructure Investment and Jobs Act (Public Law 117-58), also known as the Bipartisan Infrastructure Law, specifically that which amends Title VIII of the Energy Policy Act of 2005 (EPACT-2005) by adding **Section 814 - National Clean Hydrogen Strategy and Roadmap**. Section 814 states:

(A) DEVELOPMENT.—

> **(1)** IN GENERAL.—In carrying out the programs established under sections 805 and 813, the Secretary, in consultation with the heads of relevant offices of the Department, shall develop a technologically and economically feasible national strategy and roadmap to facilitate widescale production, processing, delivery, storage, and use of clean hydrogen.
>
> **(2)** INCLUSIONS.—The national clean hydrogen strategy and roadmap developed under paragraph (1) shall focus on—
>
> > **(a)** establishing a standard of hydrogen production that achieves the standard developed under section 822(a), including interim goals towards meeting that standard;
> >
> > **(b)**
> >
> > > **(i)** clean hydrogen production and use from natural gas, coal, renewable energy sources, nuclear energy, and biomass; and
> > >
> > > **(ii)** identifying potential barriers, pathways, and opportunities, including Federal policy needs, to transition to a clean hydrogen economy;

(c) identifying—

> **(i)** economic opportunities for the production, processing, transport, storage, and use of clean hydrogen that exist in the major shale natural gas-producing regions of the United States;
>
> **(ii)** economic opportunities for the production, processing, transport, storage, and use of clean hydrogen that exist for merchant nuclear power plants operating in deregulated markets; and
>
> **(iii)** environmental risks associated with potential deployment of clean hydrogen technologies in those regions, and ways to mitigate those risks;

(d) approaches, including sub-strategies, that reflect geographic diversity across the country, to advance clean hydrogen based on resources, industry sectors, environmental benefits, and economic impacts in regional economies;

(e) identifying opportunities to use, and barriers to using, existing infrastructure, including all components of the natural gas infrastructure system, the carbon dioxide pipeline infrastructure system, end-use local distribution networks, end-use power generators, LNG terminals, industrial users of natural gas, and residential and commercial consumers of natural gas, for clean hydrogen deployment;

(f) identifying the needs for and barriers and pathways to developing clean hydrogen hubs (including, where appropriate, clean hydrogen hubs coupled with carbon capture, utilization, and storage hubs) that—

> **(i)** are regionally dispersed across the United States and can leverage natural gas to the maximum extent practicable;

(ii) can demonstrate the efficient production, processing, delivery, and use of clean hydrogen;

(iii) include transportation corridors and modes of transportation, including transportation of clean hydrogen by pipeline and rail and through ports; and

(iv) where appropriate, could serve as joint clean hydrogen and carbon capture, utilization, and storage hubs;

(g) prioritizing activities that improve the ability of the Department to develop tools to model, analyze, and optimize single-input, multiple-output integrated hybrid energy systems and multiple-input, multiple-output integrated hybrid energy systems that maximize efficiency in providing hydrogen, high-value heat, electricity, and chemical synthesis services;

(h) identifying the appropriate points of interaction between and among Federal agencies involved in the production, processing, delivery, storage, and use of clean hydrogen and clarifying the responsibilities of those Federal agencies, and potential regulatory obstacles and recommendations for modifications, in order to support the deployment of clean hydrogen; and

(i) identifying geographic zones or regions in which clean hydrogen technologies could efficiently and economically be introduced in order to transition existing infrastructure to rely on clean hydrogen, in support of decarbonizing all relevant sectors of the economy.

(B) REPORTS TO CONGRESS.—

(1) IN GENERAL.—Not later than 180 days after the date of enactment of the Infrastructure Investment and Jobs Act, the Secretary shall submit to Congress the clean hydrogen strategy and roadmap developed under subsection (a).

(2) UPDATES.—The Secretary shall submit to Congress updates to the clean hydrogen strategy and roadmap under paragraph (1) not less frequently than once every 3 years after the date on which the Secretary initially submits the report and roadmap."

Foreword

More than half a century ago, the U.S. moonshot initiative put the first human beings on the moon, using hydrogen as a fuel for rocket propulsion and American-made fuel cells on-board the spacecraft. Since then, the Nation has continued to be a world leader in hydrogen and fuel cells. Thousands of hydrogen and fuel cell systems have been developed and commercialized across sectors. U.S. Department of Energy (DOE) funding has resulted in more than 1,100 hydrogen and fuel cell patents, 30 commercial technologies, and more than 65 technologies that could be commercial within the next several years.[3] But DOE must accelerate both the pace and scale of innovation from research through deployment. Building off the moonshot, DOE launched **Hydrogen Shot** with a bold and ambitious goal of "1 1 1" – $1 for 1 kilogram of clean hydrogen in 1 decade – to unlock the potential for hydrogen across sectors.[4]

Based on market success, the global hydrogen industry has projected the potential for $2.5 trillion in annual revenues and 30 million jobs, along with 20% global emissions reductions by 2050 when achieving clean hydrogen at scale.[5] The United States already produces more than 10% of the global hydrogen supply and plays an important role in developing the global hydrogen economy.[6] The country can strengthen its energy leadership, create significant new investment and job opportunities, and help the world decarbonize by advancing and harnessing hydrogen technologies in a sustainable, competitive, and equitable manner. The Nation is in a unique position to lead, given its research, development, and deployment prowess, along with abundant supplies, including renewables, nuclear, fossil, waste, and other carbon-based resources coupled with carbon capture and sequestration.

Historic investments through the Bipartisan Infrastructure Law and Inflation Reduction Act and the creation of this DOE national strategy and roadmap for clean hydrogen are spurring momentum towards achieving the benefits of clean hydrogen. **Acceleration** is key to meeting our climate goals. However, this must be done **in a strategic and holistic way,** taking into consideration the potential role of hydrogen within a portfolio of solutions to tackle the climate crisis. DOE's actions will depend on an understanding of optimal geographic regions where hydrogen may be most advantageous from an overall emissions, resilience, equity, and sustainability perspective.

This roadmap is the first step in the process of acceleration. It is only the beginning and will set the stage for further updates and refinements as required in the BIL enactment, no less frequently than every three years.

Introduction

The 2020s is a decisive decade for the world to confront climate change and avoid the worst and irreversible impacts of the crisis by keeping the goal of a 1.5-degree Celsius limit on global average temperature rise within reach.[7] The Biden-Harris Administration has established ambitious goals to reduce greenhouse gas pollution from 2005 levels by 50 to 52 percent in 2030 under the Paris Agreement, create a carbon pollution-free power sector by 2035, and reach net-zero emissions no later than 2050.[8, 9] The White House also launched the landmark, first-of-its-kind Justice40 Initiative, which pledges that at least 40 percent of overall benefits from Federal investments in climate and clean energy be delivered to disadvantaged communities.[10] Many of the Department's vital hydrogen programs moving forward, including the Regional Clean Hydrogen Hubs Program, and the Clean Hydrogen Manufacturing and Recycling Research, Development and Demonstration Program, are included in the Justice40 Initiative.[11]

The National Clean Hydrogen Strategy and Roadmap aligns with the Administration's goals, including:

A 50% to 52% reduction in U.S. GHG emissions from 2005 levels by 2030

100% carbon pollution-free electricity by 2035

Net zero GHG emissions no later than 2050

40% of the benefits of federal climate investments are delivered to disadvantaged communities.

Hydrogen is one part of a comprehensive portfolio of energy technologies that can support the Nation's transition to net-zero while leveraging regional resources and creating equitable and sustainable growth. The development and use of hydrogen technologies will be strategic and will take into consideration multiple technologies across sectors for the most efficient, affordable, and sustainable pathways enabled by market adoption. Sectors that are difficult to decarbonize with traditional approaches are expected to become priority markets for clean hydrogen, such as steel and chemicals manufacturing, heavy-duty transportation, and production of liquid fuels. Hydrogen is also seen as an **enabling** technology - enabling renewables through long-duration energy storage and offering flexibility and multiple revenue streams to clean power generation such as today's nuclear fleet as well as advanced nuclear and other innovative technologies.

To unlock the market potential for clean hydrogen, the U.S. Department of Energy (DOE) launched the Hydrogen Energy Earthshot (Hydrogen Shot)[12] in June 2021, to reduce the cost of clean hydrogen by 80 percent to $1 per 1 kilogram in 1 decade ("1 1 1"). The Hydrogen Shot is the first of the DOE's Energy Earthshots, which aim to accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade while creating good-paying union jobs and growing the economy.

Building on this momentum, the Infrastructure Investment and Jobs Act (IIJA), also known as the Bipartisan Infrastructure Law (BIL), was signed by President Biden on November 15, 2021, making a once-in-a-generation investment in the Nation's infrastructure and competitiveness to deliver a more equitable clean energy future for the American people. Major investments made by the BIL will accelerate progress toward the Hydrogen Shot and stimulate new markets for clean hydrogen. These investments and initiatives include:

- **$1 billion for a Clean Hydrogen Electrolysis Program:** This program will improve the efficiency and cost-effectiveness of electrolysis technologies by supporting the entire innovation chain – from research, development, and demonstration to commercialization and deployment to enable $2/kg clean hydrogen from electrolysis by 2026.[13]
- **$500 million for Clean Hydrogen Manufacturing and Recycling RDD&D Activities[14]:** This effort will also support American manufacturing of clean hydrogen equipment, including projects that improve efficiency and cost-effectiveness and support domestic supply chains for key components.

- **$8 billion for Regional Clean Hydrogen Hubs[15]:** This provision enables the demonstration and development of networks of clean hydrogen producers, potential consumers, and connective infrastructure. These hubs will advance the production, processing, delivery, storage, and end-use of clean hydrogen, enabling sustainable and equitable regional benefits as well as market uptake.
- **Clean Hydrogen Production Standard[16]:** This provision calls for the development of a clean hydrogen production standard that is to be a point of reference for specified programs under the BIL. The Clean Hydrogen Production Standard (CHPS) is not a regulatory standard. Instead, it serves as a guide to actions DOE takes under Title VIII of the Energy Policy Act of 2005 including the regional Clean Hydrogen Hubs, which directs DOE to select projects that "demonstrably aid the achievement" of the standard, and the Clean Hydrogen Research and Development Program, which directs DOE to establish a series of technology cost goals oriented toward achieving the standard.
- **National Clean Hydrogen Strategy and Roadmap[17]:** This provision requires DOE to develop a technologically and economically feasible national strategy and roadmap to facilitate widescale production, processing, delivery, storage, and use of clean hydrogen, within 180 days of the enactment of the BIL and to be updated every three years after that.

In addition to the BIL provisions above, the IRA, signed into law in August 2022, provides a Hydrogen Production Tax Credit (PTC) that will further incentivize the production of clean hydrogen in the U.S.[18] The IRA may also incentivize the development of demand sectors for clean hydrogen through additional programs, including:

- Grants and loans for auto manufacturing facilities to manufacture clean vehicles, including FCEVs;[19]
- A tax credit for producing sustainable aviation fuels, which can require hydrogen feedstock;[20]
- Grants to reduce emissions at ports, which could fund deployments of fuel cells;[21] and

- Grants for clean heavy-duty vehicles, including FCEVs.[22]

The DOE National Clean Hydrogen Strategy Vision: "Affordable clean hydrogen for a net-zero carbon future and a sustainable, resilient, and equitable economy."

DOE prepared this national clean hydrogen strategy and roadmap, as required by the BIL, by collaborating with other Federal agencies and other stakeholders to identify key actions the nation should take to enable successful market adoption of clean hydrogen technologies in support of a net-zero economy by 2050.

The roadmap builds on three decades of DOE strategy that has guided funding to National Laboratories, industry, and academia toward research, development, demonstration, and deployment (RDD&D) activities that have enabled the commercialization of hydrogen and fuel cell technologies. The Department's 2020 Hydrogen Program Plan[23] described its strategy for coordinated RDD&D activities that enable the adoption of hydrogen technologies across multiple applications and sectors. The DOE national strategy and roadmap are informed by the DOE Hydrogen Program Plan, multiple analysis activities, and the industry-led U.S. hydrogen roadmap published in 2020[24] and further builds upon DOE-supported tools and models and prior work by diverse stakeholders to evaluate the growth potential and impacts of new hydrogen markets.

This report comprises three sections:

Section A outlines the overarching long-term national strategy for the United States to achieve its climate goals. It provides a snapshot of hydrogen production and use in the United States today and the opportunity clean hydrogen could potentially provide in contributing to national goals across sectors. Pathways for clean hydrogen to decarbonize applications are informed by demand scenarios for 2030, 2040, and 2050 – **with strategic opportunities for 10 million metric tonnes (MMT) per year of clean hydrogen by 2030, 20 MMT per year by 2040, and 50 MMT per year by 2050.** These scenarios are based on achieving cost competitiveness to enable demand in specific sectors and where there are fewer alternatives, such as direct electrification or the use of biofuels. As technologies and markets develop, more detailed analyses will be forthcoming in the required updates to this document, including the optimal use of hydrogen in "no regrets" sectors, avoiding stranded assets by creating demand certainty, and prioritizing energy and environmental justice.

Section B describes the challenges to realizing the benefits of hydrogen in the United States and three primary strategies to address them: (1) Focus on hard-to-decarbonize sectors for the use of clean hydrogen, (2) Reduce the cost of clean hydrogen, and (3) Focus on regional networks, co-locating large-scale clean hydrogen production and end-use, including through hydrogen hubs to enable critical mass infrastructure, drive scale, and facilitate market lift-off, that centers and leverages place-based opportunities for equity, inclusion, and sustainability. This section also describes pathways to clean hydrogen production, distribution, and storage and their associated costs today and in the future. Maps in this section illustrate resource, infrastructure, and demand potential in regions across the United States.

Section C describes the set of actions needed to support and develop the industry in the near, mid, and long term, alongside guiding principles and metrics to measure progress.

This strategy will leverage U.S. strengths in RDD&D and manufacturing innovation and ingenuity to reduce emissions, increase U.S. energy independence, and build a robust domestic market for clean hydrogen supported by domestic supply chains and sustainable jobs, including good-paying union jobs. The strategy also targets initiatives to create new regional economic opportunities while reducing greenhouse gas (GHG) emissions and improving air quality. These benefits can foster diversity, equity, and inclusion when projects are coupled with meaningful stakeholder engagement and ongoing support. Long-term strategies include a U.S. leadership role in supporting the global transition from fossil fuels, enabling energy security and resiliency by exporting clean hydrogen. The DOE National Hydrogen Strategy approaches hydrogen RDD&D holistically, leveraging place-based approaches to maximize positive benefits to the Nation and the world.

A: National Decarbonization Goals

The time is now for strategic, bold, and concrete action to meet the ambitious goals set by the United States to tackle the climate crisis. These goals include 100 percent carbon pollution-free electricity by 2035 and net-zero GHG emissions by 2050.[25] The U.S. national climate strategy[26] lays out a long-term approach and pathways for the United States to meet its 2030 Nationally Determined Contribution (NDC) toward global climate objectives—an ambitious 50 to 52 percent reduction relative to 2005 emissions. The challenge, as visualized in Figure 1, is daunting. Still, it is achievable through an all-hands-on-deck call to action and a portfolio of technologies and strategies to accelerate scale.

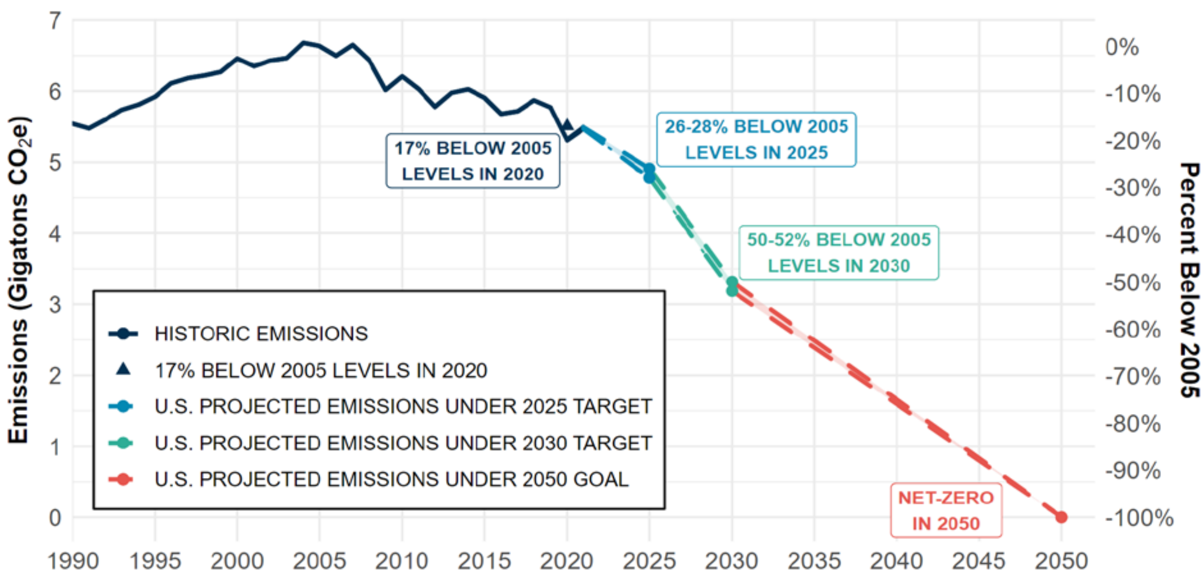


Figure 1: U.S. economy-wide net greenhouse gas emissions. A net-zero system will require transformative technologies to be deployed across sectors.[27]

Achieving a net-zero economy by 2050 requires transformational advances in every aspect of our energy infrastructure and many other sectors of the economy. Hydrogen can serve as a key enabler of our goal due to its versatility and potential to complement other clean technologies in three of the most energy and emissions-intensive sectors in the United States: industry, transportation, and electricity generation.

As shown in Figure 2, each of these sectors contributes substantially to annual U.S. greenhouse gas emissions, and each sector's decarbonization strategy will be dependent on its numerous industries, which have distinct operating requirements and drivers.

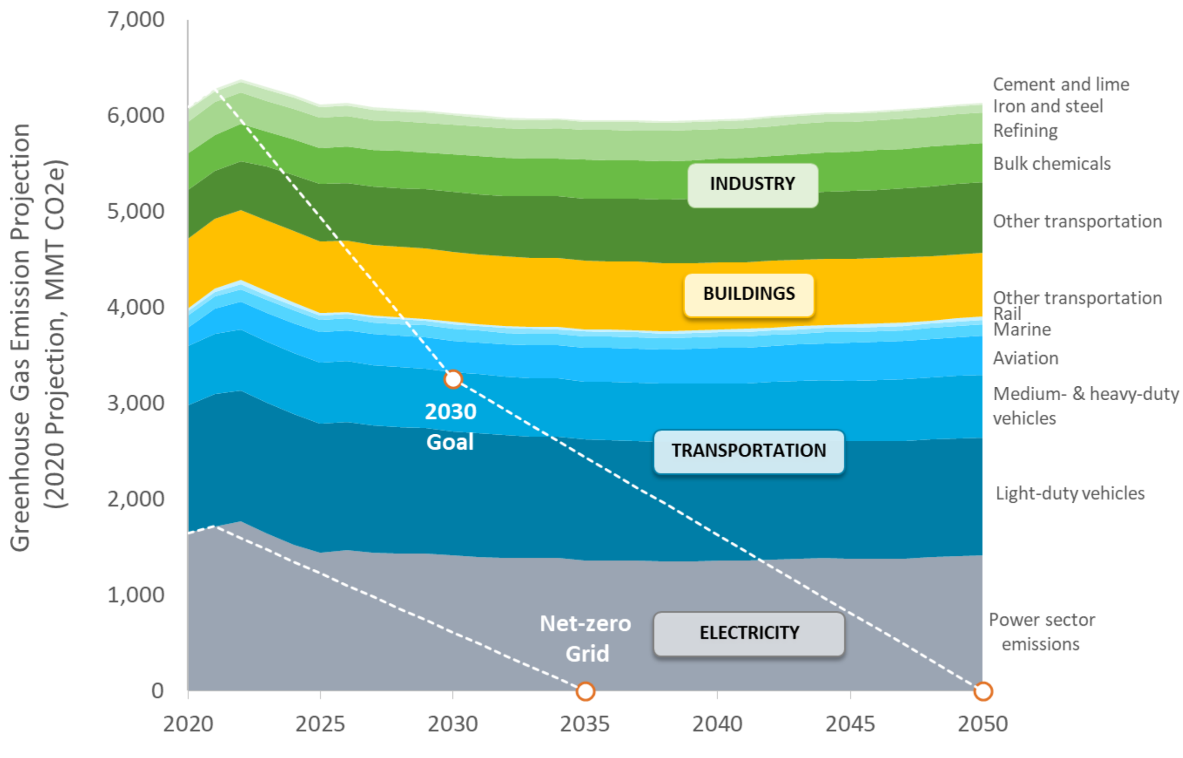


Figure 2: U.S. net greenhouse gas emissions projected to 2050 (horizontal bars),[28] relative to national goals to enable a clean grid and net zero emissions by 2050 (dashed lines).

Hydrogen, as a versatile energy carrier and chemical feedstock, offers advantages that can also leverage all our nation's energy resources—renewables, nuclear, and fossil fuels with carbon capture and storage (CCS)—and can couple baseload power with variable generation to offer resiliency and energy storage. It can then be used as a fuel or feedstock for applications that lack competitive and efficient clean alternatives.

Though there are many opportunities for hydrogen, an integral component of our strategy will be a holistic approach that includes addressing environmental and energy justice and equity. The clean hydrogen strategy also supports the Administration's Justice40 Initiative, which pledges that at least 40 percent of overall benefits from Federal investments in climate and clean energy be delivered to disadvantaged communities.[29]

The strategies and pathways will be designed to benefit all Americans, not only in terms of emissions reduction but also in public health, economic growth, jobs – including good-paying union jobs, and improving quality of life.

H2@Scale Enabler for Deep Decarbonization

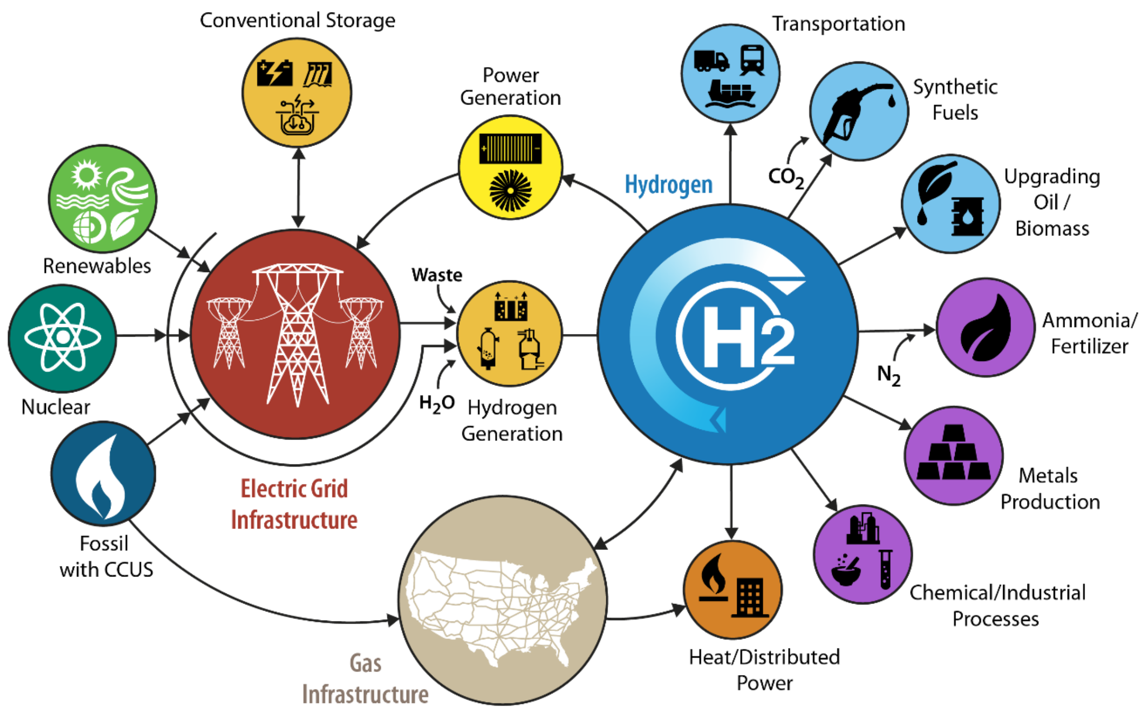


Figure 3: DOE's H2@Scale initiative to enable decarbonization across sectors using clean hydrogen

As shown in Figure 3, which illustrates the H2@Scale® vision launched in 2016 by DOE and its National Laboratories, clean hydrogen can be produced from diverse domestic resources and used across sectors.[30] Production can be centralized or decentralized, grid-connected or off-grid, offering scalability, versatility, and regionality. Hydrogen provides more options across sectors and can complement today's conventional grid and natural gas infrastructure. Rather than only "electrons to electrons" pathways such as the electric grid to batteries, hydrogen can be stored and used where electrification may be challenging.

Several technologies can produce clean hydrogen, including electrolyzers powered by the Nation's growing share of clean energy, methane reformation with carbon capture and storage, gasification or thermal conversion of biomass and/or solid wastes with carbon capture and storage, and many other emerging technologies. Initial deployments using clean hydrogen are expected to leverage regional energy resources and target industries that currently rely on conventional natural gas to hydrogen technologies (without carbon capture and storage (CCS)). These industries can rapidly generate scale and create near-term impact in terms of emissions reductions, paving the way for deployments of new hydrogen technologies that can displace fossil fuels in other sectors.

Policymakers worldwide recognize the need to complement electrification strategies with fuels like clean hydrogen. Numerous studies show the potential role of hydrogen in global energy systems, though estimates vary significantly, as shown in Figure 4.[31] Countries that have identified hydrogen as part of their decarbonization strategy also see hydrogen's role as enabling energy security and resiliency.

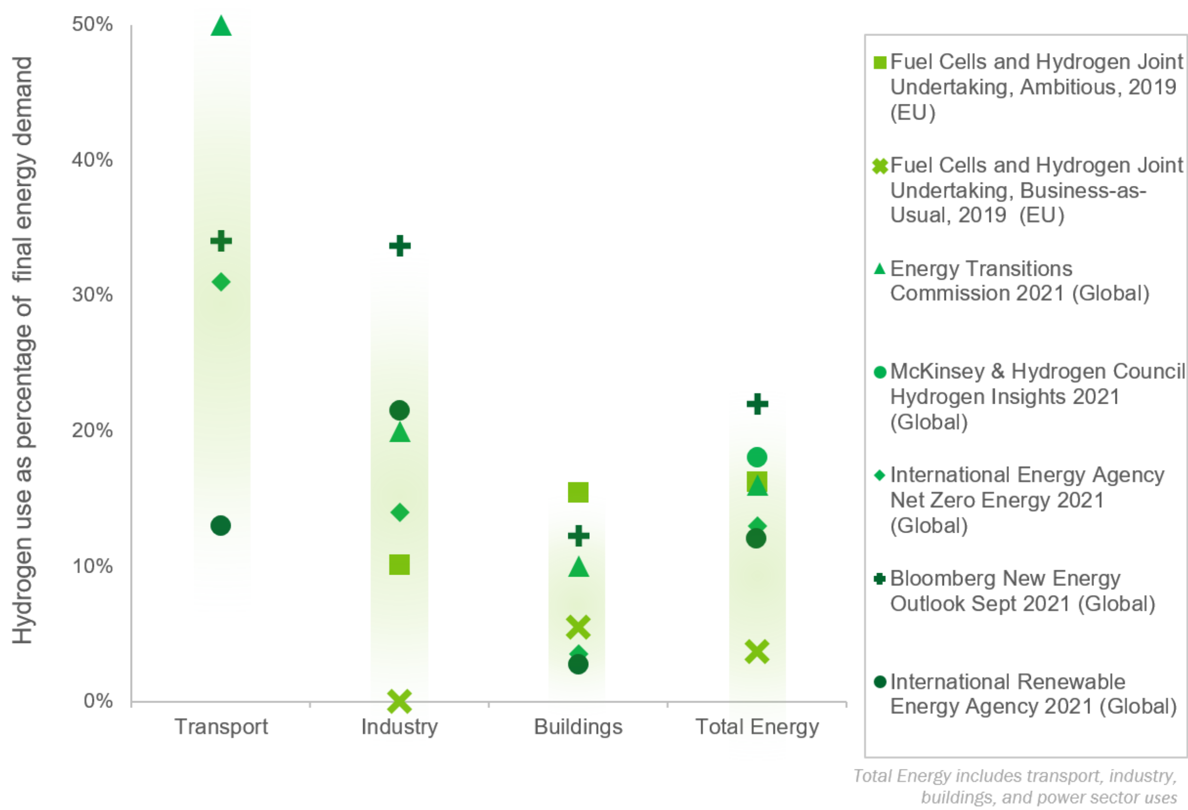


Figure 4: The range of hydrogen's role in final energy use according to global and regional estimates shows a wide range of applications in each sector. [32]

The actions laid out in this roadmap will bolster rigorous analytical models and frameworks and foster global collaboration to determine the best use of hydrogen and maximize impact.

Based on several models and analyses for the United States, DOE lays out **the opportunity for hydrogen,** as shown in Figure 5. DOE aims to increase clean hydrogen production from nearly zero today to **10 MMT per year by 2030, 20 MMT per year by 2040, and 50 MMT per year by 2050.** Although clearly ambitious, these goals are achievable and are based on demand scenarios assuming cost competitiveness for hydrogen use in specific sectors such as industrial applications, heavy-duty transportation, and long-duration energy storage. By achieving a **5-fold increase** in hydrogen production and utilization by 2050, DOE expects the country can reduce total GHG emissions in the United States by approximately 10 percent relative to 2005 levels when all hydrogen is cleanly produced. As DOE continues to refine and optimize its analyses, DOE **will continue to assess the cleanest, most sustainable, and holistic pathways** for hydrogen production through end-use, with particular emphasis on place-based and regional benefits.

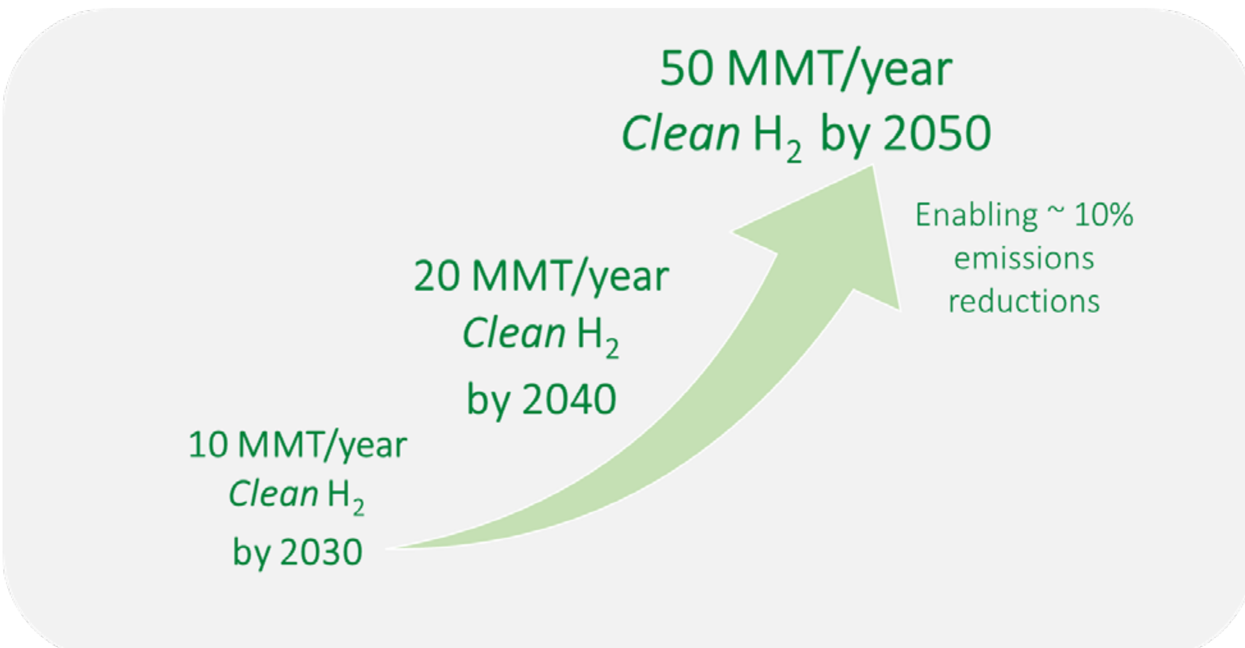


Figure 5: The opportunity for clean hydrogen in the United States

Hydrogen Production and Use in the United States

Clean hydrogen can be produced through a various pathways, including water-splitting using renewable or nuclear power, from fossil fuels with carbon capture and storage, and biomass or waste feedstocks. Other pathways in earlier stages of development include thermochemical, biological, and photoelectrochemical processes. The emissions intensity of each of these pathways depends on key variables, such as carbon capture and methane leak rates or fugitive emissions and the use of clean electricity.

Industry produces about 10 MMT of hydrogen per year in the United States,[33] compared to roughly 90 MMT per year globally,[34] mostly for the petroleum refining, ammonia, and the chemical industry. Some of that hydrogen is produced and used within the fence," (i.e., at the same facility), so the total hydrogen consumption can be modestly higher.[35] Figure 6 shows the allocation of hydrogen use across sectors in 2021. Today, hydrogen production generates about 100 million metric tonnes of greenhouse gas (tonnes of CO_2-equivalent) per year on a well-to-gate basis.[36]

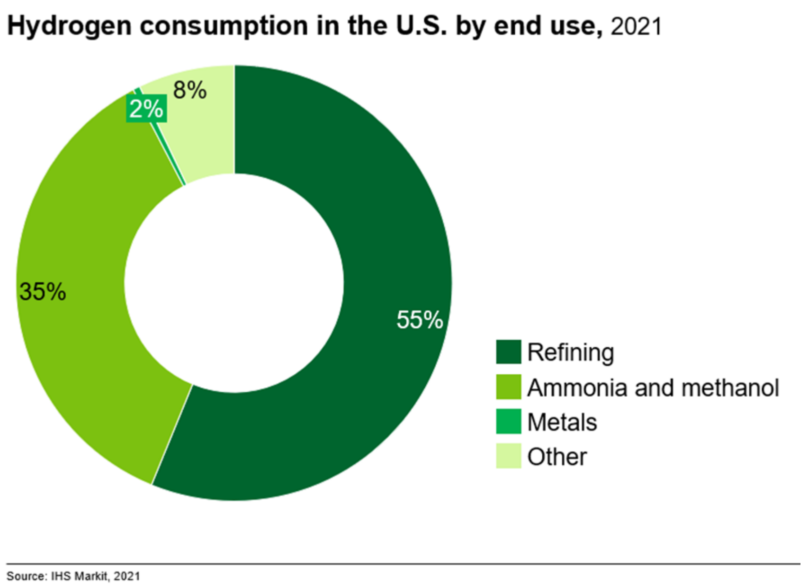


Figure 6: Consumption of hydrogen in the United States by end-use in 2021[37]

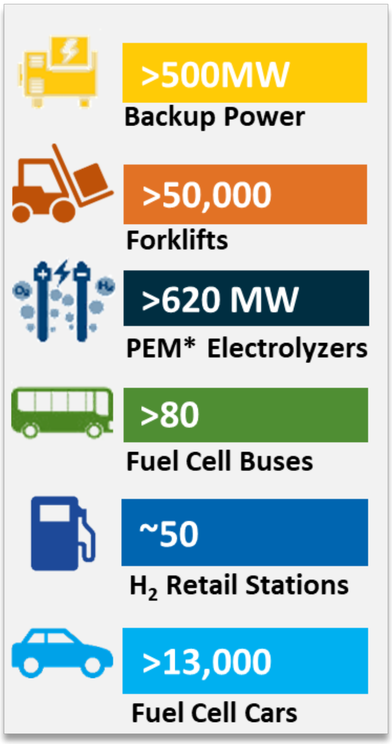
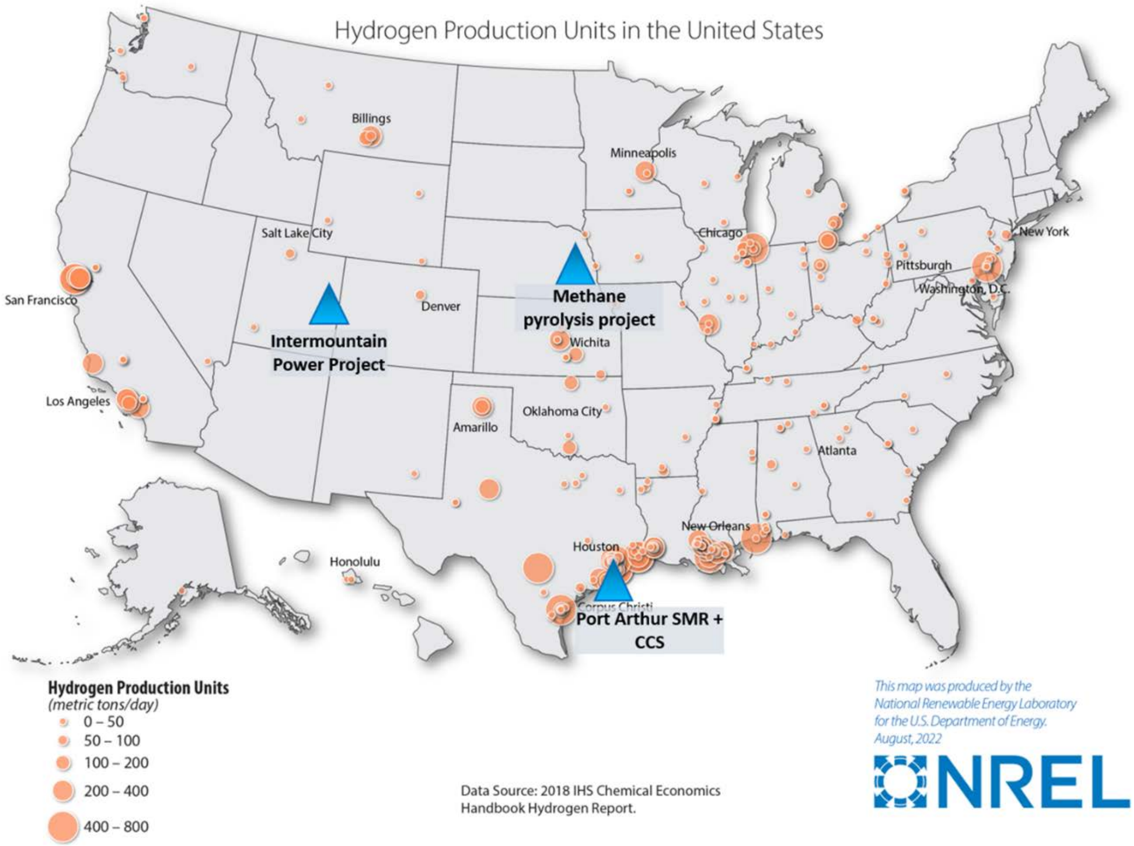


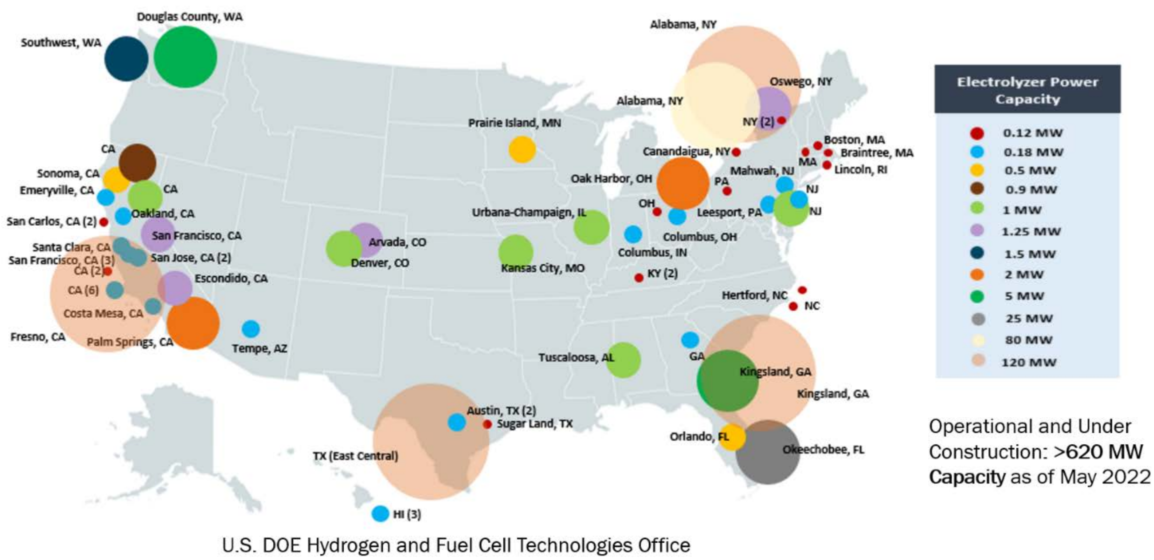
Figure 7: Examples of hydrogen and fuel cell technology deployments in the United States

To support these industries, the United States currently has approximately 1,600 miles of dedicated hydrogen pipeline and three geological caverns, including the world's largest, which can store 350 gigawatt-hour (GWh) of thermal energy or enough to back up a nuclear plant for a week.[38] Outside of petroleum and fertilizer production, hydrogen use is now making its way into other end-use applications. These include more than 50,000 fuel cell forklifts,[39] nearly 50 open retail hydrogen fueling stations, approximately 70 fuel cell buses,[39] more than 13,000 fuel cell vehicles, and over 500 megawatts (MW) of fuel cells for stationary and backup power (e.g., for telecommunications), as detailed in Figure 7.[39] Flagship projects in industry and energy storage are also putting the United States on the global map in terms of hydrogen deployment. The Intermountain Power Project being built in Utah will enable multiple gigawatt-hours of power generation using blends of natural gas and hydrogen produced via electrolysis.[40] In Louisiana, a developing clean energy complex will use methane reforming with CCS at a 95 percent capture rate to supply clean hydrogen to regional markets and to export globally. This project will also be the world's largest carbon capture for sequestration operation, sequestering more than 5 million tonnes of CO_2 per year of carbon dioxide.[41]

Several states and regions across the Nation are actively pursuing clean hydrogen projects, ranging from production through end-use. The pace of new project announcements is accelerating. The values shown in Figure 8 reflect a snapshot of projects announced or operational by May 2022 based on publicly available information and DOE-funded project data.



(a) Hydrogen production deployment sites at-scale and traditional production



(b) Planned and operational PEM electrolyzer capacity

Figure 8: Examples of hydrogen production technology deployments in the United States. The scale of production capacity is approximately indicated by the size of the circle.[42]

Opportunities for Clean Hydrogen to Support Net-Zero

As shown in Figure 9, today's commercial availability of hydrogen technologies is limited. New applications for clean hydrogen in the coming decade, however, could include several opportunities, including steelmaking, heavy-duty transportation, and the production of liquid fuels for marine and aviation applications. It will be important to prioritize hydrogen deployment where other high-efficiency and low-cost options, such as electrification, are less likely to occur. As additional energy technologies advance and the entire energy system decarbonizes, new demands for hydrogen may emerge, including long-duration energy storage to enable a carbon-free electric grid or stationary heat and power generation, including combined heat and power using fuel cells and other low- or zero-emission technologies.

Over time, the growth of clean hydrogen supply across these sectors may also spur the deployment of large-scale distribution infrastructure that connects regions of low-cost supply with large-scale demand. In all cases, forming regional networks will depend on understanding optimal geographic regions where hydrogen may be most advantageous from an overall emissions, resilience, resources, and sustainability perspective. DOE will solicit input and feedback from communities impacted by issues such as co-location with legacy fossil infrastructure and increased risk of drought to mitigate risk to already burdened communities. Further elaboration of stakeholder engagement processes and actions is in Section C.

	Industrial feedstocks	Transportation	Power generation & energy storage	Hydrogen blending in natural gas
Existing demands at limited current scales	• Oil refining • Ammonia • Methanol	• Forklifts and other material-handling equipment • Buses • Light-duty vehicles	• Distributed generation: primary and backup power • Renewable grid integration with storage and other ancillary services	• Low percentage hydrogen blending
Emerging demands and potential new opportunities	• Steel and cement manufacturing • Industrial heat • Bio/Synthetic fuels	• Medium- and heavy-duty vehicles • Rail • Maritime • Aviation • Offroad equipment (mining, construction, agriculture)	• Hydrogen low NOx combustion • Long-duration energy storage • Direct/reversible fuel cells • Nuclear/hydrogen hybrids • Fossil/waste/biomass hydrogen hybrids with CCUS	• High percentage hydrogen blending • Industry, building or district heating for hard to electrify or limited options

Adapted from DOE Hydrogen Program Plan

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Figure 9: Current and emerging demands for hydrogen

The BIL requires DOE to develop a program to demonstrate regional clean hydrogen hubs, defined as a network of clean hydrogen producers, clean hydrogen consumers, and connective infrastructure located "in close proximity" to each other. [43] Co-location of hydrogen supply and demand can reduce the need for new long-distance infrastructure, lowering the cost of early market growth until large-scale, stable demand develops regionally and nationally. Federal, state, and local stakeholders can support the deployment of clean hydrogen through targeted regional outreach and the creation of networking opportunities, such as DOE's H2 Matchmaker online portal launched in January of 2022.[44]

The BIL also requires clean hydrogen hubs to target, "to the maximum extent practicable," specific end-use sectors —including power generation, industry, residential and commercial heating, and transportation. In many applications within these sectors, the use of clean hydrogen can enable a 40-90 percent reduction in cradle-to-grave emissions by displacing incumbent fossil fuels.[45] The magnitude of reductions in each sector varies widely, depending on the performance of the incumbent technology and other alternatives available for decarbonization.

Scenario and Tipping Point Analyses

For clean hydrogen to be competitive from a long-term sustainable market perspective, it must be available below a minimum threshold price point, depending on the fuel and processes its use would displace in each sector. In practice, particularly during the transition, hydrogen can also provide value that is not typically monetized, such as grid services or arbitrage and fuel flexibility, beyond a conventional cost parity perspective. However, a cost-based perspective provides a conservative view of market demand potential.

Figure 10 depicts the price range at which hydrogen would be competitive with incumbent fuels (such as diesel, natural gas, or coal) in various applications and the approximate time frame at which large-scale deployments of clean hydrogen are expected to occur in each sector. The "willingness to pay" for each application reflects the total price at which hydrogen must be available to the end-user, including the cost of production, distribution, and additional conditioning onsite, such as compression, storage, and dispensing. Importantly, each sector has different onsite requirements. While some sectors, such as transportation, have a higher willingness to pay, infrastructure requirements, such as compression and dispensing at fueling stations and the potential need for liquefaction, can contribute significantly to the total cost of hydrogen experienced by the end-user.

In the U.S., the niche market for fuel cell forklifts, catalyzed by the American Recovery and Reinvestment Act (ARRA) in 2009, paved the way for more than 50,000 fuel cell forklifts at commercial warehouses around the nation and over 115 fueling stations.[46] These applications can be competitive at higher hydrogen costs due to faster fueling times, higher operational throughput, and less space required versus battery forklifts. Fuel cell trucks and buses offer another opportunity for early market adoption; however, based on rigorous analysis[47] and industry feedback through prior workshops and critical reviews of lab and DOE publications, the total cost to the end-user, including infrastructure, needs to reach about \$5/kg. Other markets—such as biofuels, chemicals, and steel—require lower costs to be competitive in the long term. The current cost of clean hydrogen production and the Hydrogen Shot cost target for clean hydrogen production (not including downstream infrastructure such as delivery, storage, and dispensing) are depicted in this figure for context.

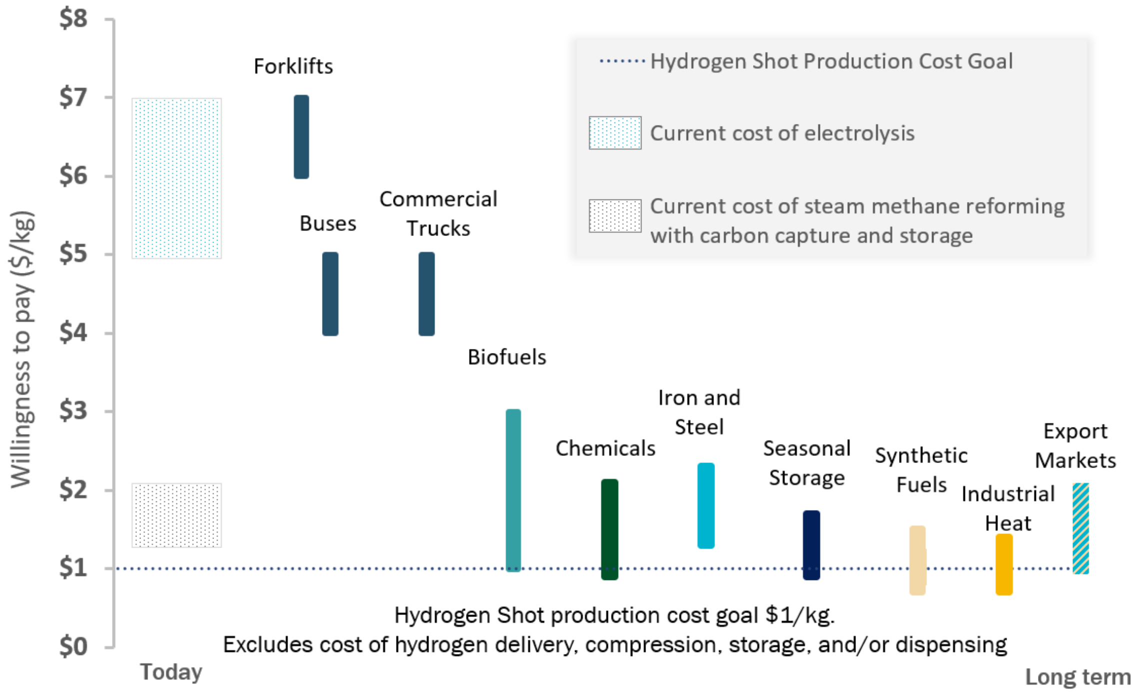


Figure 10: Willingness to pay, or threshold price, for clean hydrogen in several current and emerging sectors (including production, delivery, and conditioning onsite, such as additional compression, storage, cooling, and/or dispensing).[48]

The amount of hydrogen demand at the respective threshold cost in each of these sectors will depend on the extent to which other competing and incumbent technologies and fuels evolve.[49]

Figure 11, below, depicts scenarios for the demand expected in each sector if clean hydrogen is available (produced, delivered, and dispensed) at the threshold price shown. For instance, approximately $5/kg for hydrogen produced, delivered, compressed, and dispensed would pave the way for early adopters in the fuel cell truck market. [49] At approximately $4/kg, scenario analyses have shown that 10-14 percent of all medium and heavy-duty fuel cell trucks would demand about 5-8 MMT/year of hydrogen.[50] The lighter shaded bars represent a more optimistic demand scenario for each market shown. Given the uncertainty in other variables such as fuel cell cost, efficiency, durability, on-board hydrogen storage, and infrastructure, as well as the cost of incumbent fuels and technologies, analyses will continue to be refined. However, these results indicate large potential volumes for clean hydrogen demand, assuming DOE targets for clean hydrogen costs are met.

Other current, emerging, and future markets with higher ranges of uncertainty today, such as hydrogen exports, power-to-liquid fuels, and petroleum refining could generate additional demand. Figure 12 depicts potential scenarios for end-use of clean hydrogen in 2030, 2040, and 2050, enabling at least 20 MMT per year by 2040 and 50 MMT per year by 2050.

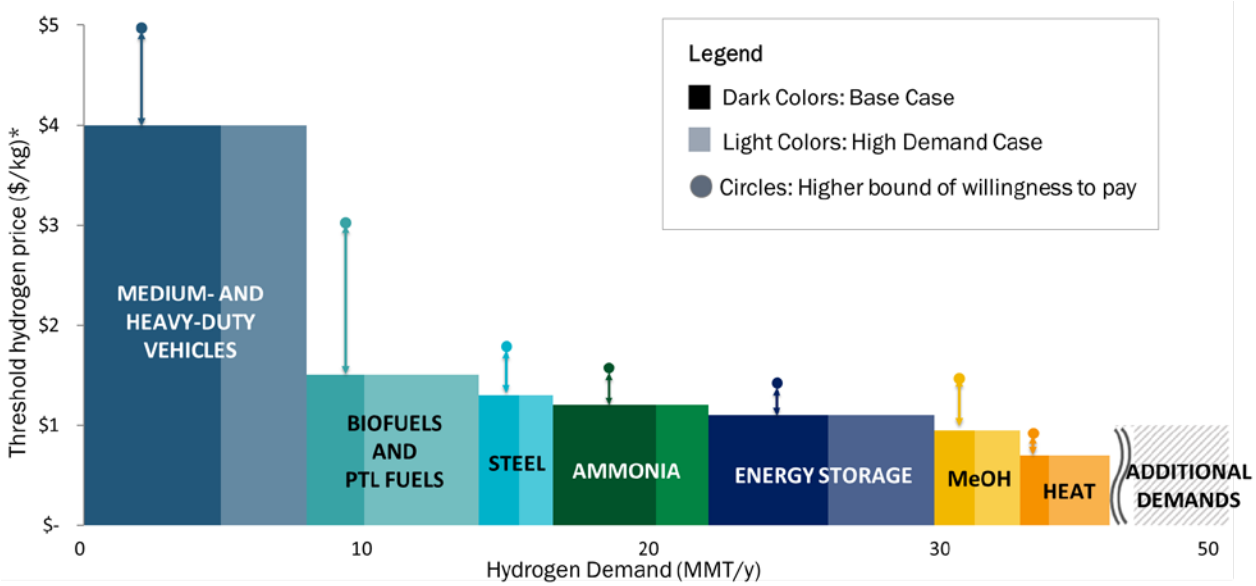


Figure 11: Scenarios showing estimates of potential clean hydrogen demand in key sectors of transportation, industry, and the grid, assuming hydrogen is available at the corresponding threshold cost.

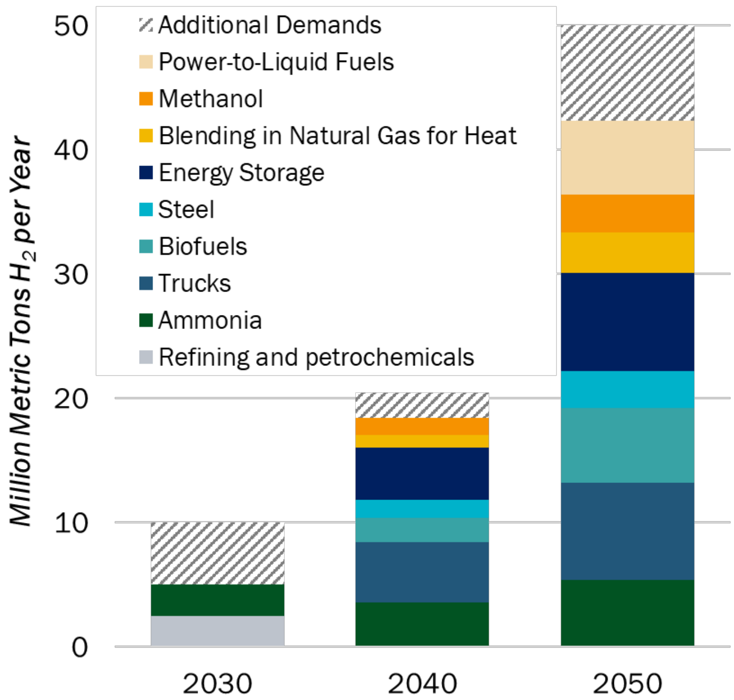


Figure 12: Deployments of clean hydrogen to decarbonize industry, transportation, and the power grid can enable 10 MMT/year of demand by 2030, ~20 MMT/year of demand by 2040, and ~50 MMT in 2050

In addition to hydrogen and fuel cells for the trucking sector, hydrogen will also be an essential feedstock to biofuels, including sustainable aviation fuels (SAF) and power-to-liquid fuels, that could decarbonize offroad vehicles and applications where direct electrification or fuel cells may not be competitive. If the U.S. replaces all jet fuel consumption with SAF by 2050, approximately 2-6 MMT/year of hydrogen could be required to produce 35 billion gallons of SAF from biofuels.[51] An additional 6 MMT/year would be required to produce 4 billion gallons of power-to-liquid fuels using 44 MMT of carbon dioxide (approximately the amount of concentrated CO2 currently available from ethanol plants in the U.S.).[52]

Hydrogen can also play a key role in decarbonizing the industrial sector to enable a net-zero economy by 2050, including steelmaking, chemicals, and heat generation. Depending on the evolution of competing options, the use of hydrogen in iron refining could account for 10-20 percent of steelmaking in 2050, enabling about 1-3 MMT/year of demand.[53] An additional 4-5 MMT/year of clean hydrogen could be consumed by ammonia plants to decarbonize all domestic demand for conventional uses, such as fertilizer production.[54,75] Since hydrogen is an essential feedstock for ammonia production, and using clean sources would therefore be necessary for decarbonization, the ammonia market is expected to be one of the early opportunities for creating large-scale demand for clean hydrogen.

In the methanol sector, alternatives to clean hydrogen include deploying CCS technologies with conventional fossil feedstocks or using biomass feedstock. If clean hydrogen were used for half of the U.S. methanol supply in 2050, 1-3 MMT/year would be required to satisfy demand.[55] In addition to its chemical properties, hydrogen can support decarbonization by displacing natural gas in sectors that require high-temperature heat, an application that is difficult to electrify. The use of blends of clean hydrogen and natural gas of 20-50% (by volume) to produce high-temperature heat (>550°C) for chemicals and steelmaking would generate approximately 1-3 MMT/year of demand.[56] It is important to note that high concentrations of hydrogen are needed to achieve significant abatement of emissions since the energy content of hydrogen is only about a third of natural gas by volume. Life cycle analysis within the HyBlend initiative will characterize the decarbonization potential of blends, accounting for different approaches to producing hydrogen.

Achieving the Administration's goals for a 100 percent clean electricity grid will create demand for long-duration energy storage (LDES), where hydrogen can also play a key role. Estimates of the magnitude of LDES required in a clean grid have high variability, depending on the degree of electrification, buildout of transmission lines, and the rate at which other offsetting technologies, such as direct air capture, are deployed. Based on a range of studies with varying assumptions around these constraints, it is estimated that about 4-8 MMT/year of hydrogen would be needed in 2050 to supply energy storage for a 100 percent clean grid.[57]

It should be emphasized that these are all cost-driven demand scenarios, and there is scope for flexibility in the volumes of hydrogen described above for each sector. Initial large-scale deployments of clean hydrogen are expected to target industries with established supply chains and economies of scale, such as ammonia production and the petrochemical industry. These deployments will be supplemented with smaller-scale deployments in new applications and growing sectors as the infrastructure develops. Based on the success of early deployments and the momentum provided by the Hydrogen Shot, the United States has an opportunity to achieve aggressive growth in clean hydrogen supply to 20 MMT/year by 2040 and 50 MMT/year by 2050, as shown in

Figure 12. This demand-based opportunity can be achieved even while focusing hydrogen on decarbonizing key sectors of the economy that cannot be easily electrified and can help integrate renewables into a clean grid.

While Figure 12. depicts scenarios of demand growth, the demands that ultimately materialize may vary due to a wide range of market forces, policies (such as the production tax credit for clean hydrogen created by the Inflation Reduction Act), and evolutions in technology performance and costs feasible by 2050. A sensitivity analysis accounting for these variables is depicted in Figure 13. In each sector, the "core range" reflects the amount of hydrogen demand estimated for 2040 and 2050 (as shown in Figure 12), while the "additional scenarios" reflect demands under other technology or market conditions.

In transportation, the additional scenarios depict varying assumptions regarding the cost of hydrogen fuel.[58] For biofuels and power-to-liquid fuels, the ranges reflect approaches to optimize biofuel production from different feedstocks and variability in demand for power-to-liquid fuels, assuming up to 6 MMT H_2/year could be used for power-to-liquid fuels as described above. For industrial applications, the low end of the range assumes that ammonia is the only market sector that adopts clean hydrogen. The high end assumes ammonia, steelmaking, and methanol production adopt clean hydrogen to a degree consistent with the core range and that clean hydrogen is additionally used for petroleum refining at the same rate that steam methane reforming (SMR) is used for this sector today (~6 MMT/year, as shown in Figure 6). Additional demand for ammonia, methanol, or other chemical hydrogen carriers for potential export of hydrogen are not included in these values.

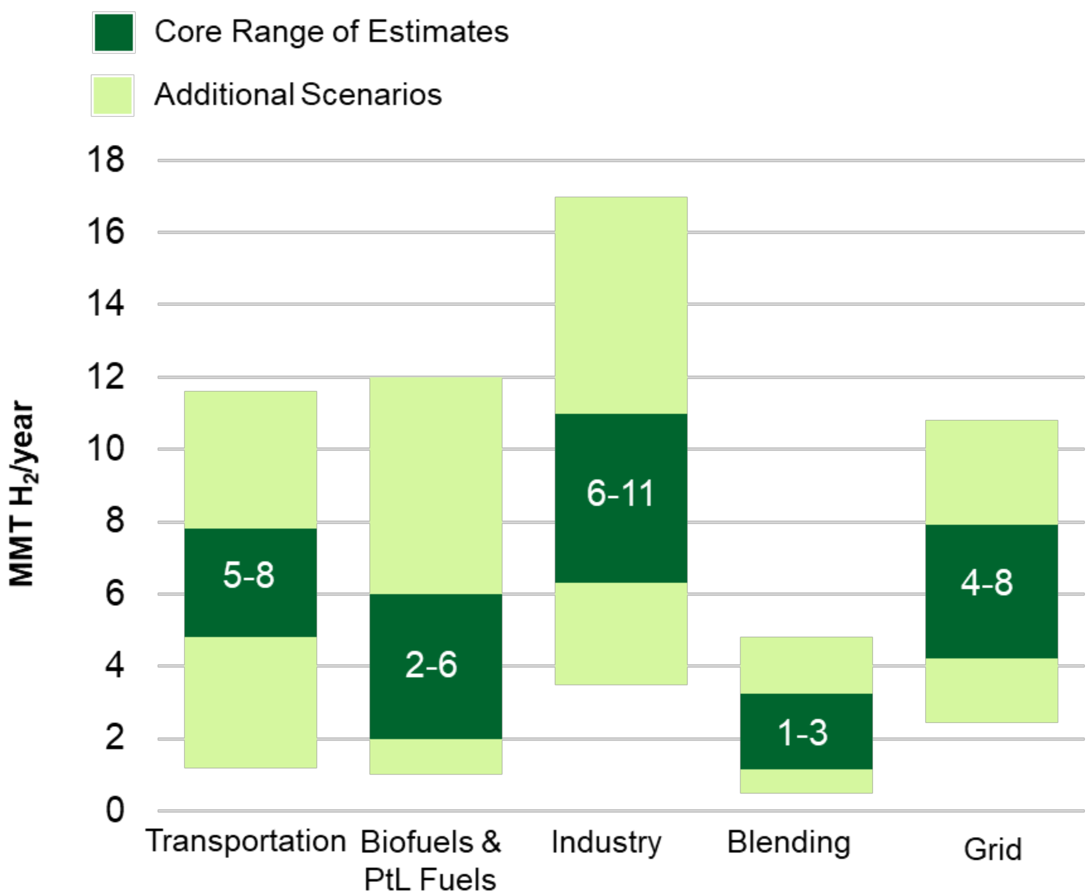


Figure 13: Ranges in potential hydrogen demand in five key sectors: transportation, biofuels and power-to-liquid fuels, industry, blending, and energy storage and grid balancing.

The range of hydrogen in natural gas blending reflects its use to decarbonize industrial heat. The lower bound of the sensitivity range assumes that 10 percent hydrogen by volume is used in industrial sectors consuming heat at ≥ 550°C, while the upper bound assumes that 50% hydrogen by volume is used in industrial sectors consuming heat at ≥300°C.[59]

In the power sector, the factors affecting hydrogen use are complex and interdependent. Hydrogen is one option for providing flexible, reliable, and dispatchable power as well as long-duration energy storage, including in the form of renewable natural gas, ammonia, and other fuels. The emissions benefit of these energy carriers varies, however, depending on how these carriers are produced, distributed, and utilized. Even if hydrogen itself is not the storage medium for energy, renewable natural gas and other chemical storage media, such as ammonia, would require clean hydrogen.

Electrolyzers can also dynamically respond to fluctuations in renewable power, thereby providing grid services in addition to energy storage. Large buildouts of wind, solar, and zero-emission power are needed to develop a clean grid. Still, hydrogen and other technologies are needed to integrate renewables with a highly electrified, resilient, and equitable power system. The range of potential demands for hydrogen energy storage on the grid draws from several studies that modeled a clean grid with varying levels of electrification and demand side flexibility.[60]

The range of clean hydrogen use will depend on various barriers to market adoption, including challenges in building storage and infrastructure. By lowering these barriers, including an emphasis on addressing energy and environmental justice, clean hydrogen can be deployed safely and rapidly to lower emissions in hard-to-decarbonize sectors.

Barriers to Achieving the Benefits of Clean Hydrogen

While clean hydrogen technology costs have already been substantially reduced, the technologies themselves are still very much in the early stages of commercial deployment and some significant challenges remain. These remaining challenges include lack of hydrogen infrastructure, lack of manufacturing at scale, cost, durability, reliability, and availability challenges in the supply base across the entire value chain.[61] Stakeholder input continuously identifies the cost of clean hydrogen as a key barrier. At DOE's Hydrogen Summit in September 2021, attended by more than 3,000 stakeholders from 34 countries, multiple challenges were identified to the question posed regarding "what is preventing widespread public acceptance and market adoption of hydrogen in the United States?"[62] As shown in Figure 14, cost was the most widely selected barrier, but the lack of infrastructure and the need for public awareness and acceptance were also identified as major challenges.

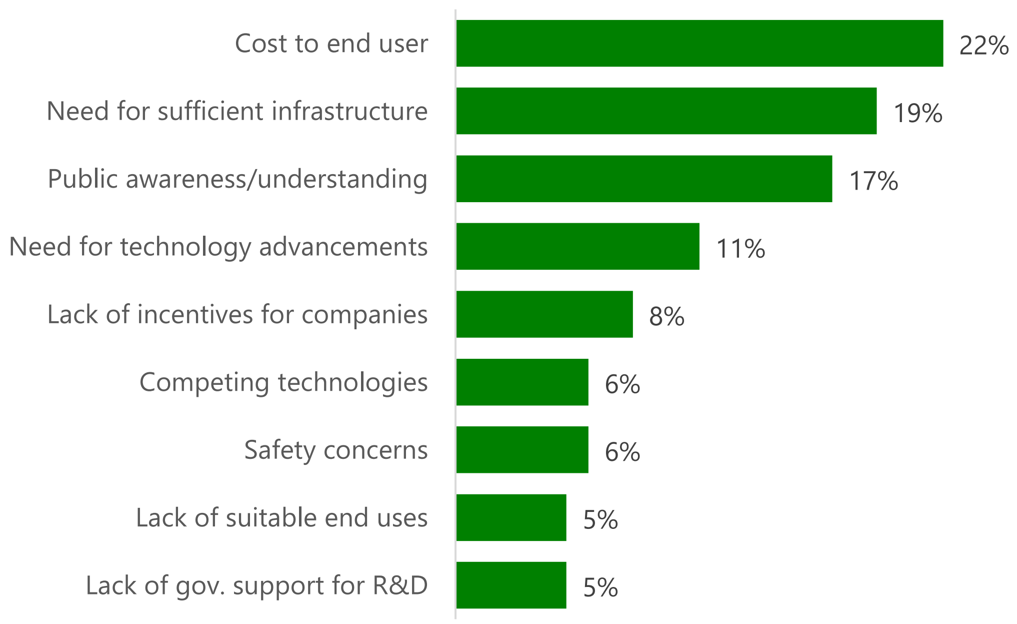


Figure 14: Stakeholder identification of potential barriers preventing widespread public acceptance and market adoption of hydrogen in the United States.

The levelized cost of hydrogen must be reduced significantly. For example, based on analysis in 2020, the cost of clean hydrogen using proton exchange (or polymer electrolyte) membrane (PEM) electrolysis can be more than $5/kg when using renewable electricity.[63] Furthermore, the cost of electrolysis depends heavily on the cost of electricity used. Hydrogen from low-volume PEM electrolysis requires an 80 percent reduction in cost to achieve the Hydrogen Shot goals and to be competitive.[64] While advanced and high-temperature electrolyzers are progressing, challenges to market adoption include the cost, durability, and scale of manufacturing capacity. Additionally, high-temperature electrolysis requires integration and optimization with thermal sources such as nuclear plants to increase the efficiencies for hydrogen production.

In addition to hydrogen production costs, challenges in hydrogen transport—such as pipelines, tube trailers, liquefaction, siting, permitting, and materials compatibility—need to be addressed. For instance, operational data from California show that the delivered cost of hydrogen to fueling stations, including compressing and dispensing, for fueling vehicles can be more than $13/kg[65] – more than three times higher than the cost required to be competitive.[66]

Storing hydrogen efficiently and safely is also a significant challenge. Although hydrogen has nearly three times the energy content per unit of mass compared to gasoline,[67] the volumetric energy density of gaseous hydrogen is very low, making it difficult to store, particularly in compact containers or tanks. The weight and volume of hydrogen storage systems need to be reduced, as well as cost, with targets varying depending on the application. While safety has been demonstrated in thousands of commercial systems and through rigorous testing, continual effort is needed to ensure safety and apply best practices.

While compressed hydrogen is typically stored at ambient temperatures, reducing the temperature to cold or cryogenic temperatures can significantly increase the density of hydrogen. In liquid form, hydrogen is stored at extremely low cryogenic temperatures in highly insulated double-walled tanks. Such tanks are commercially available and used today for industrial-scale storage and transport. However, the need for insulation as well as the boil-off and venting (releasing built-up pressure to ensure safety), present added cost and challenges to system performance. Material, component, and system-level RDD&D are needed to address these challenges. Additional work on using hydrogen carriers, such as ammonia or liquid organic hydrogen carriers (LOHCs), including the cost, life cycle emissions, and toxicity of the carriers is also needed.

Figure 15 shows the cost status at low volume and the modeled cost of hydrogen technologies used in the transportation sector, assuming high volume manufacturing compared to the ultimate cost targets shown in green. These targets have been developed through analyses characterizing the total cost of ownership (TCO) of hydrogen-based systems, such as heavy-duty fuel cell trucks, relative to those using incumbent fuels, such as diesel. Additional TCO analysis is currently underway to inform hydrogen cost and performance targets for other applications across industry and transportation. Across applications, costs need to fall significantly compared to their current level to become competitive from a sustainable, market-driven perspective.

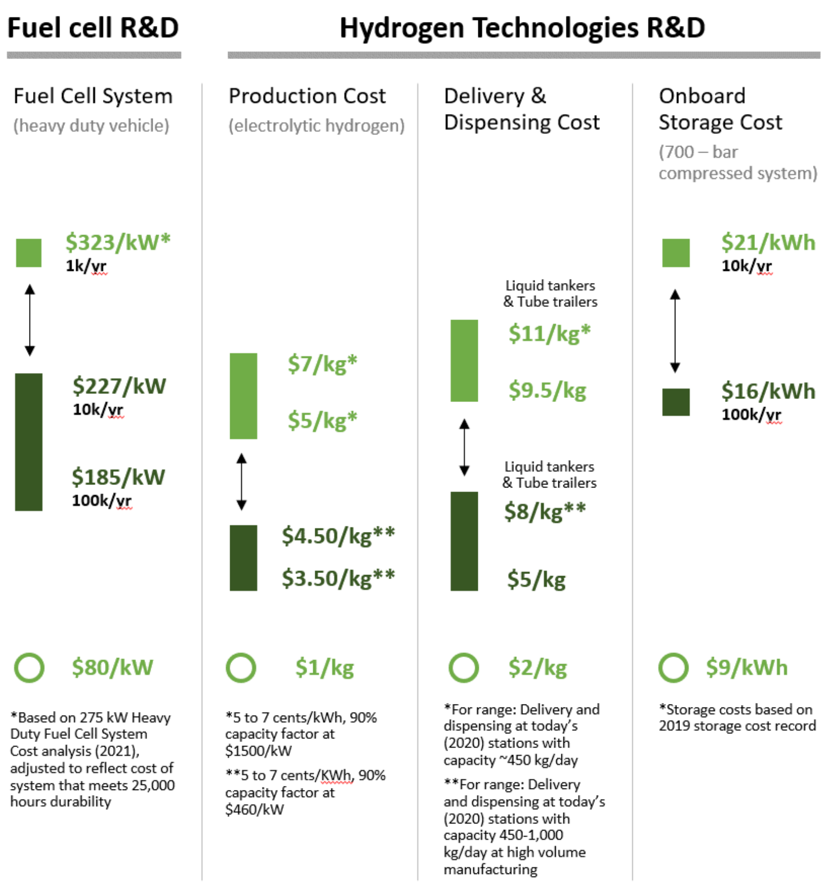


Figure 15: The status of production, delivery and dispensing, and onboard storage costs relative to the cost projection for high-volumes and the ultimate cost target for market competitiveness. [68]

In addition to the technology and cost challenges described above, from an overarching energy *systems* perspective, the optimal use of hydrogen still needs to be determined for the most suitable applications where lower cost or more efficient alternatives do not exist. A comprehensive assessment is needed of the interplay between hydrogen demands and electrification, evolutions of the energy grid (including in supply of clean baseload power, grid reliability, and rates of effective CCS), biofuels, and sectors that use hydrogen as a feedstock or fuel. A detailed regional approach, informed by the availability of resources and end-uses, and bolstered by the funding available for hydrogen hubs, will inform how best the hydrogen ecosystem can evolve to enable maximum benefit. All these challenges will need to be addressed in the most efficient, effective, and comprehensive manner through the strategies outlined in Sections B and C.

B: Strategies to Enable the Benefits of Clean Hydrogen

The foundation of this roadmap is based on prioritizing three key strategies to ensure that clean hydrogen is developed and adopted as an effective decarbonization tool and for maximum benefits for the United States.

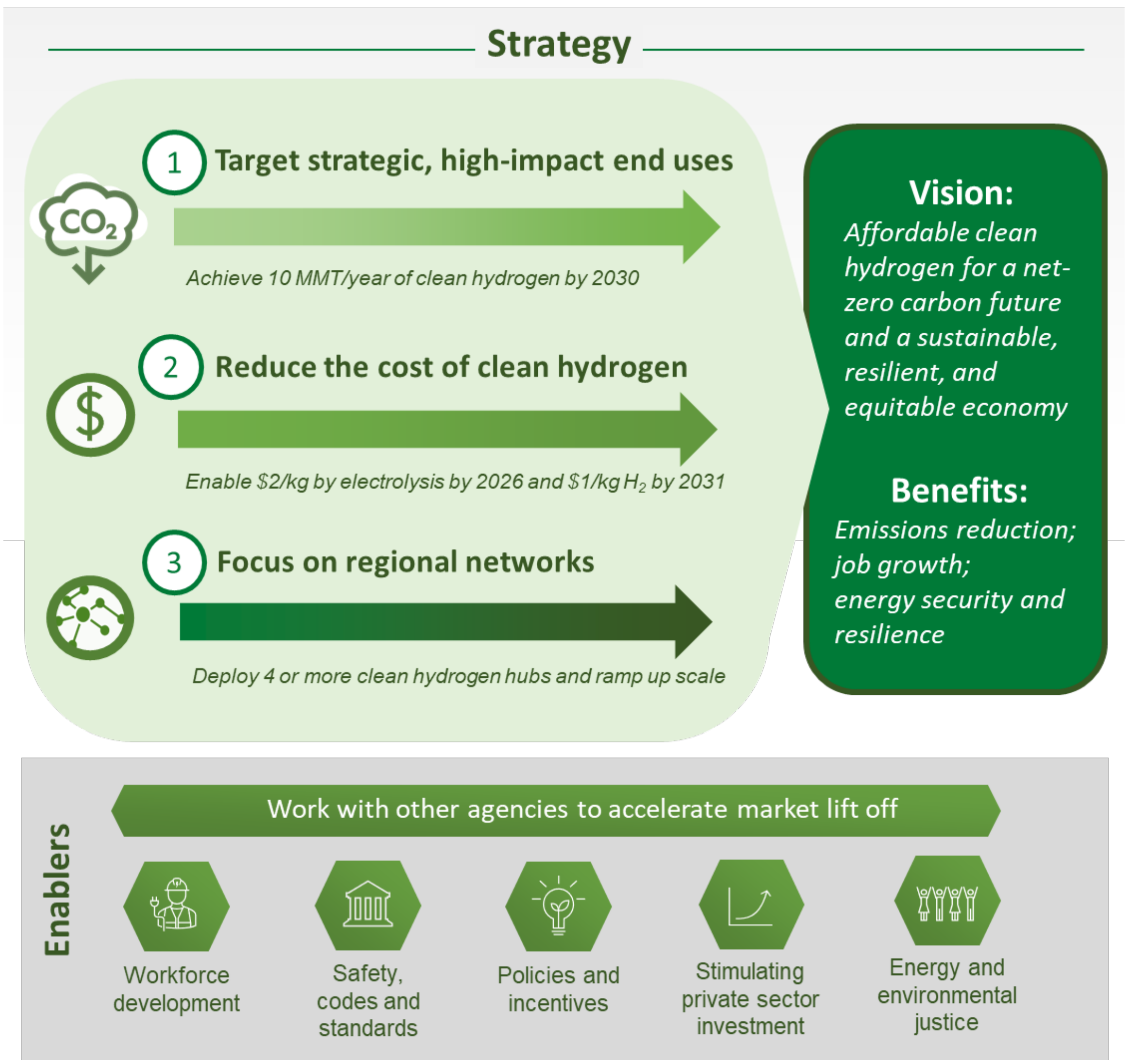


Figure 16 The national strategies for clean hydrogen and the Department of Energy's Hydrogen Program mission and context

First, DOE will **focus the use of hydrogen strategically to provide maximum benefits, particularly in sectors that are hard-to-decarbonize.** Rather than competing with alternative low-cost and efficient decarbonization technologies, such as electrification, clean hydrogen adoption will focus on end-uses that lack alternatives and are in industries that can build momentum to enable scale, increase benefits, and drive down cost.

Second, **the United States will dramatically lower the cost of clean hydrogen** by developing sustainable and supply-resilient pathways, including electrolysis, thermal conversion with CCS, and advanced or hybrid production pathways. Harnessing the innovation and entrepreneurial spirit of Americans and world-class National Laboratories, industry, and academic facilities, in addition to ramping up deployments, will help drive down costs rapidly and achieve scale within a decade. Regional factors and availability of resources such as waste, water, and other resources will also be strategically considered in the build-out of clean hydrogen production.

Third, DOE's strategic approach to scale will **focus on regional networks by ramping up hydrogen production and end-use in close proximity** to drive down transport and infrastructure costs and create holistic ecosystems that provide local benefits. By leveraging the hydrogen hub program as established in the BIL, DOE will focus on matching supplies with off-takers, avoiding stranded assets and unlocking private capital. DOE strategies will aim for a resilient, sustainable, and equitable hydrogen economy.

To implement all of DOE's strategies, DOE will work with other agencies through a coordinated and efficient "whole of government" approach to accelerate progress. DOE will focus on **foundational enablers** as DOE executes these strategies, including **advancing diversity, equity, and inclusion** and promoting **energy and environmental justice;** addressing safety and developing the necessary codes, standards, and workforce; and **stimulating private investment to enable market lift-off.**

Strategy 1: Target Strategic, High-Impact Uses of Hydrogen

While hydrogen's versatility enables it to be used in numerous applications, DOE's focus will be on clean hydrogen for decarbonizing segments such as in industry and heavy-duty transportation that are difficult to electrify. Within these segments, processes that use fossil fuels as a chemical feedstock or in the generation of high-temperature heat or long-duration, dispatchable power will require clean fuels, such as hydrogen, to decarbonize. For instance, ammonia and methanol manufacturing account for the majority of global GHG emissions from chemicals, and both sectors rely on natural gas as a feedstock.[69] These processes can be decarbonized by over 90 percent if they use clean hydrogen.[70,71] Steelmaking accounts for about 7 percent of global greenhouse gas emissions,[72] and relies on coke and natural gas to reduce iron ore. Transitioning to clean hydrogen as a reductant can reduce emissions by 40-70 percent.[73]

Over half of emissions from industry today are due to the direct combustion of fossil fuels to produce heat and power for industrial processes.[74] While lower grades of heat generation are typically feasible to electrify, about 30 percent of heat used in industry is at temperatures above 300°C and would likely require clean fuels to decarbonize.[75] Furnaces that burn pure hydrogen or blends of hydrogen with natural gas are key options in these applications.

As the power grid is decarbonized, long-duration energy storage technologies will become essential to enable growth in using clean electricity across sectors. The use of hydrogen in fuel cells or low-NO_x turbines is a leading option to enable multi-day, dispatchable power to the grid. In scenarios with high electrification rates, more clean hydrogen and other clean fuels may be needed to provide reliable power and integrate variable renewable energy into the grid for firm, dispatchable power.

In transportation, hydrogen has a strong value proposition in the trucking sector, particularly for fleets with heavy-duty vehicles, long-distance (>500-mile) routes, or multi-shift operations that require rapid refueling. Hydrogen is also an essential feedstock for producing liquid fuels that will be necessary for large-scale energy applications, such as aviation, rail, and marine. In the near-term, clean hydrogen can displace conventional hydrogen in petroleum refining for conventional transportation. In the mid- to long-term, hydrogen can be used to produce biofuels from biomass (to increase the yield of fuel produced from a given feedstock and pathway, and to refine the fuel's properties) and power-to-liquid fuels that can displace petroleum, particularly in offroad markets, discussed further below.

The following sections summarize the role clean hydrogen can have in each of the applications described above and provides examples that DOE and other agencies are funding to address these sectors.

Hydrogen in industrial applications

Globally, industry is the largest end-use sector in terms of energy consumption, accounting for 38% of total energy demand.[76] Approximately 6% of total energy demand is used to produce hydrogen, which is used primarily in producing ammonia and other chemicals.[77] The International Energy Agency (IEA) reports that global industrial demand for hydrogen was 51 MMT in 2020 out of 90 MMT used in all sectors.[78]

Hydrogen in steelmaking

Steel is one of society's most important engineering and construction materials. Today, it is typically made using basic oxygen furnaces (BOFs) or electric arc furnaces (EAFs), depending on whether it is primary (from iron ore) or secondary (from recycled scrap). Following the BOF pathway, iron ore is reduced with coke in a blast furnace and refined with oxygen. In the EAF pathway, electricity is used to refine a mixture of recycled steel and iron. While the iron ore BOF process is more common globally,[79] in the United States, roughly 70 percent of steelmaking uses the EAF process in which steel is recycled.[80]

Using clean hydrogen as a reductant in iron ore refining, instead of coke or natural gas, can reduce the life cycle emissions for making primary steel by 40-70 percent.[81] Other approaches to decarbonizing this sector include near term methods such as improvements to the efficiency of blast furnace as well as longer term innovation such as direct electrolytic processes.[82]

The future market for green iron ore-based steel production will depend on economic growth that creates new demand for steel consumption, as well as incentives for decarbonization and domestic production to displace imports. In recent years, imports have accounted for about 25-30 percent of U.S. steel consumption.[83] The Biden-Harris

Administration is advancing carbon-based trade policies to reward American manufacturers of clean steel. Working with the European Union, the Administration is taking steps to align global trade with climate goals, which will keep out dirty products and result in more jobs and lower prices for Americans.[84]

DOE has two active projects to jumpstart the use of hydrogen for steel manufacturing that will help optimize direct reduction using hydrogen and will enable the development of a 1 ton per week operation, with the potential for 5,000 tonnes per day of steel production.[85,86] Several workshops organized by DOE's Advanced Manufacturing Office and Hydrogen and Fuel Cell Technologies Office (HFTO) have helped identify key challenges and opportunities which will be addressed as part of the national hydrogen strategy.[87,88,89]

Hydrogen in chemicals

Hydrogen is already used as an essential feedstock in the production of ammonia and methanol. In conventional ammonia and methanol plants in the United States, natural gas reforming is used to produce syngas that is then converted into ammonia (in combination with nitrogen from compressed air) or methanol immediately downstream. Production pathways for both chemicals can be decarbonized by replacing the use of natural gas reforming with clean hydrogen production supply, such as the use of CCS along with mitigation of fugitive methane emissions or the use of electrolysis.

Future use of clean hydrogen in these chemicals will depend largely on the markets for each, and drivers to decarbonize. Today, 88 percent of ammonia consumption in the United States is for fertilizer production; the remaining 12 percent is used to produce plastics, explosives, synthetic fibers, resins, and other chemicals.[90] Future applications for ammonia may also include its use as a fuel for offroad vehicles or in power generation, although these concepts are still in the early stages of development. The primary use of methanol today is as a building block for other chemicals, such as formaldehyde, acetic acid, and plastics. Growth in the methanol market depends on the overall growth of chemicals production, rates of plastics recycling, and the development of new end-uses of methanol, such as its use as a fuel or as a hydrogen carrier.

DOE-supported activities in this sector include several analyses to assess the cost and life cycle emissions to produce hydrogen carriers, including methanol, ammonia, and methylcyclohexane. DOE's Advanced Research Projects Agency–Energy (ARPA-E) is also funding innovative, game-changing approaches for ammonia production and a modular, scalable system for hydrogen to ammonia.[91]

Blending for Industrial Heat

Process heating is the largest driver of energy consumption within the U.S. manufacturing sector and relies primarily on the combustion of fossil fuels.[92], [93] Options to decarbonize this sector include electrification, particularly at lower grades of heat (<300°C); CCS; use of low-carbon sources of heat, such as solar thermal or nuclear power; and use of blends of hydrogen in natural gas or pure hydrogen, particularly for applications requiring high temperatures. Sectors that currently consume heat at >300°C include refining, chemicals, cement, and steelmaking.

Due to the low cost of fossil fuel combustion, the heat and power sector has a lower willingness to pay for hydrogen than chemical processes and is expected to adopt clean hydrogen at scale when it is widely available at low cost or strong policy drivers for decarbonization emerge. The use of hydrogen in this sector will require the advancement of low-NOx hydrogen combustion technologies, as well as an improved understanding of the impacts of hydrogen on infrastructure and turbine materials.

DOE's HyBlend initiative was launched in 2020 to address knowledge gaps in blending hydrogen in natural gas, bringing together DOE National Labs and industry.[94] HyBlend currently includes several projects with national laboratories and over 30 industry partners focused on materials compatibility, cost and emissions analysis of blending, underground storage of hydrogen blends, hydrogen appliances, and low-NOx hydrogen turbines.

The use of renewable natural gas is another approach to decarbonizing the heat and power sector and has the advantage of being fully compatible with existing infrastructure. One of the pioneering projects funded by DOE in this area demonstrated the integration of an electrolyzer with a bioreactor to produce renewable natural gas from hydrogen and carbon dioxide.[95] This novel bioreactor design is now being commercialized by industry through deployments in California and the Northeast. Additional longer-term concepts for RNG production include the catalysis of hydrogen and carbon dioxide to produce synthetic methane. Decarbonization via this approach will also require management and mitigation of fugitive methane emissions throughout the delivery infrastructure. Life cycle analyses of renewable natural gas relative to hydrogen blending are currently underway within DOE's HyBlend initiative.

Future work, which will be done in collaboration across agencies and states, will enable the development of injection standards for blending hydrogen into natural gas pipelines--including the upper blend limits. Other work includes assessing opportunities to repurpose natural gas infrastructure for hydrogen and identifying conditions under which deployment of new infrastructure would be necessary to enable the use of high concentrations of blends. Priorities for HyBlend include reducing the risk for all communities – especially vulnerable and disadvantaged communities – and spearheading policies, such as "dig once" strategies, as the Nation installs transmission, CCS, CO_2 pipelines and other infrastructure.

Hydrogen in transportation

The transportation sector accounts for roughly 30 percent of greenhouse gas emissions in the United States and 58 percent is due to light-duty vehicles.[96] While industry has focused primarily on battery electrification for light-duty vehicles, hydrogen and fuel cells offer significant opportunities for applications requiring long driving ranges, fast fueling, and large or heavy payloads.[97]

Hydrogen for medium and heavy-duty trucks and buses

Medium- and heavy-duty (MDHD) vehicles are used across the country for numerous applications from product delivery to vehicle towing to waste collection, and account for about 20 percent of emissions from the transportation sector.[98] DOE and other Federal agencies are working with industry and national laboratories through the 21st Century Truck Partnership to reduce emissions from trucks and buses through safe and cost-effective approaches.[99] Members of 21CTP meet regularly to share information that can inform pre-competitive R&D activities. Batteries and fuel cells are both focus areas of 21CTP and can each play complementary roles in decarbonizing the trucking sector. Fuel cells are particularly viable for applications such as heavy-duty trucks that require fast fill times comparable to diesel today, or long driving ranges above 500 miles.[100]

DOE launched the Million Mile Fuel Cell Truck Consortium (M2FCT) in 2020 to enable the fuel cell durability, cost, and performance required for the long-haul heavy-duty truck market.[101] DOE also selected hydrogen and fuel cell truck projects under the Super

Truck program to demonstrate medium- and heavy-duty hydrogen fuel cell trucks under real-world operating conditions within the next five years.[102] Other projects supporting this strategy include developing the required infrastructure, fueling components, hydrogen storage and dispensing technologies, and a project that will demonstrate 15 parcel delivery trucks operating in disadvantaged communities.[103,104] Transit agencies with large bus fleets or coach buses with long driving ranges can also benefit by using hydrogen and fuel cells. DOE has been working with the Federal Transit Administration to evaluate fuel cell buses and continues to collect real-world deployment data to guide future advances.[105] By focusing the strategy on fleets, freight, and corridors where clusters of dedicated infrastructure can be developed, the United States will reduce the risk of stranded assets and ensure the utilization of the developing hydrogen fueling infrastructure.

Hydrogen for maritime applications

In addition to on-road vehicles, opportunities for hydrogen and hydrogen carriers are also emerging in the maritime industry, ranging from inland and harbor vessels to recreational and pier-side applications. New emissions regulations by the International Maritime Organization (IMO) limit the sulfur content in fuel oil used on ships (or "bunker fuel") from 3.5 percent to 0.5 percent, starting in 2020.[106] These limits are further reduced to 0.1 percent for ships operating in Emissions Control Areas, including certain coastal regions of the United States and the European Union.[107] Given increasingly stringent requirements, hydrogen and hydrogen carriers, such as ammonia and methanol, may offer an attractive alternative to bunker fuel. Furthermore, the use of hydrogen in various marine vessels and at ports for drayage trucks, shore power (electricity for ships while docked), and cargo equipment all offer the potential to reduce carbon dioxide and other emissions and to develop infrastructure in targeted regions to scale up use.[108]

DOE, in collaboration with the Maritime Administration (MARAD), has been developing and demonstrating hydrogen and fuel cell technologies for maritime applications over the past decade, including the world's first pier-side hydrogen fuel cell for auxiliary power in lieu of diesel generators.[109] In collaboration with state agencies and industry, the U.S. is deploying the first hydrogen fuel cell passenger ferry in the Western hemisphere.[110] DOE launched a new project to demonstrate a MW-scale electrolyzer on a floating barge to fuel a passenger ferry, in addition to using a fuel cell to charge a battery electric vessel.[111] Such first-of-a-kind demonstrations are integral to Strategy One – "Target Strategic, High-Impact Uses of Hydrogen" – to de-risk technologies for additional private sector investment and market adoption. Other activities include addressing safety and developing the relevant codes, standards, and ensuring global harmonization, in conjunction with other organizations, including IMO, MARAD, and international collaborators.

Hydrogen for aviation and sustainable aviation fuel production

Prior to the COVID-19 pandemic, aviation accounted for about 11 percent of U.S. transportation emissions; without increased action, its share will continue to grow as more people and goods are transported by air.[112] The deployment of SAFs, such as biofuels and power-to-liquid fuels that can be used instead of conventional jet fuel, is essential to decarbonizing this sector.[113] In 2021, DOE, DOT, and USDA launched a government-wide SAF Grand Challenge to reduce the cost, enhance the sustainability, and expand the production and use of SAFs that achieve a 50% reduction in lifecycle GHGs or greater, compared to conventional fuel.[114] The Grand Challenge further set goals to supply 3 billion gallons of SAFs per year by 2030 and 35 billion gallons by 2050 to meet 100 percent of aviation fuel demand by 2050.[115] These national goals form the basis for hydrogen demand in this sector.

Many different biofuel and power-to-liquid fuel pathways are being explored to meet the SAF Grand Challenge goal. The pathways that have been approved to date for use by aviation require hydrogen as a feedstock[116] and could additionally co-produce renewable fuels for use elsewhere in the transport sector. The Net Zero Tech team, a collaboration between DOE and industry through the U.S. Driving Research and Innovation for Vehicle efficiency and Energy sustainability (U.S. DRIVE) partnership, is conducting cost and emissions analysis of future pathways, to identify fuels with the greatest potential.

In addition, direct use of hydrogen is being demonstrated for aircraft in specific market segments such as short-duration flights and uncrewed aerial vehicles (UAVs). While hydrogen storage density is a challenge, hydrogen fuel cells offer the benefit of both zero carbon and zero criteria pollutant emissions from the exhaust. DOD is demonstrating direct hydrogen fuel cells for UAVs.[117]

There are also several industry projects on hydrogen fuel cells and engines for aircraft. For example, ZeroAvia and Otto have announced a partnership to develop a 19-seat aircraft that can travel 1,000 nautical miles, potentially targeting niche market needs in private flights.[118] Airbus announced three design concepts for direct hydrogen use, including fuel cell and hydrogen combustion systems.[119] DOE convened industry stakeholders at the H2@Airports workshop in November 2020, which identified key challenges and potential opportunities to address them.[120]

Hydrogen in rail

The rail system in the United States spans over 140,000 route-miles, delivers critical goods, moves passengers across the country, and supports over 167,000 jobs.[121] Although rail accounts for only about 2 percent of transportation-sector emissions,[122] this mode is hard to decarbonize due to conventional low-cost legacy systems and the low diesel costs. However, liquid fuels (including biofuels), as well as batteries and hydrogen, can all play complementary roles in completely decarbonizing this sector. The cost competitiveness of each powertrain will vary by region and by each system's demand profile.

Several early demonstrations of hydrogen and fuel cells have already been commissioned in both passenger and freight rail around the world and will inform future RDD&D. Hydrogen-powered trains have been in service in Germany since 2018 and have completed trials in Austria, the Netherlands, Sweden, and France.[123] In the U.S., California's San Bernardino Transportation system is developing a hydrogen fuel cell passenger train expected to be in service in early 2024.[124]

DOE held an H2@Rail workshop in 2019 to identify opportunities for hydrogen and fuel cells in collaboration with the Department of Transportation's Federal Railroad Administration (FRA).[125] DOE's ongoing analysis efforts inform performance and cost targets and specific locomotive market segments in this sector. Progress toward targets will be monitored and validated in coordination with FRA.[126, 127]

Power sector applications

As more renewable and zero-carbon generation assets are deployed, hydrogen can offer versatility as a medium for long-duration energy storage and grid services and can offer additional revenue streams by providing hydrogen as a feedstock or fuel for other sectors.

Hydrogen for backup power and stationary power

Backup power and stationary power from fuel cells can replace diesel generators to provide resiliency to critical facilities that require 24/7 power, such as hospitals and data centers. Systems that need steady, reliable power in remote locations, such as microgrids and telecom towers, are also promising opportunities. Although backup power utilization is low, moving from diesel to clean hydrogen can still provide a meaningful step on the path to net zero. Fuel cells operating on hydrogen have zero emissions and are quieter and more reliable than diesel generators and offer benefits for health and air quality—particularly for disadvantaged communities who are often in non-attainment zones.

Examples of DOE-funded projects supporting this sector include the world's first trigeneration system at a wastewater treatment plant to co-produce power, heat, and hydrogen through a high-temperature fuel cell;[128] first of a kind demonstration of hydrogen fuel cells for data center applications; projects to lower fuel cell cost and improve durability;[129] reversible fuel cell RDD&D;[130] and hundreds of fuel cell deployments for backup power applications.[131]

Energy Storage

Energy storage on the grid can have several different roles, including time shifting, firm capacity, avoiding transmission line buildout, and ancillary services.[132] Today, grid energy storage is dominated by pumped hydropower deployments capable of discharging power for 12 hours or less.[133] Lithium-ion batteries are the fastest growing mode of energy storage, commonly for shorter durations of 4 hours or less.[134]

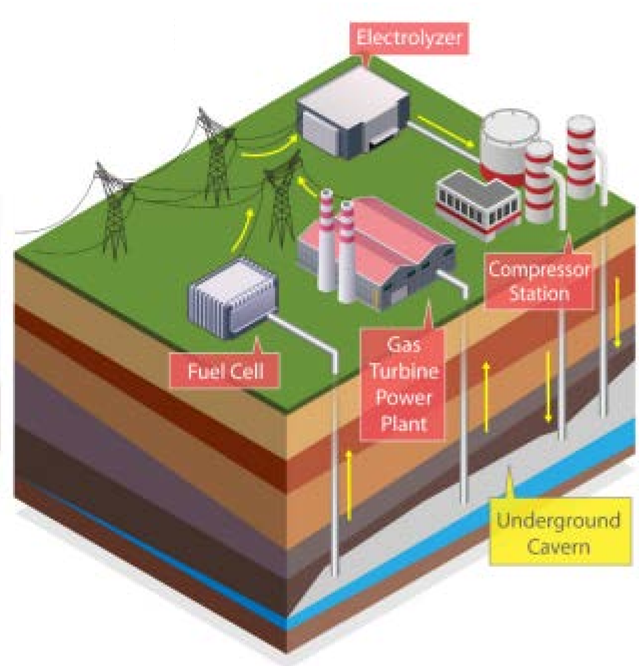


Figure 17: Hydrogen energy storage systems involve the use of electrolyzers to produce hydrogen from excess power on the grid, bulk storage, followed by power generation using fuel cells or turbines. (Source: NREL)

As the grid transforms to 100 percent clean power, longer-duration energy storage technologies that can discharge for multiple days at a time will be needed. As shown in Figure 17, hydrogen energy storage systems at scale could involve the use of electrolyzers to produce hydrogen using excess power on the grid, storage of the hydrogen in bulk (e.g., underground), and then use hydrogen to generate power at times of high demand.[135] Optimized co-siting of renewables, nuclear plants, high temperature heat sources, and the storage infrastructure for hydrogen and carbon dioxide can help reduce the environmental, economic, and community impact compared to completely independent build-out of such systems.

Large-scale deployments of hydrogen energy storage will require reductions in the cost of electrolyzers and fuel cells, the development of low-NOx combustion technologies for use in hydrogen turbines, and the development of new low-cost bulk hydrogen storage technologies that are not geographically constrained. To support this sector, DOE has established unique national laboratory test facilities to demonstrate and test the performance of electrolyzers integrated with various power and thermal sources.[136] These facilities allow industry to de-risk systems integration and validate new technologies before deployment. DOE is also funding RDD&D on low NOx turbines and has funded numerous analysis projects and tools to quantify the economic benefits of hydrogen energy storage under specific grid conditions in collaboration with industry.[137] Additionally, DOE has funded five projects demonstrating the integration of electrolyzers with nuclear power plants to create another revenue stream for these baseload generators that also support grid stability.[138, 139]

In 2022, DOE's Loan Programs Office (LPO) announced a conditional commitment for an approximately $500 million loan guarantee to the Advanced Clean Energy Storage Project, which would be a first-of-its-kind clean hydrogen production and storage facility capable of providing long-term seasonal energy storage.[140] The facility in Delta, Utah will combine a 220 MW alkaline electrolyzer with salt cavern storage for grid-scale energy conversion and storage using hydrogen as the energy carrier. Advanced Clean Energy Storage is expected to benefit Utah by creating up to 400 construction and 25 operations jobs and could help catalyze long-term job opportunities and transition the state to a new, clean energy economy for the future.

Carbon Intensity of Hydrogen Production

Hydrogen production pathways vary in carbon intensity, depending on their energy source, efficiency, and design. In fossil pathways, for instance, the amount of carbon capture and sequestration, the energy efficiency of the systems, and the amount of fugitive emissions, all determine the carbon footprint of hydrogen production. In electrolysis, the carbon intensity of electricity, whether it is from dedicated renewables, nuclear, or bulk grid electricity, is the primary variable that influences lifecycle emissions.

As directed in the BIL, DOE is required to develop an initial standard for the carbon intensity of clean hydrogen as a point of reference for select programs under the BIL. The standard will be developed in consultation with the U.S. Environmental Protection Agency (EPA) and considering input from industry and other stakeholders.[141] The BIL requires DOE to set a clean hydrogen production standard that:

- Supports clean hydrogen production from specified low carbon energy sources (e.g., including but not limited to fossil fuels with carbon capture, utilization, and storage (CCUS); hydrogen-carrier fuels (including ethanol and methanol); renewable energy resources, including biomass; nuclear energy);
- Defines the term "clean hydrogen" to mean hydrogen produced with a carbon intensity equal to or less than 2 kilograms of carbon dioxide-equivalent produced at the site of production per kilogram of hydrogen produced; and
- Considers "technological and economic feasibility"

DOE is also required to update the standard within five years of setting the initial standard.[142]

An important component of future clean hydrogen demonstrations or deployments supporting the BIL will be stakeholder engagement and analyses to determine actual life cycle emissions along the entire value chain. DOE tools, such as the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model,[143] will be valuable in characterizing the decarbonization potential of deployments consistently, including well-to-gate emissions of hydrogen production, as well as emissions of hydrogen distribution and end-use. For example, well-to-gate emissions of SMR with CCS can range from 3-5 kg-CO_2e/kg-H_2 depending on the degree of fugitive emissions, capture rate, and carbon intensity of the electricity grid. Well-to-gate emissions of electrolysis are near zero when the electricity supply is 100 percent carbon pollution free – as is the Administration's goal by 2035 – but can be double those of SMR when using the current average U.S. grid mix.[144,145]

As global trade develops for hydrogen, consistent international methods for lifecycle analysis will also be required. This was one of the highest priority actions voted on by over 20 countries under the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), a global government partnership launched in 2003 to accelerate progress in hydrogen and fuel cell technologies.[146] The U.S. is currently a Vice Chair of IPHE, after completing a term as Chair, and is also a lead member of the IPHE Hydrogen Production Analysis (H2PA),[147] a task force under IPHE developing mutually agreed-upon methods of lifecycle analysis for hydrogen production. Analysis guidance developed to date has focused on specific hydrogen production pathways of interest across over 20 countries in the near term. Ongoing work is expanding this guidance to include additional pathways and to account for the emissions associated with hydrogen distribution. While guidance developed by IPHE is not binding, it can inform accounting frameworks implemented by member countries to ensure consistency. As such, the U.S. will engage in global collaboration and coordination to accelerate progress and foster transparency and rigor in the analyses of emissions across the value chain of hydrogen, including potential indirect impacts, from multiple pathways.

Strategy 2: Reduce the Cost of Clean Hydrogen

While there are several significant challenges across the entire hydrogen value chain from production through end-use, Strategy 2 prioritizes reducing the cost of clean hydrogen. There are many ways to produce hydrogen at various technology readiness levels and a wide range of associated carbon emissions and other environmental impacts. To address Strategy 2, DOE will identify and focus on the primary barriers to cost reduction. DOE will prioritize and accelerate its actions, foster partnerships across industry, academia, and national laboratories, continuously track and adjust its portfolio based on performance-driven metrics and catalyze technology innovation and deployment at scale.

Hydrogen Shot

In June 2021, the DOE launched the first in a series of Energy Earthshots to accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade. This "Hydrogen Shot" – "111" – aims to reduce the cost of clean hydrogen to $1 per kilogram in just a decade

DOE is also working closely with industry to expand low-carbon hydrogen production capacity, including through grants, loans, and other tools and incentives. We will support multiple production routes with potential to achieve the Hydrogen Shot, to stimulate competition, innovation, investment, and commercialization, to catalyze sharp declines in cost, across the value chain.

In response to President Biden's April 2021 Climate Summit request to DOE to accelerate progress towards tackling the climate crisis, DOE established the Energy Earthshot initiative, creating bold, ambitious goals to galvanize the domestic and global industry.[148]

Hydrogen Shot is one of DOE's flagship initiatives to drive down the cost of clean hydrogen, in concert with accelerating deployment and scale, such as through hydrogen hubs, loan guarantees, and other mechanisms. As shown in Figure 18, the Hydrogen Shot can enable a wide range of use cases and impacts and builds on the current progress across the spectrum of production pathways.

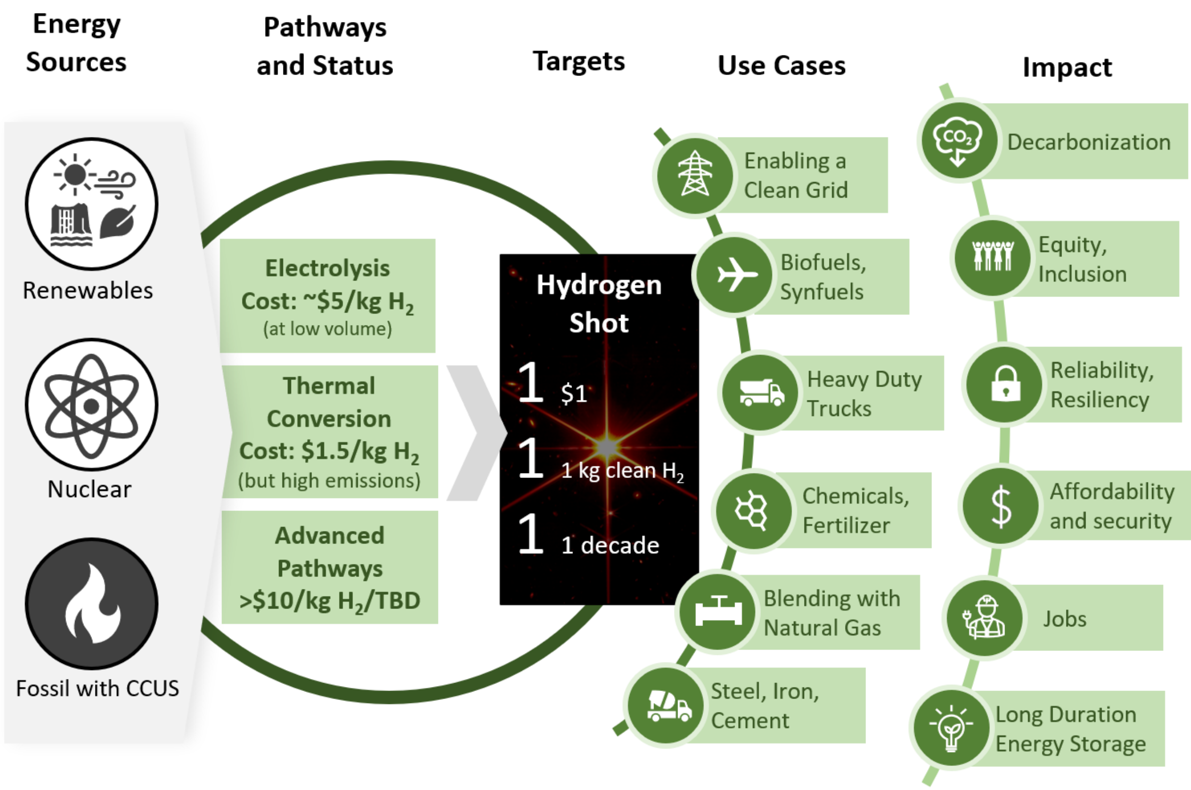


Figure 18: The Hydrogen Shot targets build on progress for a variety of pathways, enabling a range of use cases and impacts

Continuing to advance RDD&D efforts, and reducing costs and associated lifecycle emissions, remain important for all hydrogen production pathways. A mix of hydrogen production from water electrolysis, hydrogen production from fossil fuels with carbon capture and storage, and hydrogen production from biomass and waste feedstocks will likely be used in the United States through at least 2050. Today, thermal conversion pathways are the dominant approach to hydrogen supply worldwide, and typically have a low cost but high emissions. Electrolyzers using clean energy and advanced pathways (i.e., technologies at lab scale, such as photoelectrochemical and thermochemical water splitting) can achieve near zero emissions but are currently much higher in cost.

Hydrogen Production Through Water Splitting

Electrolysis uses electricity and an electrolyte or membrane to split water into hydrogen and oxygen. Most electrolysis uses one of three technologies: alkaline, PEM, and solid oxide electrolyzer cells (SOECs). The alkaline process is the most established, having been used for over a century. PEM electrolyzers can operate effectively at a range of loads with sub-second response times, which makes them particularly compatible with variable energy sources, such as sun and wind power. SOECs use a ceramic electrolyte at high temperatures and are the least commercialized of the three technologies. With higher electrical efficiency than PEM and alkaline systems, SOECs are likely to be more cost-effective in scenarios where high-temperature heat is available, such as from nuclear power plants and concentrated solar power.

The cost of clean electricity is critical, now accounting for over half of the cost of hydrogen production from electrolysis.[149, 150] RDD&D can all drive costs toward the Hydrogen Shot target by lowering the cost of renewables, boosting the efficiency of electrolysis, reducing electrolyzer and balance-of-plant capital costs and enabling dynamic integration electrolyzers with the grid and with renewable generators to access low-cost variable power.

Figure 19 shows one scenario for reducing the cost of clean hydrogen from electrolysis, which requires dramatically lowering capital costs, lowering energy costs, increasing efficiencies, and improving durability and reliability to reduce maintenance costs. The 2020 baseline cost of $5/kg is the levelized cost of hydrogen calculated using DOE's H2A model using a conservative $1,500/kW for PEM electrolyzer capital cost (at low volume manufacturing), a $50/MWh electricity price, and a capacity or utilization factor of 90

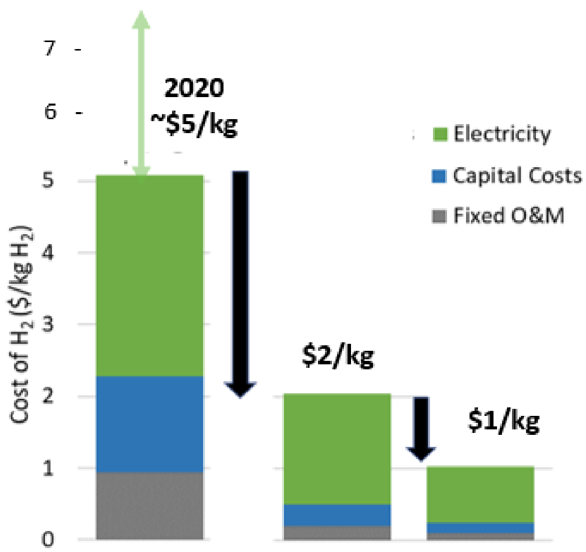


Figure 19: Achieving $1/kg using electrolyzers requires lower electricity cost, significantly lower capital costs, improvement in efficiency and durability, and higher utilization

percent.[151] In comparison, using today's $29/MWh for solar and 35 percent capacity factor, based on the 2020 National Renewable Energy Laboratory (NREL) Annual Technology Baseline, results in a levelized hydrogen cost of about $7.50/kg, as shown by the green arrow. As shown, the levelized cost of hydrogen production is highly sensitive to the cost of electricity. Access to low-cost energy with a high capacity factor (e.g., through integration with existing nuclear power plants) can facilitate much lower levelized costs.

The example shown of what would be needed to achieve $2/kg– required by the BIL by 2026 – is based on $30/MWh energy costs and $300/kW capital costs, and the $1/kg Hydrogen Shot goal would require $20/MWh and $150/kW. In all these cases, a 90 percent electrolyzer capacity factor is assumed, meaning renewables need to be complemented by clean baseload electricity, such as nuclear. This scenario illustrates that capital costs would need to be reduced by 80 percent and the operating and maintenance costs would need to be reduced by 90 percent. It should be emphasized that these are just scenarios that could achieve these cost targets. Still, other combinations of cost, efficiency, electricity prices, utilization factors, and durability, including the use of thermal sources for high-temperature electrolyzers, could enable meeting the Hydrogen Shot goal.

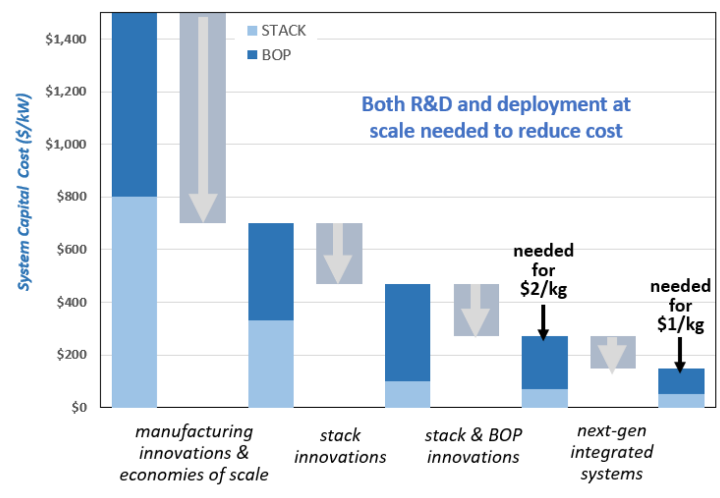


Figure 20: Reducing electrolyzer capital costs will require reaching economies of scale and innovating the electrolyzer stack and balance-of-plant components

In 2020, DOE launched a new consortium bringing together national labs, industry, and academia - H2NEW (Hydrogen from Next-generation Electrolyzers of Water) – on electrolyzer technologies to complement HydroGEN, a consortium that investigates all water splitting technologies, including direct photoelectrochemical and thermochemical methods.[152] H2NEW will accelerate progress in electrolyzer technologies and help reduce costs. As shown in Figure 20, these cost reductions will require high-volume manufacturing, innovations in electrolyzer stacks and balance of plant components, and electrolyzer integration in next-generation systems. While analyses on various system configurations are ongoing, the figure shows just one example of the magnitude of cost reductions in each category. These values will be updated as the industry advances.

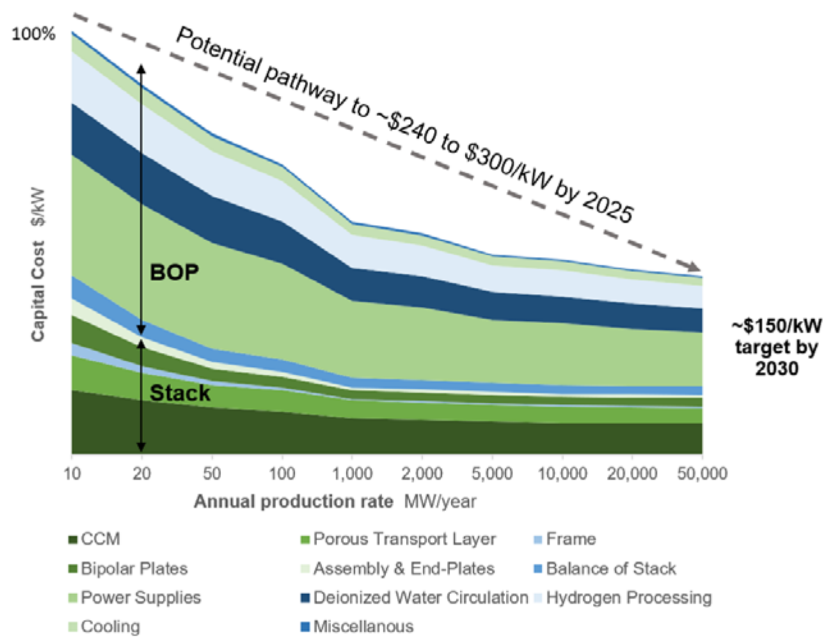


Figure 21: There are many drivers for electrolyzer stack and balance-of-plant capital cost reductions.

There is no single overarching cost driver for capital cost reduction. As shown in Figure 21, multiple components encompassing electrolysis stacks and balance-of-plant systems must be addressed.[153]

As demand rises for energy storage and clean power, stakeholders must continue exploring innovative mechanisms of on-grid and off-grid integration of electrolyzers to enable access to variable clean energy at low cost.

Hydrogen Production from Fossil Fuels with Carbon Capture and Storage

The BIL requires DOE to account for and support opportunities for hydrogen production from diverse energy, including fossil fuels with CCS. Opportunities include regions of the U.S. with abundant natural gas, reservoirs for CO_2 storage, or existing natural gas supply infrastructure. As shown in Figure 22, below, the current network of natural gas infrastructure and SMR plants are both largely concentrated in the Gulf Coast region, given the availability of natural gas and hydrogen demand for the petrochemical sector. Hydrogen is currently an essential feedstock within refining, used primarily to crack heavy crude oil and desulfurize product streams. Displacing hydrogen used at current petroleum refineries with clean hydrogen can reduce the life cycle emissions of the refining process by ~12 percent, depending on the hydrogen supply source.[154]

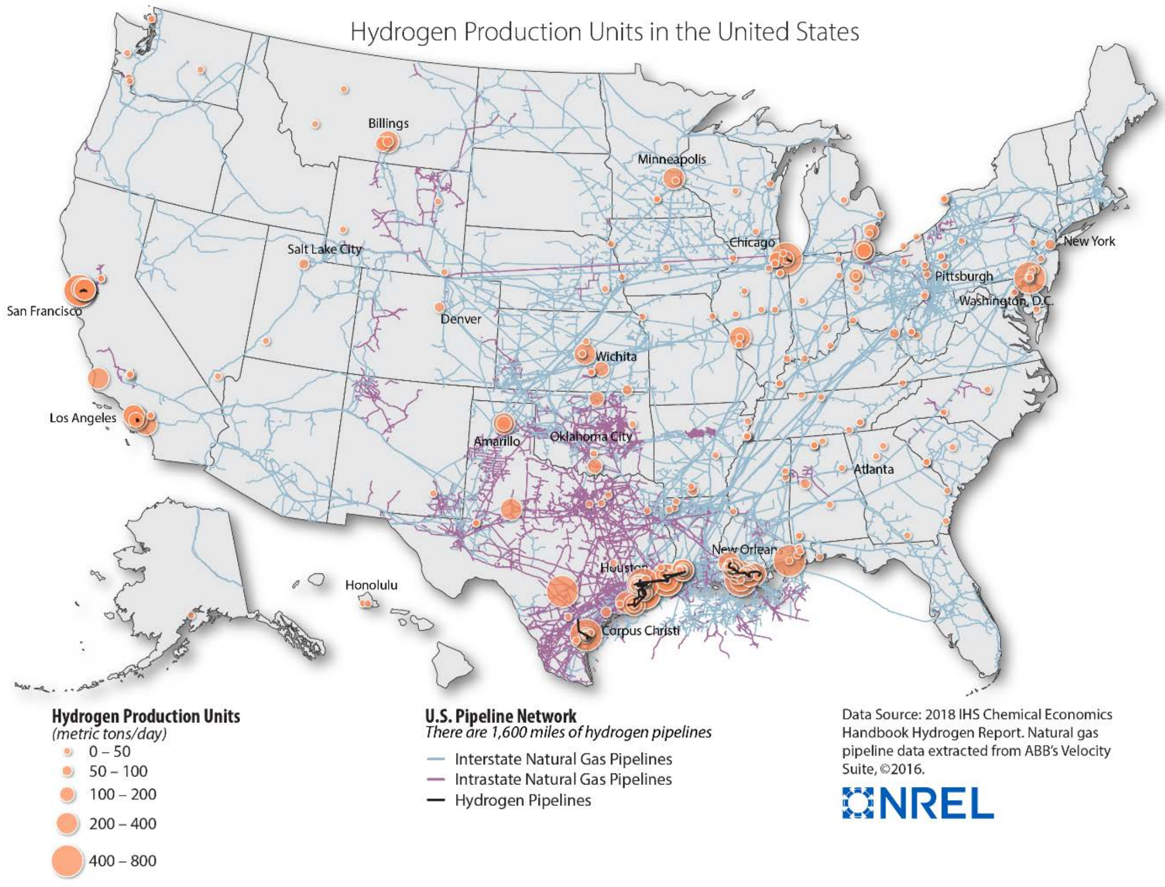


Figure 22: Hydrogen production units and pipelines for hydrogen and natural gas in the United States

Capturing and storing SMR's carbon dioxide before it is emitted into the atmosphere can reduce the life cycle carbon intensity of hydrogen production by over 50 percent, depending on CCS rates and upstream emissions, including fugitive releases during natural gas excavation, transmission, and use.[155, 156] Autothermal reforming (ATR) with carbon capture is another approach to producing hydrogen from natural gas that is expected to cost less than conventional SMR. This approach entails integrating fuel combustion with the SMR process to improve heat use. A third type of natural gas-based production, methane pyrolysis, uses high heat to split methane into hydrogen and solid carbon – this can be an attractive option since the solid carbon can provide a value-added co-product for applications such as industrial rubber and tire manufacturing and for specialty products such as inks, catalysts, plastics, and coatings.

Recent DOE investments are supporting RDD&D and providing loans for scale-up and deployment of pyrolysis pathways.[157, 158, 159]

Today, hydrogen production from SMR systems equipped with CCS is roughly 55 percent more expensive than that of SMR alone.[160] Cost reductions in CO_2 transport and storage, variable costs, and capital costs could help meet the Hydrogen Shot target, as shown in Figure 23.

Captured carbon can also be utilized in industrial processes rather than stored underground. Emerging utilization pathways include liquid fuel production, construction of building materials, and production of chemicals.

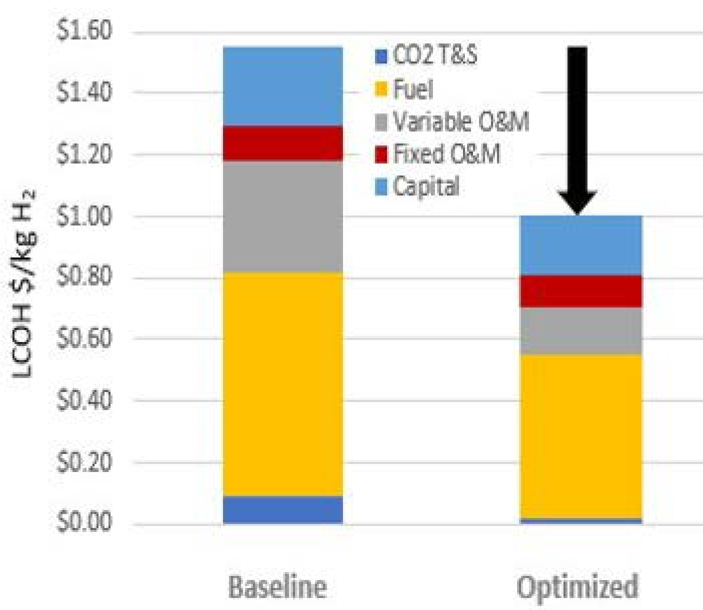


Figure 23: Cost reductions necessary to achieve $1/kg production cost for methane feedstocks with CCS. Baseline assumes autothermal reforming with CCS.

There are a growing number of carbon capture, storage, and utilization projects in the United States. For instance, in Louisiana, Air Products is building a facility expected to come online in 2026 and produce 750 million cubic feet of reformation-based hydrogen daily. The site will take advantage of Louisiana's geology to sequester 5 million tonnes of CO_2 each year, announced as the world's largest.[161] In Iowa, Green Plains, Inc., has announced a carbon offtake agreement for three ethanol biorefineries, where captured carbon dioxide will be transported via pipeline to underground geological structures in North Dakota for storage. This project is expected to begin operations in 2025 and should sequester 10 million tonnes of CO_2 each year.[162] Policies such as the 45Q tax credit for CCS can pave the way for clean hydrogen production at scale.[163]

In all cases when using fossil fuels, DOE will prioritize reducing emissions across the value chain from production through end-use. In addition, it will be important to develop measurement and monitoring solutions and to factor in hydrogen leakage risks into decisions to build out hydrogen transport infrastructure, regardless of primary resource. Finally, DOE will prioritize stakeholder engagement to address potential environmental concerns and cumulative burdens imposed on communities that may host fossil fuel-based hydrogen and CCS technologies.

Hydrogen Production from Biomass and Waste Feedstocks

Additional pathways to hydrogen production include biomass gasification with carbon capture and storage and SMR or ATR using feedstocks such as biogas from organic landfill matter, sewage, or agricultural wastes in place of natural gas. These production methods have the potential to be low-carbon or carbon-negative depending on the feedstock. The CO_2 emissions released when crops are used to produce hydrogen are potentially carbon-neutral since they represent GHGs captured in feedstock's growth. However, lifecycle emissions across the entire biomass supply chain, including direct and indirect land-use changes, and agricultural inputs such as fertilizer should also be considered.

When biomass pathways are coupled with CCS, their net emissions have the potential to be negative. For example, when the waste feedstock is diverted from landfills and instead used to make hydrogen, some of the methane generated by processing the waste is also diverted from the atmosphere and thermally converted to clean hydrogen (i.e., methane that would not otherwise have been flared, given regional best practices and regulations).

Other System Costs

Cost reduction is not limited to hydrogen production alone. For instance, the costs for various technologies and components across the hydrogen value chain are shown in Figure 24. DOE will continue to strengthen its activities to reduce the cost of all key technologies across the value chain, including reducing supply chain vulnerabilities. DOE has released a set of clean energy supply chain assessments, including the supply chain for fuel cells and electrolyzers.[164] The BIL electrolyzer and clean hydrogen manufacturing and recycling provisions ($1.5 billion over five years) will be used, along with annual appropriations, to address this strategy.[165]

The cost of hydrogen delivery, storage, and dispensing to an end-user varies widely given the mode of supply used. There are four main hydrogen methods of hydrogen delivery at scale today: gaseous tube trailers, liquid tankers, pipelines (for gaseous hydrogen), and chemical hydrogen carriers. Tube trailers and liquid tankers are commonly used in regions where hydrogen demand is developing and not yet stable. Gaseous pipelines are commonly used when demand is predictable for decades and at a regional scale of thousands of tonnes per day. Chemical carriers are of interest for long-distance hydrogen delivery and export markets and can be broadly classified as one-way or two-way carriers. One-way carriers are materials that do not release a by-product for re-use or disposal after the hydrogen is released (such as ammonia). Two-way carriers are those whose products are typically returned for processing for reuse or disposal after the hydrogen is released (such as methylcyclohexane/toluene). The use of chemical hydrogen carriers is in the early stages of commercialization and RD&D efforts are needed to increase the hydrogen-carrying capacity of these materials and improve the charge-and-discharge rates, reversibility, and overall round-trip efficiency.

After delivery, hydrogen may need to be conditioned onsite (e.g., pressurized, pre-cooled, or purified) before use. At hydrogen fueling stations for vehicles, compression, storage, and dispensing are the three largest drivers of levelized cost. R&D efforts are needed to reduce the cost, improve reliability, and increase throughput of these components. Once it is dispensed, hydrogen is typically stored onboard vehicles in all-metal or composite-overwrapped pressure vessels. R&D is needed to reduce the cost of current designs, such as through reductions in the cost of carbon fiber overwrap, and to advance novel approaches to onboard storage, such as in insulated liquid tanks.

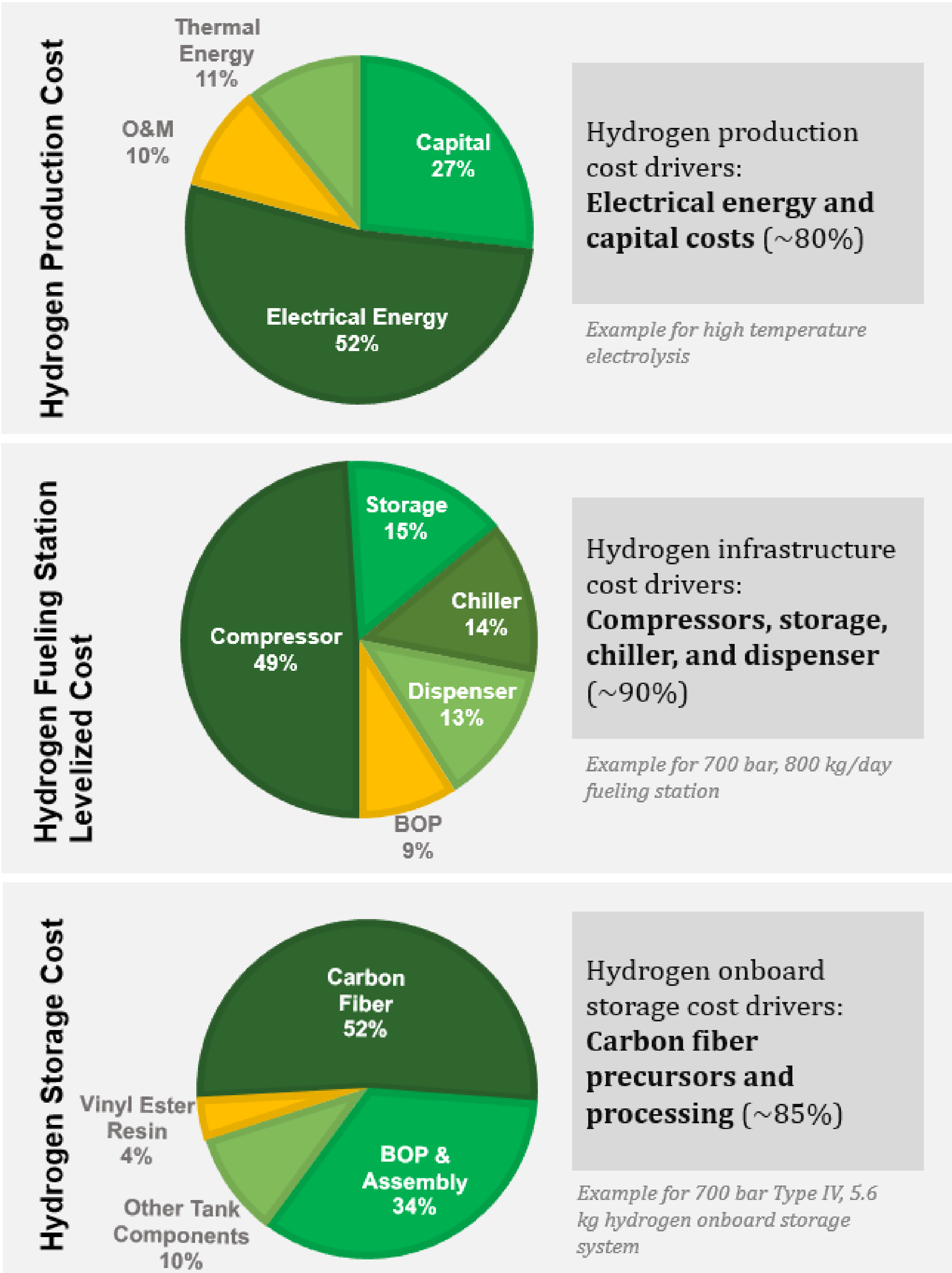


Figure 24: Examples of cost drivers for hydrogen production, distribution, and storage technologies. [166]

Strategy 3: Focus on Regional Networks

The third strategy will focus on achieving large-scale, commercially viable deployment of clean hydrogen by matching the scaleup of clean hydrogen supplies with a concomitant and growing regional demand. Co-locating large-scale clean hydrogen production with multiple end-uses can foster the development of low-cost hydrogen and the necessary supporting infrastructure to jumpstart the hydrogen economy in important market segments. Regional hydrogen networks will create near-term and long-term jobs, increase tax revenues for regional economies, and reduce emissions.

The Hydrogen Shot Request for Information (RFI), issued in 2021, received over 200 responses describing diverse resources, end-uses, and impact potential in various regions. Figure 25 is based on those RFI responses and synthesizes distinct regional examples and advantages in clean hydrogen production, storage, and end-use potential. Respondents identified very specific end-use opportunities for clean hydrogen in some regions, such as port communities or offshore wind generation. In other regions, stakeholders indicated a strong interest in leveraging abundant energy resources like biomass, or infrastructure, such as energy storage or geological caverns. Stakeholders also provided examples where disadvantaged or tribal communities could be engaged, and examples of potential job opportunities. Details and examples were provided in presentations at the Hydrogen Shot Summit and DOE webinars.[167,168]

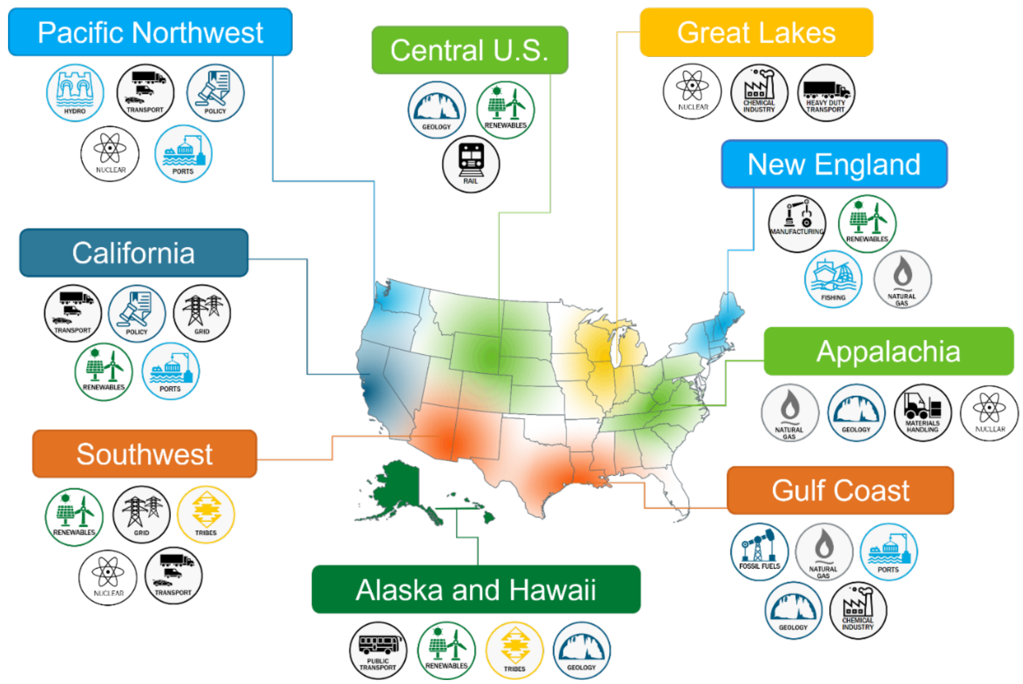


Figure 25: Examples of regions identified by responses to the Hydrogen Shot Request for Information (RFI).

The Hydrogen Shot RFI underlined the numerous opportunities for strategic hydrogen use across the United States. In many cases, the current infrastructure that respondents highlighted can support early regional deployment needs. The BIL's regional clean hydrogen hub provision provides a unique, unprecedented opportunity for the U.S. to jumpstart a clean hydrogen economy while achieving tangible regional and community-level benefits. Data gathered from the hubs will be used in future analyses to identify optimal approaches to market liftoff, such as using contracts for difference, matching production with off-takers, creating targeted, large-scale demand with anchor tenants, and strategies to use existing infrastructure where applicable, including CCS and other pipeline infrastructure. Figure 26 summarizes the critical elements of successful clean hydrogen hubs, the three "pillars" that characterize the hubs (per the BIL), and outlines key desired outcomes.

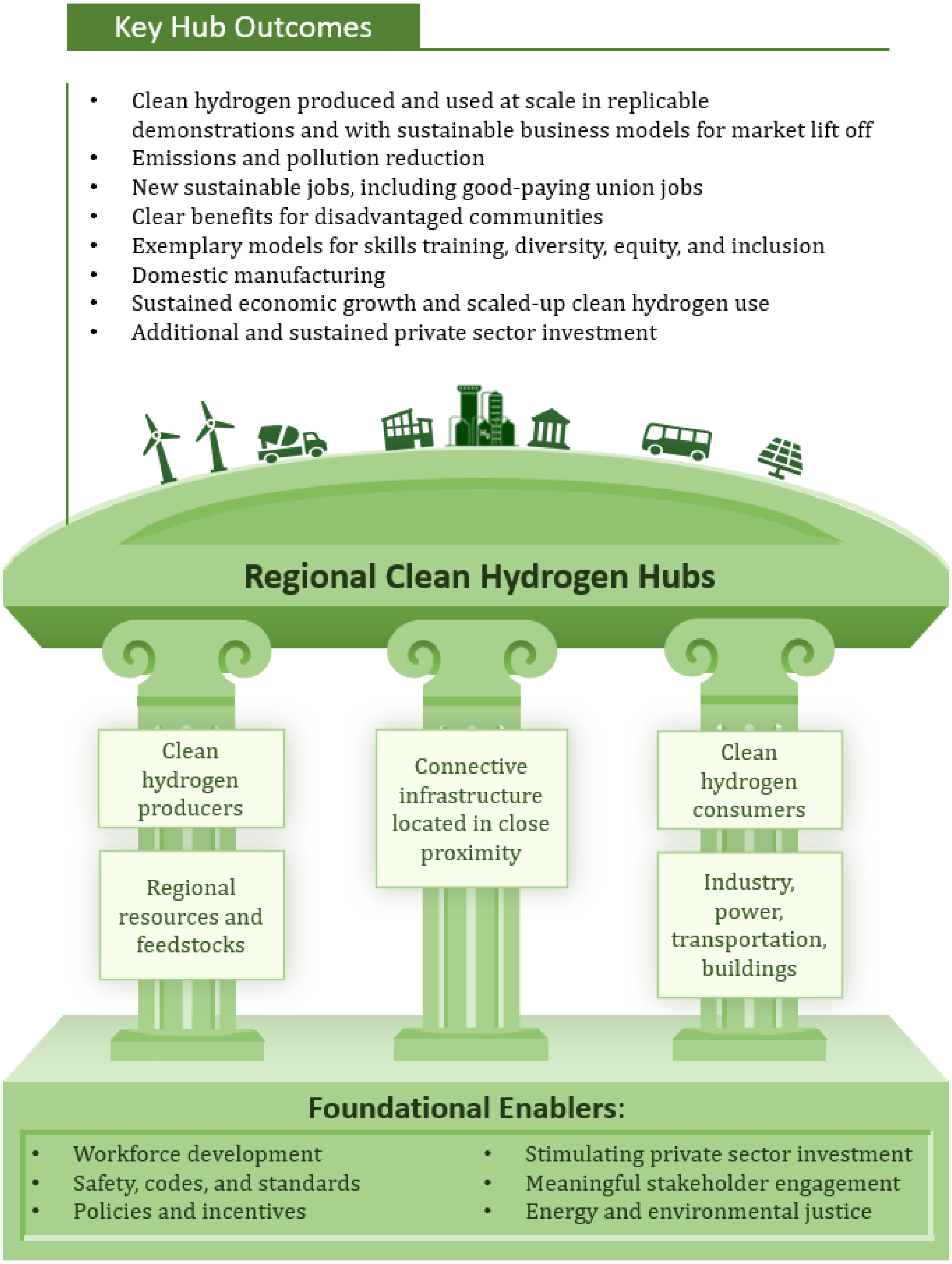


Figure 26: Critical elements of successful clean hydrogen hubs and key outcomes.

Regional production potential

As part of the strategy, DOE will continue to refine and update regional analyses across the hydrogen value chain, including the availability of water and other resources. Using data from national laboratory and industry analyses, DOE estimated the technical potential for producing hydrogen from diverse domestic resources. The technical potential estimates for these renewable resources are shown in Figure 27. and Figure 28.

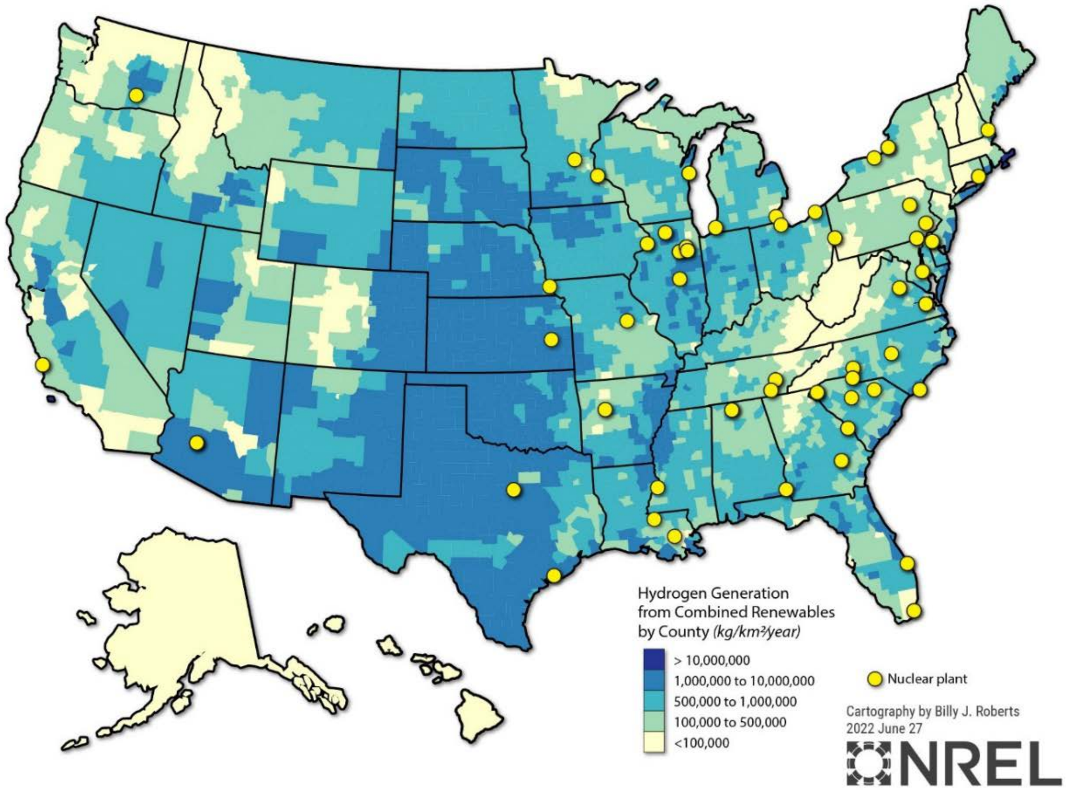


Figure 27 Production Potential of Hydrogen Across the United States[169]

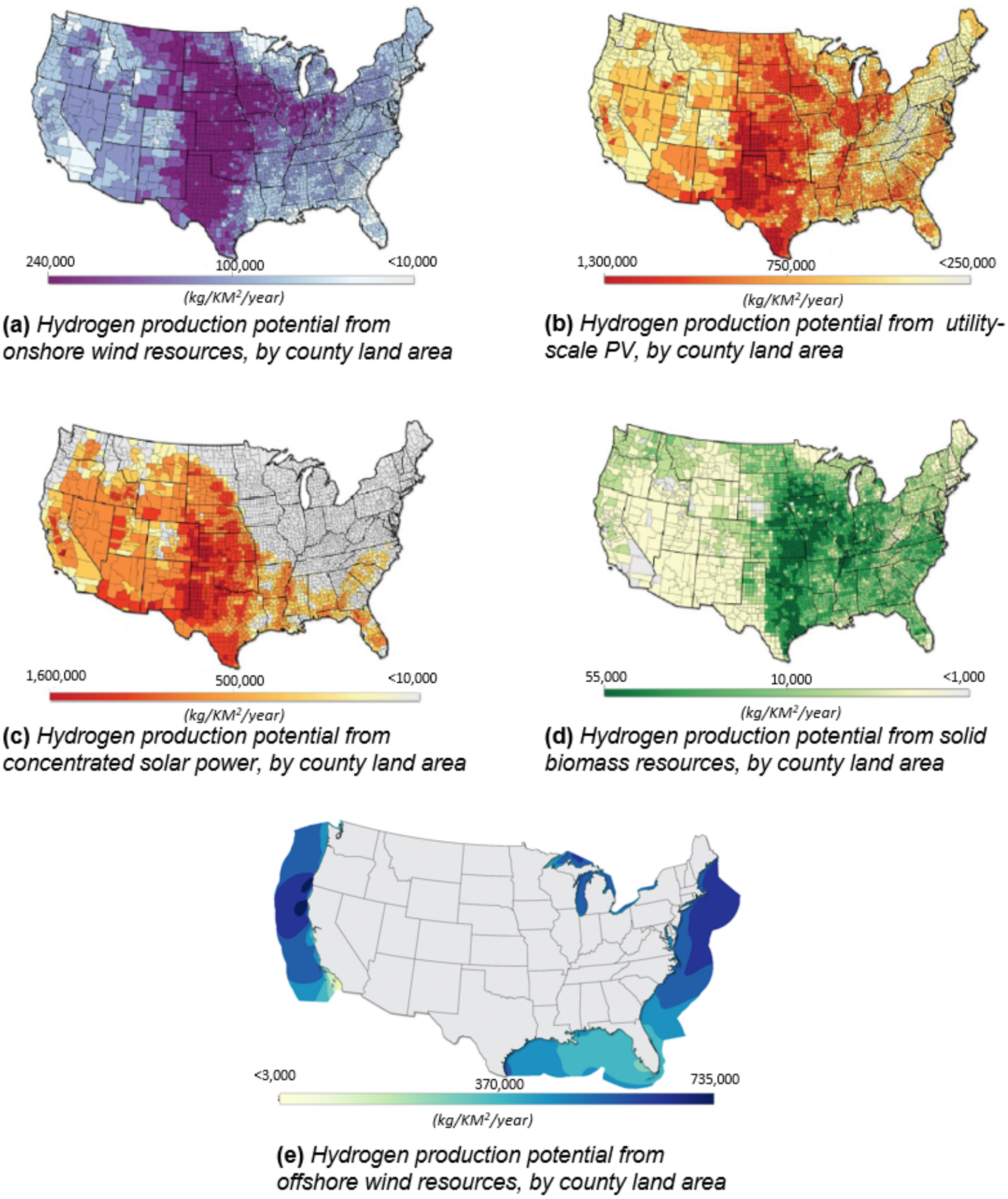


Figure 28: Production potential for clean hydrogen from onshore wind, utility-scale photovoltaic solar power, offshore wind, concentrated solar power, and biomass resources. (Source: NREL[170])

Lowest-cost production methods for clean hydrogen will depend upon regional resource availability, and early market developments will need to be located near end-users to reduce the costs of hydrogen delivery. The combination of natural resources, infrastructure assets, and hydrogen demand opportunities varies from region to region and will determine optimal region-specific approaches. Solar and wind resource potentials dominate in the plains, southwest, and mountain regions. Biomass resources are prevalent in the midwestern, northeastern, and southeastern United States. Geologic CO_2 storage potential is dominant in the industrial heartland and the Gulf Coast, where natural gas resources are also prevalent, as shown in Figure 30. With today's nuclear fleet and next-generation, advanced nuclear approaches (including small modular reactors), there are multiple regional opportunities for clean, baseload nuclear power.

Electrolyzers would likely need to be in regions with high wind and solar potential and near nuclear power plants. In regions with high renewables penetration, electrolysis can help manage variable loads on the grid, utilizing excess capacity during peak production to produce hydrogen rather than letting power be curtailed. For instance, electrolyzers integrated with offshore wind in regions with transmission constraints could create another revenue stream for the renewable generation. DOE will assess various options in collaboration with relevant agencies, states, and local communities

Regional storage potential

As real-world hydrogen projects ramp up, DOE will continue to assess optimal approaches and siting opportunities for hydrogen storage at scale. Hydrogen storage can decouple power generation from energy use and achieve lower costs than other technologies at scales of multiple days or weeks.[171] Hydrogen can be stored in gaseous or liquid vessels, in underground formations, or in materials, such as hydrogen carriers, depending on how it will be used. Each approach has both advantages and disadvantages; several DOE and industry projects and analyses are underway to reduce cost and potential emissions and improve efficiency and storage capacity.

Tanks and liquid dewars are already commercially used in industry and at hydrogen fueling stations to store hydrogen at scales of hundreds of kilograms to many metric tonnes. Limited deployments of larger-scale vessels have primarily stored hydrogen in liquid form for aerospace applications that require the use of liquid hydrogen onboard. The world's largest liquid hydrogen storage vessel today is at Kennedy Space Center in Florida, storing 1.25 million gallons or over 330 tonnes of liquid hydrogen.[172] Even larger scales of hydrogen storage currently employ underground caverns and are used to buffer seasonal differences between hydrogen supply and demand for the petrochemical sector. The United States has three large-scale geological hydrogen storage caverns including the world's largest in Beaumont, TX, storing over 7,000 tonnes underground.[173]

Underground hydrogen storage caverns have primarily been excavated in salt deposits near the point of hydrogen use, with limited demonstrations in hard rock. Additional geologies used for natural gas storage and could potentially be used for hydrogen in the future include depleted oil and gas reservoirs and aquifers. Figure 29, below, shows the approximate availability of these geological formations throughout the United States. In many cases, these regions overlap with the dominant production potential regions shown in Figure 27. DOE will continue its analyses and RDD&D on storage location opportunities and on technologies including advanced hydrogen carriers, such as ammonia and liquid organic hydrogen carriers, as these can carry hydrogen at high energy densities.

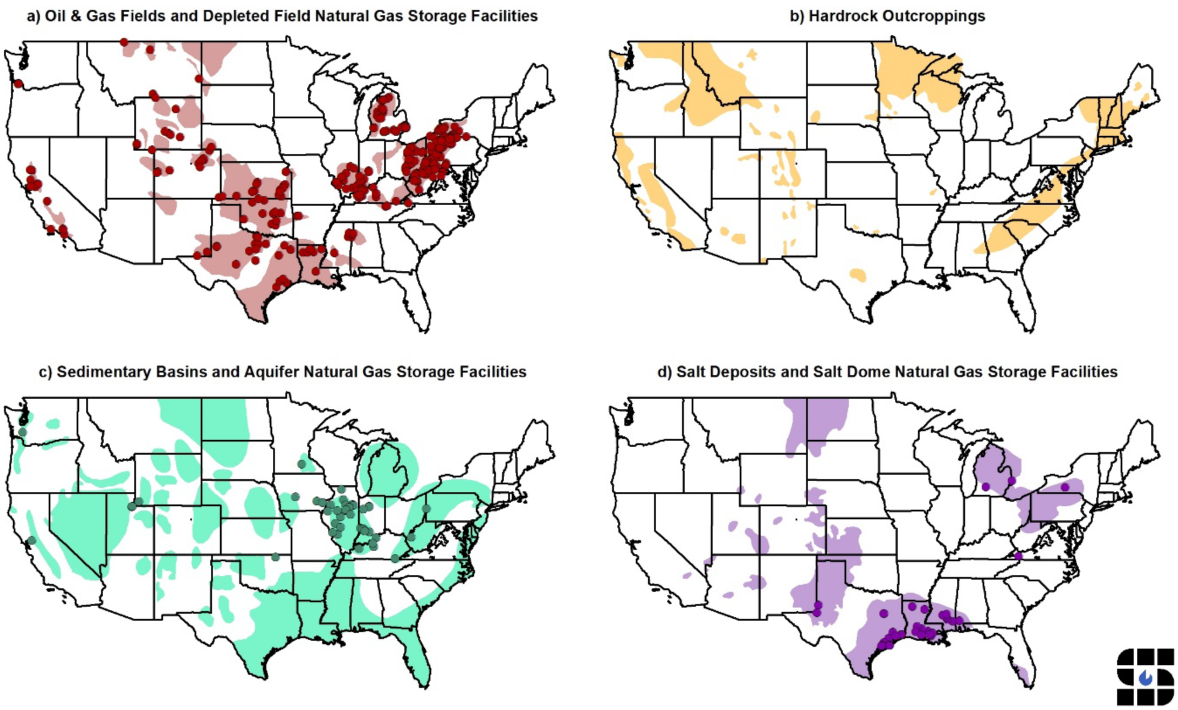


Figure 29: Underground storage opportunities in the United States (Source: SHASTA[174])

Many of these geologies and reservoirs can also be used for permanent CO_2 storage in support of clean hydrogen production. Figure 30 depicts the locations of potential CCS along with existing hydrogen and ammonia production plants. Ongoing analysis projects are currently identifying approaches to optimally leverage these resources and deploy future CO_2 and hydrogen infrastructure for cross-sector decarbonization.

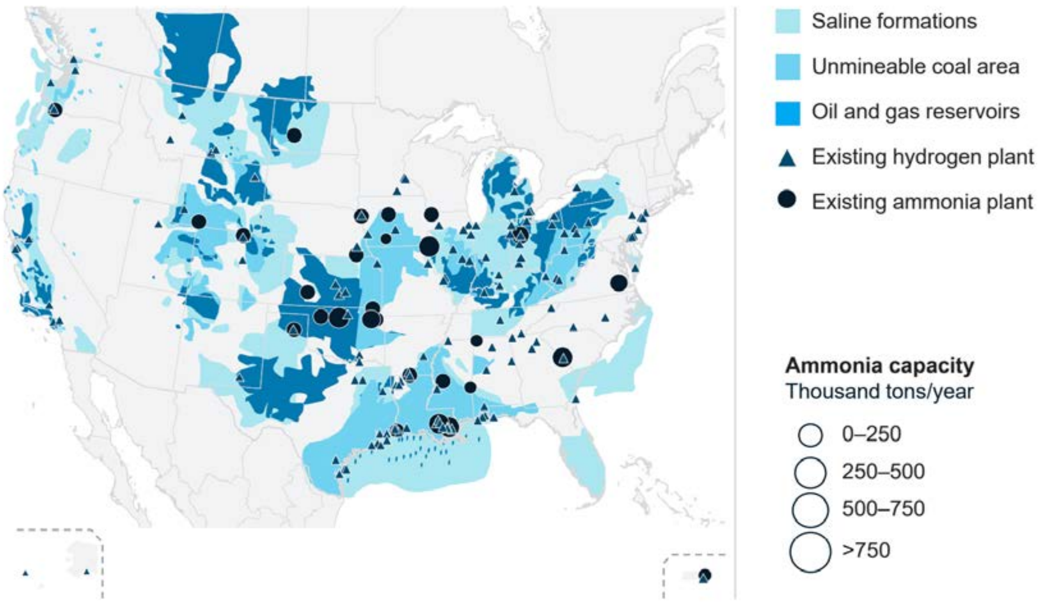


Figure 30: Potential locations for CCS based on geologic formations and existing hydrogen and ammonia plants in the United States. (Source: Teletzke, G.F.[175])

Regional end-use potential

As shown in Figure 31, some regions in the country have industrial clusters where several industries are potential candidates to adopt hydrogen as a feedstock or energy source. Decarbonizing these industry segments will depend on the viability of integrating clean hydrogen on a sector-by-sector and region-by-region basis. Yet, there is strong potential to leverage networks that can enable hydrogen infrastructure or large-scale CCS and develop best practices that can be used in other sectors.

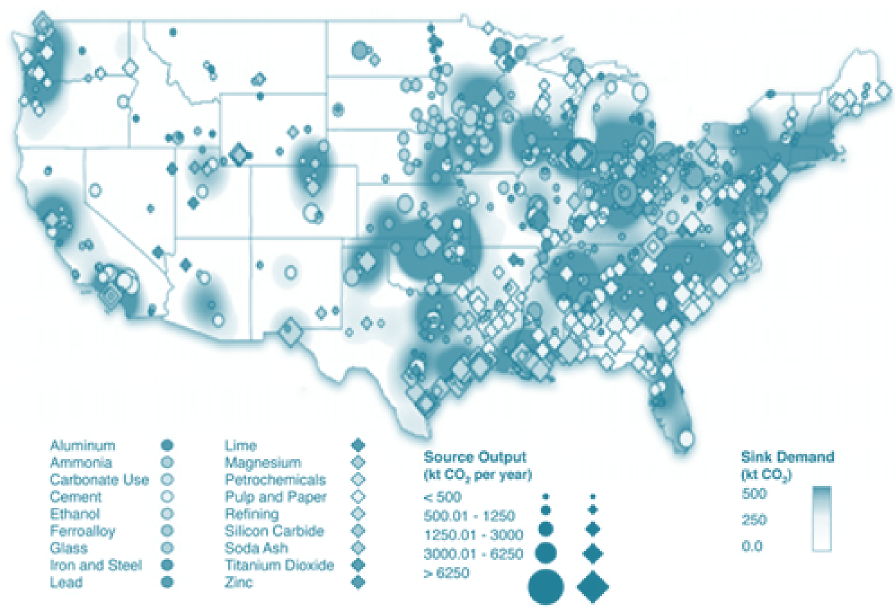


Figure 31: Industrial clusters in the United States create potential regions for decarbonization hubs. (Source: Psarras et al.[176])

Strategic deployment of clean hydrogen will need to ensure clusters are not just a collection of disparate projects. Projects should be sized, scoped, and planned in coordination with each other to match scale, cost, and duration. Coordinated projects will help avoid stranded assets by providing a critical mass of off-takers, leveraging CCS and other infrastructure, and ensuring public investments pay dividends to meet our net-zero goal.

Clean hydrogen hubs will demonstrate the efficacy of coordinating regional decarbonization efforts and support the business case of these projects to stimulate private capital investment. The hubs will also create avenues to engage stakeholders at every stage of the process to earn public support, develop community benefit agreements, and ensure projects advance environmental, health, and equity goals.

Industries that already consume hydrogen at scale, such as ammonia production, are likely to be early adopters of clean hydrogen, given their existing supply chains and economies of scale. Figure 32 and Figure 33 show examples of current and future hydrogen production potential and the existing ammonia production sites.

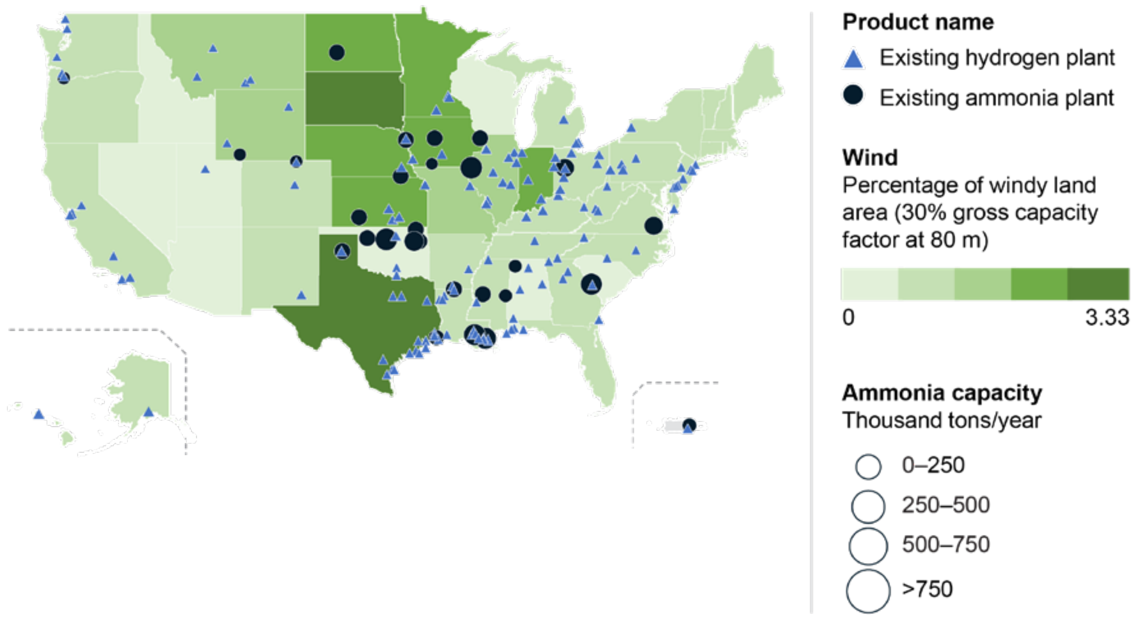


Figure 32: Existing hydrogen and ammonia production plants and potential wind energy resources in the United States.

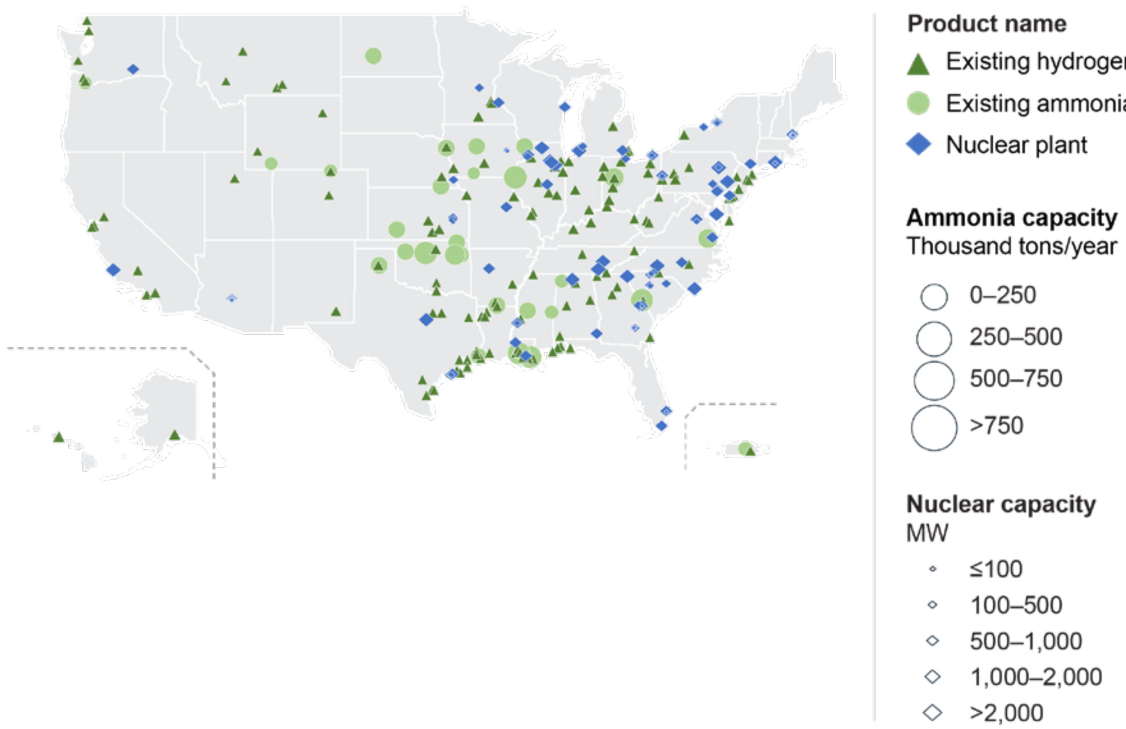


Figure 33: Existing hydrogen and ammonia production plants and nuclear energy plants in the United States.

Supporting Each Strategy

To support all three key strategies, DOE will leverage the entire continuum of activities across basic science[177] through applied research, development, demonstration, and large-scale deployments. As shown in Figure 34, the continuum of activities will be supported by foundational and crosscutting efforts to promote diversity, equity, and inclusion; engage stakeholders, ranging from environmental justice groups to Tribal communities and labor unions; develop the workforce; advance policy; support the technology and energy transition; and enable market adoption at scale.

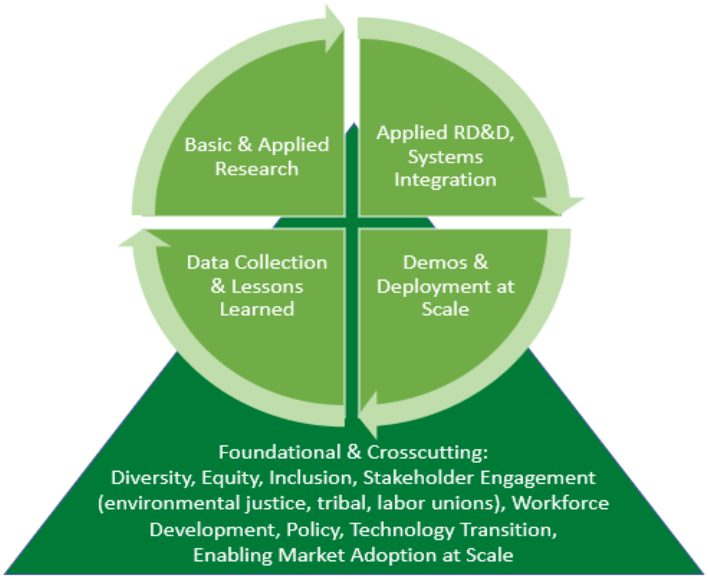


Figure 34: Foundational and crosscutting efforts will support the entire lifecycle of activities at DOE, from basic research through large-scale deployment.

DOE's RDD&D activities are informed by market-based technical targets that enable hydrogen use to be competitive with incumbent fuels across sectors. The BIL also requires DOE to develop targets for the program to address near-term (up to 2 years), mid-term (up to 7 years), and long-term (up to 15 years) challenges to the advancement of clean hydrogen systems and technologies. [178] Key targets are shown in Table 1.

Activities across government, industry, and academia will need to work in concert to advance technologies toward these targets. Many of DOE's existing consortia and initiatives are already working to achieve these goals through collaborations between national laboratories, industry, and academia. Key examples include the H2NEW consortium on electrolyzer technologies, the M2FCT consortium to advance fuel cells for heavy-duty trucks, the Hydrogen Materials Compatibility Consortium (H-Mat), and other R&D projects and first-of-a-kind demonstrations funded through previous solicitations.

Table 1: Key Program Targets 2022-2036

	2022-2023	2024-2028	2029-2036
Production	• **3 or more** pathways identified with potential to meet Hydrogen Shot • **10,000 hours** of high-temperature electrolyzer testing • **3 or more** pathways assessed for life cycle emissions • **1.25 MW** of electrolyzers integrated with nuclear for H_2 production • **2 or more** conditional loan program agreements	• **10 or more** demos with renewables (including offshore wind), and/or nuclear, and waste/fossil with CCS • $2/kg clean H_2 from electrolysis at scale by 2026* • **51 kWh/kg** efficiency; **80,000-hr** life; and **$250/kW** for low temperature electrolyzers • **44 kWh/kg** efficiency; **60,000-hr life**; and **$300/kW** for high temperature electrolyzers • **20 MW** of nuclear heat extraction, distribution and control for electrolysis	• **10 MMT** per year or more of clean H_2 produced in the U.S. from diverse sources • **$1/kg** clean H_2 production from diverse resources at scale* • **46 kWh/kg** efficiency; **80,000-hr** life; **$100/kW** uninstalled cost for low temperature electrolyzers • **80,000-hr** life **$200/kW** cost for high temperature electrolyzers while maintaining or improving efficiency
Infrastructure & Supply Chains	• **10 kg/min** average H_2 fueling rate for heavy-duty applications • **40%** reduction in footprint of liquid H_2 fueling stations vs. current (2016) code. • **50%** increase in seal and metal durability in H_2 service vs. 2018 baseline • **400 kg/hr** high-pressure compressors and cryopumps • **5%** or better accuracy for H_2 flow meters at up to 20 kg/min flow	• **7 kWh/kg** efficiency for H_2 liquefaction • **50%** cost reduction of carbon fiber for H_2 storage vessels (vs. 2020) • **50%** of membrane/ionomer material recovery and >**95%** of platinum group metals (PGMs) recovery from fuel cell membrane electrode assemblies (MEA) pathways identified through recycling and upcycling • **3 GW or more** electrolyzer manufacturing capacity in the United States	• **$4/kg** H_2 cost at scale (including production, delivery, and dispensing at fueling stations) • **70%** of membrane/ionomer material recovery and **99%** of PGMs from MEA pathways identified through recycling and upcycling • **3 or more** pathways validated for emissions reductions, while meeting environmental and energy justice priorities
End-Use and Enablers	• **$170/kW** heavy-duty truck fuel cell cost vs. $200/kW baseline • **18,000-hr** fuel cell durability for buses. • **1.5 MW** or more of H_2 fuel cells for data center resiliency • **1 MW** scale electrolyzer and fueling marine applications • **15** fuel cell delivery trucks operating in disadvantaged community, creating potential for market growth that reduces emissions and creates jobs • **1 or more** integrated H_2 for ammonia production demonstration	• **$140/kW** heavy-duty truck fuel cell cost • **50% reduction** of fuel cell PGMs vs. 2020 baseline • **1 ton/week** reduction of iron with H_2 and pathway to **5,000 tonnes/day** • **9 ppm** NOx emissions for 100% H_2 turbines, **2 ppm** with selective catalytic reduction • **3** H_2 fuel cell Super Truck projects completed • **2 or more** pilot projects with tribes • **4** template community benefit agreements • **4 or more** regional clean hydrogen hubs using diverse resources and for multiple strategic end-uses	• **$80/kW** heavy-duty truck fuel cell cost while also meeting durability and performance • **$900/kW** and **40,000-hr** durability fuel-flexible stationary fuel cells • **4 or more** end-use demos (e.g., steel, ammonia, storage) at scale • **10 MMT** per year or more of clean H_2 used in strategic markets at scale aligned with the DOE National Hydrogen Strategy goal

** modeled cost at scale to meet Hydrogen Shot goal*

C: Guiding Principles and National Actions

Guiding Principles

DOE will adhere to guiding principles in eight categories

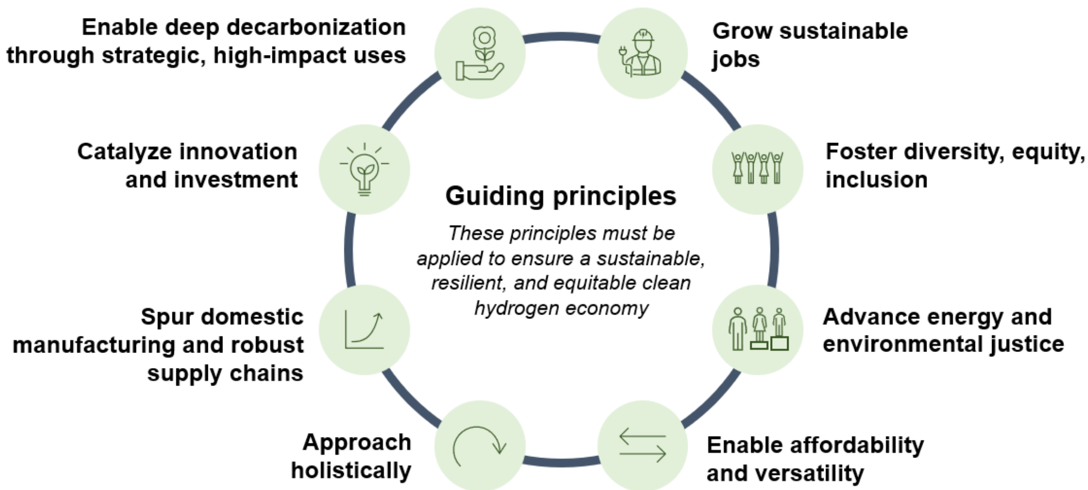


Figure 35: Eight guiding principles for the development of clean hydrogen production, transport, delivery, storage, and use

- **Enable deep decarbonization through strategic, high-impact uses:** DOE will enable the national net-zero and clean grid goals through *targeted* deployments of clean hydrogen in sectors where its use has the most impact, including industrial processes, heavy-duty transport, high-temperature heat, and long duration energy storage. These strategic deployments will be informed through analyses and stakeholder input to address key priorities including environmental, energy justice, and economic benefits.

- **Catalyze innovation and investment:** DOE will foster partnerships with industry, academia, national laboratories, and other stakeholders to invest in innovation across the entire RDD&D value chain for clean hydrogen technologies. DOE's actions will stimulate growth, a competitive domestic industry, and sustained private investment, building upon American ingenuity, talent, and initiative.

- **Foster Diversity, Equity, Inclusion:** DOE will promote diversity, equity, and inclusion to effectively advance the U.S. research, innovation, and commercialization enterprise. DOE's actions will support stewardship and promotion of diverse and inclusive workplaces that value and celebrate a diversity of people, ideas, cultures, and educational backgrounds that are foundational to delivering on the clean hydrogen strategy.

- **Advance Environmental Justice:** DOE will prioritize energy and environmental justice. DOE's actions will seek to create new economic opportunities and place-based initiatives to improve the health and well-being of communities, including Tribal Nations and other communities who have been historically underserved in alignment with the Justice40 Initiative. Siting and benefits of clean hydrogen deployments should be developed through meaningful engagement with each community that desires to take part in the clean hydrogen economy.

- **Grow Sustainable Jobs:** DOE will focus on preserving and growing sustainable jobs, defined as good-paying union jobs. DOE's actions will also provide opportunities for workers and communities transitioning away from carbon-intensive sectors, leveraging existing and developing new skills across industries by utilizing and expanding registered apprenticeship programs, developing sectoral strategies for workforce development, and supporting job growth at each step in the hydrogen value chain - from equipment manufacturing and trucking to pipeline construction and CCS.

- **Spur domestic manufacturing and robust supply chains:** DOE will promote U.S. manufacturing, ensure robust, secure, and resilient supply chains, and increase exports. DOE's actions will utilize multiple tools, from grants to financing to facilitating partnerships. DOE will design for recyclability and reduce vulnerabilities in critical mineral and material supply chains for hydrogen and fuel cell technologies.

- **Enable affordability and versatility:** DOE will target affordability and create flexibility in the energy system by leveraging and coupling diverse sources, including renewables and nuclear, utilizing fossil and CCS infrastructure where appropriate, and enabling resiliency and energy security. By using clean hydrogen as a fuel or feedstock or as an energy carrier and storage medium, DOE can provide multiple revenue streams across sectors and avoid stranded assets.

- **Approach holistically:** DOE will approach clean hydrogen development and deployment holistically and will cultivate sustainable best practices through targeted development to support – not compete with – other decarbonization technologies such as electrification. DOE will foster rigorous and transparent analyses on social, environmental, economic, and energy impacts to help guide sustainable development of the nascent global clean hydrogen industry.

DOE will use these guiding principles as DOE develops and continuously refines the actions and milestones in the National Clean Hydrogen Strategy and Roadmap. Principles of equity and justice are a high priority, consistent with the Biden Administration's commitments to ensure that overburdened, underserved, and underrepresented individuals and communities have access to Federal resources pursuant to EO 13985, Advancing Racial Equity and Support for Underserved Communities;[179] EO 14020, Establishment of the White House Gender Policy Council;[180] and EO 14008, Tackling the Climate Crisis at Home and Abroad.[181]

Stakeholder engagement and collaboration, including through community benefit agreements, will be critical. By recognizing and addressing the challenges early on and across the hydrogen value chain, we will collectively accelerate progress towards our goals. With the right strategy and implementation plan, clean hydrogen technologies can reduce not only GHG emissions, but emissions of nitrogen oxides and particulates from heavy-duty road transportation and stationary power, improve human and environmental health, and provide resiliency and energy security - all while creating new regional economic opportunities and positioning the United States as a global leader in a nascent industry.

Actions Supporting the National Clean Hydrogen Strategy and Roadmap

DOE, in partnership with other Federal agencies, state, local, and Tribal governments, and other stakeholders will take action to develop and deploy clean hydrogen technologies. Planned actions are outlined across the near-term through 2025, mid-term to 2029, and longer term to 2035. The plans outlined in this report will be used to fulfill the reporting requirement in the BIL after stakeholder feedback, and are expected to be continually refined and updated. They are based on lessons learned and best practices from the development of both hydrogen and other advanced technologies, considering local and regional opportunities with a focus on environmental and energy justice, and forging partnerships across government, industry, investors, and academic and research institutions to speed progress.

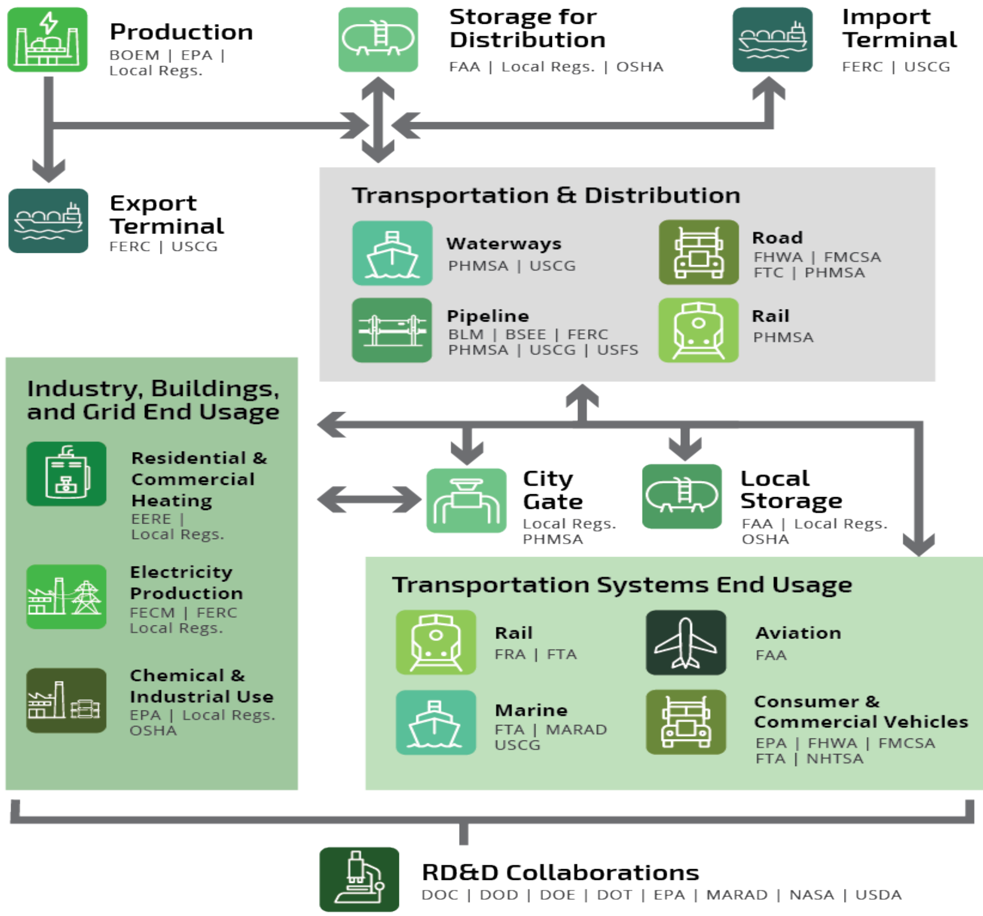
Several of these actions are already in progress and will be supported by existing and recently announced public funding opportunities, such as initiatives under LPO and regional clean hydrogen hubs under BIL. Subject to annual congressional appropriations and private sector investment, DOE and other stakeholders will undertake additional actions across the RDD&D pipeline. DOE will track key indicators and metrics to track progress of the U.S. hydrogen strategy.

This is only the beginning of the national effort to innovate and build the full value chain for clean hydrogen from production through delivery and storage infrastructure, market adoption and economic development – much more public and private investment will be required. The Department of Energy is taking a holistic view of catalyzing investments and actions required across the Nation.

	2022	2023	2024	2025	2026
National Strategy and Roadmap		Ongoing analysis: supply, demand, emissions, jobs, infrastructure, policies, investments, etc.		Update National Strategy and Roadmap	Continue to refine and iterate
Clean Hydrogen Standard		DOE, in consultation with EPA, to develop Clean Hydrogen Production Qualifications and update Standard within five years of enactment			
Hydrogen Hubs Solicitation		Select at least 4 regional clean hydrogen hubs within 1 year of proposal submissions and execute. Total: $8B from FY22 through FY26			
Electrolysis RD&D		Additional electrolysis and related RD&D. Total: $1B from FY22 through FY26			Meet $2/kg H_2 from electrolysis
Manufacturing & Recycling RD&D		Additional Manufacturing & Recycling RD&D. Total: $0.5B from FY22 through FY26			

Figure 36: Timeline for key hydrogen provisions in the Bipartisan Infrastructure Law

The DOE National Strategy and Roadmap aligns with the key hydrogen provisions in the BIL, as shown in Figure 36, and will advance the broader national effort to innovate and build the full value chain for clean hydrogen.



BLM - Bureau of Land Management
BOEM – Bureau of Ocean Energy Management
BSEE – Bureau of Safety and Environmental Enforcement
DOC – Department of Commerce
DOD – Department of Defense
DOE – Department of Energy
DOT – Department of Transportation
EERE – Office of Energy Efficiency and Renewable Energy
EPA – Environmental Protection Agency
FAA – Federal Aviation Administration
FECM – Fossil Energy and Carbon Management
FERC – Federal Energy Regulatory Commission
FHWA – Federal Highway Administration
FMCSA – Federal Motor Carrier Safety Administration
FRA– Federal Railroad Administration
FTA – Federal Transportation Administration
FTC– Federal Trade Commission
MARAD - Maritime Administration
NASA – National Aeronautics and Space Administration
NHTSA – National Highway Traffic Safety Administration
OSHA – Occupational Safety and Health Administration
PHMSA – Pipeline & Hazardous Materials Safety Administration
USCG - U.S. Coast Guard
USDA - U.S. Department of Agriculture
USFS - U.S. Forest Service

Figure 37: The regulatory landscape involves a suite of federal and local regulators who may oversee each segment of the hydrogen value chain. (Source: Sandia National Lab)

DOE will work with other Federal agencies, states, Tribal governments, communities, and other stakeholders to identify regulatory gaps and develop strategies to address them. Figure 37, based on input across agencies, shows various segments of the hydrogen value chain from production through end-use and lists the agencies that may have jurisdiction in key areas. Based on a DOE-funded report by Sandia National Laboratories, Table 2 and Table 3 (below) show examples of specific regulatory activities by the various agencies. Agencies will work together to regularly update this assessment **and to identify and prioritize actions** that will be needed to ensure the U.S. can accelerate the buildout of hydrogen production, delivery, storage, and end-use, while also addressing potential environmental concerns and ensuring equity and justice for overburdened, underserved, and underrepresented individuals and communities.

Table 2: Examples of regulatory activities by U.S. agencies relevant to hydrogen production, storage, and delivery

Production, Storage and Delivery

System	Agency	Regulation	Summary
Production	EPA	40 CFR Part 98	Defines source categories and emissions thresholds for a hydrogen production facility
	DOE	IIJA Sec 40314 (Sec 822)	Directs DOE to develop a clean hydrogen production standard as a point of reference for specified BIL programs
Storage	FAA	14 CFR Part 420	Dictates the separation distance requirements for storage of liquid hydrogen and any incompatible energetic liquids
	FERC	18 CFR Part 157	Issuance of certificates of public convenience and necessity to prospective companies providing energy services or constructing and operating interstate natural gas pipelines and storage facilities.
	OSHA	29 CFR Part 1910	Dictates the safety of the structural components and operations of gaseous and liquid hydrogen storage and delivery
Transportation by Pipeline	BSEE	43 USC Part 29	Manages compliance programs governing oil, gas, and mineral operations on the Outer Continental Shelf (OCS)
	FERC	18 CFR Part 153, 157, and 284	Applications for authorization to construct, operate, or modify facilities used for the export or import of natural gas. Issuance of certificates of public convenience and necessity to prospective companies providing energy services or constructing and operating interstate natural gas pipelines and storage facilities. Regulation of natural gas transportation in interstate commerce.
	PHMSA	49 CFR Part 192, 195	Prescribes minimum safety requirements for pipeline facilities, pipelines, and the transportation of gas or hazardous liquids within the limits of the outer continental shelf
	USCG	33 CFR Part 154	Regulations for facilities transferring hazardous materials back and forth from a vessel to a facility
Transportation by Rail	PHMSA	49 USC 5117 and 49 CFR Part 172, 173, 174, 179, 180	Lists and classifies hazardous materials for transportation and prescribes the requirements for papers, markings, labeling, and vehicle placarding Provides requirements for preparing hazardous materials for shipment as well inspection, testing, and other requirements for transportation of hazardous materials in or on rail cars, including construction & usage instructions for DOT-113A60W tank cars Gives the authority to authorize a variance that is still at the same safety level, special permit is required to use an alternative fuel that does not have a safety standard
Transportation by Road	FHWA	23 CFR Part 924	Regulates highway safety which includes bridges, tunnels, and other associated elements
	FMCSA	49 CFR Part 356, 389, 397	Motor carrier routing requirements, general motor carrier safety regulations, and transportation of hazardous materials
	FTC	16 CFR Part 306	Describes the certification and posting of automotive fuel ratings in commerce

	PHMSA	49 CFR Part 172, 173, 177, 178, 180	Lists and classifies hazardous materials for transportation, and prescribes requirements for papers, markings, labeling, and vehicle placarding Provides requirements for preparing hazardous materials for shipment, and inspection, testing, and other requirements for transportation of hazardous materials via public highways (including transportation containers)
Transportation by Waterways	PHMSA	49 CFR Part 172, 173, 176, 178, 180	Lists and classifies hazardous materials for transportation and prescribes the requirements for papers, markings, labeling, and vehicle placarding Provides requirements for preparing hazardous materials for shipment, as well inspection, testing, and other requirements for containers Requirements for transportation by vessel
	USCG	33 CFR Part 154, 156 and 46 CFR Part 38, 150, 151, 153, 154	Regulations for transferring hazardous materials back and forth from a vessel to a facility Transfer of oil or hazardous material on the navigable waters or contiguous zone of the U.S. Requirements for transportation of liquified or compressed flammable gases, including incompatibility of hazardous materials and rules for containers Regulations for ships and vessels carrying bulk cargo, including bulk liquified gases as cargo, residue, or vapor

Table 3: Examples of regulatory activities by U.S. agencies relevant to end-use of hydrogen

End-Use

System	Agency	Regulation	Summary
Auxiliary Power and Alternative Power Supply	FAA	14 CFR Part 23, 25, 27, 29 Subpart E	Requirements for electrical generating systems including auxiliary and backup power for airplanes and rotorcraft
	FHWA	49 CFR Part 390	Regulates additional equipment on commercial vehicles to ensure it does not reduce the overall safety of the vehicle
	FRA	49 CFR Part 229	Regulations for electrical systems, generators, protection from hazardous gases from exhaust and batteries, and crashworthiness for locomotives
	USCG	46 CFR Part 111	Regulations for power supply systems on ships
Chemical and Industrial Use	EPA	40 CFR Part 98	Requires reporting of GHG emissions due to combustion or use of products in a process
	OSHA	29 CFR Part 1910	Dictates the safety of the structural components and operations of gaseous and liquid hydrogen in terms of storage as well as delivery
Electricity Production	DOE	10 CFR Part 503, 504	Prohibits any new baseload powerplant without the ability to use coal or another alternative fuel as a primary energy source, and may prohibit existing powerplants from using petroleum or natural gas as a primary energy source
	FERC	18 CFR Part 292	Regulations with regard to small power production and cogeneration facilities.
Import/Export Terminals	USCG	33 CFR Part 154, 156	Regulations for self-propelled vessels that contain bulk liquified gases as cargo, cargo residue, or vapor Transfer of oil or hazardous materials on the navigable waters or contiguous zone of the U.S.
Residential & Commercial Heating	DOE	10 CFR Part 431	Provides regulation of commercial heaters, hot water boilers, and similar heating appliances
Use in Aviation	FAA	14 CFR Part 23, 25,26, 27, 29, 33	Provides requirements and airworthiness standards for airplanes and rotorcraft
Use in Consumer and Commercial Vehicles	FHWA	23 CFR Part 924	Regulates highway safety which includes bridges, tunnels, and other associated elements
	NHTSA	49 CFR 571	Provides Federal Motor Vehicle Safety Standards for motor vehicles and motor vehicle equipment
Use in Maritime	FTA	49 USC Chapter 53	Requirements for National Public Transportation Safety Plan for public transportation that receives federal funding
	USCG	46 CFR Parts 24–196	Regulation of vessel construction for both passenger and cargo applications as well as general fuel requirements based on the flash point of the fuel
Use in Rail	FRA	49 CFR Part 229, 238	Locomotive safety design and crashworthiness requirements, including safety requirements for passenger locomotives
	FTA	49 CFR Part 659, 674	Provides guidance for rail fixed guideway systems and the oversight of safety, including hazard management and safety and security plans and review Mandates state safety oversight of fixed guideway public transportation systems

Actions and Milestones for the Near, Mid, and Long-term

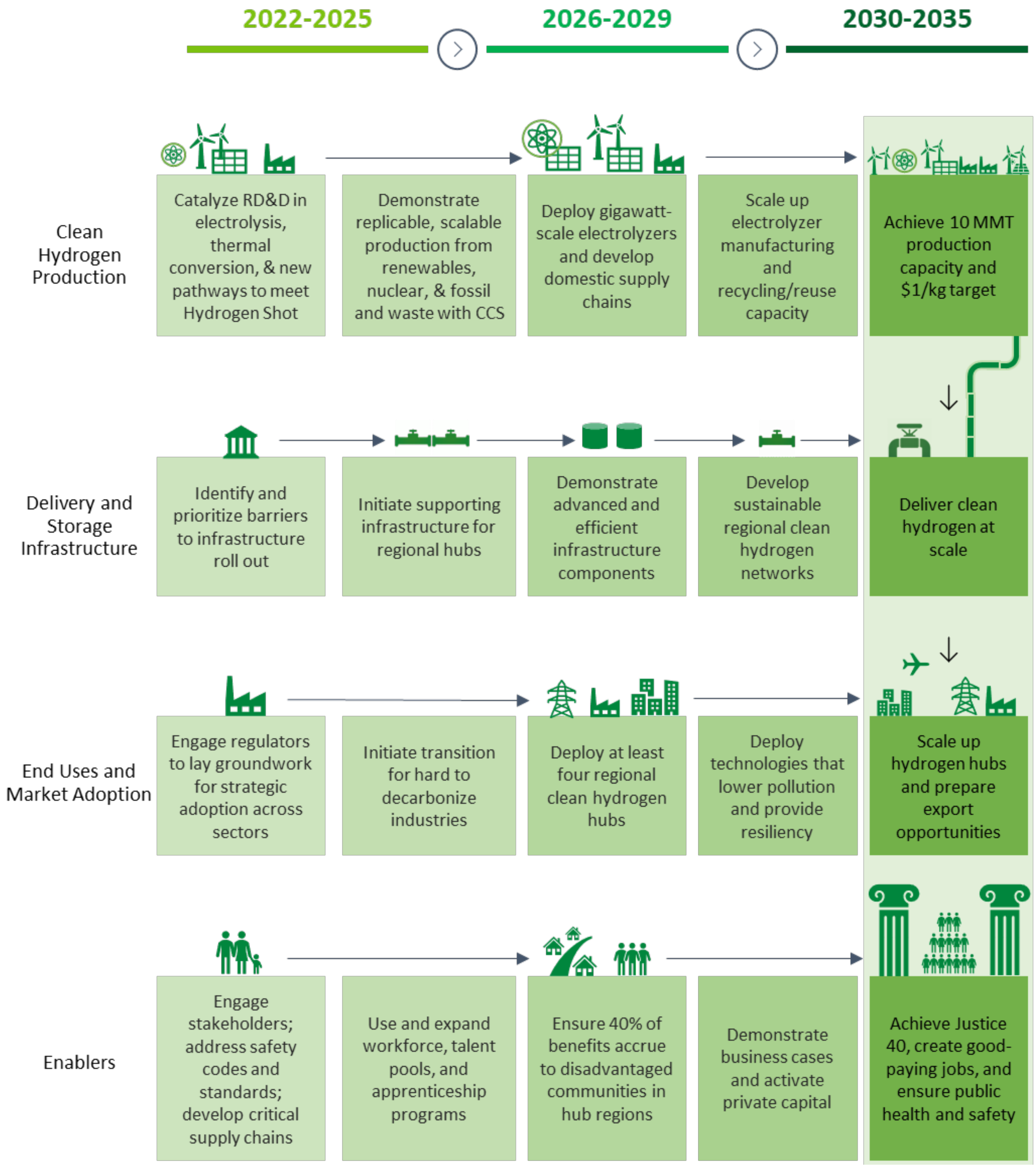


Figure 38: The national action plan for clean hydrogen

Actions to support clean, affordable, and sustainable hydrogen production

Clean Hydrogen Production

2022-2025

- Assess pathways from lifecycle, sustainability, cost, regional, and equity perspectives to prioritize strategies, determine gaps.
- Establish clean hydrogen standard.
- Demonstrate clean hydrogen production technologies from multiple pathways, including pyrolysis, waste, renewables, and nuclear.
- Reduce the cost of electrolyzers at scale through RDD&D on manufacturing, stacks, and BOP components.
- Reduce the cost of thermal conversion technologies through RDD&D on modular designs and process intensification
- Develop low-cost, durable membranes and separation materials.
- Identify opportunities for standardization of components, reduce dependence on critical materials, and foster a robust supply chain.
- Design and conduct accelerated stress testing techniques to assess and improve durability.
- Publish case studies on pathways, emissions, and cost.
- Develop rigorous data collection and monitoring framework for future deployments.

2026-2029

- Deploy clean hydrogen from renewables, nuclear, fossil + CCS at scale.
- Enable clean hydrogen production from electrolysis at $2/kg.[1]
- Enable multi-gigawatt-scale domestic electrolyzer manufacturing capacity.
- Demonstrate catalysts and components that minimize use of critical materials while achieving competitive performance and durability.
- Optimize integration between electrolyzers and clean energy supplies to reduce cost and improve efficiency and resiliency.
- Advance the most promising concepts for hydrogen production currently at lab scale, such as thermochemical, photoelectrochemical or biological approaches.
- Collect data from real-world demonstrations to inform RDD&D and continue improving performance and durability.
- Refine and update pathways assessments to ensure the most sustainable, equitable, resilient, and affordable approaches are targeted.
- Use rigorous analyses, lessons learned, best practices, and broad stakeholder feedback to identify pathways for scale up with highest benefits.

2030-2035

- Produce at least 10 MMT/year of clean hydrogen by 2030.
- Enable clean hydrogen production at $1/kg[2] from diverse resources.
- Demonstrate electrolysis stacks that minimize the use of critical materials and achieve targeted performance and durability.
- Demonstrate novel, commercially viable approaches to hydrogen production leveraging diverse feedstocks, such as wastewater or high-temperature heat, at scale.
- Ensure resilient and sustainable domestic supply chains are available for all production pathways employed and enable independence from imports.
- Continue to collect data from real-world deployments to inform RDD&D, identify remaining gaps and refine strategies.
- Apply best practices, lessons learned, and rigorous analyses, including through global collaboration and sustainability frameworks to ensure the most sustainable, equitable, resilient, and affordable approaches are advanced to maximize benefits.

[1] Modeled cost at scale, meets BIL provision (Sec. 816) $2/kg by 2026
[2] Modeled cost at scale to meet Hydrogen Shot goal.

Actions to support safe, efficient, and reliable clean hydrogen delivery and storage infrastructure

Delivery and Storage Infrastructure

2022-2025

- Develop and update rigorous analytical models and tools to assess delivery and storage pathways, determine gaps, and prioritize strategies.
- Develop technologies to tightly monitor and mitigate hydrogen leaks and boil-off.
- Assess compatibility of pipeline and component materials with hydrogen and hydrogen blends with natural gas.
- Advance novel approaches for low cost, high efficiency hydrogen liquefaction and boil-off mitigation.
- Conduct discovery and development of hydrogen carrier materials for use in bulk storage and distribution
- Identify geologic formations that can be used for bulk hydrogen storage, and associated development and operating requirements.
- Develop and optimize designs for hydrogen infrastructure in key applications, such as industry and energy storage.
- Develop technologies for high throughput dispensing of hydrogen for heavy-duty vehicles.
- Develop and harmonize fueling protocols for heavy-duty and off-road vehicles for which hydrogen is the optimal solution.
- Accelerate RDD&D to reduce the cost of high pressure and liquid hydrogen storage tanks, including carbon fiber composite vessels.
- Establish data monitoring and collection framework to assess upstream and on-site emissions.

2026-2029

- Validate and refine analyses, models, and tools to prioritize delivery and storage pathways for various applications.
- Demonstrate efficient and reliable hydrogen pipeline compressor operation.
- Quantify loss rates from gaseous and liquid hydrogen infrastructure to inform mitigation requirements in large-scale deployments.
- Develop designs for commercial-scale novel, high efficiency systems for hydrogen liquefaction.
- Advance promising concepts for hydrogen carriers and design reliable, low-cost regenerator systems.
- Initiate regional bulk hydrogen storage demonstrations, including underground approaches, and ensure local and regional benefits.
- Demonstrate novel, efficient, and low-cost approaches to bulk hydrogen delivery.
- Deploy scalable hydrogen fueling stations to support early fleet markets, such as heavy-duty trucks and buses.
- Ensure monitoring systems and data collection are in place for potential hydrogen and other emissions/releases
- Design sustainable and equitable regional clean hydrogen networks in key locations to maximize benefits, ensuring energy and environmental justice and equity.

2030-2035

- Design networks of hydrogen infrastructure optimized for regional supply and demand, in collaboration with local communities and stakeholders to maximize benefits and ensure energy, environmental, and equity goals are addressed.
- Demonstrate advanced liquefaction with double the efficiency of current concepts.
- Develop long term storage plan/strategic hydrogen reserve to ensure resiliency of supply.
- Deploy at least 4 regional clean hydrogen hubs with advanced low-cost clean hydrogen storage and infrastructure.
- Collect data, including emissions data, from demonstrations of bulk hydrogen distribution (e.g., through pipelines or carriers) in real-world environments to inform RDD&D that reduces cost and improves reliability.
- Continue collecting data to inform scale up of optimal delivery and storage pathways and RDD&D.
- Ensure any safety or other best practices related to hydrogen infrastructure are shared across diverse stakeholders to enable continuous improvement.
- Leverage global collaborations on hydrogen infrastructure to inform long term investment plans and hydrogen exports opportunities..

Actions to support clean hydrogen use and broader market adoption

End-Use and Market Adoption

2022-2025

- Lay regulatory groundwork for large-scale clean hydrogen deployments across production, processing, delivery, storage, and end-use.
- Work across industries (e.g., nuclear, renewables, fossil, CCS, energy storage) to identify regulatory, and policy gaps, and key strategies to address them (e.g., "Dig Once" approaches to co-locate transmission, CO2, hydrogen, and other conduits) to minimize impacts.
- Develop streamlined guidance on hydrogen pipeline and large-scale project permitting with stakeholder engagement and addressing environmental, energy, and equity priorities.
- Initiate transition to clean hydrogen for hard-to-decarbonize industrial applications and identify specific locations for potential scale up (e.g., ammonia, refineries, steel).
- Advance efficient end-use technologies (fuel cells/other power conversion with low/zero emissions) and down-select for scale up.
- Complete robust modeling and improve data collection to quantify climate impacts of hydrogen leakage.
- Develop best practices and guidance to assess life cycle emissions of real-world deployments of clean hydrogen and inform "guarantees of origin" and certification schemes.

2026-2029

- Enable international harmonization of codes and standards related to hydrogen technologies.
- Develop market structures (e.g., contracts for difference, incentivizing off-takers) to accelerate progress and address regulatory barriers to increase electrolyzer access to renewable energy.
- Share safety best practices and lessons learned from early deployments through publicly accessible platforms.
- Deploy at least two clean hydrogen hubs, demonstrating hydrogen use in hard-to-decarbonize sectors (e.g., industry and heavy-duty transport)
- Develop national guidance for hydrogen blending limits.
- Supply clean hydrogen to produce at least 3 billion gallons of sustainable aviation fuels from biomass and wastes by 2030.
- Increase the efficiency and cost-effectiveness of recovery and recycling of raw materials from electrolyzers, fuel cells, and other components across the hydrogen value chain to ensure independence from foreign imports.

2030-2035

- Develop market structures and regulatory guidance to enable clean hydrogen exports.
- Utilize lessons learned from large-scale deployments to identify priority sectors for future growth with a focus on holistic approaches that support the most efficient, affordable, and climate-aligned goals that maximize public health safety and the environment.
- Demonstrate and quantify the benefits of hydrogen in enabling the resilience of future clean energy systems and addressing disaster mitigation (e.g., microgrids, cyber security, remote communities)
- Demonstrate ultra-low-NOx turbine operation and low-PGM fuel cell operation on 100% hydrogen for power generation by 2030.
- Launch at least one clean hydrogen hub demonstrating hydrogen use in energy storage for a clean grid and quantify opportunities for hydrogen to support achieving a carbon pollution free grid by 2035 including regional factors.

Actions to enable a safe, affordable, and sustainable clean hydrogen economy and ensure energy justice

Enablers and Environmental and Energy Justice

2022-2025

- Develop and implement frameworks for broad and inclusive stakeholder engagement, including from environmental and energy justice, disadvantaged, and tribal communities, labor unions, industry, academia, national labs, and federal, state, and local governments to ensure broad participation and hold listening sessions to gather stakeholder feedback.
- Identify metrics for diversity, equity, inclusion, and other key priorities, for teams and organizations, and geographical/community locations for federally funded demonstrations.
- Launch tools and platforms (e.g., H2Matchmaker) to facilitate partnerships, inclusion, and market success.
- Develop retraining programs for workers (e.g., from fossil industries), enabling both near- and long-term good paying jobs.
- Develop recruitment and career programs for students from underrepresented communities and foster diversity, equity, and inclusion.
- Develop and implement sustainability frameworks and NEPA best practices.
- Develop education resources to support Hub community outreach and engagement strategies.
- Improve data collection on regional priorities (e.g., criteria pollution) and identify applications to inform clean hydrogen deployments.

2026-2029

- Refine and continuously improve stakeholder engagement and inclusion and apply lessons learned.
- Foster public-private partnerships to enable inclusion and accelerate progress.
- Develop and implement community benefit agreements with disadvantaged communities in Hub regions.
- Launch deployments of hydrogen technologies that reduce criteria pollution in nonattainment areas and provide resiliency, jobs, and other key benefits for local and disadvantaged communities.
- Conduct impact assessments of hydrogen technologies on regional water supply and other regional resources.
- Identify and apply lessons learned for environmental and risk assessments, including through global and regional collaborations.
- Work with unions to develop and expand registered apprenticeship programs for hydrogen technologies.
- Establish education and engagement pathways for first responders and code officials.
- Utilize the Center for Hydrogen Safety and other platforms to share best practices and lessons learned.

2030-2035

- Quantify benefits from deployments and identify additional policy or program priorities to accelerate progress in targeted, no-regrets areas.
- Deploy manufacturing facilities for clean hydrogen technologies in disadvantaged communities for local and regional benefits.
- Evaluate the techno-socio-economic impact of regional clean hydrogen Hubs.
- Develop and refine market structures to distribute costs and benefits of new technologies equitably.
- Ensure adaptation, cyber, resilience, and other mitigation approaches are included in strategic plans for scale up.
- Update and refine sustainability frameworks and best practices to inform future deployments of hydrogen.
- Leverage global collaborations and initiatives to maximize success across the RDD&D pipeline and ensuring an equitable clean energy transition.

Phases of Clean Hydrogen Development

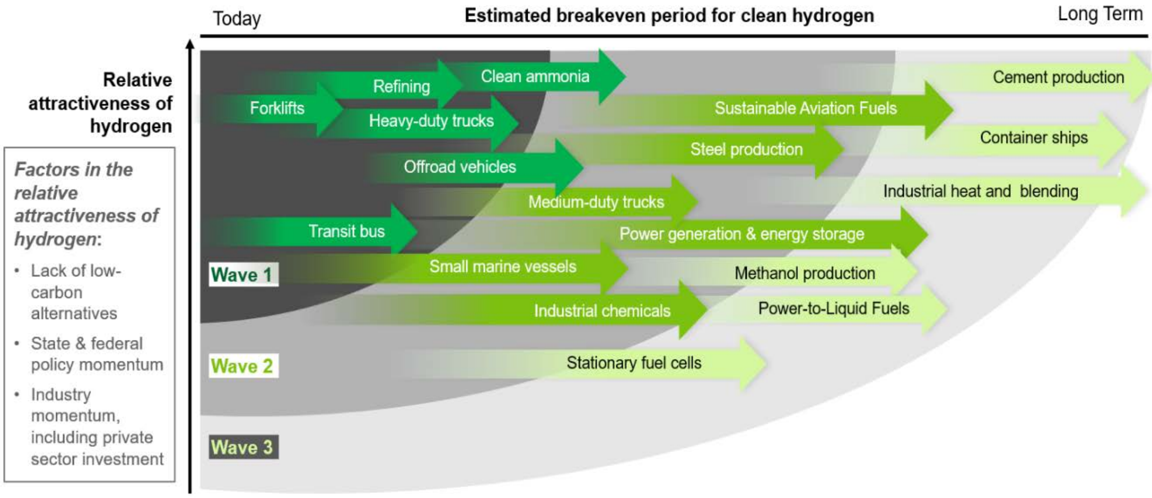


Figure 39: Clean hydrogen will be developed in waves, based on the relative attractiveness in each end-use application

The market penetration of hydrogen technologies will depend on numerous factors including technical maturity, cost, infrastructure availability, manufacturing and supply chain capacities, the cost of other low-carbon solutions, the policy and regulatory landscape, regional and state initiatives, industry momentum and commitments, and unlocking private capital and investment.

Based on two key factors – estimated break-even and the relative attractiveness of hydrogen as a decarbonization solution – as well as stakeholder input, DOE envisions three application adoption phases or “waves” for clean hydrogen use in the United States. The relative placement of end-use applications in each phase is based on a range of quantitative and qualitative factors and will be updated over time and as the industry and policy landscape evolves. For instance, if the U.S. adopts a federal clean hydrogen production tax credit as well as other demand creation and regulatory frameworks, the placement of certain applications along the timeline shown in Figure 39 may shift. Nonetheless, the figure depicts how potential markets will evolve in the U.S. and ramp up in the early, mid, and long term.

First Wave

Applications of clean hydrogen in the first wave will be jumpstarted by existing markets that have few alternatives to clean hydrogen for decarbonization. This includes existing refining and ammonia production plants. Industrial clusters that co-locate large scale production with end-use for such applications can help drive down costs and create the infrastructure that could be leveraged for other markets in subsequent phases.

- **Forklifts and other material handling equipment** in warehouses, ports, and other industrial sites have high utilization, predictable refueling locations and a need for fast refueling. DOE has already catalyzed this niche application in the U.S., enabling thousands of systems in the market and a nascent infrastructure.
- **Refineries** represent the largest hydrogen market today and have no alternative for cracking heavy crude oil and for desulfurization. Switching to the use of clean hydrogen will create demand in the near term and immediately reduce emissions.
- **Transit buses** could be an attractive use case, particularly in regions that require long-distance operation and high uptimes and for transit agencies with large bus fleets where individual battery electric vehicle charging may be challenging.
- **Long-haul heavy-duty trucks** have high utilization, high energy requirements, and need to refuel quickly. Together with MDVs, they produce about 20% of transportation-sector greenhouse gas emissions in the United States.[182]
- **Heavy machinery in mining, construction and agriculture** could benefit from fuel cell propulsion, since they have high power requirements, need to be refueled quickly, and may need to operate far from power grids. These applications require large volumes of hydrogen and will create demand.
- **Ammonia production** uses carbon-intensive hydrogen as a feedstock today can be replaced with clean hydrogen without retrofitting plants. As the second largest captive market requiring hydrogen following refining, ammonia can also offer stable demand for clean hydrogen.

By supporting demonstrations and infrastructure for many of the above markets, DOE can enable high volumes of hydrogen in limited regions and provide tangible benefits to disadvantaged communities or workers that would otherwise be exposed to diesel exhaust and other pollutants.

Second Wave

Applications in the second wave include use cases where clean hydrogen offers a growing economic value proposition, supported by commitments by industry and policy momentum. This phase includes a broader range of transportation uses cases and widens to include greater use of industrial fuel and feedstock. A few examples of additional applications beyond those in the first wave include:

- **Medium-duty trucks** powered by hydrogen fuel cells should become increasingly available at scale as heavy-duty transport leads the way in expanding hydrogen distribution and refueling infrastructure.
- **Regional ferries** powered by fuel cells, which could transport people or goods over short distances, are likely to become cost-competitive with internal combustion engines as hydrogen and fuel cell costs decline.
- **Certain industrial chemical production,** such as in the plastics industry, requires high-temperature heat that is difficult to achieve with electricity, or rely on hydrogen feedstock from fossil sources today. These sectors could be decarbonized using clean hydrogen for heat generation, and as a feedstock.
- **Steel production** can decarbonize with clean hydrogen when applied to iron ore-based steel production that needs carbon-free reductants and high temperatures, where electrolytic production would not yet be viable.
- **Energy storage & power generation** can transition to gas turbines fueled with mixtures of hydrogen and natural gas or pure hydrogen as technologies become available that produce low nitrogen oxides. Fuel cells can also be used as a power conversion technology. Clean hydrogen can play a key role in seasonal storage that is needed to fully decarbonize the grid and eliminate fossil-based generation.
- **Aviation** can transition to sustainable fuels that are produced using clean hydrogen and biomass and waste feedstocks, contributing to the Biden-Harris Administration goal of 3 billion gallons of sustainable aviation fuel.[183] The production of clean hydrogen at scale will also lay the groundwork for the production of power-to-liquids in the longer term. Industry feedback suggest certain market segments could additionally use hydrogen directly, though cryogenic storage may be required due to energy density requirements.

Third Wave

Applications in the third wave will become competitive as clean hydrogen production scales significantly and as costs decline and infrastructure becomes available. For example:

- **Backup power & stationary power** from fuel cells can replace diesel generators in providing resiliency to critical 24/7 facilities such as hospitals and data centers, also offering advantages to disadvantaged communities and improving air quality. Backup power is distinct from energy storage as its role is to provide resilience for a singular customer or microgrid, whereas energy storage supports the macro grid.
- **Methanol** produced with clean hydrogen can also be used directly as a fuel or fuel supplement, for container ships, rail, or other maritime applications, and as an energy carrier.
- **Container ships** carry about 90 percent of global trade by volume, producing about 3% of global carbon emissions and a larger share of sulfur dioxide emissions.[184] Potential alternatives during the third wave include clean ammonia, clean methanol, and liquified clean hydrogen.
- **Cement** can use clean hydrogen to decrease direct CO_2 emissions where electrification is not an option due to high heat requirements.
- **Blending with existing natural gas networks** can support targeted decarbonization of high-temperature heating systems, primarily in the industrial sector where high temperatures are needed for certain sectors, such as chemicals. While this application can start even during the first wave, costs must decline considerably to be economically viable.

The phases of clean hydrogen deployment are highly dependent on the development of technology, research, and supportive policy structures. However, concentrating efforts on sectors that are more commercially viable, lack decarbonization alternatives, and enjoy industry momentum will make public investments more sustainable.

Systems Analysis Will Continue to Inform the National Clean Hydrogen Strategy and Actions

Robust and transparent analysis and modeling efforts completed through collaborations between national laboratories, industry, and academia will continue to inform priorities, milestones, and actions to advance clean hydrogen deployment in priority sectors. Over the past several decades, the DOE has funded the development of tools, such as those listed in Figure 40, to evaluate the role of hydrogen in industry, transportation, and the energy sector. Data from real-world deployments in the coming years will be used to continually refine these tools to ensure they reflect status of technology cost and performance.

Analysis tools that the DOE has funded to date cut across many different aspects of hydrogen markets. Foundational tools evaluate the cost and performance of individual technologies, such as hydrogen production or infrastructure equipment. Technology assessments can then be used in supply chain analyses and to characterize the total cost and emissions of an application in a region. Supply chain analyses then inform market adoption analysis—for example, estimating the value proposition of hydrogen energy storage and sales of fuel cell trucks. All analyses are used to inform RDD&D activities and real-world data from technical demonstrations are fed back into foundational models to improve assessments in the future.

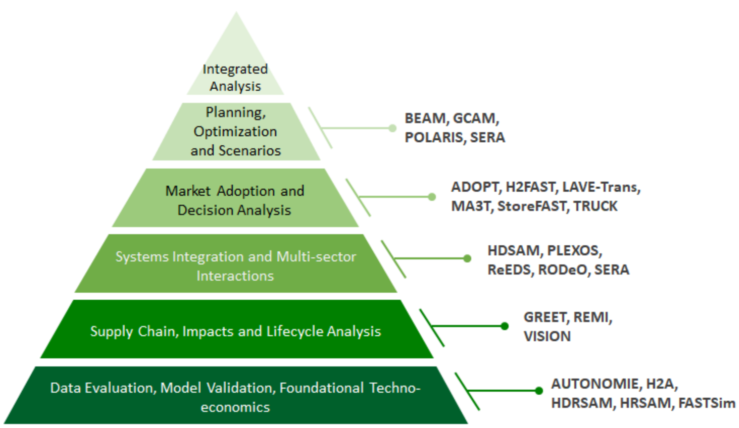


Figure 40: A suite of tools and models support systems analysis work from fundamental model validation and techno-economic work, to planning, optimization, and integrated analysis.

ADOPT: Automotive Deployment Options Projection Tool; **Autonomie**: (a vehicle system simulation tool); **BEAM**: Behavior, Energy, Autonomy, and Mobility; **FASTSim**: Future Automotive Systems Technology Simulator; **GCAM**: Global Change Assessment Model; **GREET**: Greenhouse gases, regulated emissions, and energy use in Technologies Model; **H2A**: The Hydrogen Analysis Project; **H2FAST**: Hydrogen Financial Analysis Scenario Tool; **HDRSAM**: Heavy-Duty Refueling Station Analysis Model; **HDSAM**: Hydrogen Delivery Scenario Analysis Model; **HRSAM**: Hydrogen Refueling Station Analysis Model; **LAVE-Trans**: Light-Duty Alternative Vehicle Energy Transitions; **PLEXOS**: (an integrated energy model); **POLARIS**: (a predictive transportation system model); **ReEDS**: Regional Energy Deployment System; **REMI**: Regional Economic Models, Inc.; **RODeO**: Revenue Operation and Device Optimization Model; **SERA**: Scenario Evaluation and Regionalization Analysis; **StoreFAST**: Storage Financial Analysis Scenario Tool; **VISION**: (a transportation energy use prediction model)

Collaboration and Coordination

Efficient and effective collaboration and coordination are vital to implement the national clean hydrogen strategy. DOE has already been coordinating across its offices, with other agencies, and with industry, states, and numerous stakeholders to execute on its hydrogen program.[185] As DOE moves forward, DOE will operationalize and streamline processes for joint strategy development and implementation to accelerate progress. DOE will ramp up engagement across the entire spectrum of stakeholders from industry and academia to labor unions, the environmental community, and tribal communities.

The U.S. will also continue to work across countries to enable an affordable, clean, and sustainable global hydrogen economy and to achieving DOE's collective climate goals. Multiple government representatives discussed a potential framework for global hydrogen coordination at the launch of the Hydrogen Breakthrough Agenda in Glasgow at COP26 in November 2021. Such a coordination framework would help unify various organizations and initiatives[186] to avoid duplication, leverage resources, and **accelerate** the successful scale up of clean hydrogen technologies. The DOE Hydrogen Program will work with the UK and other countries to strengthen coordination and will continue to play a key role in several multi-lateral and bi-lateral hydrogen partnerships. Table 4 shows examples of preliminary feedback from over 30 countries engaged in clean hydrogen initiatives, developed through the Hydrogen Breakthrough Agenda. As specific activities and mutually agreed upon priorities are defined, DOE's Hydrogen Program will continue to play a leadership role to foster collaboration, share information, and accelerate action towards tangible outcomes and successes.

Table 4: Emerging priorities for strengthened global collaboration

Demand Creation & Management	Finance & Investment	Research & Innovation	Regulation, Standards & Certification
Demand signals along with **matching supply** to avoid stranded assets are an **important driver of investment** in clean hydrogen infrastructure and will build investor confidence. Some activity exists but coordination should be strengthened at **sufficient scale, visibility, and breadth.** Scope to explore how public and private sector actors can strengthen demand signals to ensure off-takers and supply chains to reduce risk.	Access to appropriate finance is critical. **Investments are starting** to be made **but scale is still small** relative to needs. Developed countries face challenges but **particularly acute for developing world.** Some activity exists but **not widely coordinated, visible or with sufficient scale and breadth**. Scope exists to increase public and private sector investment, particularly enabling investment and coordination with developing countries.	R&I underpins progress across hydrogen systems – helping **reduce costs, improve performance, address supply chains, and broaden applicability.** **Significant activity exists** driving action in multiple countries. Scope exists to **accelerate innovation to reduce cost** and **increase scale** – particularly for pilot and demo projects and to include more countries. Scope exists to **build on existing initiatives** to **increase diversity and scalability of demo projects**, involve more countries and share learnings more widely to guide additional RDD&D.	Regulatory frameworks including **internationally accepted and implemented standards & certification** schemes across the hydrogen value chain are essential enablers of production, trade, and use. Significant work is underway by a wide range of actors on key elements. **Activities are not yet closely coordinated,** and gaps are unclear. Ensuring **rapid and wide adoption remains challenging.** Scope exists to **connect** existing work across entities, identify and address gaps and elevate and broaden political support.

The U.S. National Clean Hydrogen Strategy and Roadmap also supports recommendations outlined in the IEA Future of Hydrogen report released at the 2019 G20 Summit:[187]

1. "Establish a role for hydrogen in long-term energy strategies." "Key sectors include refining, chemicals, iron and steel, freight and long-distance transport, buildings, and power generation and storage."
2. "Stimulate commercial demand for clean hydrogen." This includes scaling up both hydrogen from fossil fuels with (CCS) and hydrogen (using renewables) as well as water electrolysis using nuclear resources.
3. "Address investment risks of first-movers." New applications for hydrogen, as well as clean hydrogen supply and infrastructure projects can be supported through tools such as loan guarantees to reduce risk.
4. "Support R&D to bring down costs." Alongside cost reductions from economies of scale, R&D is crucial to lower costs and improve performance.
5. "Eliminate unnecessary regulatory barriers and harmonize standards." Project developers face hurdles where regulations and permit requirements are unclear. Addressing safety, codes and standards is necessary for a harmonized global supply chain.
6. "Engage internationally and track progress." Enhanced international co-operation is essential and supported by a number or partnerships.
7. "Focus on four key opportunities to further increase momentum over the next decade." These include enabling industrial ports as hubs for hydrogen at scale; using existing gas infrastructure to spur new clean hydrogen supplies; supporting transportation fleets, freight, and corridor; and enabling hydrogen shipping to jumpstart international hydrogen trade.

DOE activities as outlined in this document are also aligned with the Global Action Agenda as developed through the Hydrogen Energy Ministerial in September 2019. Key pillars include:[188]

1. "Collaboration on technologies and coordination on the harmonization of regulation, codes and standards"
2. "Promotion of information sharing international joint research and development emphasizing hydrogen safety and infrastructure supply chains"

3. "Study and evaluation of hydrogen's potential across sectors including its potential for reducing both carbon dioxide emissions and other pollutants"
4. "Communication, Education and Outreach"

DOE has already played a strong leadership role in convening and supporting its counterparts in multiple nations. As co-leads for the hydrogen initiatives under the auspices of both the Clean Energy Ministerial and Mission Innovation, and as former chair and current vice chair of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), and as a strong contributor to the IEA's hydrogen and fuel cell programs, DOE has long been recognized as instrumental in accelerating progress through tangible outcomes.

Concrete actions include launching the H_2 Twin Cities initiative to foster partnerships between cities across continents deploying hydrogen technologies, with emphasis on equity and justice, co-leading initiatives to facilitate international trade and develop a common methodology for assessing the carbon footprint of hydrogen, harmonizing codes and standards, and launching an early career network which is run entirely by students and early career professionals from more than 34 countries. DOE will continue to advance these and additional concrete actions as global momentum builds for clean hydrogen.

In summary, through the cohesive and coordinated efforts by DOE, along with other agencies, states, industry, National Labs, academia, and through extensive stakeholder input and collaboration, implementation of this plan will contribute to achieving the vision set forth for hydrogen in the United States: Affordable clean hydrogen for a net-zero carbon future and a sustainable, resilient, and equitable economy.

Conclusion

Clean hydrogen, as shown in the Administration's Long-Term Strategy of the United States, will be an important element of the nation's path to decarbonization. Though much remains uncertain, the potential for hydrogen is clear. **Focused investment and action** in the near, mid, and long-term are needed to lay the foundation for broader clean hydrogen adoption, to drive down cost, and increase scale in a sustainable and holistic manner. Clean hydrogen across the entire RDD&D spectrum, catalyzed by the Bipartisan Infrastructure Law, can not only enable decarbonization of hard-to-abate sectors, but can also create and preserve new jobs, provide environmental and energy justice benefits, and create energy independence and export opportunities for the United States.

Government actions can support and **catalyze** investment across the value chain for clean hydrogen. The Department of Energy is committed to working with its partners in government, industry, academia, and more to advance this transition and will leverage a broad array of tools including policies, financial assistance, loans, apprenticeship programs, and stakeholder engagement, to accelerate progress. DOE is publishing this draft report, which sets forth the initial strategy and roadmap for hydrogen, in order to seek feedback to include in the final publication. DOE will continue to develop further details and appendices to ensure the most up to date information is available[189] and will update this document at least every three years, as required.

Through effective and efficient collaboration and coordination and with the right strategies and implementation plans, the United States can and must succeed in the development of a sustainable, resilient, and equitable clean hydrogen economy.

Acknowledgments

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Laboratories. DOE is also grateful for stakeholder feedback through Requests for Information issued on February 15, 2022, on the BIL hydrogen hub, electrolyzer, and clean hydrogen manufacturing provisions.

List of key figures

Glossary of Acronyms

ARPA-E	Advanced Research Projects Agency–Energy
ARRA	American Recovery and Reinvestment Act
ATR	Autothermal Reforming
BIL	Bipartisan Infrastructure Law
BOF	Basic Oxygen Furnaces
BOP	Balance of Plant
BSEE	Bureau of Safety and Environmental Enforcement
CCS	Carbon Capture And Storage
CCUS	Carbon Capture, Utilization, And Storage
CEM	Clean Energy Ministerial
DOE	U.S. Department of Energy
EAF	Electric Arc Furnaces
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EPACT-2005	Energy Policy Act of 2005
FAA	Federal Aviation Administration
FERC	Federal Energy Regulatory Commission
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration (of the U.S. Department of Transportation)
FTC	Federal Trade Commission

GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (model)
GWh	Gigawatt-hour
H2NEW	Hydrogen from Next-generation Electrolyzers of Water (consortium)
HEM	Hydrogen Energy Ministerial
HFTO	Hydrogen and Fuel Cell Technologies Office
H-Mat	Hydrogen Materials Compatibility Consortium
IEA	International Energy Agency
IIJA	Infrastructure Investment and Jobs Act
IMO	International Maritime Organization
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
LDES	Long-Duration Energy Storage
LOHC	Liquid Organic Hydrogen Carriers
LPO	Loan Programs Office
MARAD	Maritime Administration (of the U.S. Department of Transportation)
MDHD	Medium- and Heavy-Duty (vehicle types)
MI	Mission Innovation
MMT	Million Metric Tonnes
MW	Megawatt
M2FCT	Million Mile Fuel Cell Truck Consortium
NDC	Nationally Determined Contribution (to meet climate goals of Paris Climate Accords)
NHTSA	National Highway Transportation Safety Administration

NREL	National Renewable Energy Laboratory
OCS	Outer Continental Shelf
OSHA	Occupational Safety and Health Administration
PEM	Proton Exchange Membrane or Polymer Electrolyte Membrane (a type of electrolyzer or fuel cell)
PGM	Platinum Group Metal
PHMSA	Pipeline and Hazardous Materials Safety Administration
PTC	Production Tax Credit
R&D	Research And Development
RD&D	Research, Development, and Demonstration
RDD&D	Research, Development, Demonstration, And Deployment
RFI	Request For Information
SAF	Sustainable Aviation Fuel
SHASTA	Subsurface Hydrogen Assessment, Storage, and Technology Acceleration
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyzer Cells
TCO	Total Cost Of Ownership
UAV	Unmanned Aerial Vehicle
USCG	United States Coast Guard
USDA	U.S. Department of Agriculture
21CTP	21st Century Truck Partnership

References

[1] Emission savings based on ranges of hydrogen production carbon intensities, accounting for hydrogen fossil and clean electrolysis pathways, as well as hydrogen demands across transportation, industry, and grid energy storage. Estimates of emissions savings per unit of hydrogen consumed across pathways were approximately 10 kgCO2e/kg-H_2. Estimates were developed using Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy Use in Technologies Model.

Source: Argonne National Laboratory, "GREET Model," Argonne National Laboratory, Argonne, IL https://greet.es.anl.gov/.

[2] Emission savings based on ranges of hydrogen production carbon intensities, accounting for hydrogen fossil and clean electrolysis pathways, as well as hydrogen demands across transportation, industry, and grid energy storage. Estimates of emissions savings per unit of hydrogen consumed across pathways were approximately 10 kgCO2e/kg-H_2. Estimates were developed using Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy Use in Technologies Model.

Source: Argonne National Laboratory, "GREET Model," Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/.

[3] L. Steele, Pacific Northwest National Laboratory. "2019 Patent Analysis for the U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office," U.S. Department of Energy, Washington, DC, September 2020. https://www.energy.gov/sites/prod/files/2020/10/f79/hfto-2019-patent-analysis.pdf

[4] U.S. Department of Energy Hydrogen Program, "Hydrogen Shot," U.S. Department of Energy, Washington, DC, 2021. https://www.energy.gov/eere/fuelcells/hydrogen-shot.

[5] The Study Task Force of the Hydrogen Council. "Hydrogen Scaling Up," The Hydrogen Council, November 2017. https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf

[6] E. Connelly, A. Elgowainy, and M. Ruth, U.S. Department of Energy Hydrogen Program, "Current Hydrogen Market Size: Domestic and Global," U.S. Department of Energy, October 2019. https://www.hydrogen.energy.gov/pdfs/19002-hydrogen-market-domestic-global.pdf.

[7] The Intergovernmental Panel on Climate Change, "Special Report: Global Warming Of 1.5 ºC: Summary for Policy Makers," The Intergovernmental Panel on Climate Change, October 2018. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-24. https://doi.org/10.1017/9781009157940.001

[8] The White House Office of Domestic Climate Policy, "National Climate Task Force," The White House, Washington, DC, January 2021. https://www.whitehouse.gov/climate/.

[9] The U.S. Department of State and the U.S. Executive Office of the President, "The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050," The White House, Washington, DC, November 2021. https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf.

[10] S. Young, B. Mallory, and G. McCarthy, "The Path to Achieving Justice40," The Whitehouse, Washington, DC, July 2021. https://www.whitehouse.gov/omb/briefing-room/2021/07/20/the-path-to-achieving-justice40/.

[11] Office of Economic Impact and Diversity, "DOE Justice40 Covered Programs," U.S. Department of Energy, Washington, DC. https://www.energy.gov/diversity/doe-justice40-covered-programs.

[12] U.S. Department of Energy Hydrogen Program, "Hydrogen Shot," U.S. Department of Energy, Washington, DC, 2021. https://www.energy.gov/eere/fuelcells/hydrogen-shot.

[13] Infrastructure Investment and Jobs Act, Pub. L. No. 117-28, sec. 40314, §816 (codified as 42 U.S.C. 16161d (2021)).

[14] Infrastructure Investment and Jobs Act, Pub. L. No. 117-28, sec. 40314, §815 (codified as 42 U.S.C. 16161c (2021)).

[15] Infrastructure Investment and Jobs Act, Pub. L. No. 117-28, sec. 40314, §813 (codified as 42 U.S.C. 16161a (2021)).

[16] Infrastructure Investment and Jobs Act, Pub. L. No. 117-28, sec. 40315, §82 (codified as 42 U.S.C. 16166 (2021)).

[17] Infrastructure Investment and Jobs Act, Pub. L. No. 117-28, sec. 40314, §814 (codified as 42 U.S.C. 16161b (2021)).

[18] Inflation Reduction Act, Pub. L. No. 117-169, sec. 13204, §45V (codified as 26 U.S.C. 45V (2022)).

[19] Inflation Reduction Act, Pub. L. No. 117-169, sec. 50142 and sec. 50143.

[20] Inflation Reduction Act, Pub. L. No. 117-169, sec. 13203, §40B (codified as 26 U.S.C. 40B (2022)).

[21] Inflation Reduction Act, Pub. L. No. 117-169, sec. 60102, §133.

[22] Inflation Reduction Act, Pub. L. No. 117-169, sec. 60101, §132.

[23] U.S. Department of Energy Hydrogen Program, "Department of Energy Hydrogen Program Plan," U.S. Department of Energy, Washington, DC, November 2020. https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf.

[24] Fuel Cell and Hydrogen Energy Association, "Road Map to a US Hydrogen Economy," Fuel Cell and Hydrogen energy Association, Washington, DC, 2020. https://www.fchea.org/us-hydrogen-study.

[25] Executive Office of the President, "Exec. Order No. 14008, Tackling the Climate Crisis at Home and Abroad," Federal Register, Washington, DC, February 2021. https://www.federalregister.gov/documents/2021/02/01/2021-02177/tackling-the-climate-crisis-at-home-and-abroad

[26] The U.S. Department of State and the U.S. Executive Office of the President, "The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050," The White House, Washington, DC, November 2021. https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf.

[27] The U.S. Department of State and the U.S. Executive Office of the President, "The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050," The White House, Washington, DC, November 2021. https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf.

[28] U.S. Energy Information Administration, 2021 Annual Energy Outlook, February 2021. https://www.eia.gov/outlooks/archive/aeo21/.

[29] S. Young, B. Mallory, and G. McCarthy, "The Path to Achieving Justice40," The Whitehouse, Washington, DC, July 2021, https://www.whitehouse.gov/omb/briefing-room/2021/07/20/the-path-to-achieving-justice40/.

[30] U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office and Hydrogen Program, "H2@Scale," U.S. Department of Energy, Washington, DC. https://www.energy.gov/eere/fuelcells/h2scale.

[31] Not all sectors are shown on the figure given limitations in reported results. If sectoral energy demand was not reported, the proportion of energy demand for hydrogen is not shown, despite hydrogen being consumed in that sector.

[32] 1) Fuel Cells and Hydrogen Joint Undertaking, "Hydrogen Roadmap Europe: A Sustainable Pathway For The European Energy Transition," Fuel Cells and Hydrogen Joint Undertaking, Brussels, Belgium, January 2019. https://www.fch.europa.eu/publications/hydrogen-roadmap-europe-sustainable-pathway-european-energy-transition; 2) The Energy Transitions Commission, "Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy," The Energy Transitions Commission, April 2021. https://energy-transitions.org/wp-content/uploads/2021/04/ETC-

Global-Hydrogen-Report.pdf; 3) The Hydrogen Council and McKinsey & Company, "Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness," The Hydrogen Council, January 2021. https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf; 4) International Energy Agency, "Net Zero by 2050," International Energy Agency, Paris, France, May 2021. https://www.iea.org/reports/net-zero-by-2050; 5) Bloomberg New Energy Finance, "New Energy Outlook 2021," Bloomberg New Energy Finance, July 2021. https://www.bnef.com/insights/26815; 6) International Renewable Energy Agency, "World Energy Transitions Outlook: 1.5°C Pathway," International Renewable Energy Agency, Abu Dhabi, United Arab Emirates, June 2021. https://irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook.

[33]Elizabeth Connelly, Amgad Elgowainy, and Mark Ruth, "DOE Hydrogen and Fuel Cells Program rRecord: Current Hydrogen Market Size: Domestic and Global," U.S. Department of Energy, Washington, DC, October 2019. https://www.hydrogen.energy.gov/pdfs/19002-hydrogen-market-domestic-global.pdf

[34] International Energy Agency, "Global Hydrogen Review 2021," International Energy Agency, Paris, France, 2021. https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf.

[35] Fuel Cell and Hydrogen Energy Association, "Road Map to a US Hydrogen Economy," Fuel Cell and Hydrogen Energy Association, Washington, DC, 2020. https://www.fchea.org/us-hydrogen-study.

[36] Estimate assumes that SMR produces ~10 kg-CO_2e/kg-H_2 on average (Source: Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy Use in Technologies model, https://greet.es.anl.gov/, and National Energy Technology Laboratory "Comparison of Commercial, State-of-the-art, Fossil-based Hydrogen Production Technologies. https://www.netl.doe.gov/projects/files/ComparisonofCommercialStateofArtFossilBasedHydrogenProductionTechnologies_041222.pdf), assuming upstream fugitive methane emissions of ~1% and GWP of methane of 30, and that the U.S. produces about 10 million metric tonnes of hydrogen per year (Source: https://www.hydrogen.energy.gov/pdfs/19002-hydrogen-market-domestic-global.pdf).

[37] R. Gubler, B. Suresh, H. He, and Y. Yamaguchi, "Hydrogen," *Chemical Economics Handbook,* IHS Markit, May 2021. https://ihsmarkit.com/products/hydrogen-chemical-economics-handbook.html.

[38] M. Graff, "Statement of Mr. Michael J. Graff Chairman & CEO, American Air Liquide Holdings Inc. Executive Vice President & Executive Committee Member Air Liquide Group Before the Committee on Energy and Natural Resources," U. S. Senate, Washington, DC, February 10, 2022. https://www.energy.senate.gov/services/files/C00CE119-046B-4E3C-8C7C-B534B4A1674B.

[39] S. Satyapal. "2022 AMR Plenary Session," U.S. Department of Energy, Washington, DC, June 2022. https://www.hydrogen.energy.gov/pdfs/review22/plenary4_satyapal_2022_o.pdf.

[40] U.S. Department of Energy, "DOE Announces First Loan Guarantee for a Clean Energy Project in Nearly a Decade," U.S. Department of Energy, Washington, DC, June 2022. https://www.energy.gov/articles/doe-announces-first-loan-guarantee-clean-energy-project-nearly-decade.

[41] Air Products "Landmark U.S. $4.5 Billion Louisiana Clean Energy Complex," Air Products, Allentown, PA. https://www.airproducts.com/campaigns/la-blue-hydrogen-project.

[42] V. Arjona, "PEM Electrolyzer Capacity Installations in the United States," U.S. Department of Energy, Washington, DC, May 2022. https://www.hydrogen.energy.gov/pdfs/22001-electrolyzers-installed-in-united-states.pdf.

[43] Infrastructure Investment and Jobs Act, Pub. L. No. 117-28, sec. 40314, §813 (codified as 42 U.S.C. 16161a (2021).

[44] U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office, "H2 Matchmaker," U.S. Department of Energy, Washington, DC. https://www.energy.gov/eere/fuelcells/h2-matchmaker.

[45] N. Rustagi, "Systems Analysis Overview," U.S. Department of Energy, Washington, DC, June 2022. https://www.hydrogen.energy.gov/pdfs/review22/plenary9_rustagi_2022_o.pdf.

[46] U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office funded approximately $40 million through ARRA for fuel cell forklifts and backup power units. First-of-a-kind demonstrations were conducted through collaboration with DOE and DOD's Defense Logistics Agency more than a decade ago.
Source: P. Devlin and G. Morland, "DOE Hydrogen and Fuel Cells Program Record #18002: Industry Deployed Fuel Cell Powered Lift Trucks," U.S. Department of Energy, Washington, DC, May 2018. https://www.hydrogen.energy.gov/pdfs/18002_industry_deployed_fc_powered_lift_trucks.pdf.

[47] J. Marcinkoski, "Hydrogen Class 8 Long Haul Truck Targets," U.S. Department of Energy, October 31, 2019. https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf.

[48] Hydrogen Shot, electrolysis, and SMR with CCS costs shown are for reference and exclusively depict the cost of production, not including any downstream costs, such as compression, storage, and dispensing. Willingness to pay values based on numerous sources, including: 1) Forklift costs and industrial heat costs based on Hydrogen Council "Path to hydrogen competitiveness", January 2020. https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf 2) Transportation costs from Ledna, C., et. al. "Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis". 2022. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy22osti/82081.pdf 2) 3) Biofuels, ammonia, chemicals, steel, seasonal storage, and industrial heat costs based largely on Elgowainy, et. al., "Assessment of Potential Future Demands for Hydrogen in the United States". 2020 Argonne National Laboratory, https://greet.es.anl.gov/publication-us_future_h2 4) Chemicals costs additionally based on Zang, et. al., "Technoeconomic and Life Cycle Analysis of Synthetic Methanol Production from Hydrogen and Industrial Byproduct CO2". Environmental Science & Technology 2021 55 (8), 5248-5257 , https://pubs.acs.org/doi/10.1021/acs.est.0c08237 5) Steel costs additionally based on preliminary analysis from Argonne National Laboratory, https://www.hydrogen.energy.gov/pdfs/review21/sa174_elgowainy_2021_o.pdf 6) Power-to-liquid, or synthetic fuel, costs additionally based on Zang, et. al. "Performance and cost analysis of liquid fuel production from hydrogen and CO_2 based on the Fischer-Tropsch process". Journal of CO2 Utilization 2021 46, 101459, https://www.sciencedirect.com/science/article/abs/pii/S2212982021000263 6) Industrial heat costs based on Hydrogen Council "Path to hydrogen competitiveness", January 2020. Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf (hydrogencouncil.com).

[49] J. Marcinkoski, R. Vijayagopal, J. Adams, B. James, J. Kopasz, R. Ahluwalia, "DOE Hydrogen And Fuel Cells Program Record: Hydrogen Class 8 Long Haul Truck Targets," U.S. Department of Energy, Washington, DC, October 2019. https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf.

[50] The National Renewable Energy Laboratory, "TEMPO: Transportation Energy & Mobility Pathway Options," The National Renewable Energy Laboratory, Golden, CO. https://www.nrel.gov/transportation/tempo-model.html.

[51] In 2021, the U.S. Department of Energy, U.S. Department of Transportation, and U.S. Department of Agriculture adopted a goal of supplying sufficient SAF to meet 100% of aviation fuel demand in 2050, estimated at 35 billion gallons. (Source: The White House, "FACT SHEET: Biden Administration Advances the Future of Sustainable Fuels in American Aviation," 9 September 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/) While a variety of different biofuel and power-to-liquid fuel pathways could meet this supply, the estimate of 4 MMT/year of hydrogen is based on preliminary modeling from NREL of 11 different biofuel production pathways with varying endogenous and exogenous hydrogen supply requirements.

[52] A. Elgowainy, M. Mintz, U. Lee, T. Stephens, P. Sun, K. Reddi, Y. Zhou, G. Zang, M. Ruth, P. Jadun, E. Connelly, and R. Boardman, "Assessment of Potential Future Demands for Hydrogen in the United States," Argonne National Laboratory, Argonne, IL, October 2020. https://greet.es.anl.gov/publication-us_future_h2.

[53] The lower end of this estimate assumes production of 120 MMT steel per year in 2050, consistent with the U.S. Department of Energy's Industrial Decarbonization Roadmap. The higher end assumes production of 130 MMT steel per year to enable exports of 8% of U.S. steel production, consistent with current practice

Source: International Trade Administration, "Global Steel Trade Monitor – Steel Exports Report: United States," International Trade Administration, Washington, DC, May 2020. https://legacy.trade.gov/steel/countries/pdfs/exports-us.pdf.

[54] A. Elgowainy, M. Mintz, U. Lee, T. Stephens, P. Sun, K. Reddi, Y. Zhou, G. Zang, M. Ruth, P. Jadun, E. Connelly, and R. Boardman, "Assessment of Potential Future Demands for Hydrogen in the United States," Argonne National Laboratory, Argonne, IL, October 2020. https://greet.es.anl.gov/publication-us_future_h2.

[55] Range of estimates of U.S. methanol demand are based on: 1) Low end: International Energy Agency estimate for North America (Source: International Energy Agency and Organisation for Economic Co-operation and Development, "The Future of Petrochemicals Towards more sustainable plastics and fertilisers," International Energy Agency, France, October 2018. https://iea.blob.core.windows.net/assets/bee4ef3a-8876-4566-98cf-7a130c013805/The_Future_of_Petrochemicals.pdf), and 2) High end: Global estimates developed by the International Renewable Energy Agency (Source: International Renewable Energy Agency and Methanol Institute, "Innovation Outlook: Renewable Methanol," International Renewable Energy Agency, Abu Dhabi, United Arab Emirates, 2021. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf), and an assumption that the U.S. share of global demand remains at ~6% (Source: IHS Markit, "Methanol: Chemical Economics Handbook," IHS Markit, March 2021. https://ihsmarkit.com/products/methanol-chemical-economics-handbook.html).

[56] Estimates of high-temperature heat demand in 2050 are based on DOE Industrial Decarbonization Roadmap. (Source: U.S. Department of Energy, "Industrial Decarbonization Roadmap," September 2022. https://www.energy.gov/sites/default/files/2022-09/Industrial Decarbonization Roadmap.pdf).

[57] 1) Low end: P. Denholm, P. Brown, W. Cole, T. Mai, B. Sergi, M. Brown, P. Jadun, J. Ho, J. Mayernik, C. McMillan, R. Sreenath, Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035 (2022). NREL/TP-6A40-81644. 2) High end: U.S. Department of Energy Solar 2021 Futures Study Source: U.S. Department of Energy Solar Energy Technologies Office, "Solar Futures Study," U.S. Department of Energy, Washington, DC, September 2021. https://www.energy.gov/eere/solar/solar-futures-study

[58] C. Ledna, M. Muratori, A. Yip, P. Jadun, and C. Hoehne, "Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis," March 2022. https://www.nrel.gov/docs/fy22osti/82081.pdf.

[59] C. A. McMillan, M. Ruth, "Using facility-level emissions data to estimate the technical potential of alternative thermal sources to meet industrial heat demand," Applied Energy, Volume 239, Pages 1077-1090, February, 2019. https://doi.org/10.1016/j.apenergy.2019.01.077.

[60] Studies used to develop estimates of energy storage included: 1) Lowest bound, from Princeton Net-Zero America (Source: Net Zero America "Potential Pathways, Infrastructure, and Impacts," Princeton University, December 2020. https://netzeroamerica.princeton.edu/?explorer=year&state=national&table=2020&limit=200), 2) Lower end of core range from, 3) Higher end of core range and upper bound based on DOE Solar Futures Study (U.S. Department of Energy Solar 2021 Futures

Study Source: U.S. Department of Energy Solar Energy Technologies Office, "Solar Futures Study," U.S. Department of Energy, Washington, DC, September 2021. https://www.energy.gov/eere/solar/solar-futures-study.)

[61] S. Satyapal, "Testimony of Dr. Sunita Satyapal Director for a Hearing on Hydrogen," U.S. Senate Energy and Natural Resources Committee, February 2022. https://www.energy.senate.gov/services/files/FE1C53B0-3925-46E3-B1D3-B8E2C0DD92B6.

[62] S. Satyapal, "High-level Recap and Menti Questions Results," U.S. Department of Energy Hydrogen Shot Summit, Sept 1, 2021. https://www.energy.gov/sites/default/files/2021-09/h2-shot-summit-closing-plenary-recap.pdf.

[63] S. Satyapal, J. Litynski, L. Horton, "Overview," U.S. Department of Energy Hydrogen Shot Summit, Sept 1, 2021. https://www.energy.gov/sites/default/files/2021-09/h2-shot-summit-plenary-doe-overview.pdf.

[64] U.S. Department of Energy, "Hydrogen Shot," https://www.energy.gov/eere/fuelcells/hydrogen-shot.

[65] California Fuel Cell Partnership, "Cost to refill," https://cafcp.org/content/cost-refill.

[66] S. Satyapal, "2021 AMR Plenary Session," U.S. Department of Energy, June 2021. https://www.energy.gov/sites/default/files/2021-06/hfto-amr-plenary-satyapal-2021.pdf

[67] The energy content of hydrogen is 33 kWh/kg, while the energy content of gasoline is 12 kWh/kg, based on the lower heating value.

[68] Current hydrogen production cost based on: U.S. Department of Energy, "Cost of Electrolytic Hydrogen Production with Existing Technology," September 22, 2020. https://www.hydrogen.energy.gov/pdfs/20004-cost-electrolytic-hydrogen-production.pdf.

Projected cost at economies of scale assumes $460/kW electrolyzer, based on: D. Peterson, J. Vickers, and D. DeSantis, "Hydrogen Production Cost From PEM Electrolysis – 2019," U.S. Department of Energy, 3 February 2020. https://www.hydrogen.energy.gov/pdfs/19009_h2_production_cost_pem_electrolysis_2019.pdf.

Delivery and dispensing costs based on: N. Rustagi, A. Elgowainy, and J. Vickers, "Current Status of Hydrogen Delivery and Dispensing Costs and Pathways to Future Cost Reductions," U.S. Department of Energy, 17 December 2018. https://www.hydrogen.energy.gov/pdfs/18003_current_status_hydrogen_delivery_dispensing_costs.pdf and Hydrogen Delivery Scenario Analysis Model (https://hdsam.es.anl.gov/index.php?content=hdsam)

Fuel cell costs based on analysis from Strategic Analysis, Inc., 2021 (https://www.hydrogen.energy.gov/pdfs/review21/fc163_james_2021_o.pdf).

[69] International Energy Agency, "Chemicals," https://www.iea.org/reports/chemicals.

[70] Guiyan Zang*, Pingping Sun, Amgad Elgowainy, and Michael Wang, "Technoeconomic and Life Cycle Analysis of Synthetic Methanol Production from Hydrogen and Industrial Byproduct CO2," Environmental Science & Technology, 2021, 55 (8), 5248-5257. https://pubs.acs.org/doi/abs/10.1021/acs.est.0c08237.

[71] X. Liu, A. Elgowainy and M. Wang, "Life cycle energy use and greenhouse gas emissions of ammonia production from renewable resources and industrial by-products," ***Green Chem.***, 2020, **22**, 5751-5761. https://pubs.rsc.org/en/content/articlelanding/2020/gc/d0gc02301a.

[72] International Energy Agency, "Iron and Steel Technology Roadmap," October 2020. https://www.iea.org/reports/iron-and-steel-technology-roadmap.

[73] A. Elgowainy, "Technoeconomic and Life Cycle Analysis of Synthetic Fuels and Steelmaking," Argonne National Laboratory, Argonne, IL, June 2021. https://www.hydrogen.energy.gov/pdfs/review21/sa174_elgowainy_2021_o.pdf.

[74] U.S. Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020," 2022, EPA 430-R-22-003. https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-main-text.pdf.

[75] U.S. Department of Energy, "Industrial Decarbonization Roadmap," September 2022. https://www.energy.gov/sites/default/files/2022-09/Industrial Decarbonization Roadmap.pdf.

[76] International Energy Agency, "Global Hydrogen Review 2021," International Energy Agency, Paris, France, 2021. https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf.

[77] International Energy Agency, "Global Hydrogen Review 2021," International Energy Agency, Paris, France, 2021. https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf.

[78] International Energy Agency, "Global Hydrogen Review 2021," International Energy Agency, Paris, France, 2021. https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf.

[79] International Energy Agency, "Global crude steel production by process route and scenario, 2019-2050," 8 October 2020. https://www.iea.org/data-and-statistics/charts/global-crude-steel-production-by-process-route-and-scenario-2019-2050.

[80] American Iron and Steel Institute, "Steel Production," https://www.steel.org/steel-technology/steel-production/.

[81] A. Elgowainy, "Technoeconomic and Life Cycle Analysis of Synthetic Fuels and Steelmaking," Argonne National Laboratory. Argonne, IL, June 2021, https://www.hydrogen.energy.gov/pdfs/review21/sa174_elgowainy_2021_o.pdf.

[82] U.S. Department of Energy, "Industrial Decarbonization Roadmap," September 2022. https://www.energy.gov/sites/default/files/2022-09/Industrial Decarbonization Roadmap.pdf.

[83] U.S. Department of Commerce International Trade Administration, "Steel Imports Report: United States," May 2020. https://legacy.trade.gov/steel/countries/pdfs/imports-us.pdf.

[84] The White House, "FACT SHEET: The United States and European Union To Negotiate World's First Carbon-Based Sectoral Arrangement on Steel and Aluminum Trade," October 31, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/10/31/fact-sheet-the-united-states-and-european-union-to-negotiate-worlds-first-carbon-based-sectoral-arrangement-on-steel-and-aluminum-trade/.

[85] J. Brouwer and L. Mastropasqua, "Solid Oxide Electrolysis Cells (SOEC) Integrated with Direct Reduced Iron (DRI) Plants for Producing Green Steel," University of California, Irvine, 2021. https://www.hydrogen.energy.gov/pdfs/review21/ta052_brouwer_2021_p.pdf.

[86] R.J. O'Malley, "Grid-Interactive Steelmaking with Hydrogen (GISH)," Missouri University of Science & Technology, February 2021. https://www.hydrogen.energy.gov/pdfs/review21/ta053_omalley_2021_p.pdf.

[87] U.S. Department of Energy, "AMO Steel Industry Roundtable," 20 February 2020. https://www.energy.gov/eere/amo/downloads/amo-steel-industry-roundtable.

[88] U.S. Department of Energy, "TRANSSFORM Workshop Presentations," 25 October 2021. https://www.energy.gov/eere/amo/articles/transsform-workshop-presentations.

[89] U.S. Department of Energy, "H2@Scale," https://www.energy.gov/eere/fuelcells/h2scale.

[90] U.S. Geological Survey, *Mineral Commodity Summaries 2017*, National Minerals Information Center, Reston, VA, 2017. https://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/mcs-2017-nitro.pdf.

[91] U.S. Department of Energy, "REFUEL," Advanced Research Projects Agency–Energy. https://arpa-e.energy.gov/technologies/programs/refuel.

[92] U.S. Department of Energy, "Industrial Decarbonization Roadmap," September 2022. https://www.energy.gov/sites/default/files/2022-09/Industrial Decarbonization Roadmap.pdf.

[93] U.S. Department of Energy, "Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing," Quadrennial Technology Review, 2015. https://www.energy.gov/sites/prod/files/2016/06/f32/QTR2015-6I-Process-Heating.pdf.

[94] U.S. DOE, "HyBlend: Opportunities for Hydrogen Blending in Natural Gas Pipelines," https://www.energy.gov/eere/fuelcells/hyblend-opportunities-hydrogen-blending-natural-gas-pipelines.

[95] NREL, "NREL Marks Partner Forum With Dedication of Bioreactor," August 22, 2019. https://www.nrel.gov/news/program/2019/nrel-marks-partner-forum-with-dedication-of-bioreactor.html.

[96] U.S. Environmental Protection Agency, "Fast Facts: U.S. Transport Sector Greenhouse Gas Emissions 1990-2019," December 2021. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1013NR3.pdf.

[97] C. Hunter, M. Penev, E. Reznicek, J. Lustbader, A. Birky, and C. Zhang, "Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks," National Renewable Energy Laboratory, NREL/TP-5400-71796, September 2021. https://www.nrel.gov/docs/fy21osti/71796.pdf.

[98] C. Ledna, M. Muratori, A. Yip, P. Jadun, and C. Hoehne, "Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis," National Renewable Energy Laboratory, March 2022. https://www.nrel.gov/docs/fy22osti/82081.pdf.

[99] U.S. Department of Energy, "21st Century Truck Partnership," https://www.energy.gov/eere/vehicles/21st-century-truck-partnership.

[100] U.S. Environmental Protection Agency, "Hydrogen Fuel Cell Vehicles," https://www.epa.gov/greenvehicles/hydrogen-fuel-cell-vehicles.

[101] M2FCT was launched by DOE's Hydrogen and Fuel Cell Technologies Office in 2020 and brings together national labs, industry, and academia to achieve specific targets for commercial viability of long-haul trucks. https://millionmilefuelcelltruck.org/.

[102] U.S. Department of Energy, "DOE Announces Nearly $200 Million to Reduce Emissions From Cars and Trucks," 1 November 2021. https://www.energy.gov/articles/doe-announces-nearly-200-million-reduce-emissions-cars-and-trucks.

[103] J. Hanlin and E. Brewer, "Fuel Cell Hybrid Electric Delivery Van Project," Center for Transportation and the Environment, 21 May 2021. https://www.hydrogen.energy.gov/pdfs/review21/ta016_hanlin_2021_o.pdf.

[104] J. Adams, "Technology Acceleration Overview," U.S. Department of Energy, 7 June 2021. https://www.hydrogen.energy.gov/pdfs/review21/plenary10_adams_2021_o.pdf.

[105] National Renewable Energy Laboratory, "Fuel Cell Electric Bus Evaluations," https://www.nrel.gov/hydrogen/fuel-cell-bus-evaluation.html.

[106] The Maritime Executive, "IMO Answers Questions on the 2020 SOx Regulation," 2018. https://www.maritime-executive.com/article/imo-answers-questionson-the-2020-sox-regulation.

[107] O. Merk, "Shipping Emissions in Ports," International Transport Forum, p. 15, 2014. https://www.itf-oecd.org/sites/default/files/docs/dp201420.pdf.

[108] International Energy Agency. "The Future of Hydrogen. Seizing Today's Opportunities," June, 2019. https://www.iea.org/reports/the-future-of-hydrogen.

Note: The report recommends that governments and industry "make industrial ports the nerve centers for scaling up the use of clean hydrogen."

[109] U.S. Department of Transportation, "Fuel Cells," Maritime Environmental and Technical Assistance (META) Program. https://www.maritime.dot.gov/innovation/meta/maritime-environmental-and-technical-assistance-meta-program#Fuel%20Cells.

[110] Leslie Goodbody, "Medium/Heavy Duty & Marine Applications for Hydrogen and Fuel Cells in California," November 4, 2019. https://www.hydrogen.energy.gov/pdfs/htac_nov19_04_goodbody.pdf.

[111] N. Pal, "SF Waterfront Maritime Hydrogen Demonstration Project," U.S. Department of Energy Hydrogen Program Annual Merit Review. https://www.hydrogen.energy.gov/pdfs/review22/ta045_pal_2022_o.pdf.

[112] The White House, "FACT SHEET: Biden Administration Advances the Future of Sustainable Fuels in American Aviation," 9 September 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/.

[113] Federal Aviation Administration, "Aviation Climate Action Plan," November 2021. https://www.faa.gov/sustainability/aviation-climate-action-plan.

[114] U.S. Department of Energy, "Sustainable Aviation Fuel Grand Challenge," https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge.

[115] U.S. Department of Energy, "Sustainable Aviation Fuel Grand Challenge," https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge.

[116] ASTM International, "Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons," July 15, 2021. https://www.astm.org/d7566-21.html.

[117] K. Swider-Lyons, "Hydrogen Fuel Cells for Small Unmanned Air Vehicles," U.S. Naval Research Laboratory, May 26, 2016. https://www.energy.gov/sites/prod/files/2016/05/f32/fcto_webinarslides_h2_fc_small_unmanned_air_vehicles_052616.pdf.

[118] ZeroAvia, "ZeroAvia & Otto Aviation Partner to Deliver First New Airframe Design with Hydrogen-Electric Engine Option," 15 June 2022. https://www.zeroavia.com/otto-aviation.

[119] C. Ryan and S. Philip, "Airbus turboprop design gaining favor as first hydrogen plane," Bloomberg, February 11, 2021. https://www.bloomberg.com/news/articles/2021-02-11/airbus-turboprop-design-gaining-favor-as-first-hydrogen-plane.

[120] Argonne National Laboratory, "H2@Airports Workshop Report," November 2020. https://www.anl.gov/aet/reference/h2airports-workshop-report.

[121] Federal Railroad Administration, "Freight Rail Overview," U.S. Department of Transportation. https://railroads.dot.gov/rail-network-development/freight-rail-overview.

[122] U.S. Environmental Protection Agency, "Fast Facts on Transportation Greenhouse Gas Emissions," https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions.

[123] Alstom, "Alstom's Coradia iLint hydrogen train runs for the first time in France," Sept. 6, 2022. https://www.alstom.com/press-releases-news/2021/9/alstoms-coradia-ilint-hydrogen-train-runs-first-time-france.

[124] San Bernadino County Transportation Authority, "Green-Tech for the US: Stadler Signs First Ever Contract for Hydrogen-Powered Train," November 14, 2019. https://www.gosbcta.com/green-tech-for-the-us-stadler-signs-first-ever-contract-for-hydrogen-powered-train/.

[125] U.S. Department of Energy, "H2@Rail Workshop," August 2019. https://www.energy.gov/eere/fuelcells/h2rail-workshop.

[126] R.K. Ahluwalia, J-K Peng, F. Cetinbas, D. D. Papadias, X. Wang, J. Kopasz, and T. Krause, "Rail, Aviation, and Maritime Metrics," Argonne National Laboratory, Argonne, IL, June 2021. https://www.hydrogen.energy.gov/pdfs/review21/ta034_ahluwalia_2021_o.pdf.

[127] T. Krause, D. Papadias, R. Ahluwalia, J-K Peng, and G. Moreland, "Total Cost of Ownership and Hydrogen Demand for Fuel Cell-Powered Railroad Locomotives," Transportation Research Board Annual Meeting, 29 January 2021. https://annualmeeting.mytrb.org/OnlineProgramArchive/Details/15394.

[128] U.S. Department of Energy, "Tri-Generation Success Story," December, 2016, https://www.energy.gov/sites/default/files/2016/12/f34/fcto_fountain_valley_success_story.pdf

[129] U.S. Department of Energy, "Durability Working Group," https://www.energy.gov/eere/fuelcells/durability-working-group.

[130] U.S. Department of Energy, "Reversible Fuel Cells Workshop," https://www.energy.gov/eere/fuelcells/reversible-fuel-cells-workshop.

[131] U.S. Department of Energy, "Early Markets: Fuel Cells for Backup Power," October 2014. https://www.energy.gov/sites/prod/files/2014/10/f19/ftco_early_mkts_fc_backup_power_fact_sheet.pdf.

[132] P. Denholm, W. Cole, A.W. Frazier, K. Podkaminer, and N. Blair, "The Four Phases of Storage Deployment: A Framework for the Expanding Role of Storage in the U.S. Power System," National Renewable Energy Laboratory, Golden, CO, 2021. https://www.nrel.gov/docs/fy21osti/77480.pdf.

[133] A.W. Frazier, W. Cole, P. Denholm, S. Machen, N. Gates, and N. Blair, "Storage Futures Study: Economic Potential of Diurnal Storage in the U.S. Power Sector," National Renewable Energy Laboratory, Golden, CO, NREL/TP-6A20-77449. https://www.nrel.gov/docs/fy21osti/77449.pdf.

[134] P. Denholm, W. Cole, A.W. Frazier, K. Podkaminer, and N. Blair, "The Four Phases of Storage Deployment: A Framework for the Expanding Role of Storage in the U.S. Power System," National Renewable Energy Laboratory, Golden, CO, 2021. https://www.nrel.gov/docs/fy21osti/77480.pdf.

[135] P. Denholm, W. Cole, A.W. Frazier, K. Podkaminer, and N. Blair, "The Four Phases of Storage Deployment: A Framework for the Expanding Role of Storage in the U.S. Power System," National Renewable Energy Laboratory, Golden, CO, 2021. https://www.nrel.gov/docs/fy21osti/77480.pdf.

[136] National Renewable Energy Laboratory, "ARIES: Advanced Research on Integrated Energy Systems," https://www.nrel.gov/aries/.

[137] U.S. Department of Energy, "Advanced Turbine Systems," https://www.energy.gov/fecm/science-innovation/clean-coal-research/hydrogen-turbines.

[138] J. Adams, "Technology Acceleration Overview," U.S. Department of Energy, Hydrogen Annual Merit Review, 6 June 2022. https://www.hydrogen.energy.gov/pdfs/review22/plenary8_adams_2022_o.pdf

[139] S. Satyapal, R. Schrecengost, J. Marcinkoski, J. Vetrano, and T. Shrader, "DOE Hydrogen Program Panel Discussion," U.S. Department of Energy, Hydrogen Annual Merit Review, 6 June 2022. https://www.hydrogen.energy.gov/pdfs/review22/plenary5_program_panel_2022_o.pdf

[140] U.S. Department of Energy, "Innovative Clean Energy Loan Guarantees Gathering Momentum, New Conditional Commitment Offered for Hydrogen Production and Storage Project," Loan Programs Office, 26 April 2022. https://www.energy.gov/lpo/articles/innovative-clean-energy-loan-guarantees-gathering-momentum-new-conditional-commitment

[141] Infrastructure Investment and Jobs Act, Pub. L. No. 117-28, sec. 40315, §82 (codified as 42 U.S.C. 16166 (2021).

[142] Infrastructure Investment and Jobs Act, Pub. L. No. 117-28, sec. 40315, §822 (codified as 42 U.S.C. 16166(b)(2) (2021).

[143] U.S. Department of Energy, "The H2IQ Hour: Learn to use the GREET Model for Emissions Life Cycle Analysis," Oct. 28, 2021. https://www.energy.gov/sites/default/files/2021-11/h2iq-hour-10282021.pdf.

[144] Argonne National Laboratory, GREET model, https://greet.es.anl.gov/.

[145] National Energy Technology Laboratory, "Comparison Of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies," DOE/NETL-2022/3241, 12 April 2022. https://www.netl.doe.gov/projects/files/ComparisonofCommercialStateofArtFossilBasedHydrogenProductionTechnologies_041222.pdf.

[146] International Partnership for Hydrogen and Fuel Cells in the Economy, www.iphe.net.

[147] International Partnership for Hydrogen and Fuel Cells in the Economy, "Methodology for Determining the Greenhouse Gas Emissions Associated With the Production of Hydrogen," October 2021. https://www.iphe.net/_files/ugd/45185a_ef588ba32fc54e0eb57b0b7444cfa5f9.pdf.

[148] U.S. Department of Energy, "Energy Earthshots Initiative," https://www.energy.gov/policy/energy-earthshots-initiative.

[149] A. Mayyas, M. Ruth, B. Pivovar, G. Bender, and K. Wipke, "Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers," National Renewable Energy Laboratory, NREL/TP-6A20-72740, August 2019. https://www.nrel.gov/docs/fy19osti/72740.pdf.

[150] D. Peterson, J. Vickers, and D. DeSantis, "Hydrogen Production Cost From PEM Electrolysis – 2019," U.S. Department of Energy, 3 February 2020. https://www.hydrogen.energy.gov/pdfs/19009_h2_production_cost_pem_electrolysis_2019.pdf

[151] U.S. Department of Energy, "Cost of Electrolytic Hydrogen Production with Existing Technology," 22 September 2020. https://www.hydrogen.energy.gov/pdfs/20004-cost-electrolytic-hydrogen-production.pdf.

[152] U.S. Department of Energy, "Hydrogen from Next-generation Electrolyzers of Water (H2NEW)," https://h2new.energy.gov/.

[153] B. Pivovar, "Current Status of (Low Temperature) Electrolyzer Technology and Needs for Successful Widespread Commercialization and Meeting Hydrogen Shot Targets," U.S. Department of Energy, Hydrogen Shot Summit, September 2021. https://www.energy.gov/sites/default/files/2021-09/h2-shot-summit-panel1-lte-status.pdf

[154] Sun, Pinging, et. al. "The Analysis of U.S. Refinery Sector Decarbonization Potential and Cost". Argonne National Laboratory. (Manuscript in press).

[155] National Energy Technology Laboratory, "Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies," National Energy Technology Laboratory, Pittsburgh, PA, DOE/NETL-2022/3241, 2022. https://www.netl.doe.gov/energy-analysis/details?id=ed4825aa-8f04-4df7-abef-60e564f636c9.

[156] A. Elgowainy, M. Mintz, U. Lee, T. Stephens, P. Sun, K. Reddi, Y. Zhou, G. Zang, M. Ruth, P. Jadun, E. Connelly, and R. Boardman, "Assessment of Potential Future Demands for Hydrogen in the United States," Argonne National Laboratory, Argonne, IL, 29 October 2020. https://greet.es.anl.gov/publication-us_future_h2.

[157] U.S. Department of Energy, "2022 Methane Pyrolysis Cohort Annual Meeting," Advanced Research Projects Agency–Energy, 12 January 2022. https://arpa-e.energy.gov/2022-methane-pyrolysis-cohort-annual-meeting.

[158] U.S. Department of Energy, "U.S. Department of Energy Announces $28 Million to Develop Clean Hydrogen," Office of Fossil Energy and Carbon Management, 7 February 2022. https://www.energy.gov/fecm/articles/us-department-energy-announces-28-million-develop-clean-hydrogen.

[159] U.S. Department of Energy, "Open For Business: LPO Issues New Conditional Commitment for Loan Guarantee," Loan Programs Office, 23 December 2021. https://www.energy.gov/lpo/articles/open-business-lpo-issues-new-conditional-commitment-loan-guarantee.

[160] National Energy Technology Laboratory, "Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies," National Energy Technology Laboratory, Pittsburgh, PA, DOE/NETL-2022/3241, 2022. https://www.netl.doe.gov/energy-analysis/details?id=ed4825aa-8f04-4df7-abef-60e564f636c9.

[161] Air Products, "Landmark U.S. $4.5 Billion Louisiana Clean Energy Complex," Air Products. https://www.airproducts.com/campaigns/la-blue-hydrogen-project.

[162] Green Plains, "Green Plains Announces Carbon Sequestration Partnership with Summit Carbon Solutions," 18 February 2021. https://investor.gpreinc.com/news-releases/news-release-details/green-plains-announces-carbon-sequestration-partnership-summit.

[163] Congressional Research Service, "The Tax Credit for Carbon Sequestration (Section 45Q)," 8 June 2021. https://sgp.fas.org/crs/misc/IF11455.pdf.

[164] Department of Energy, *Securing America's Clean Energy Supply Chain*, 2022. https://www.energy.gov/policy/securing-americas-clean-energy-supply-chain.

[165] Infrastructure Investment and Jobs Act, Pub. L. No. 117-28, sec. 40314, §815-816(codified as 42 U.S.C. 16161c-d (2021).

[166] Hydrogen production costs based on high-temperature electrolysis and assuming $0.03/kWh electricity: D. Peterson, J. Vickers, and D. DeSantis, "Hydrogen Production Cost From High Temperature Electrolysis – 2020," U.S. Department of Energy, 14 February 2020. https://www.hydrogen.energy.gov/pdfs/20006-production-cost-high-temperature-electrolysis.pdf.

Hydrogen fueling station costs developed using Hydrogen Delivery Scenario Analysis Model: Argonne National Laboratory, "Hydrogen Delivery Scenario Analysis Model (HDSAM)," https://hdsam.es.anl.gov/index.php?content=hdsam.

Hydrogen storage costs based on: M. Kolyva and N. Rustagi, "Hydrogen Delivery and Dispensing Cost," U.S. Department of Energy, 25 August 2020. https://www.hydrogen.energy.gov/pdfs/20007-hydrogen-delivery-dispensing-cost.pdf.

[167] U.S. Department of Energy, "Hydrogen Shot Summit," https://www.energy.gov/eere/fuelcells/hydrogen-shot-summit.

[168] U.S. Department of Energy, "2021 Hydrogen and Fuel Cell Technologies Office Webinar Archives," https://www.energy.gov/eere/fuelcells/2021-hydrogen-and-fuel-cell-technologies-office-webinar-archives#12082021.

[169] E. Connelly, M. Penev, A. Milbrandt, B. Roberts, N. Gilroy, and M. Melaina, "Resource Assessment for Hydrogen Production," National Renewable Energy Laboratory, Golden, CO, NREL/TP-5400-77198. https://www.nrel.gov/docs/fy20osti/77198.pdf.

[170] E. Connelly, M. Penev, A. Milbrandt, B. Roberts, N. Gilroy, and M. Melaina, "Resource Assessment for Hydrogen Production," National Renewable Energy Laboratory, Golden, CO, NREL/TP-5400-77198. https://www.nrel.gov/docs/fy20osti/77198.pdf.

[171] C. Hunter, M. Penev, E. Reznicek, J. Eichman, N. Rustagi, and S. Baldwin, "Techno-economic analysis of long-duration energy storage and flexible power generation technologies to support high-variable renewable energy grids," Joule 5, 2077–2101, August 18, 2021. https://www.cell.com/joule/pdf/S2542-4351(21)00306-8.pdf.

[172] J.E. Fesmire and A. Swanger, "Overview of the New LH2 Sphere at NASA Kennedy Space Center," August 18, 2021. https://www.energy.gov/sites/default/files/2021-10/new-lh2-sphere.pdf.

[173] M. Graff, "Statement of Mr. Michael J. Graff Chairman & CEO, American Air Liquide Holdings Inc. Executive Vice President & Executive Committee Member Air Liquide Group Before the Committee on Energy and Natural Resources," U. S. Senate, February 10, 2022. https://www.energy.senate.gov/services/files/C00CE119-046B-4E3C-8C7C-B534B4A1674B.

[174] National Energy Technology Laboratory, Pacific Northwest National Laboratory, and Lawrence Livermore National Laboratory, *Subsurface Hydrogen and Natural Gas Storage: State of Knowledge and Research Recommendations Report*, DOE/NETL-2022/3236, NETL Technical Report Series, U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2022; p. 6. https://www.netl.doe.gov/projects/files/SubsurfaceHydrogenandNaturalGasStorageStateofKnowledgeandResearchRecommendationsReport_041122.pdf.

[175] G.F. Teletzke et al., "Evaluation of Practicable Subsurface CO2 Storage Capacity and Potential CO2 Transportation Networks," Onshore North America, 14th Greenhouse Gas Control Technologies Conference, Melbourne, October 2018. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3366176.

[176] P. Psarras et al., "Carbon Capture and Utilization in the Industrial Sector," Environ. Sci. Technol. 2017, 51, 19, 11440–11449. https://doi.org/10.1021/acs.est.7b01723.

[177] For example, see DOE's Office of Science report: U.S. Department of Energy, "Basic Energy Sciences Roundtable Foundational Science for Carbon-Neutral Hydrogen Technologies," 2021. https://science.osti.gov/-/media/bes/pdf/reports/2021/Hydrogen_Roundtable_Brochure.pdf?la=en&hash=08CACFB80F803504B7D6C629FEB1426BBD6CBF69.

[178] Infrastructure Investment and Jobs Act, Pub. L. No. 117-28, sec. 40313, §805(j) (codified as 42 U.S.C. 16154(j) (2021).

[179] The White House, Executive Order on Diversity, Equity, Inclusion, and Accessibility in the Federal Workforce, June 25, 22021. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/06/25/executive-order-on-diversity-equity-inclusion-and-accessibility-in-the-federal-workforce/.

[180] The White House, Executive Order on Establishment of the White House Gender Policy Council, March 8, 2021. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/03/08/executive-order-on-establishment-of-the-white-house-gender-policy-council/.

[181] The White House, Executive Order on Tackling the Climate Crisis at Home and Abroad, January 27, 2021. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/.

[182] C. Ledna, M. Muratori, A. Yip, P. Jadun, and C. Hoehne, "Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis," National Renewable Energy Laboratory, March 2022. https://www.nrel.gov/docs/fy22osti/82081.pdf.

[183] The White House, "FACT SHEET: Biden Administration Advances the Future of Sustainable Fuels in American Aviation," September 9, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/.

[184] Umair Irfan, "How to save the planet from the largest vehicles on Earth," Vox, April 21, 2022. https://www.vox.com/recode/22973218/container-shipping-industry-climate-change-emissions-maersk.

[185] U.S. Department of Energy, "Internal and External Coordination and Collaboration," *Department of Energy Hydrogen Program Plan*, Nov 2020, pp. 36-43. https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf.

[186] Examples of global partnerships involving hydrogen include but are not limited to: IEA (International Energy Agency) launched in the 1974; IPHE (International Partnership for Hydrogen and Fuel Cells in the Economy) launched by the U.S. in 2003 (with Netherlands as current Chair, U.S. and Japan as Vice-Chairs); IRENA, launched in 2009; HEM (Hydrogen Energy Ministerial) launched by Japan in 2018; the Hydrogen Council, launched by industry in 2017; CEM (Clean Energy Ministerial) Hydrogen Initiative launched by Canada in 2019 (with the European Commission, Japan, Netherlands, and U.S. as co-leads), MI (Mission Innovation) Clean Hydrogen Mission launched by the UK in 2021 (with Australia, Chile, EC, Saudi Arabia, and U.S. as co-leads).

[187] International Energy Agency, "The Future of Hydrogen. Seizing Today's Opportunities," June 2019. https://www.iea.org/reports/the-future-of-hydrogen.

[188] Global Action Agenda, "Chair's Summary of 2nd Hydrogen Energy Ministerial Meeting – Global Action Agenda of Tokyo Statement," 2019. https://www.meti.go.jp/press/2019/09/20190927003/20190927003-5.pdf.

[189] Further technical details and appendices may be made available at www.hydrogen.energy.gov to provide transparency and the most up-to-date information to stakeholders and the public.