U.S. Hydrogen Demand Action Plan – Appendices

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ENERGY FUTURES INITIATIVE

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Appendix A. The Current Hydrogen Landscape

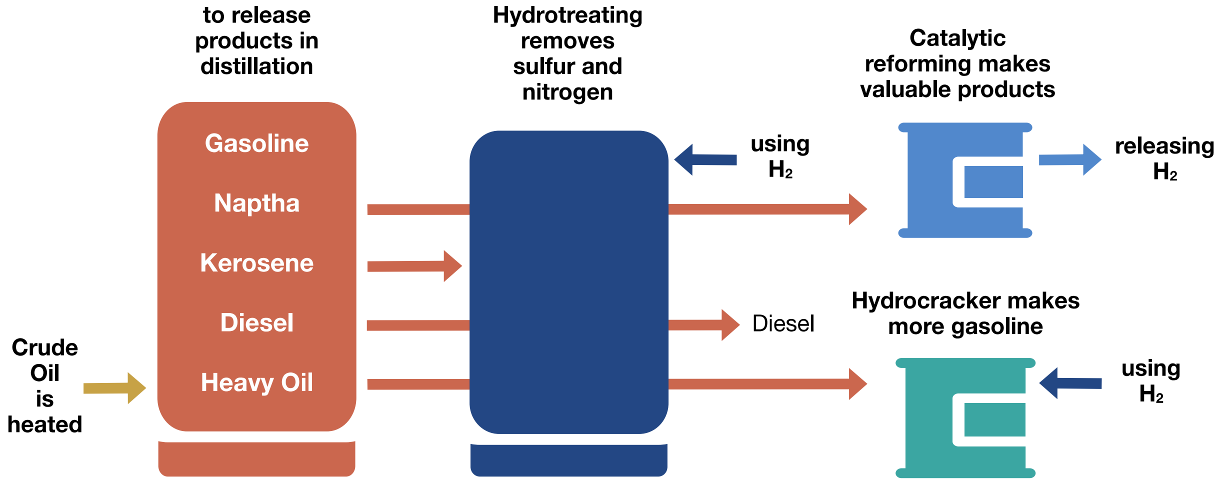
The United States maintains a robust hydrogen industry. Hydrogen is primarily used today as a chemical feedstock in industrial applications. These existing industries use hydrogen for its unique attributes: it is storable, has high energy content per unit of weight, and can be readily produced at industrial scale.

Globally, nearly all of today's hydrogen production relies on fossil fuels (76 percent natural gas, 23 percent coal), with very small amounts from electrolysis-based pathways.[1] Nearly all U.S. hydrogen production is supplied by industrial gas companies (IGCs). The current U.S. hydrogen industry consists exclusively of bilateral contracts between producers and consumers.[2] While the bilateral contract model works effectively today, new models may need to emerge to enable expanded trade to serve growth in different sectors and regions. Also, increasing the number of market players will increase the competitiveness of hydrogen. Ultimately, the formation of a clean hydrogen market will depend on the growth of demand.

The United States produced roughly 11.4 megaton (Mt) of hydrogen in 2020, more than 15 percent of the world's total.[3] As of 2021, there were approximately 257 dedicated hydrogen production facilities in the United States. Steam methane reforming (SMR) accounts for about three-quarters of total U.S. hydrogen production, and 23 percent comes as a by-product of other industrial processes and is typically consumed onsite.[4] Just under half of U.S. hydrogen is produced and consumed by the same entity (i.e., captively), with the remaining production coming from merchant providers who sell hydrogen to end users, delivered by pipeline or truck.[5] There are 25 hydrogen pipelines in the United States collectively spanning approximately 1,600 miles.[6] Currently, four underground hydrogen storage facilities are in use or development in the United States—three of which are in the U.S. Gulf Coast.[7]

The refining sector accounts for about 57 percent of U.S. hydrogen demand, making it the largest hydrogen-consuming industrial subsector.[8] Refineries use hydrogen primarily to remove sulfur from products (i.e., hydrotreating) and in the process of cracking heavy oil into gasoline and other lighter products (i.e., hydrocracking) (Figure A1).[9] The amount of hydrogen used by U.S. refineries depends on the types of crude oil being processed, especially the American Petroleum Institute (API) gravity, and the types of products being produced. U.S. refineries that regularly process heavy crudes from Mexico or Venezuela often have hydrogen production integrated within the facility, while facilities producing lighter crudes may purchase from an IGC. On average, hydrogen is responsible for around 10 percent to 20 percent of total refinery emissions. Hydrogen is also often a byproduct of the refining process, especially during catalytic reforming, a chemical process that yields high-octane products.[10]

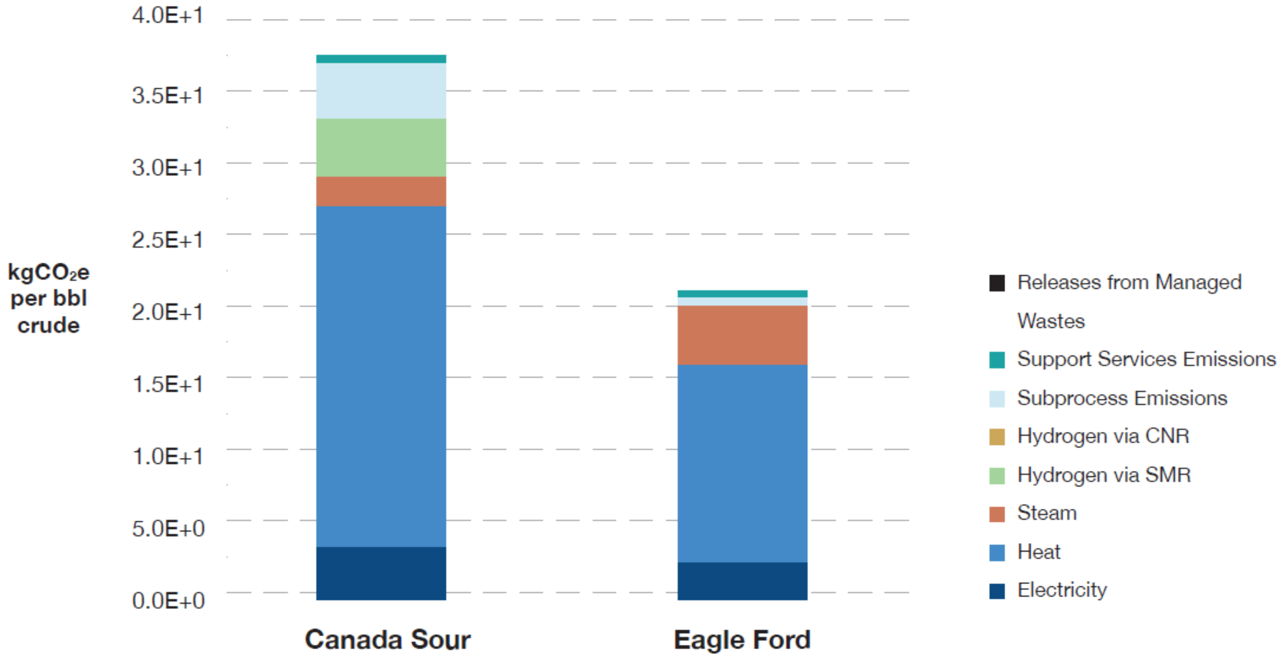
Figure A1
Hydrogen in Refining Process: Feedstock and Byproduct



Hydrogen is used as a feedstock in the refining process to desulfurize petroleum products and produce gasoline. Hydrogen can also be produced as a byproduct when the refined petroleum products are used in catalytic reforming.

Refineries use hydrogen mostly for reducing the sulfur content of crude during processing. There are a few factors to consider when switching to clean hydrogen for U.S. refining. The amount of hydrogen used depends on the crudes being processed. For Canadian Sour, hydrogen demand is higher; the hydrogen production process is usually integrated within the facility, and hydrogen contributes to a much greater share of a refinery's total emissions (i.e., higher than 10 percent) (Figure A2). For a refinery processing mostly light sweet U.S. crude (i.e., Eagle Ford), the hydrogen use is very small. These facilities usually purchase hydrogen via a bilateral contract with an IGC.

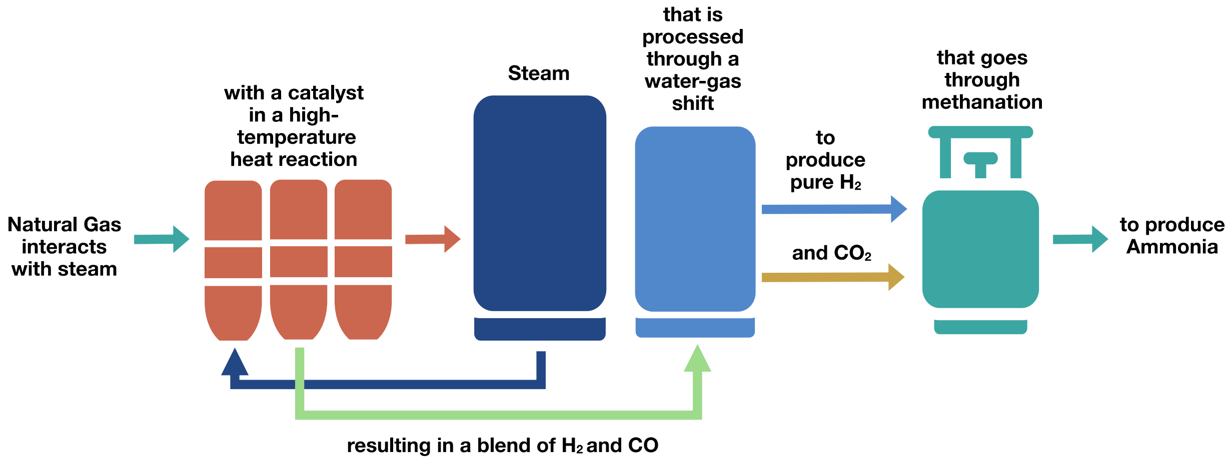
Figure A2
Carbon Intensity of Two Crude Oils Processed in the Same Refinery Configuration



This graph highlights the differing carbon intensities between two common types of crude oil used in U.S. refineries, Canada Sour and Eagle Ford. The higher sulfur content in Canada Sour increases the amount of hydrogen needed to refine the crude oil, which ultimately results in more greenhouse gas emissions at those facilities. "Hydrogen via CNR" is hydrogen produced internally through non-SMR based processes (i.e., catalytic naptha reformer). Source: Sustainable Energy System Analysis Modelling Environment (SESAME, see Appendix E).

Ammonia production accounts for roughly 20 percent of U.S. hydrogen demand.[11] Ammonia is primarily used for fertilizer production, supporting farming and other agricultural industries. Hydrogen is a primary feedstock for making ammonia; ammonia production facilities can have integrated hydrogen production (Figure A3). In 2021, the United States produced 17 Mt of ammonia, requiring 2.6 Mt of hydrogen, across 32 facilities.[12] The largest SMR in the United States is at an ammonia plant. Producing nearly 590,000 tons of hydrogen per year, it is twice as large as the next largest hydrogen production facility. The United States maintains an extensive ammonia trucking, rail, and pipeline infrastructure connecting producers to end users across the country. In the United States today, ammonia production involves the Haber-Bosch process, powered by fossil fuels to achieve high temperatures (400°C to 500°C) and pressures (150 bar to 300 bar), often with an iron catalyst.[13]

Figure A3
Ammonia Production Process with Integrated H_2 Production

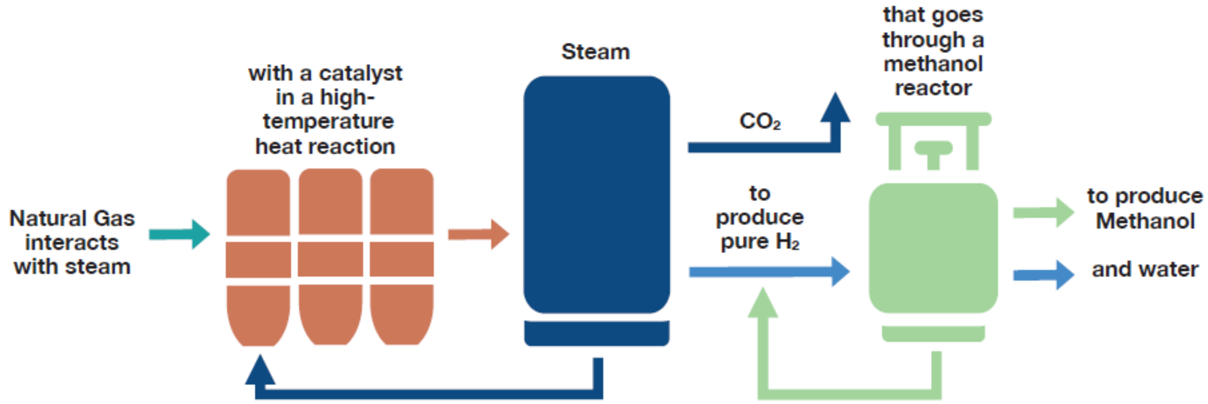


Ammonia production uses the steam methane reformation process which begins with natural gas and steam interacting at high temperatures to form hydrogen and carbon monoxide. These components are put through a water-gas shift reaction to form pure hydrogen and carbon dioxide. Ammonia is produced when hydrogen and carbon dioxide undergo methanation.

Methanol production accounts for around 10 percent of U.S. hydrogen demand. Methanol is used as a feedstock to produce chemicals and products, such as plastics and fuels. The U.S. methanol industry, located primarily in the U.S. Gulf Coast, supports a relatively stable domestic market and a rapidly growing export market, primarily in Europe and Asia.[14] Similar to ammonia plants, U.S. methanol producers may have integrated SMRs that produce hydrogen (Figure A4). Methanol is produced by reforming natural gas, resulting in a synthetic gas that includes hydrogen, which is then synthesized into methanol.[15] In 2021, nine U.S. facilities made around 10 Mt of methanol and 1.6 Mt of hydrogen.[16] According to U.S. Energy Information Administration (EIA), "methanol plants are among the most natural gas-intensive industrial end users and require natural gas as a feedstock and for process heat."[17]

Figure A4

Methanol Production Process with Integrated H_2 Production



Similar to ammonia production, methanol is also produced using steam methane reformation where steam and natural gas interact at high temperatures. However, no water-gas shift is required and the pure hydrogen byproduct is used directly in a methanol reactor to produce methanol and water.

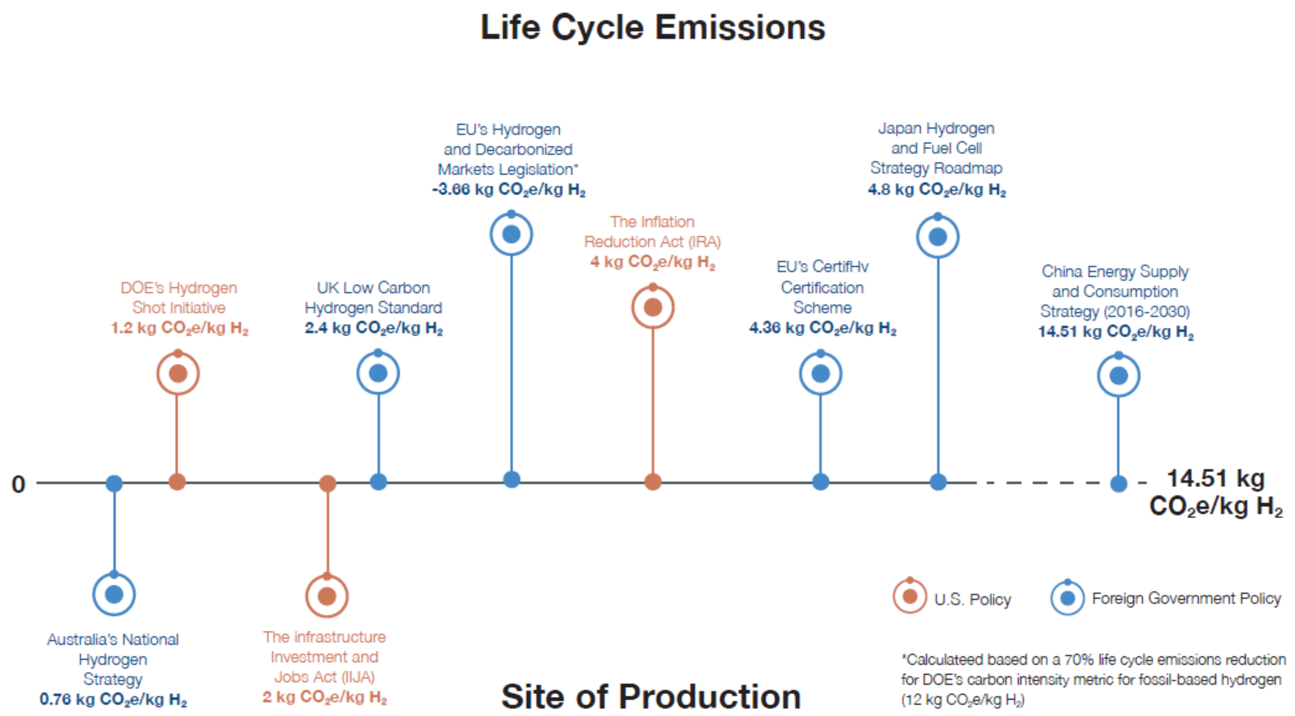
Shifting to new clean hydrogen supplies requires strong alignment of both producers and consumers. About half of U.S. hydrogen is produced and consumed by the same entity (usually a refinery), while the other half comes from merchant providers who sell hydrogen to end users. In all cases, hydrogen production and use are currently a highly integrated process. Providing hydrogen consumers with a clean feedstock will require existing system retrofits, new contracts (or amendments to existing bilateral agreements), and agreement on carbon-intensity levels, cost, and delivery schedules. This will include managing the supply risks of new clean hydrogen supply contracts. This point is especially true for “green” hydrogen projects powered by intermittent renewable sources, which currently accounts for only 0.1 percent of global production—or less than 0.07 Mt.[18]

Defining Clean Hydrogen

The term “clean hydrogen” is often used without specific definition but refers to the carbon intensity of hydrogen, often focused on emissions at the site of production or total life cycle emissions. To date, there is no universal standard definition for clean hydrogen, which could range from slightly less emissions-intensive than conventional pathways to zero-emission hydrogen across the life cycle.

Additionally, individual countries may have multiple targets for hydrogen to be considered clean, such as the United States (Figure A5). The Infrastructure Investment and Jobs Act (IIJA) set the clean hydrogen production target as 2.0 kilograms of carbon dioxide equivalent per kilogram of hydrogen (kg CO_2e/kg H_2) at the site of production. The U.S. Department of Energy’s (DOE) “Hydrogen Shot” program defines its ambitions to lower the life cycle emissions of hydrogen production by at least 90 percent from current levels, which roughly translates to 1.2 kg CO_2e/kg H_2.[19] The Inflation Reduction Act (IRA) provides tax incentives for clean hydrogen production to projects with less than 4.0 kg CO_2e/kg H_2 life cycle emissions.

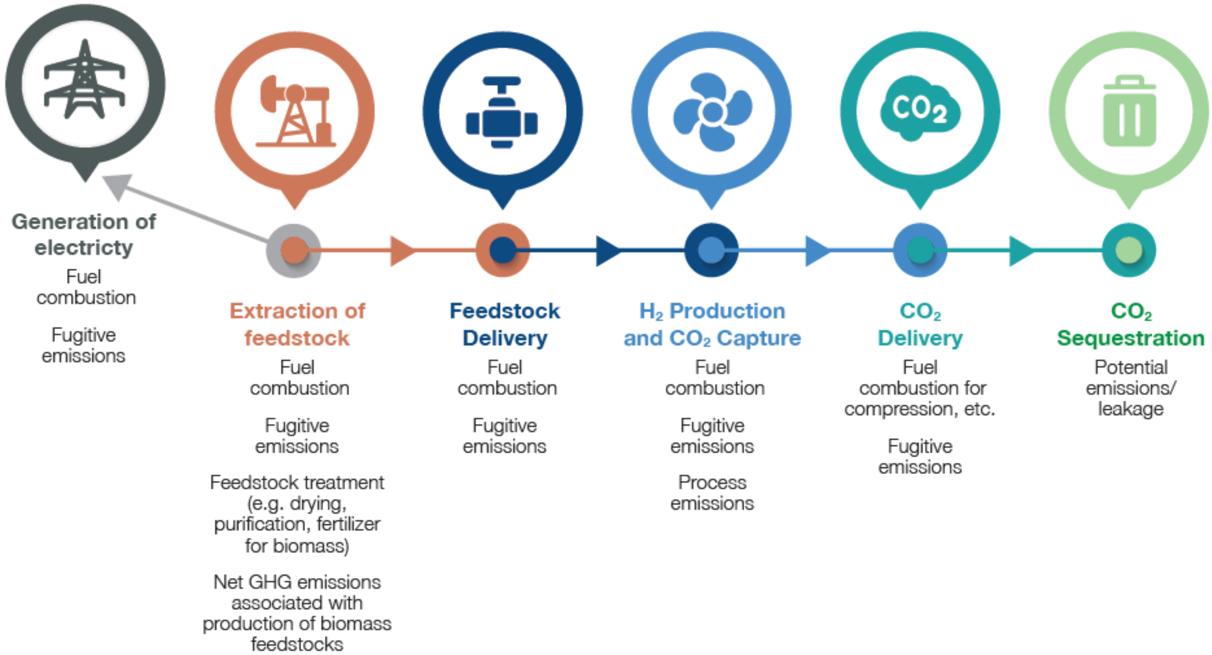
Figure A5
Definitions of "Clean" Hydrogen Vary by Region and Policy



Definitions for clean hydrogen from U.S. policy and policies from foreign governments range from 0.76 to 14.51 kg CO_2e/kg H_2. These definitions also differ based on whether emissions intensity is calculated at the site of production or across the entire hydrogen life cycle.

In September 2022, DOE issued draft guidance on its Clean Hydrogen Production Standard (CHPS) to solicit industry feedback and guide policy implementation for the IRA and IIJA. The CHPS calls for a life cycle emissions target of 4.0 kg CO_2e/kg H_2 and finds this target is achievable for projects subject to the IIJA's emissions requirements of 2.0 kg CO_2e/kg H_2 at the site of production. The CHPS is guidance—it is not a regulatory standard. Projects are not required to meet the CHPS guidance if they "'demonstrably aid the achievement' of the CHPS by mitigating emissions as much as possible across the supply chain" (Figure A6).[20]

Figure A6
CHPS Life Cycle System Boundary[21]



The life cycle system boundaries depicted in this figure are meant to provide a consistent and comprehensive evaluation methodology for a diverse set of clean hydrogen systems. The major emissions sources in the system are detailed below each step in the system. Source: DOE, 2022.

Definitions of clean hydrogen used by countries and policies will shape technology and market development, especially as the market develops and plans emerge to trade within and between regions. The United Kingdom's standard for clean hydrogen is 2.4 kg CO_2e/kg H_2 for life cycle emissions.[22] The European Union (EU) uses multiple definitions. The EU legislation on Hydrogen and Decarbonized Markets uses a 70 percent life cycle emissions reduction compared to fossil-based hydrogen.[23,24] The EU's CertifHy uses life cycle emissions of below 4.36 kg CO_2e/kg H_2. The European Commission's RePowerEU plan could impact the current threshold under CertifHy, potentially lowering it in the future.[25,26]

Additionally, several other countries have their own definitions for low-carbon hydrogen. Australia provides specific emissions-intensity targets for each production pathway, including 0 kg CO_2e/kg H_2 for green hydrogen and 0.76 kg CO_2e/kg H_2 for blue hydrogen at the site of production.[27] China's "Energy Supply and Consumption Revolution Strategy 2016–2030" defines low-carbon hydrogen as 14.51 kg CO_2e/kg H_2 from well to gate.[28] Japan defines clean hydrogen as having a carbon intensity of 4.8 kg CO_2e/kg H_2 from well to end use.[29]

In this report, "clean hydrogen" is used as a generic term, acknowledging that—while there are multiple definitions that could apply depending on which policies are at play or the particular application for hydrogen being considered—the intention is to distinguish between conventionally produced hydrogen and pathways that contribute to broader decarbonization.

Technology Overview

Hydrogen can be produced using several different processes. Generally, hydrogen is mostly produced from natural gas or water using heat or electricity, respectively. In the United States and globally, hydrogen production today is dominated by SMR, which involves reacting steam and natural gas to produce hydrogen. This pathway is relatively scalable, emissions-intensive, and low-cost for production. Compared to splitting hydrogen from water molecules, it is less energy-intensive to split hydrogen from methane molecules. DOE estimates 0.156 million British thermal units (MMBtu) of natural gas is required per kg of hydrogen in an average-sized SMR plant, equating to about 45.7 kilowatt-hours (kWh). Using estimates for current economic potential, low-temperature electrolysis requires about 54.3 kWh per kg of hydrogen.[30] A large share of hydrogen production is located at or nearby large demand centers such as refineries, ammonia production facilities, and methanol plants. Less mature processes producing hydrogen through biological processes are also being developed.[31]

There are emerging production pathways that offer significant reductions in life cycle emissions intensity. Their cost and emissions profile vary by project and location, as energy inputs (and associated costs), capacity factors, and project design are the primary drivers of the cost of delivered hydrogen. Figure A7 shows a breakdown of delivered hydrogen cost and associated emissions intensities of select hydrogen production projects. These scenarios are built using the Sustainable Energy System Analysis Modelling Environment (SESAME) to simulate real-world data (see Appendix E). As shown in the cost profiles, energy inputs drive hydrogen costs. In all cases, levelized costs increase as capacity factors decline due to the diminished productivity of the pathway. For example, the capacity factor for a large-scale green hydrogen project that runs on excess or “free” renewable electricity is very low, reflecting the limited availability of these resources. This impacts the project’s ability to recover capital costs and adds to the overall costs. The life cycle greenhouse gas (GHG) emissions for each pathway are based on Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model assumptions, the framework used by the IRA tax credit incentives.[32]

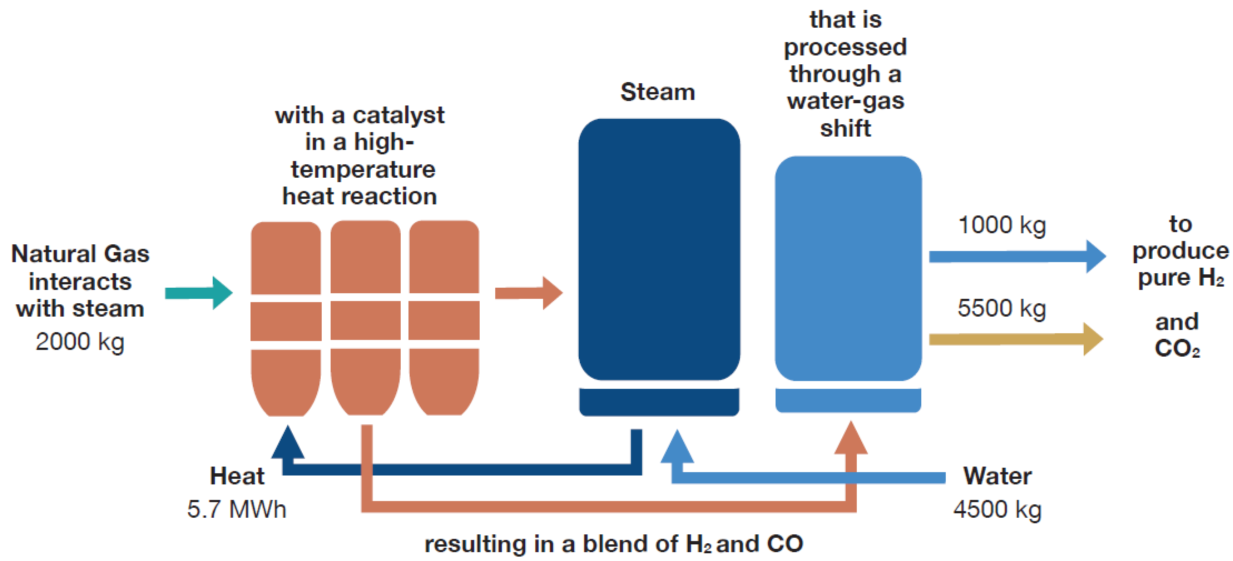
Figure A7
Cost Comparison of Major Clean Hydrogen Production Pathways

This graph shows the cost of hydrogen production from seven clean pathways compared to a conventional production pathway (i.e., gray). The bar for each pathway shows the specific cost components contributing to total production costs, all of which include capital and fixed costs. Blue hydrogen pathways require additional costs associated with natural gas and CO_2 transport and storage, while green and pink hydrogen pathway costs are dependent on electricity costs. The associated red dots represent the life cycle GHG emissions for each pathway.

Gray hydrogen uses steam reforming to extract hydrogen from natural gas. In this process, natural gas interacts with heat to produce steam, resulting in hydrogen and carbon monoxide. A separate step called a water-gas shift is used to yield pure H_2 and to separate the CO_2. SMR is the most widely used production method in the United States and the world. According to DOE, gray hydrogen results in an average of 12 kg CO_2e/kg H_2 on a life cycle emissions basis.[33] The cost of delivered gray hydrogen is nearly $1.3 per kg, based on EFI analysis, assuming a natural gas price of $4.42 per MMBtu.[a] On average, fuel costs represent 65 percent of the total costs, followed by capital costs (20 percent), fixed operations and maintenance (O&M) (13 percent), and variable O&M (2 percent). As shown in Figure A8, producing 1,000 kg of H_2 requires 2,000 kg of natural gas, 4,500 kg of water, and 5.7 megawatt-hours (MWh) of heat.

[a] This price comes from the average U.S. Henry Hub price for natural gas from December 2021 to March 2022.

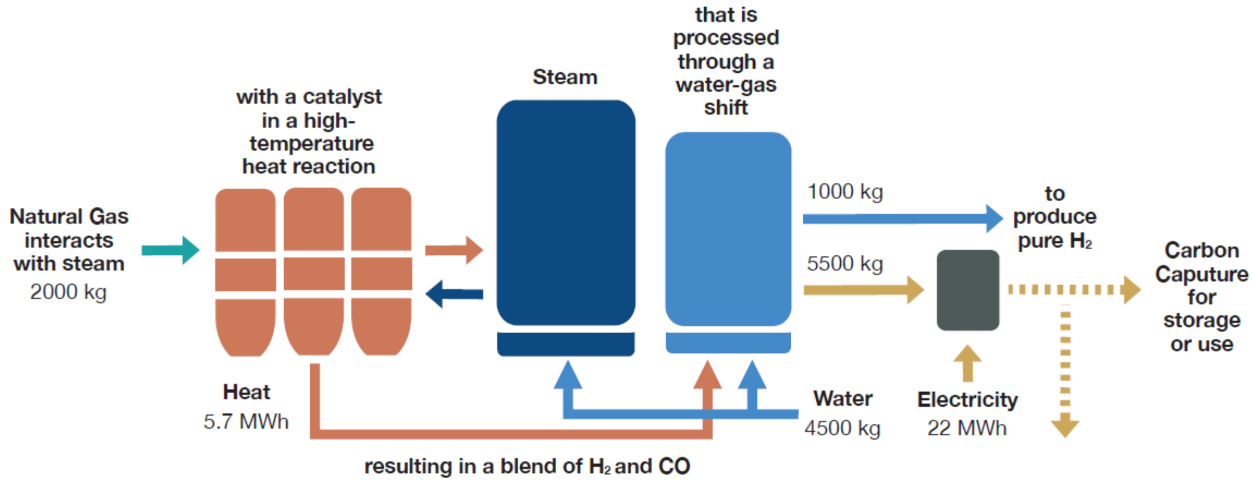
Figure A8
Gray Hydrogen Production Process Flow



Gray hydrogen is produced through the steam methane reformation process. Natural gas interacts with steam at high temperatures to create a blend of hydrogen and carbon monoxide. This blend is put through the water-gas shift reaction where the blend interacts with water to produce pure hydrogen and carbon dioxide as final products.

Blue hydrogen adds carbon capture, utilization, and storage (CCUS) to existing hydrogen production methods (i.e., SMR and Autothermal Reforming [ATR]) (Figure A9). The cost of blue hydrogen largely depends on the CO_2 capture rate and the cost of the natural gas feedstock. According to EFI modeling, 60 percent CO_2 capture results in hydrogen with an emissions intensity of 6.5 kg CO_2/kg H_2 at the site of production and costs of around $1.75 per kg. At 90 percent capture, the life cycle emissions intensity of hydrogen is 4.2 kg CO_2e/kg H_2 (1.2 kg CO_2e/kg H_2 at site of production) at a cost of around $2 per kg. Blue hydrogen costs are driven by the additional capital costs of the capture equipment, new CO_2 transportation and storage costs, and additional O&M. The energy balances of blue hydrogen are similar to gray hydrogen but require additional energy for the CO_2 capture, transport, and storage, along with associated costs.

Figure A9
Blue Hydrogen Production Process Flow



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

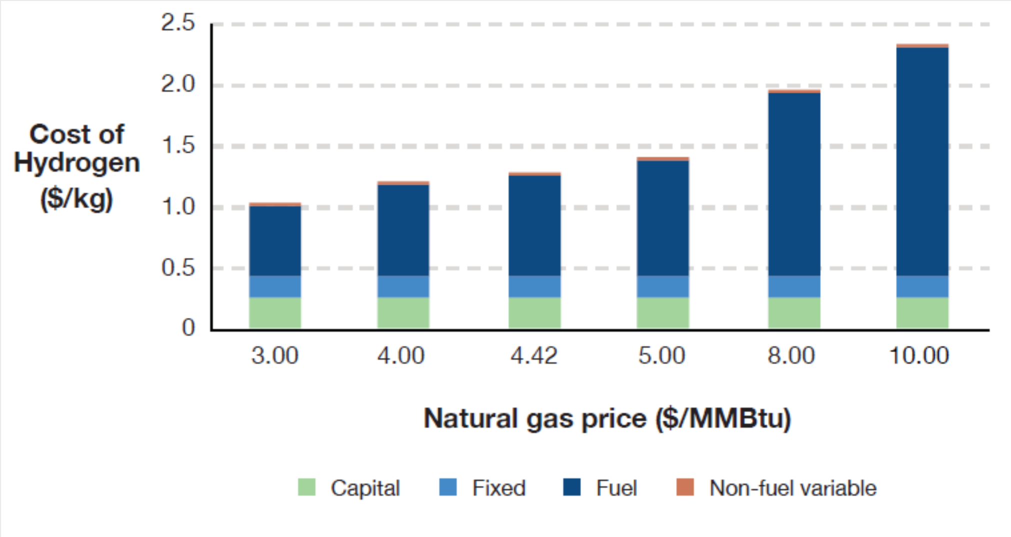
Natural gas price is the highest contributor to the cost of thermal hydrogen production pathways, including gray and blue hydrogen. The long-term economics of natural gas-based hydrogen production pathways will depend, in part, on natural gas prices. Box A1 shows the price sensitivity of gray hydrogen under different natural gas price scenarios. It also shows the economies of scale of blue hydrogen.

Box A1

Natural Gas Price Sensitivity and Economies of Scale

U.S. natural gas prices at Henry Hub averaged $4.20/MMBtu in 2021. EIA projects natural gas prices in 2022 to average $7.10/MMBtu.[34] This year-on-year change can impact the delivered costs of H_2 by 40 percent. As shown in Figure A10, the share of fuel cost between natural gas prices ranges between $3/MMBtu and $10/MMBtu, representing increases from 56 percent to 81 percent.

Figure A10
Variation of the Delivered Cost of Hydrogen with Natural Gas Price

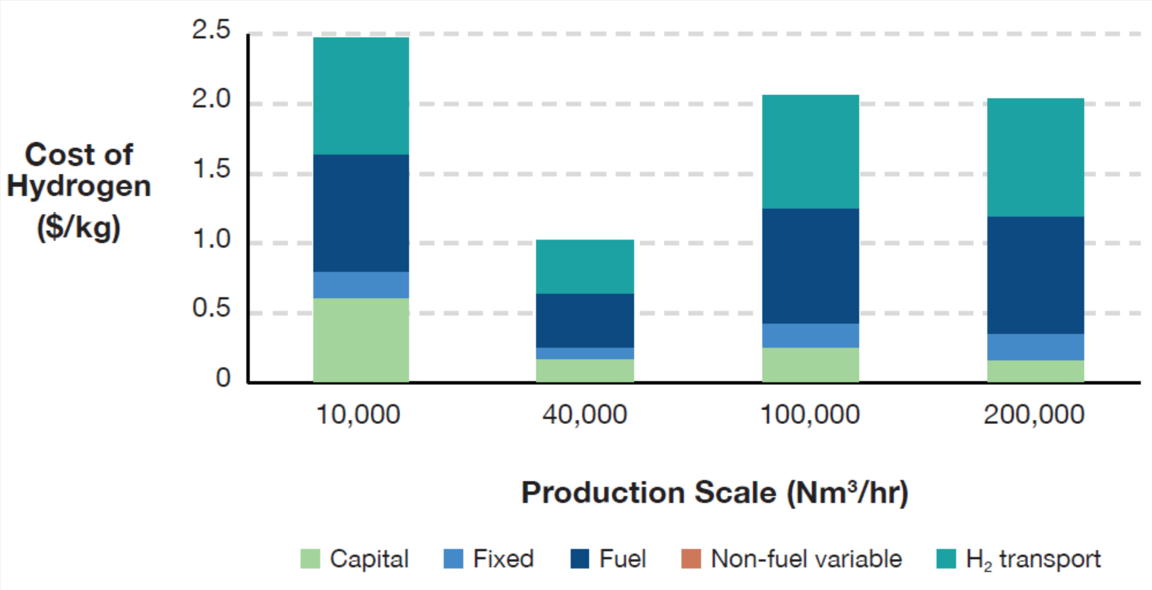


The cost of hydrogen produced via SMR increases with higher prices for natural gas. This usually has the largest impact on hydrogen production costs because it is the most variable and the other components of total production costs are relatively constant.

There are significant economies of scale for blue hydrogen projects that are not offered by other clean hydrogen production pathways. SMR technology scales cost-effectively and the energy costs do not increase linearly as a facility's production capacity ramps (Figure A11). Increasing the size of an electrolyzer, however, does add considerable cost to the overall project. The clean hydrogen production costs of a large-scale (200,000 normal cubic meters [Nm^3]) facility are 20 percent lower than a small-scale blue hydrogen plant (10,000 Nm^3). Lower capital costs, not fuel costs, are the primary driver of cost efficiency.

Figure A11

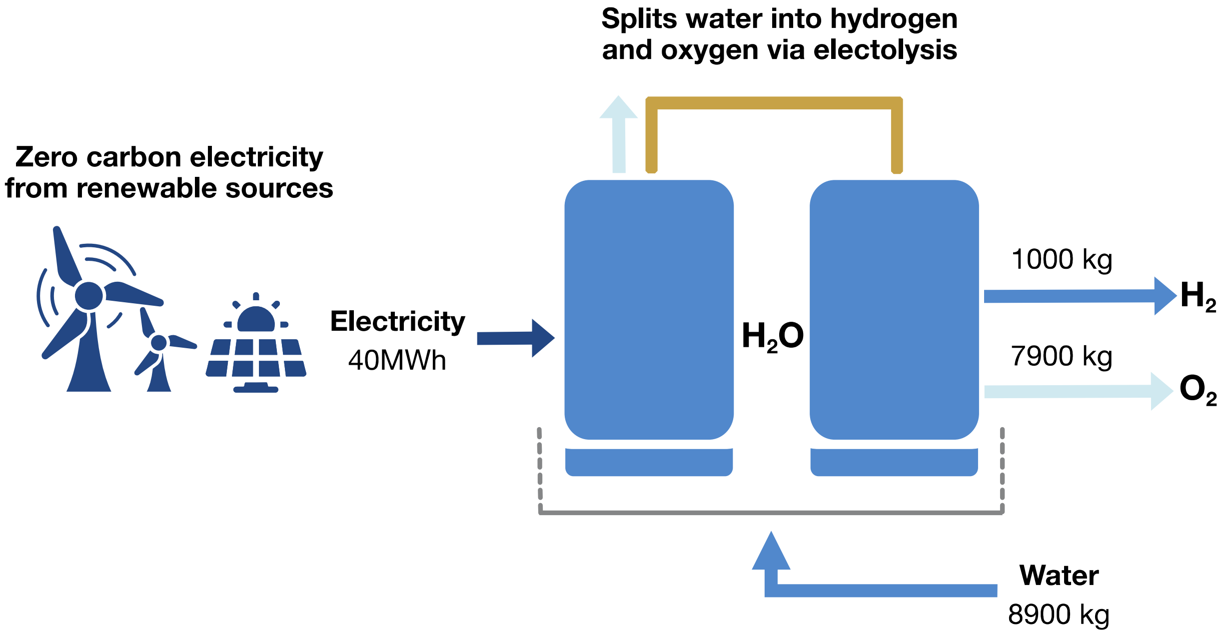
Impact of Scale of SMR Hydrogen by Delivered Cost



This figure shows SMR hydrogen production at four different scales. The smallest-scale hydrogen plant (10,000 Nm^3/hr) has a total hydrogen production cost of nearly $2.50/kg H_2. A large-scale plant (200,000 Nm^3/hr) 20 times larger in size ends up being 20 percent cheaper in total hydrogen production costs. This cost difference is largely because SMR technology benefits from economies of scale and can help lower capital costs and mainly contributes to lower costs for larger plants.

Green hydrogen is hydrogen produced with renewable electricity via electrolysis. When only Scope 1 and 2 emissions are considered, green hydrogen results in roughly no GHG emissions. Using this approach aligns with the life cycle emissions measurement used by the IRA's 45V production tax credit (see Appendix B for more details). Studies show cost estimates of green hydrogen between $3 and $8 per kg H_2.[35] Changing the electricity prices, capacity factors, and size and configuration of the electrolyzer can significantly affect costs (Box A2). For example, operating an alkaline electrolyzer at 50 percent capacity, assuming electricity prices of $40/MWh, yields a hydrogen cost of nearly $3.50/kg H_2. The energy costs of green hydrogen tend to be around three-quarters of the total production costs. The energy balances of green hydrogen are other important considerations. Also as seen in Figure A12, producing 1,000 kg of H_2 requires 40 MWh of clean electricity and 8,900 kg of water.

Figure A12
Green Hydrogen Production Process Flow



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

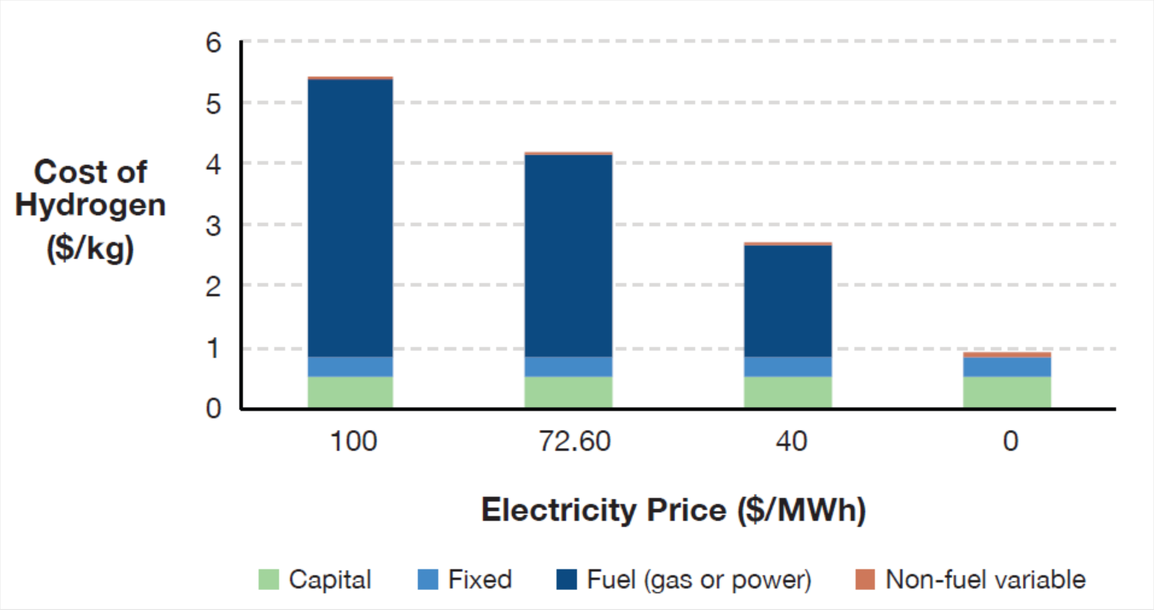
An electrolyzer uses electricity to split water and hydrogen. Like fuel cells, electrolyzers consist of an anode and a cathode separated by an electrolyte. The three typical electrolyzer technologies are alkaline, polymer electrolyte membrane (PEM), and solid oxide.[36] Alkaline and PEM electrolyzers share similar structures but carry out different chemical processes to produce hydrogen.[37] Alkaline is the most mature electrolyzer technology today and has been used by the chemical industry for nearly a century. Several megawatts of alkaline electrolyzers are in use today in the United States. Newer approaches exist for alkaline electrolyzers that use solid alkaline exchange membranes (AEM). Interest in PEM systems is growing for clean hydrogen applications as they perform better when electricity is supplied intermittently, offering obvious advantages in a clean hydrogen economy. Solid oxide electrolyzers use a solid ceramic material as the electrolyte to generate hydrogen, selectively conducting negatively charged oxygen ions (O^{2-}) at elevated temperatures. Solid oxide electrolyzers must operate at temperatures high enough for the solid oxide membranes to function properly (about 700° to 800°C, compared to PEM electrolyzers, which operate at 70°C to 90°C, and commercial alkaline electrolyzers, which typically operate at less than 100°C). Box A2 shows the price sensitivity of green hydrogen to changes in select electricity prices.

Box A2

Electricity Price Sensitivity of Electrolysis Pathways

Unlike thermal hydrogen production, the contribution of electricity price to the cost of hydrogen greatly varies by project. Electricity costs for clean hydrogen projects will depend on regions, project sizes, and technology configurations. The following costs are modeled based on real U.S. project data. For an alkaline electrolyzer operated at 90 percent capacity factor, the cost of hydrogen can be as low as \$0.91/kg H_2. This scenario is very unlikely, however. Even as low and zero electricity prices have been observed with the increase of renewables in the power system, these events are for very short periods of time (not close to the supply needed to operate an electrolyzer at 90 percent). Using an electricity price of \$40/MWh based on observed prices for solar and wind projects, electricity becomes the dominant contributor to hydrogen costs, which are \$2.70/kg H_2 (Figure A13). At \$100/MWh, the cost of electricity becomes 83 percent of the total and hydrogen cost reaches \$5.40/kg H_2.

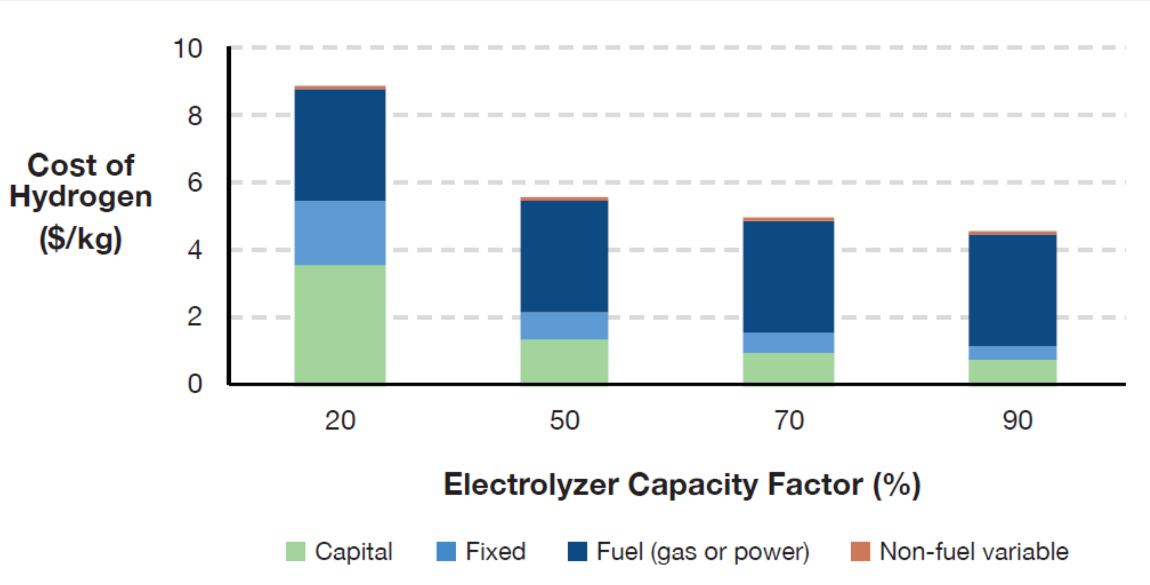
Figure A13
The Impact of Electricity Price on Hydrogen Cost



For electrolysis-based pathways, electricity price is the largest contributor to overall hydrogen production costs. While there have been some events where renewable electricity prices can be extremely low or even zero, it is more common to see electricity prices between \$40/MWh to \$100/MWh where total production costs can range from \$2.70/kg H_2 to \$5.40/kg H_2.

An important parameter in the cost of electrolytic hydrogen is the capacity factor of these units. Green hydrogen relies on intermittently available resources. The capacity factor of power supply will be lower unless it is paired with energy storage. For 50 percent or lower capacity factors, the cost of hydrogen will be dominated by capital cost of the electrolyzer and fixed operating costs. This yields a higher hydrogen cost. As shown in Figure A14, at 20 percent capacity factor, the cost of hydrogen reaches \$8.80/kg H_2 and the cost of capital and fixed expenses account for 62 percent of the total cost. At 50 percent, this contribution drops to 40 percent, lowering the cost of hydrogen to \$5.50/kg H_2. The cost share minimally declines to 27 percent at 90 percent capacity factor.

Figure A14
The Impact of Capacity Factor on Hydrogen Cost

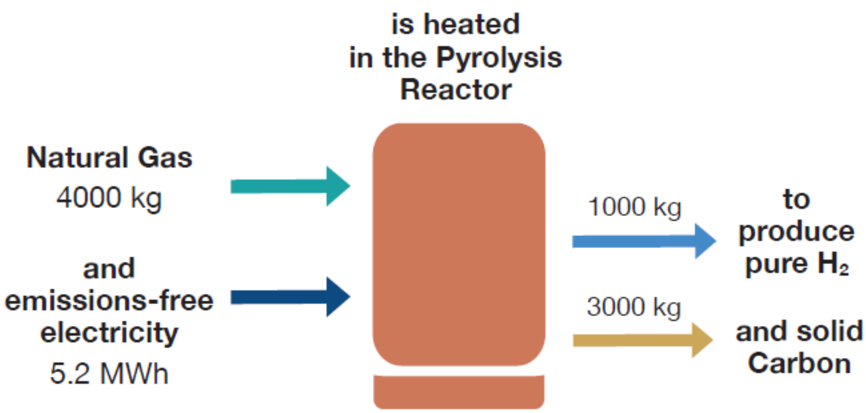


The capacity factor for electrolytic hydrogen represents the percentage of time that a unit is producing hydrogen and receiving renewable electricity resources. Given the intermittency of renewable electricity, capacity factors for these units are generally low (less than 50 percent) and the capital cost of the electrolyzer and fixed operating costs become significant contributors to higher hydrogen production costs.

Pink hydrogen is hydrogen produced using nuclear electricity via electrolysis. The process is the same as green hydrogen, though the carbon-free electricity comes from nuclear power. Pink hydrogen is considered emissions-free when only Scope 1 and 2 emissions are considered. Generally, pink hydrogen involves using a share of the nuclear-powered electricity to run an electrolyzer to produce hydrogen. Nuclear plants operate with relatively high capacity-factors (roughly 90 percent).[38] If a nuclear plant is operating but not selling into electricity markets, it may be economical to use the electricity to produce hydrogen via electrolysis. EFI estimates pink hydrogen costs are around $4.20 per kg H_2, assuming electricity costs of $72.60/MWh and an alkaline electrolyzer at 90 percent capacity factor. Note that nuclear power plants can also use heat for hydrogen production though this approach is generally not considered “pink” hydrogen.[39] This approach can support high-temperature electrolysis (HTE), where heat from the nuclear power plants creates steam—as opposed to liquid water—that is electrolyzed using electricity from the power plant. As a result, HTE supported by nuclear process heat and electricity can achieve efficiencies equivalent to SMR, but without the associated fossil fuel consumption and GHG emissions.[40]

Turquoise hydrogen uses zero-carbon electricity to heat natural gas without air combustion to produce hydrogen and solid carbon (Figure A15). Turquoise hydrogen is considered emissions-free at the site of production. Like blue hydrogen, this process uses methane as a feedstock, but does not need carbon capture and storage because the carbon is a byproduct that is a solid.[41] While this aspect makes it comparable to blue hydrogen, the costs are higher due to the larger feedstock requirements and the dependence on carbon-free electricity. Furthermore, methane pyrolysis technologies are relatively less mature than both SMR and carbon capture, though there are several companies working on development and deployment of the technology. DOE recently awarded a $1 billion (B) loan guarantee to a turquoise hydrogen project in Nebraska that plans to upgrade natural gas to hydrogen and carbon black, using the hydrogen to produce ammonia and methanol, among other industrial uses.[42]

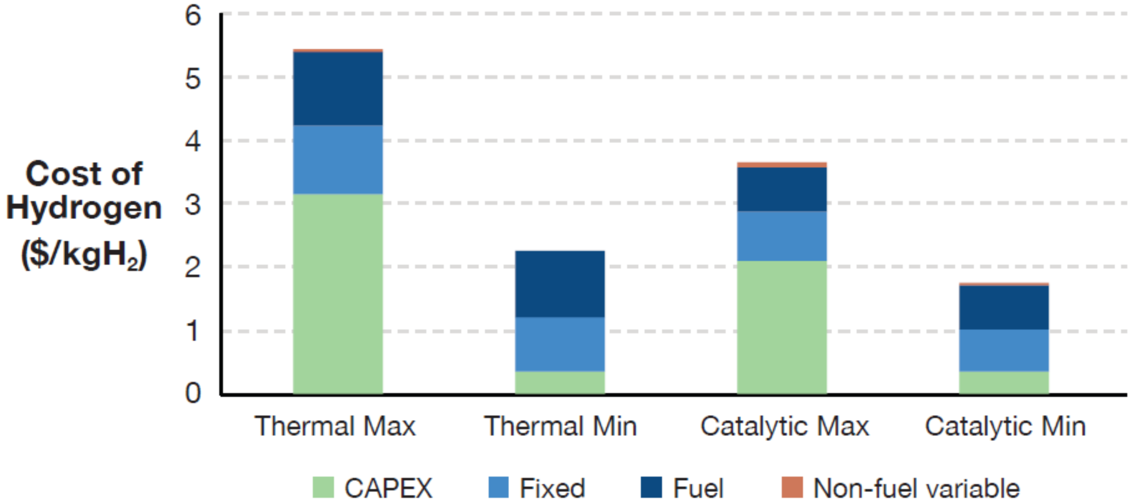
Figure A15
Turquoise Hydrogen Production Process Flow



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

Thermal and catalytic methane pyrolysis are the main technology options for turquoise hydrogen. The thermal pathway introduces a heating element (often by burning hydrogen) to boost the overall productivity. The catalytic process uses a catalyst (e.g., liquid tellurium) to improve process efficiency. A techno-economic analysis of both production pathways finds the cost of turquoise hydrogen to be between $1.80/kg H_2 to $5.50/kg H_2 (Figure A16).

Figure A16
Cost Range of Turquoise Hydrogen Produced with Different Technologies and Scales



The pyrolysis process can employ two main technologies: thermal or catalytic pyrolysis. In thermal pyrolysis, a heating element (often burning hydrogen) is used to increase productivity, while in catalytic pyrolysis a catalyst like tellurium is used to increase efficiency. Overall, the thermal pyrolysis process is more expensive than the catalytic process. Comparing across scale, the larger cases of each pathway are considerably more expensive than their smaller-scale counterparts, and hydrogen production costs are most dependent on capital expenditures. For the small-scale pyrolysis cases, fuel costs and fixed operational costs become the largest contributors to hydrogen production prices.

Turquoise hydrogen is notable compared to other production pathways, as the process results in clean hydrogen and carbon black, which is a valued commodity. The overall project economics can benefit from the carbon black revenue stream (Box A3).

Box A3
Carbon Black

Methane pyrolysis results in pure hydrogen and carbon black, a valuable commodity in the U.S. market. Carbon black is a material produced from the combustion of certain hydrocarbons, including coal, petroleum, and natural gas. There are different processes for producing carbon black (e.g., finance black, lamp black), though they all involve manufacturing it as a byproduct of other hydrocarbon production processes. Carbon black is around 95 percent pure carbon. While it has many potential uses, carbon black is most often used as a reinforcing fiber in rubber products, mainly due to its tensile strength and heat conductivity. The most common use of carbon black is in automobile tires. It is also used for industrial and automotive belts and hoses, various electronics, and in inks, coatings, and plastics.

In 2018, global demand for carbon black was over 3B metric tons (t).[43] Demand for carbon black is driven by automotive (65 percent), manufacturing industries (30 percent), and construction (5 percent). According to one estimate, the global carbon black market was valued at $15B in 2021, with projections that it will be $22B by 2027.[44] Automobile sales will likely continue to drive demand, followed by plastics, coatings, inks, and toners. Large-scale infrastructure projects in China, India, and other regions may also drive new carbon black demand due to various construction needs. Turquoise hydrogen projects may have an easier time finding financing as their business model includes the production of a highly valued commodity. According to one estimate, U.S. carbon black prices were around $140/t in 2019.

Because carbon black production is directly tied to production of hydrocarbons, it is unknown how economywide decarbonization will affect its supply and demand, including the emergence of alternatives. Fluctuations in raw materials prices, increase in the use of silica as a substitute, and environmental concerns with carbon black production may limit the market growth. Finally, tire recycling programs allowing manufacturers to recover carbon black is another interesting trend that may affect demand.[45]

Hydrogen Carriers

Compression is a common method for transporting hydrogen today. Hydrogen is often compressed in storage tanks, which can be an energy-intensive process: 6 kWh/kg H_2 at 700 bar.[46] Hydrogen is typically compressed at 200 bar to 500 bar into gas cylinders or tubes and transported via truck. These cylinders may be bundled and mounted on a truck. A typical truck, fully loaded, can carry around 500 kg H_2.[47] For pipeline transportation, hydrogen is compressed at only 50 bar to 85 bar.[48]

Hydrogen liquefaction can be very challenging. It involves cooling the hydrogen to below 400° F followed by storage in a large metal tank.[49] According to DOE, the liquefaction process can use the equivalent of 30 percent of the energy content of the hydrogen being stored. According to another study, it takes nearly 15 kWh of energy to store each kg H_2 at 700 bar.[50] Some hydrogen is lost through evaporation during liquefaction, further impacting the economics. These losses are especially problematic when using small tanks with large surface-to-volume ratios.[51] However, it may be more economical to ship hydrogen over long distances as a liquid compared to compression, as liquid tanks can hold a much larger mass than many gaseous tanks.[52]

In addition to these physical-based storage methods, there are other methods for storing hydrogen, including “circular” hydrogen carriers (e.g., ammonia and methanol) and liquid organic hydrogen carriers (LOHCs). These alternative methods often involve additional conversion before there is a usable product, but they can address other technical challenges of certain storage methods.

Ammonia is a hydrogen-rich liquid product with a volumetric energy density about 45 percent higher than hydrogen.[53] It can be liquefied and transported at room temperature and at relatively low pressures (9.2 bar). Ammonia may be cracked into hydrogen using a catalyst, consumed directly in an internal combustion engine, or converted to electricity in an alkaline fuel cell.[54] Globally, nearly 180 Mt of ammonia is produced each year and 120 international ports are already equipped with ammonia terminals, predominately for its use in agricultural fertilizers.[55]

Methanol is another hydrogen-rich energy carrier. According to one study, current oil tanker ships can carry methanol “with only minor modifications.”[56] There are a range of existing and prospective uses for methanol, especially in the transportation sector. Methanol is used as a gasoline blend (roughly 3.0 percent blend), especially in China.[57] Moreover, there are at least seven oceangoing vessels equipped to run on methanol.[58] Globally, there are over 90 methanol plants with a combined annual production capacity of 110 Mt.[59]

Liquid Organic Hydrogen Carriers (LOHCs) use chemical reactions to bond hydrogen to other molecules for storage and shipping. LOHCs result in much higher energy densities than other methods. For example, a fully loaded truck carrying an LOHC would deliver roughly three times more energy than one carrying compressed hydrogen.[60] LOHCs involve a two-step process. In the first step, hydrogenation produces the compound, requiring modest temperatures (250° F)—roughly waste-heat levels—at 50 bar.[61] A similar process is required to release hydrogen, called dehydrogenation, though at much lower pressures (3 bar).[62] LOHCs do not require releasing any other substances during the conversion and reconversion process. They can be stored for an extended period at a large scale and can use the existing hydrocarbons infrastructure. LOHCs can also store hydrogen without binding or releasing other substances.

Technical Considerations

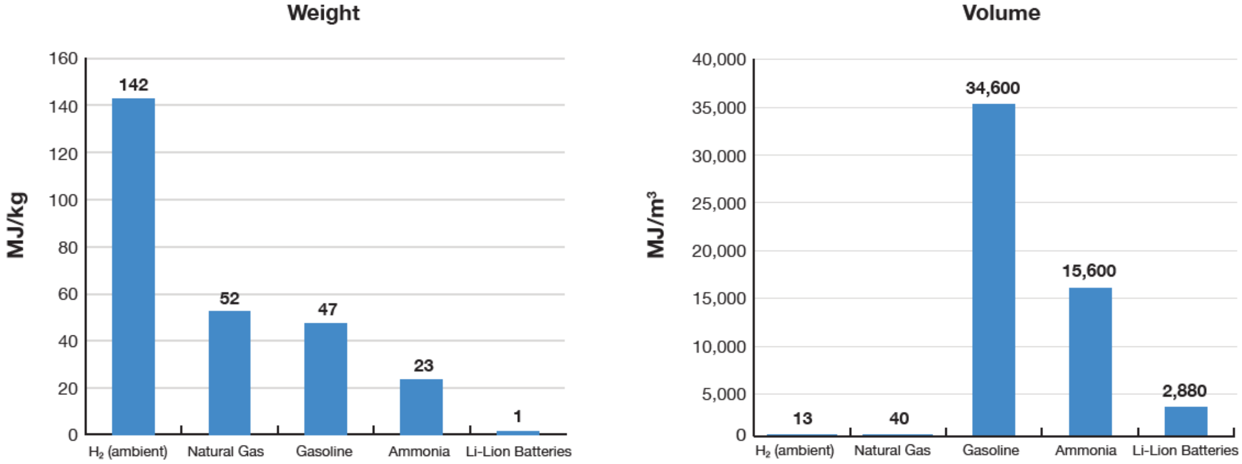
Because usable hydrogen does not exist in a natural form, hydrogen production requires energy conversion. In certain cases, hydrogen's roundtrip efficiency is much lower than direct electrification, especially for lower-temperature heating needs.[63] In other words, the amount of energy input is high compared to the energy output of hydrogen. For example, making hydrogen via electrolysis requires producing electricity to operate an electrolyzer, resulting in hydrogen and water. If the hydrogen product is then used to generate carbon free electricity, the roundtrip energy losses are up to 40 percent.[64] Roughly half of the energy is lost during production, while the other half is lost during final conversion to electricity or heat.

As a point of comparison, pumped hydroelectricity, another long-duration energy storage option, is roughly twice as energy efficient as green hydrogen, while electric heat pumps offer 5x to 6x more thermal energy output per energy input compared to hydrogen.[65,66] These examples are for relatively low heating needs. Reaching high-temperature heating (i.e., more than 400°C) is much more energy efficient using hydrogen than direct electrification.[67]

Additionally, hydrogen's energy density per volume makes it technically challenging in some applications (Figure A17). Hydrogen is produced in a gaseous form and has a very low energy density per volume; liquefied hydrogen also has a low energy density per volume compared to gasoline. In other words, considerable space is needed to store many forms of hydrogen. This aspect makes shipping hydrogen very challenging. It is critical to develop advanced storage methods that increase hydrogen's energy density and to promote use cases that require very high energy density per unit of mass. This development could encourage long-distance shipping of hydrogen in the form of ammonia, which can then be consumed directly or converted into hydrogen.

Figure A17

Comparing Hydrogen's Energy Density per Weight and Volume with Other Fuel and Energy Sources[68]



Hydrogen has a much higher energy density by mass than other conventional fuel and energy sources, but it is drastically lower when considering its energy density by volume. Regarding its mass, hydrogen is lightweight and can contain greater amounts of energy over longer periods of time. Hydrogen's energy density by volume presents technical challenges, mainly that much more space is needed to store and transport large quantities of hydrogen. Source: ETC, 2021.

Another important technical consideration is that hydrogen's scaling potential is dependent on many factors that present cost and timing challenges. Increasing hydrogen production to energy-commodity scale will require massive investments across the supply chain. For a point of comparison, running one average-sized natural gas plant (500 megawatts [MW]) on 100 percent hydrogen for one year would consume 0.23 Mt of hydrogen (Figure A18). In other words, running one gas turbine on hydrogen—out of the roughly 2,000 in the U.S. gas turbine fleet—requires two percent of total current U.S. hydrogen production (Appendix E).

Scaling clean hydrogen will depend on new energy infrastructures, such as electricity supply systems (e.g., generation, transmission, and distribution equipment), natural gas networks, CO_2 and H_2 storage facilities, among others. DOE estimates producing 10 Mt of hydrogen from solar or wind would require an enormous expansion in installed capacity (134 and 93 percent, respectively).[69] While DOE's analysis does not simulate where the new generation could be sited, such growth would require a large-scale expansion of parts of the electric grid.

In addition to the cost issues, massive siting and associated permitting of new energy infrastructure will be needed. Siting and permitting could hinder project development. Interconnection projects between 2010 to 2020 spent up to 3.5 years in the permitting queue before being built.[70] At the end of 2020, around 680 GW of zero-carbon generation capacity was seeking grid interconnection. For five of the country's Independent System Operators

(ISO), only about 24 percent of the projects reached commercial operations, with individual rates for solar (16 percent) and wind (19 percent) even lower.

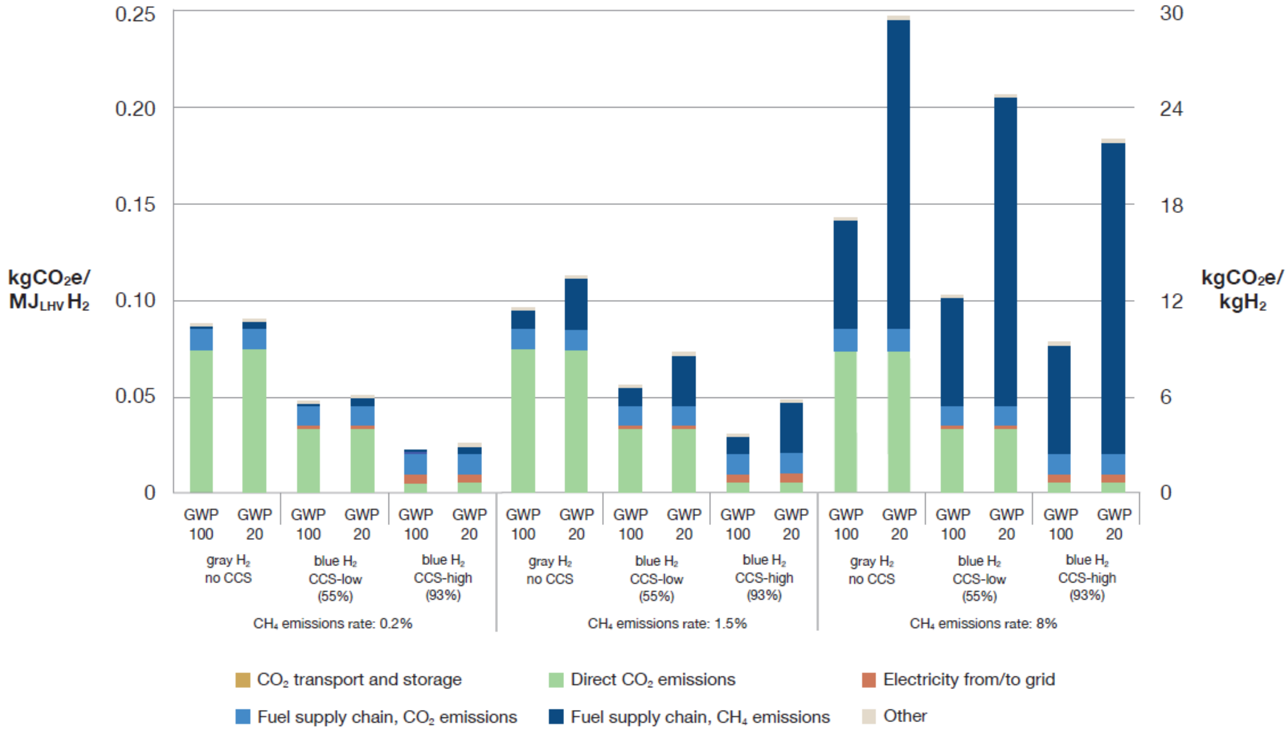
Figure A18
Comparing the Energy and Capacity Requirements of Energy Commodities with Hydrogen

How much Hydrogen is needed...	1 Barrel of Oil	1 Crude Oil Tanker Very Large Crude Carrier(VLCC)	Natural Gas Combined Cycle (NGCC) turbine (500 MW, 50% CF)	U.S. Natural Gas System
to meet the energy requirements of	.05 t	0.1 t	0.15 t	89 Mt (per year)
to meet the capacity (volume) requirements of	.01 t	0.021 t	---	288 Mt (per year)
in other words...	It takes 5 barrels of liquified H_2 to deliver the same energy as oil	It takes 5 VLCCs of liquified H_2 to deliver the same energy as one carrying crude oil	Running a single gas plant on H_2 would require 1 percent of today's U.S. H_2 production	It would take 25 years of today's H_2 production to fill the natural gas system with hydrogen

This graphic depicts how much hydrogen is needed to meet the energy and capacity requirements of major fueling infrastructure components in the fossil fuel industry. Meeting the energy requirements of these components would require a major scale up of the existing industry, while the volume requirements highlight the infrastructual challenge of delivering similar capacities with hydrogen's lower energy density by volume.

Recent research has raised important questions about the true Global Warming Potential (GWP) of hydrogen. In particular, there is concern of the effectiveness of fossil-based hydrogen pathways from a life cycle GHG emissions perspective.[71] Environmental impacts may vary and depend on a few key parameters: the methane emissions rate of the natural gas supply chain; the CO_2 removal rate at the hydrogen production plant; and the global warming metric applied. Comparing the potential GWP of different hydrogen production pathways—such as accounting for different upstream methane emission and carbon capture rates—it is evident poor management of upstream methane emissions leakage can profoundly impact the total life cycle emissions of "blue" hydrogen (Figure A19).

Figure A19
CO_2 Emissions of Hydrogen under Different Scenarios[72]



Impacts on climate change associated with the production of natural gas based hydrogen with methane emission rates of 0.2%, 1.5%, and 8%, and two plant configurations with high and low CO_2 removal rates, applying both GWP100 and GWP20. GWP measures how much energy the emissions of one ton of a gas will absorb over a given period, relative to the emissions of one ton of CO_2. The larger the GWP, the more a given gas warms the Earth compared to CO_2. The GWP can be measured at different timeframes; the 100-year measurement (GWP-100) is used the most often, but GWP-20 (or even GWP-5) is a more accurate way to measure hydrogen's impact because hydrogen is a short-lived climate pollutant and has a much larger impact over shorter time periods.[73] Stacked bars show the origin of GHG emissions along the value chain. "CCS-low" and "CCS-high" indicate low and high overall plant-wide CO_2 removal rates of 55% and 93% at the hydrogen production plant, respectively. Source: Bauer et al., 2022.

Additional research is needed on hydrogen as an indirect greenhouse gas. Hydrogen's presence in the atmosphere may increase the radiative forcing of other released chemical compounds. Hydrogen is currently a trace component of the atmosphere, at a ratio of around 500 parts per billion, the result of both anthropogenic and natural sources.[74] According to recent studies, because hydrogen reacts with key oxidants in the atmosphere, it can perturb the distributions of methane and ozone.[75,76] As a result, hydrogen may be considered an indirect greenhouse gas when leaked into the atmosphere. Moreover, hydrogen's atmospheric warming effects are short-lived (lasting a few decades), which makes analyzing its impacts somewhat difficult. A more expansive understanding of the impacts of hydrogen on the atmosphere is an important area for future research.[77]

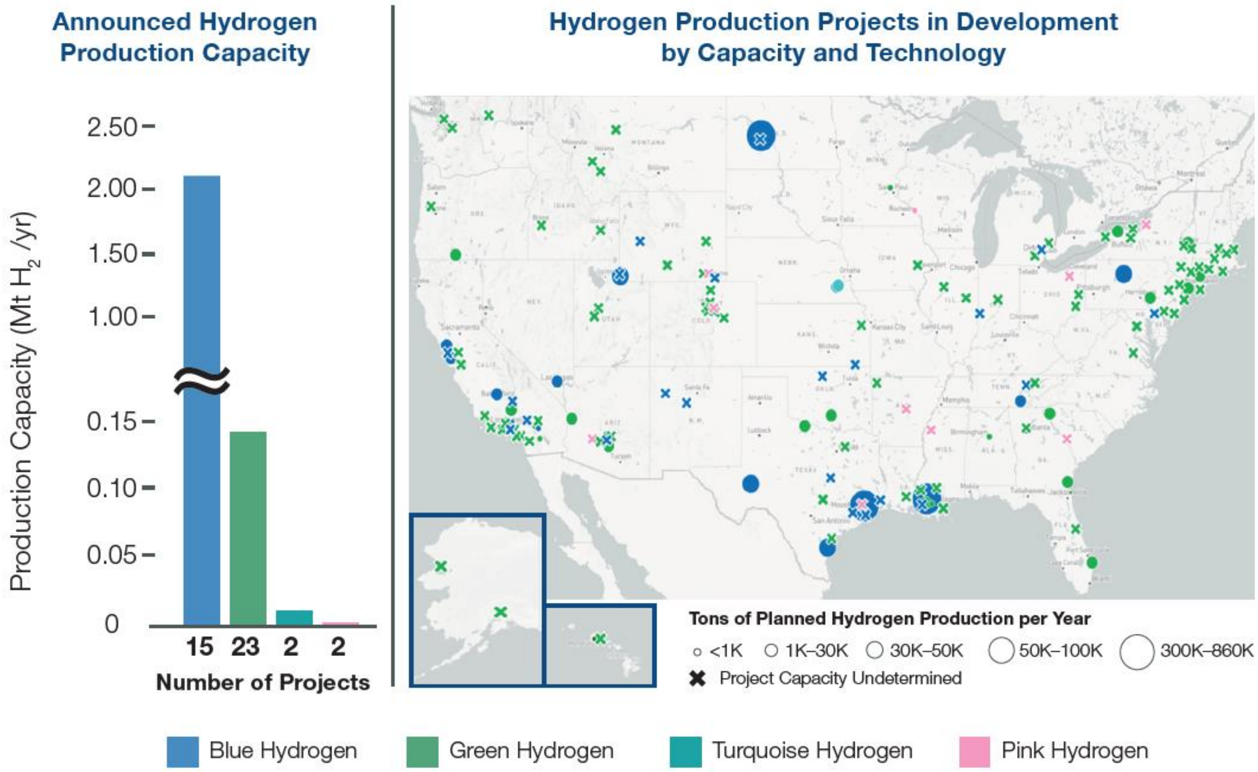
Appendix B. Clean Hydrogen Industry Trends

Clean hydrogen currently accounts for essentially zero percent of the U.S. hydrogen industry**.** However, there is a growing number of new clean hydrogen projects in the United States. Since June 2021, EFI has been tracking publicly announced hydrogen projects, partnerships, and activities in the United States. In September 2021, EFI identified 203 publicly announced projects that currently use, intend to use, or produce hydrogen in the United States, as reported in the *Views from Industry, Market Innovators, and Investors* report.[b] As of August 2022, the clean hydrogen activities inventory contained 374 distinct activities, representing an almost sevenfold increase in announced clean hydrogen projects. These announcements include a range of projects, partnerships, and activities across the value chain. This rapid growth can be attributed to new policies and funding for clean hydrogen, increasing economic interest, expanding visibility into the clean hydrogen project pipeline, and new research that compiles current hydrogen activities.

Clean hydrogen project announcements represent 2.2 Mt of potential clean hydrogen supply (Figure A20). This amount translates to roughly 21 percent of the current U.S. hydrogen industry. In total, 177 projects are production-oriented, and approximately 70 percent of those activities involve hydrogen produced with renewable energy via electrolysis. Even though activities involving blue hydrogen production make up only 20 percent of the production-oriented inventory, they have significant economies of scale and represent nearly 95 percent of the announced clean hydrogen production capacity.

[b] EFI's first iteration of the hydrogen activities inventory included in the *Views from Industry, Market Innovators, and Investors* report was predominantly composed of gray hydrogen facilities and tracked the growth of new production pathways and intended end-use sectors over time. Since that report, the inventory has shifted to focus only on clean hydrogen projects and activities.

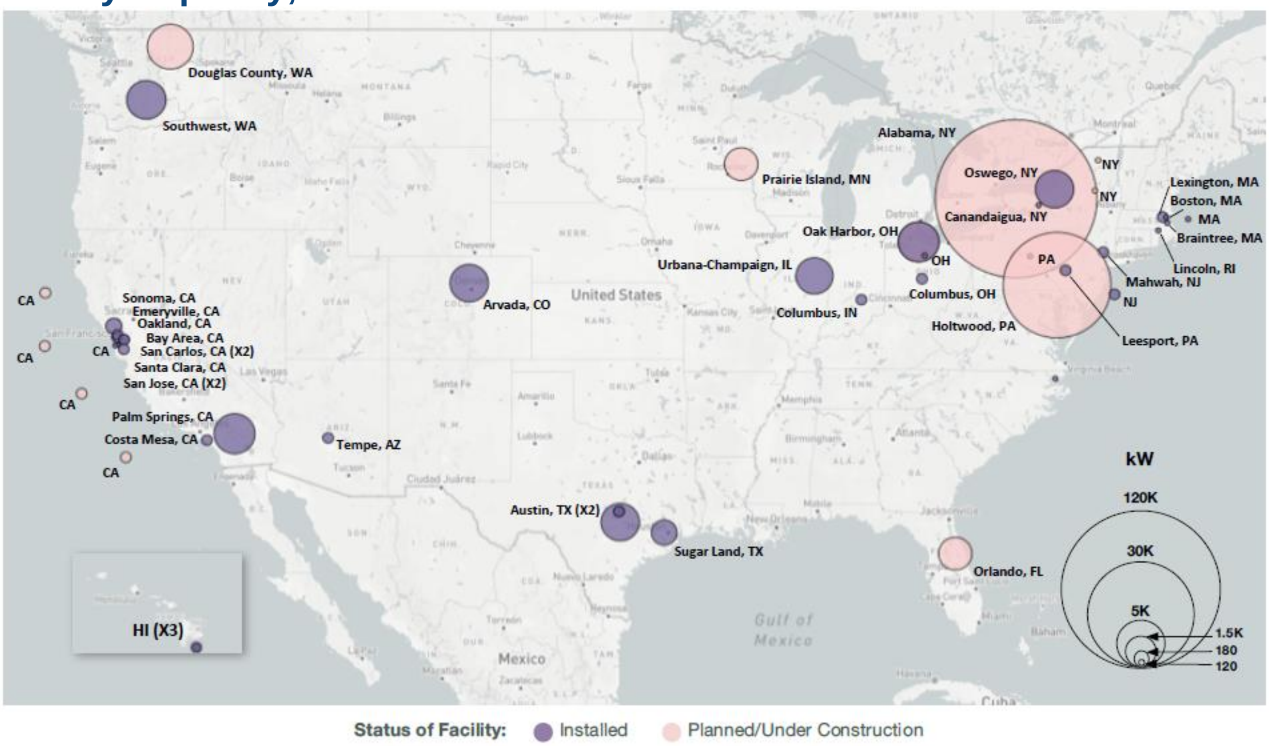
Figure A20
Announced Clean Hydrogen Project Activities



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

According to EFI's survey of investors exploring hydrogen, many favor electrolysis-based projects due to their scalability. There appears to be greater flexibility in building green hydrogen units of nearly any size, in many U.S. regions, while facing fewer dependency issues than blue hydrogen. Investors perceive blue hydrogen to be a less certain opportunity in the near term, as it depends on new CO_2 pipelines and geologic storage facilities which have their own costs and are subject to separate permitting and regulatory environments. Meanwhile, the IRA's incentives clearly favor green hydrogen pathways over others, as described in Chapter 3 of the main report. As of 2021, there was approximately 172 MW of installed or planned PEM electrolyzer capacity in the United States (Figure A21). These units range from less than 120 kilowatts (kW) (primarily used for laboratory research) to 2 MW, while the capacity for planned units ranges from 120 kW to 120 MW.[78]

Figure A21
Installed and Planned PEM Electrolyzers in the United States by Capacity, 2021[79]

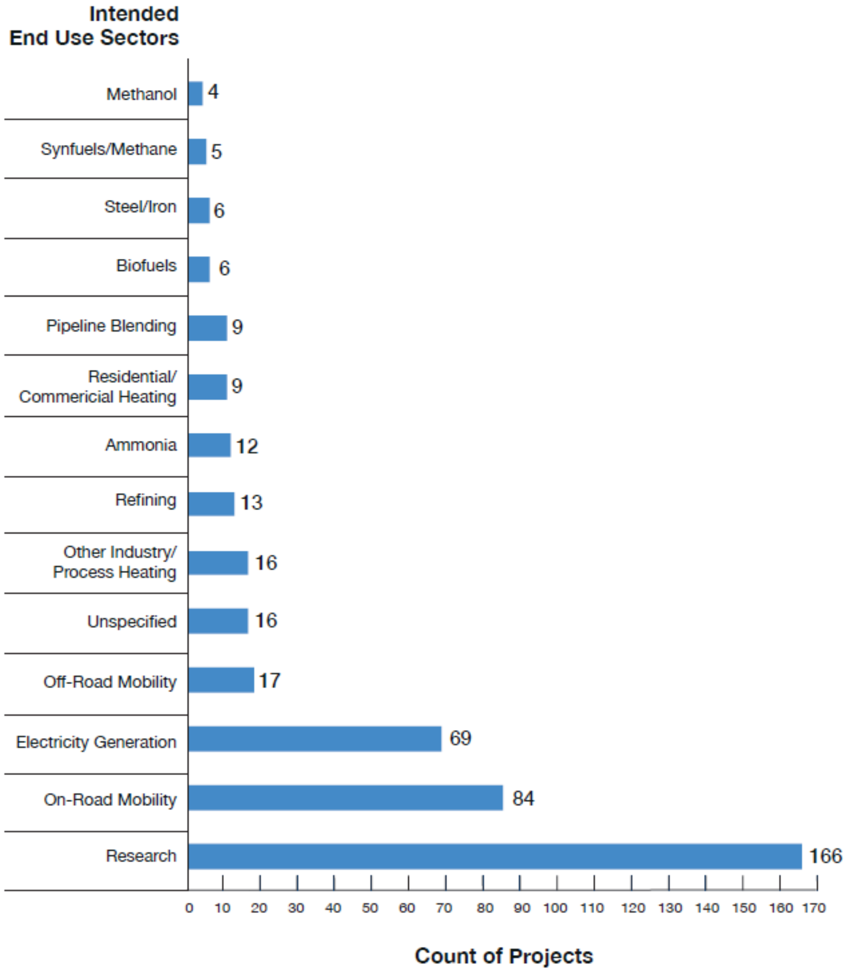


To date, electrolyzers are generally small-scale and use grid electricity, thus having a negligible effect on emissions reduction efforts. Still, the modularity of electrolyzers allows for promising developments in terms of the scale and scope of projects coming online in the next three to five years. The Alabama NY project, for example, could produce nearly 17,000 t of liquid hydrogen annually. Data from: DOE, 2021.

Announced clean hydrogen projects also involve a wide variety of intended end-use sectors. As shown in Figure A22, most announced projects and activities are related to research and development (R&D), either through the federal government or public-private partnerships. On-road mobility represents the end-use sector with the largest proportion of identified clean hydrogen activities. The prevalence of these mobility projects further supports the conclusions reached in EFI's *Views of Industry* report, which found many firms viewed on-road mobility as the most mature near-term demand growth area for hydrogen in the United States.[80]

The next most prominent end-use sector for announced clean hydrogen projects is electricity generation which includes projects using hydrogen in power plants, blending with natural gas in turbines, and using hydrogen as a form of energy storage. Other announced project end uses for clean hydrogen include industrial heating, refining, and chemical applications and suggest hydrogen could play a role across many sectors in a future, decarbonized energy system.

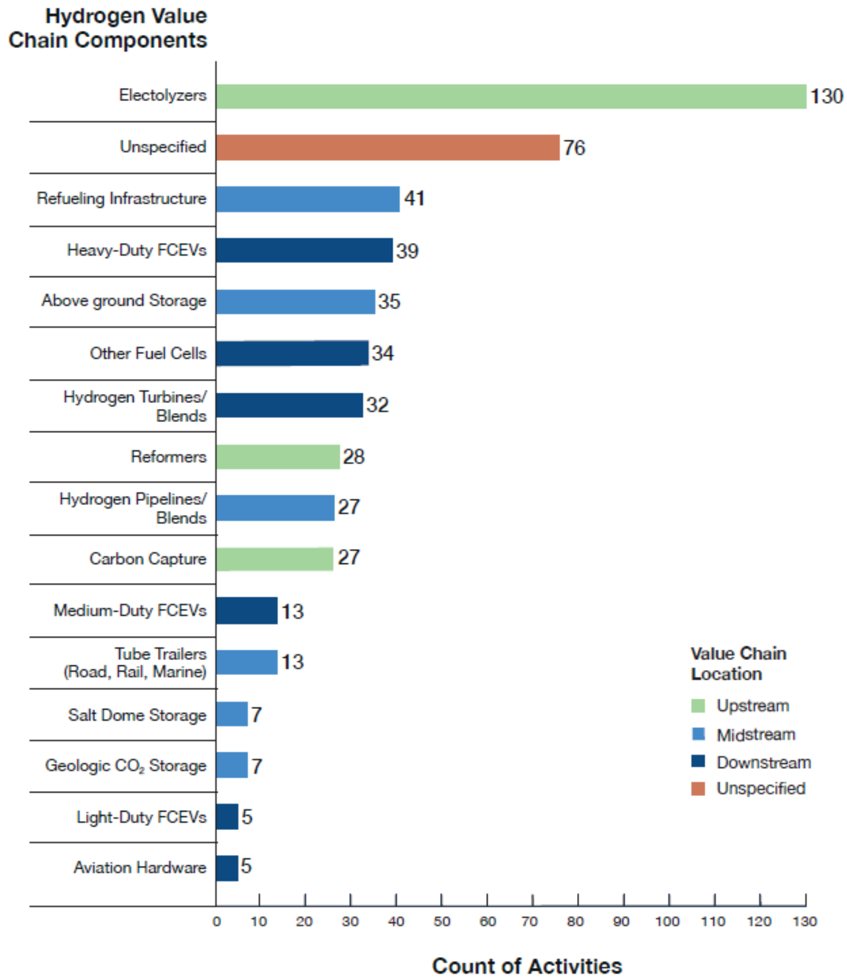
Figure A22
Intended End-Use Sectors of Announced U.S. Clean Hydrogen Projects



This graphic represents the intended end-use sectors for the 374 clean hydrogen projects, partnerships, and activities identified in the clean hydrogen activities inventory. Each individual activity identified in the database may have more than one intended end-use sector, which is represented here. Activities labeled "Unspecified" did not provide public details on intended end uses of the project. The results presented in this graphic were compiled from publicly available data and news for each announced activity as of August 2022.

Announced clean hydrogen projects involve many components of the value chain. As shown in Figure A23, electrolyzers are the most common component of the value chain for announced clean hydrogen projects. A large proportion of announced clean hydrogen projects involve on-road mobility, particularly heavy-duty fuel cell electric vehicles (FCEV) and refueling infrastructure. Hydrogen storage, fuel cells, blending infrastructure, and turbines were also mentioned regularly across the publicly announced clean hydrogen activities. While not as common as electrolyzers, reformers and carbon capture devices were identified in a handful of upstream projects. Additionally, while the quantity and scale of these clean hydrogen activities are not yet adequate to stimulate broader market formation, the inventory shows projects focused on production, distribution, and end use that could encourage other actors to enter the market across the value chain.

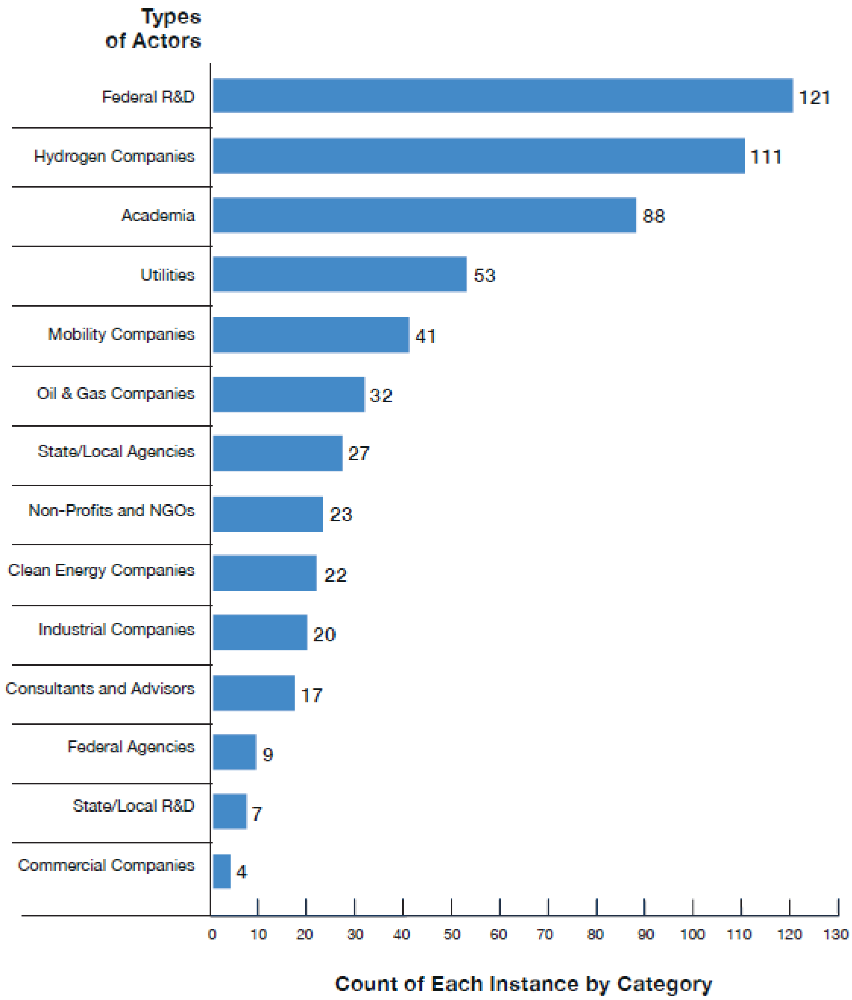
Figure A23
Value Chain Components of Announced U.S. Clean Hydrogen Projects



This graphic details the main components of the clean hydrogen value chain identified in the clean hydrogen activities inventory. The counts represent components announced by each of the 374 activities included in the inventory developers intend to use or are currently developing as part of their project. Many projects in the inventory specify one or more of these components, which have been categorized according to their location along the value chain. Approximately 76 activities did not publicly announce the intended value chain components of their project or partnership activities.

Multi-sector partnerships are a major component of announced clean hydrogen projects. More than 60 percent of announced clean hydrogen projects involve partnerships between multiple organizations, private companies, or government agencies/institutions at the federal and state levels (Figure A24). The federal government and academia participate in the largest proportion of projects identified in the inventory, as most clean hydrogen projects are R&D-focused. Companies from the current hydrogen industry are another major group in these partnerships, leveraging their experience and existing infrastructure. Utilities are active participants, mostly focusing on power applications, while mobility companies are exploring on-road transportation, and incumbent oil and gas companies are seeking to decarbonize their existing operations.

Figure A24
Partners Involved in Announced U.S. Clean Hydrogen Projects



This chart depicts the frequency of different categories of actors participating in projects that rely on partnerships and are being tracked in the clean hydrogen activities inventory. Projects or activities with only one actor are not represented *in this graphic. This chart helps to identify the industries most commonly participating in clean hydrogen partnerships and depict how frequently actors within those industries show up in inventory's partnership activities.*

Many of the announced clean hydrogen activities overlap geographically with existing industrial clusters, as seen in Figure A25. Most announced activity is in the Gulf Coast, California, throughout the East Coast, and parts of the Midwest. These existing clusters of industrial activities are particularly important for the development of hubs because they reduce the upfront costs for transmission and distribution infrastructure, ultimately supporting the co-location of supply and demand for hydrogen.

Figure A25

Hydrogen Production Projects are Often Located Near Industrial Clusters

In many cases, clean hydrogen projects are built in highly industrial areas, which can be valuable when creating a hydrogen hub. Industrial facilities are potential large suppliers or off-takers of hydrogen, and they provide much of the needed infrastructure for build out of hydrogen activity. The facilities included in this graphic represent the approximately 177 production-oriented activities identified in the clean hydrogen activities inventory.

U.S. Hydrogen Policy Trends

While some federal and state incentives for hydrogen previously existed—such as the Alternative Fuel Tax Exemption at the federal level and California's Low Carbon Fuel Standard (LCFS)—recent policy actions are creating opportunities to develop domestic clean hydrogen on an accelerated timetable. The IIJA and IRA create opportunities to build the clean hydrogen value chain, de-risking new project development. These recent policy actions represent the largest federal investment in clean hydrogen in U.S. history. Both the IIJA and IRA provide direct funding opportunities for clean hydrogen projects across the value chain. The IIJA, which became law in August 2021, provides $9.5B for clean hydrogen research, development, and demonstration programs—a considerable increase in funding for U.S. clean hydrogen R&D, which had been in the range of $200 million to $300 million (MM) per year between 2016 and 2021.[81] The IIJA's flagship hydrogen program includes $8.0B for "at least" four regional clean hydrogen hubs, authorized for FY2022 to FY2026.[82] The IIJA's regional clean hydrogen hub program is designed to support simultaneous development of supply and demand—seeking to address the biggest "chicken vs. egg" problem of new technology deployment.

Also, in August 2022, the IRA was passed, representing the largest package of federal support for clean hydrogen in U.S. history. The IRA provides $369B in new spending for clean energy, including tax credits for clean hydrogen production and support for building out the clean hydrogen value chain.[83] The IRA provides new funding opportunities for clean hydrogen projects across the value chain, from building clean supply chains through domestic clean manufacturing (of hydrogen equipment) to industrial and customer end-use. These policy opportunities may represent an inflection point in U.S. clean hydrogen market formation.

The Infrastructure Investment and Jobs Act (IIJA)

The IIJA, also known as the Bipartisan Infrastructure Law (BIL), authorizes and appropriates $9.5B for clean hydrogen development. It includes $1B for a Clean Hydrogen Electrolysis Program to reduce costs of hydrogen produced from clean electricity and $500MM for Clean Hydrogen Manufacturing and Recycling Initiatives.[84] The flagship program is $8B to $6-7B to be disbursed in a first round, with up to 50 percent cost share with industry—for developing at least four regional clean hydrogen hubs, which are defined as "a network of clean hydrogen producers, potential clean hydrogen consumers, and connective infrastructure located in close proximity." The Regional Hydrogen Hubs (H2Hub) program Funding Opportunity Announcement (FOA) states that DOE envisions selecting six to 10 hubs in the first round of funding.[85] The regional hubs must aid in the achievement of the clean hydrogen production standard, as well as demonstrate the viability of the whole hydrogen value chain, from production, processing, delivery, and storage, to end-use of clean hydrogen. Hydrogen hubs are expected to spur the development of a "national clean hydrogen network to facilitate a clean hydrogen economy."

To promote diversity in feedstock use, location, and end-use applications, IIJA outlines several selection criteria DOE must observe when selecting hydrogen hubs projects. Per this selection criteria, at least one hub shall demonstrate the production of clean hydrogen from fossil fuels, renewable energy, and nuclear energy; at least one hub shall demonstrate the end-use of clean hydrogen in the electric power generation sector, industrial sector, residential and commercial heating sector, and transportation sector; each regional clean hydrogen hub will be located in a different region of the country and will use abundant energy resources in that region. In addition, at least two regional clean hydrogen hubs must be in regions with the greatest natural gas resources, and DOE must prioritize regional clean hydrogen hubs likely to create opportunities for skilled training and long-term employment to the greatest number of residents in the region where the hub is located.

Regional clean hydrogen hubs must also conform to technical requirements. The IIJA defines "clean hydrogen" as hydrogen produced with a carbon intensity, at site of production, equal to or less than 2.0 kg CO_2e/kg H_2 from several production pathways: "renewable, fossil fuel with carbon capture, utilization and sequestration technologies, nuclear, and other fuel sources using any applicable production technology." The CHPS developed by DOE goes a step further and establishes a target of 4.0 kg CO_2e/kg H_2 for life cycle GHG emissions—in line with the IRA definition of "qualified clean hydrogen." Hydrogen hubs must "demonstrably aid achievement of, but do not necessarily need to meet, the clean hydrogen production standard," which is to be viewed "as one to orient towards but not necessarily achieve in the near term."[86] Nevertheless, hydrogen hubs that demonstrate ability to reduce emissions throughout their value chain—that is, have lower life cycle emissions—will be favorably evaluated. The bill specifies CHPS may be adjusted below the existing threshold within five years.

The IIJA requires the development of a National Clean Hydrogen Strategy and Roadmap. The bill amended Title VIII of the Energy Policy Act of 2005 by adding Section 814, which dictates DOE "shall develop a technologically and economically feasible national strategy and roadmap to facilitate widescale production, processing, delivery, storage, and use of clean hydrogen." A draft roadmap was released in September 2022 and DOE expects stakeholder feedback to finalize the report and develop updates every three years, as required by the legislation.[87]

The draft roadmap prioritizes three strategies to ensure hydrogen contributes the most to the U.S. decarbonization efforts. The first goal is to target strategic, high-impact uses for clean hydrogen by focusing on sectors that do not have a viable deep decarbonization alternative (e.g., industrial sector, heavy-duty transportation, and long-duration energy storage). The long-term opportunity of exporting clean hydrogen or hydrogen carriers, which will contribute to the energy security of the country's allies, is also considered. The second goal aims to reduce the cost of clean hydrogen through the Hydrogen Shot initiative (detailed below). Finally, by focusing on regional networks, like hydrogen hubs, DOE expects to promote critical mass infrastructure, drive scale, and foster market formation by enabling large-scale clean hydrogen production and end-use in proximity. As a result of such strategy, the roadmap expects clean hydrogen demand will reach 10 Mt, 20 Mt, and 50 Mt by 2030, 2040, and 2050, respectively, resulting in approximately 10 percent emission reduction by 2050 relative to 2005—consistent with the U.S. Long-Term climate strategy.[88]

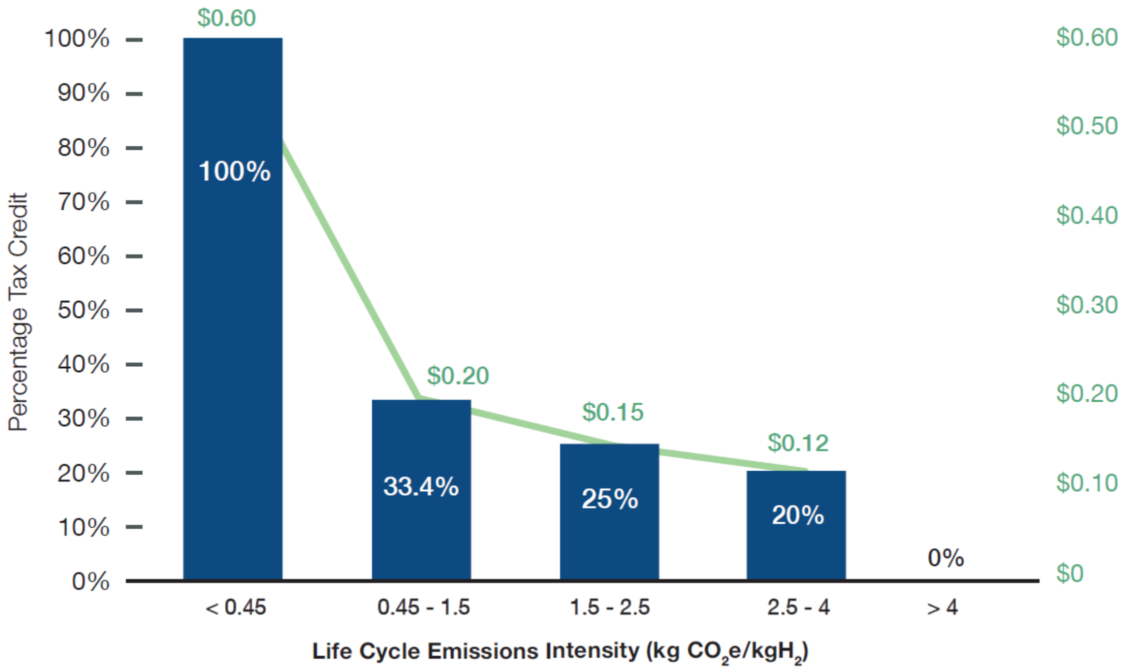
The Inflation Reduction Act (IRA)

The IRA establishes a clear federal policy framework for clean hydrogen that is technology-neutral and based on life cycle emissions. As interest in clean hydrogen has grown in the last few years, some investors have expressed concerns over whether or not federal policy will be technology neutral.[89] The new 45V tax credit provides taxpayers a 10-year production tax credit (PTC) for "qualified clean hydrogen" projects that result in a life cycle GHG emissions rate of less than 4.0 $CO_2e/kg\ H_2$ (the CHPS is also aligned with this target).[c,90]

The lower the emissions intensity, the higher the percentage of the tax credit received (Figure A26). Such requirement is important as the policy preferences emissions intensity while being technology agnostic. Tax credits begin at $0.12/kg for hydrogen produced with a life cycle GHG emissions intensity between 2.5 kg $CO_2e/kg\ H_2$ and 4.0 kg $CO_2e/kg\ H_2$, increasing to $0.60/kg for hydrogen that is lower than 0.45 kg $CO_2e/kg\ H_2$. A multiplier of five is applied to these values if the project is built within a given period and meets certain prevailing wage and apprenticeship requirements, resulting in a tax credit of up to $3/kg of hydrogen produced. Projects are eligible for a bonus 10 percent PTC if certain "domestic content requirements" are met or if the project is located in an "energy community." If eligible for both, taxpayers may stack bonus credits.[91]

Figure A26

45V Hydrogen Production Tax Credit Life Cycle Emissions Thresholds



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

[c] The term "life cycle greenhouse gas emissions" has the same meaning given such term under subparagraph (H) of section 211(o)(1) of the Clean Air Act (42 U.S.C.7545(o)(1)). The term "life cycle greenhouse gas emissions" shall only include emissions through the point of production (well-to-gate).

In addition, the IRA revises the tax code to adjust existing, and create new, credits and incentives for clean hydrogen projects**.** It changes the existing Section 45 (PTC) and Section 48 (Investment Tax Credit [ITC]) to a two-tiered system with multiplier credits based on a project's support for local economies and workers.

- **New Credits:** The IRA introduces a new tax credit system for "technology neutral" zero-emissions projects that will allow taxpayers to claim a tax credit, similar to the existing ITC and PTC. For projects already under construction (to be placed in service after 2022), it allows them to remove the credit phaseouts for the existing PTC and ITC incentives.[92,93] The IRA also improves the terms of the 12-year Section 45Q tax credits for carbon storage. It extends the deadline for eligible projects through 2032. It also enhances the credits, using the new structure of "base" and "bonus" credits (see next bulleted point for more information), adjusted for inflation. For a facility placed into service after 2022, the credit will be $85/t ($17 "base") if the CO_2 is sequestered and $60/t ($12 "base") for enhanced oil recovery (EOR).[94] The IRA also provides new credits for stand-alone energy storage facilities and other new pathways like nuclear energy and sustainable aviation fuel.[95,96,97] It adds an advanced manufacturing tax credit for manufacturers of solar and wind components in the United States.[98] Finally, the IRA also allows projects to monetize renewable tax credits by allowing certain entities to receive a cash payment instead of tax credits or selling tax credits to third parties.[99]
- **The Base and Bonus Credits:** The IRA replaces Section 45 with a two-tiered system that provides a "base credit" (20 percent of the maximum credit) and a "bonus credit" (80 percent of the maximum credit) for projects that meet prevailing wage and apprenticeship requirements, respectively.[100] To be eligible for the base credit, the taxpayer must ensure any laborers, including contractors and subcontractors, are paid the prevailing local wages, as determined by the Department of Labor, for both construction and subsequent repairs for a 5-year period. To claim the bonus credit, taxpayers must ensure a share of the total construction labor hours are performed by qualified apprentices. The applicable percentage is 10 percent for projects beginning construction before 2023, 12.5 percent for projects beginning construction during 2023, and 15 percent for projects beginning construction thereafter.[101]
- **Incremental Credits:** Incremental credits are available for projects that meet certain domestic content, energy community, and low-income community requirements.
    - ***Domestic Content:*** Projects that qualify for certain credits in Section 45 (PTC), Section 48 (ITC), and all credits under new Section 45Y (clean

electricity production) and new Section 48E (clean investment) can receive a 10 percent increase to the "base" and "bonus" credits if they meet certain domestic content requirements. Specifically, projects must ensure the steel, iron, and other manufactured products are produced in the United States. In most cases, at least 40 percent of the total component costs (20 percent for offshore wind) must be mined, produced, or manufactured domestically. In some cases, the percentages are also affected by the date of construction. The IRA allows the Treasury to provide exceptions, such as those that may result in significant (i.e., more than 25 percent) cost increases for the project.[102]

- ***Energy Communities:*** Projects located in an energy community will qualify for a 10 percent increase to the "base" and "bonus" credits. Energy communities are defined as 1) brownfield sites, 2) communities that had employment or tax revenues from coal, oil, or natural gas industries in excess of certain thresholds, 3) regions with an unemployment rate at or above the national rate for the prior year, and 4) communities with a coal mine closed after 1999 or a retired coal-fired generation station.[103]
- ***Low-Income Communities*:** Solar and wind projects of 5MW or less can receive incremental credits if they are in low-income communities or on American Indian Land (10 percent) or are part of a qualified low-income residential building (20 percent).[104]

Opportunities exist for credit stacking in the IRA, which may benefit certain regional hydrogen hubs. Many new clean energy projects combine multiple sectors and multiple technologies. The IRA makes it possible for a taxpayer to combine credits for renewable electricity generation with the incentives for clean hydrogen production and storage infrastructure. A taxpayer developing a clean hydrogen project that relies on renewable electricity may pair the 45V tax credits with certain credits from Section 45 (PTC), Section 48 (ITC), Section 45Y (clean electricity production), and the new Section 48D (clean investment) credits. Some credits, including 45Q, may not be stacked with the new 45V production tax credits.[105] As such, green hydrogen production pathways are likely to continue to receive investor preference compared to others. It is important to note that projects, such as hubs with multiple taxpaying entities, may leverage multiple credits. A regional clean hydrogen hub, for example, may use the 45Q tax incentives for geologic storage and the 45V for clean hydrogen production, so long as it is not through a single taxpaying entity.

The IRA also includes ways to improve the bankability of these incentives. There are mechanisms that give project developers options beyond tax equity markets, providing new ways to monetize credits. A direct pay option allows any taxable entity to claim the entire credit as a direct pay option for the first five years of production. This option applies to the clean hydrogen production credit, the credit for carbon capture, and the new manufacturing tax credit. Direct pay allows entities to treat the credits as tax payments or refunds. After January 2033, only defined tax-exempt organizations are eligible for the direct pay option, including certain state or political organizations (e.g., Indian tribal governments), or rural electric cooperatives.[106]

Another way the IRA provides flexibility is by allowing third party sales of the credits. Starting in 2023, taxpayers may transfer all or part of the credits to another taxpayer. The transfer must be paid in cash and will not be included in the income of the original party (nor is it tax deductible). Credits may not be transferred more than once.[107] These mechanisms are designed to give project developers some flexibility with how to monetize their tax credits without accessing tax equity markets (Box A4). While the IRA details the mechanisms to encourage greater flexibility in accessing and monetizing these tax credits, there is still a great deal of uncertainty regarding the necessary rulemaking from the Internal Revenue Service (IRS) to operationalize these tax credits. In fact, as of November 2022, the IRS had issued a request for comments on a handful of IRA provisions—including 45V and 45Q—to support the agency's construction of guidance for taxpayers to claim the energy credits.[108]

Box A4
Direct Pay, Tax Credits, and Tax Equity

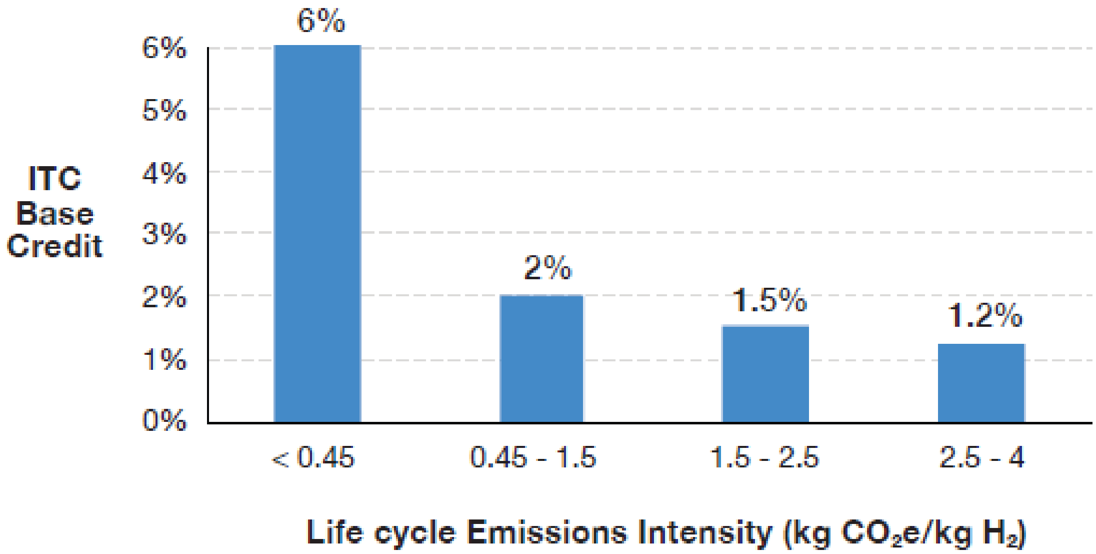
The overall value of the new IRA tax credits to enable new clean hydrogen projects is based, in part, on how they are structured. Tax credits reduce the amount of income tax owed to the federal government. Generally, they are designed to encourage or reward certain types of projects and activities considered to be beneficial to the economy or environment. In most cases, tax credits cover expenses incurred over the year and have requirements that must be satisfied before they can be claimed.[109]

Tax equity investment describes a transaction that pairs tax credits with the capital financing associated with that investment. These transactions involve one party agreeing to assign the rights to claim the tax credits to another party in exchange for an equity investment (i.e., cash financing). Importantly, the sale of federal tax credits usually occurs within a partnership or contractual agreement that legally binds the two parties.[110] The most active tax equity investors demonstrate a preference for large projects that use established and proven technologies, which have expanded to include hydrogen and other solutions due to the passing of the IRA.[111]

Direct pay refers to a refund from the Treasury Department for the amount of tax credit claimed. The IRA offers direct pay for some tax credits, including 45V, with some restrictions. Allowing hydrogen developers to access direct pay through the 45V PTC in the first five years will provide the cash flow to hasten the development of a clean domestic hydrogen market.

Clean hydrogen production facilities also have the option to make an election for the ITC in lieu of the PTC.[112] The ITC offers a base credit of 6 percent multiplied by an applicable percentage, which reaches 100 percent if the life cycle GHG emissions rate is less than 0.45 kg CO_2e/kg H_2 produced. The base credit is adjusted downward based on the life cycle GHG emissions rate (Figure A27). Credit rates are increased by five times the base rate (i.e., up to 30 percent) if certain wage and apprenticeship requirements are met.

Figure A27
ITC Thresholds Based on Hydrogen Life Cycle Emissions Intensity



Clean hydrogen producers can elect to use the ITC for zero-emission energy projects in place of the 45V PTC. The ITC offers a base credit of 6 percent for qualified facilities, which is then multiplied by the percentages depicted in this graph based on the life cycle emissions intensity of each project. Beyond this base credit, a bonus credit can also be applied if prevailing wage and apprenticeship requirements are met.

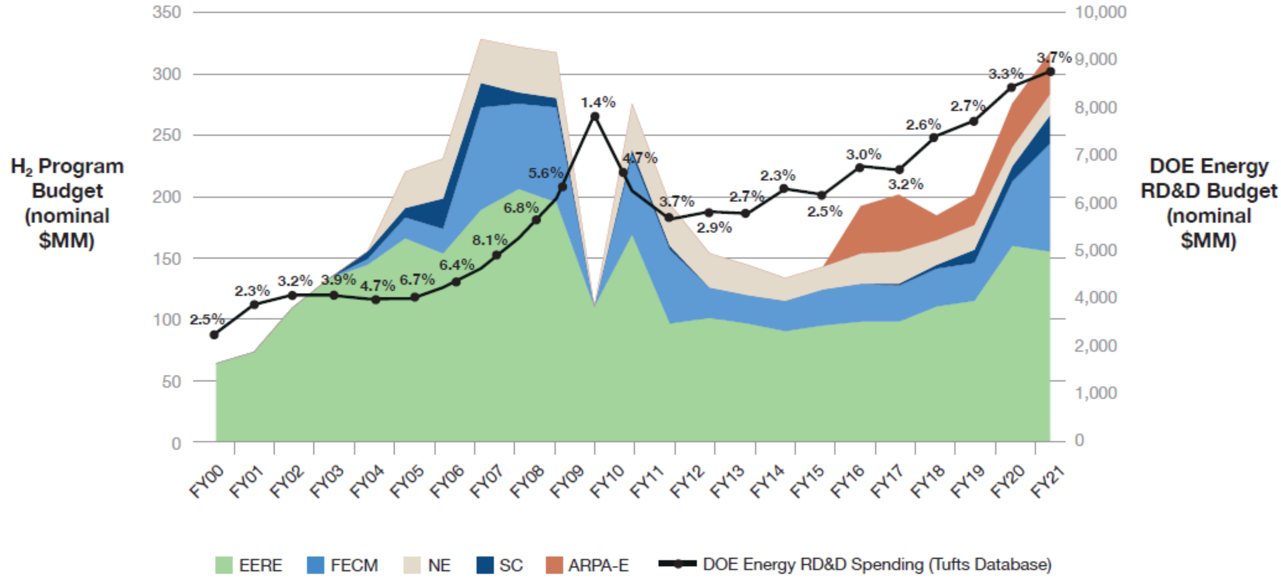
The IRA creates a new $5.8B program under the Office of Clean Energy Demonstration (OCED) to invest in projects aimed at reducing emissions from energy-intensive industries. The program offers grants, rebates, direct loans, or cooperative agreements with up to 50 percent cost share. It prioritizes projects with high emissions reductions benefits and industries with large labor forces, such as iron, steel, concrete, glass, pulp, paper, ceramics, and chemical production.

DOE’s Hydrogen Activities

Historically, the United States has not prioritized clean hydrogen research, development, and demonstration (RD&D). In fact, annual hydrogen RD&D appropriations to DOE’s Hydrogen Program have been relatively small compared to other clean energy technologies. Aside from the American Recovery and Reinvestment Act (ARRA), DOE’s hydrogen RD&D accounted for 2.3 percent to 3.7 percent of total energy R&D over the last decade (Figure A28).

Figure A28

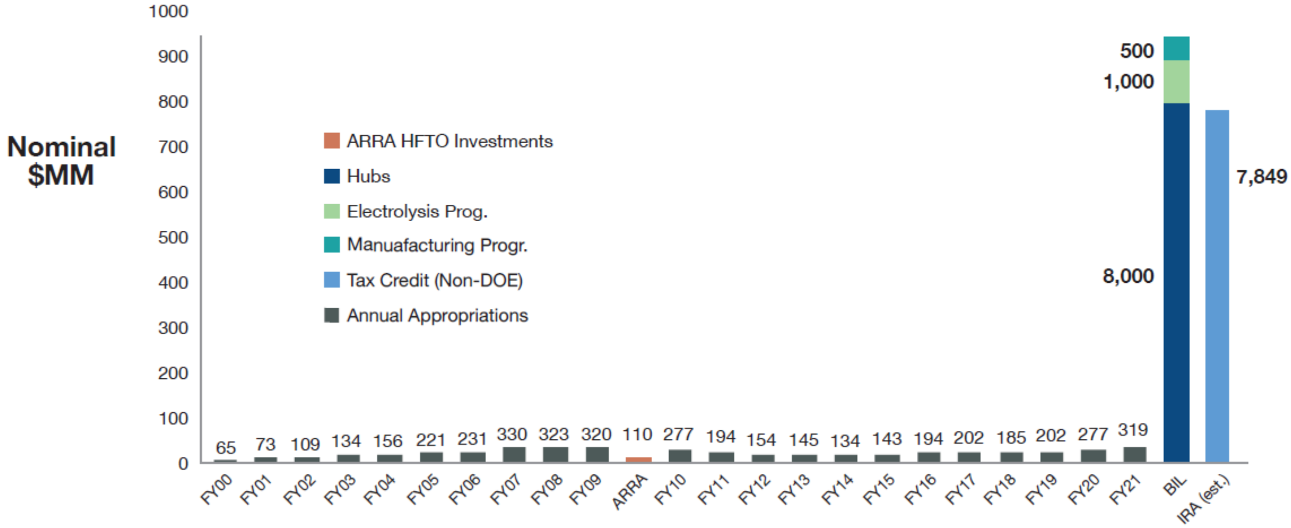
DOE Historical Hydrogen Budget by Office (and % of Total Energy RD&D)[113,114,115,116]



This graph shows DOE's Hydrogen Program budget for each office from FY00 to FY21. The visual also contains DOE's total energy RD&D budget over that timeframe along with the percentage of the total dedicated to hydrogen. Note the American Recovery and Reinvestment Act of 2009 (ARRA) provided additional stimulus appropriations between FY09 and FY10. Data from: DOE, 2022; Gallagher and Anadon, 2020; Yunzhe et al., 2020; DOE, 2016.

However, recent policy activities in both the BIL and IRA create significant opportunities for clean hydrogen project development, representing a nearly 30x increase in funding compared to previous federal investments. These activities demonstrate a concerted effort to scale up federal RD&D for clean hydrogen to ensure the RD&D pipeline will continue to be a critical aspect of long-term market development (Figure A29).

Figure A29
DOE Hydrogen Funding in Annual Appropriations, ARRA, BIL, and IRA[117,118,119,120]

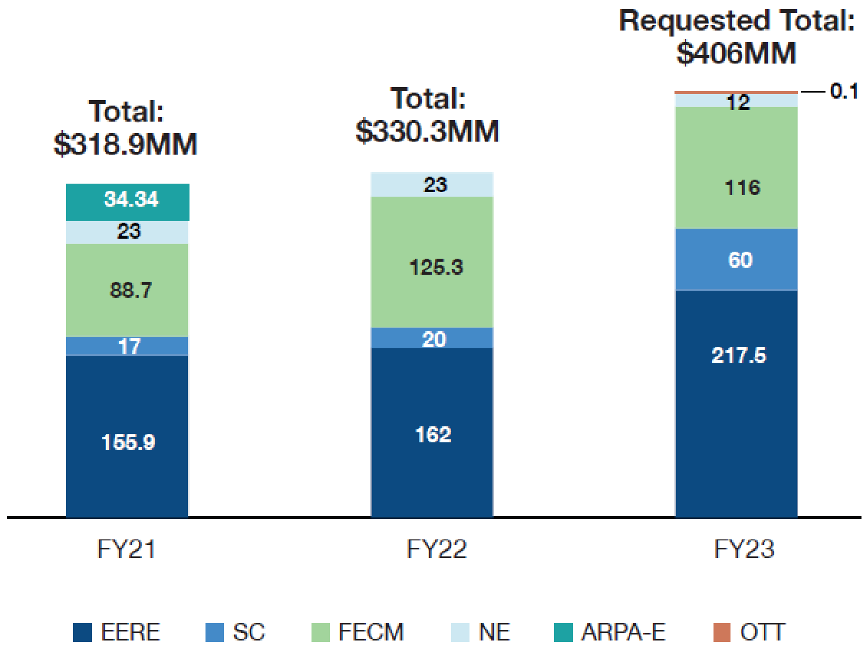


This graph shows DOE's Hydrogen Program appropriations for each office from FY00 to FY21 compared to the recently announced funding in the BIL and IRA. These recent policy provisions will drastically increase federal support for hydrogen projects and expedite their commercial readiness. Note the American Recovery and Reinvestment Act of 2009 (ARRA) provided additional stimulus appropriations between FY09 and FY10. Data from: DOE, 2022; Gallagher and Anadon, 2020; Yunzhe et al., 2020; DOE, 2016.

DOE is actively implementing programs and partnerships to bolster the R&D of clean hydrogen. For FY22, DOE received a total of $330.3MM in appropriations dedicated to its Hydrogen Program which spans five primary offices: the Office of Energy Efficiency and Renewable Energy (EERE); the Office of Science (SC); the Office of Fossil Energy and Carbon Management (FECM); the Office of Nuclear Energy (NE); and Advanced Research Projects Agency-Energy (ARPA-E). While this amount is a relatively small increase compared with FY21 ($318.9MM), DOE is requesting $406MM in appropriations related to its Hydrogen Program for FY23 (Figure A30).[121]

Figure A30

DOE Hydrogen Program Appropriations FY21-FY23 ($ Million)[122]



DOE's Hydrogen Program has received increasing appropriations over the past two fiscal year cycles across five of its primary offices. DOE has requested an increase to $406MM for FY23. Source: DOE, 2022.

Most federal funding for hydrogen goes to EERE's Hydrogen and Fuel Cells Technology Office (HFTO). HFTO's mission is to initiate RD&D activities that promote clean hydrogen and carbon removal potential across all sectors while also ensuring job creation for an equitable energy transition. HFTO has supported 1,256 patents in hydrogen and fuel cell technologies through its partnerships with National Laboratories, industry, and academia. Additionally, HFTO has helped commercialize 30 technologies through partnerships with private industry and supported 65 technologies expected to enter market in the next three years to five years. Some examples of these technologies include fuel cell catalysts, hydrogen tube trailers, storage tanks, and electrolyzers.[123] One mechanism through which HFTO has encouraged this innovation is its National Laboratory Consortia projects with universities and industry stakeholders (Table A1).

Table A1: Overview of DOE's National Laboratory Consortia Projects through the Hydrogen and Fuel Cells Technology Office (HFTO)[124]

HFTO's National Laboratory Consortia Projects	
ElectroCat	The Electrocatalysis Consortium (ElectroCat) is an initiative to accelerate the development of catalysts made without platinum group metals (PGM-free) for use in automotive fuel cell applications.
H2NEW	The Hydrogen from Next-generation Electrolyzers of Water (H2NEW) consortium will conduct R&D to achieve large-scale, affordable electrolyzers, which use electricity to split water into hydrogen and oxygen and can be powered by various energy sources, including natural gas, nuclear, and renewables. This R&D will complement and help support large industry deployment by enabling more durable, efficient, and low-cost electrolyzers.
H-Mat	The Hydrogen Materials Compatibility Consortium (H-Mat) is a framework for cross-cutting early-stage R&D on the compatibility of hydrogen materials to improve the reliability and reduce the costs of materials, and to inform codes and standards that guide development and use of pathways in hydrogen.
HyBlend	The HyBlend initiative aims to address technical barriers to blending hydrogen in natural gas pipelines. Key aspects of HyBlend include materials compatibility R&D, techno-economic analysis, and life cycle analysis that will inform the development of publicly accessible tools that characterize the opportunities, costs, and risks of blending.
HydroGEN	The HydroGEN Advanced Water Splitting Materials consortium focuses on advanced water splitting materials, initially for the photoelectrochemical, solar thermochemical, and advanced electrolytic hydrogen production pathways.
HyMARC	The Hydrogen Materials—Advanced Research Consortium (HyMARC) aims to address unsolved scientific challenges in the development of viable solid-state materials for storage of hydrogen onboard vehicles. Better onboard hydrogen storage could lead to more reliable and economic hydrogen fuel cell vehicles.
M2FCT	The Million Mile Fuel Cell Truck Consortium (M2FCT) focuses on R&D to improve fuel cell durability, performance, and cost to better position fuel cell trucks as a viable option in the long-haul trucking market. This initiative will set a five-year goal to prove the ability to have a fully competitive heavy-duty fuel cell truck that can meet all of the requirements of the trucking industry.

The seven consortia projects listed in this table are some of the key mechanisms DOE is employing to encourage innovation in hydrogen technologies and build collaborative relationships with academic and industry stakeholders. Adapted from: DOE, 2022.

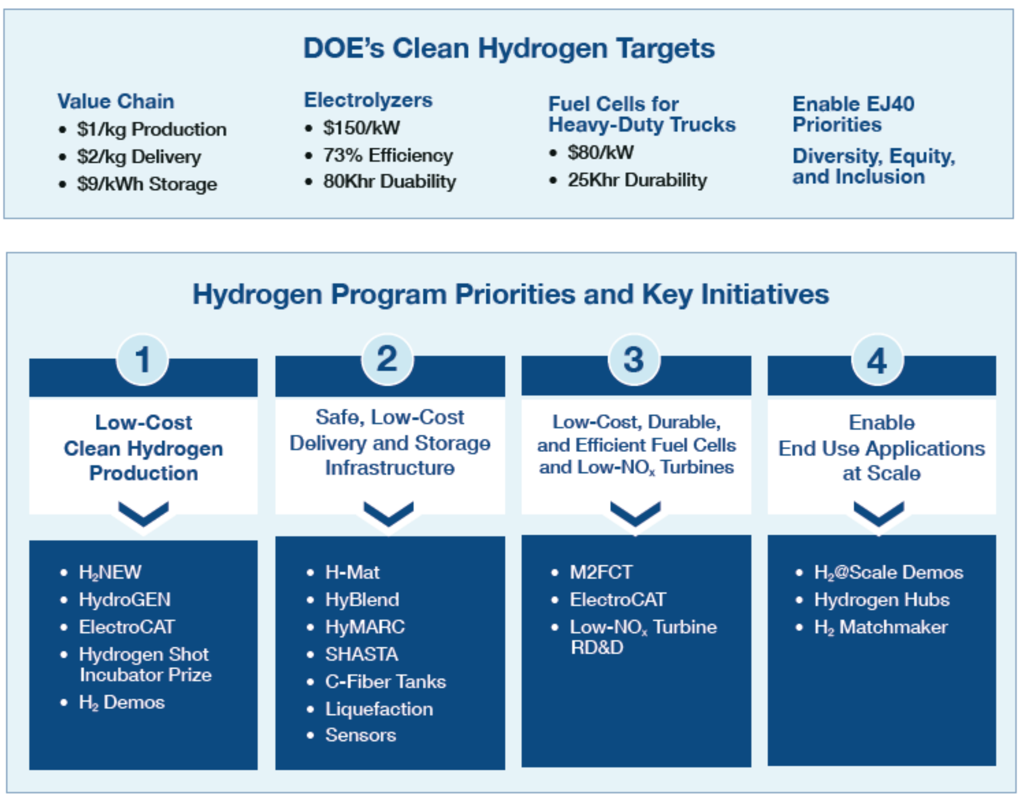
DOE has set targets to make clean hydrogen production cost effective in the next 10 years. Importantly, DOE's targets and the associated initiatives are focused on how to reduce the costs and improve the efficiency of electrolyzers and clean hydrogen production, delivery, and storage, while also enabling end uses like heavy-duty transport and guaranteeing benefits and protections for disadvantaged communities.

One of HFTO's primary activities is the Hydrogen Shot initiative, which aims to reduce the cost of clean hydrogen by 80 percent to $1.00 per one kg in one decade. The Hydrogen

Shot was introduced at the Hydrogen Program's Annual Merit Review, where DOE also issued an RFI for viable demonstration projects with a diversity of locations, that will contribute to lower hydrogen costs, reduce carbon emissions and local air pollution, and provide local community and job benefits.[125] The initiative sets up a framework for demonstration projects through the American Jobs Plan that will accelerate breakthrough pathways.

Some scenarios suggest achieving the $1/kg price level would allow for a five-time increase in clean hydrogen use, a 16 percent reduction in CO_2 emissions by 2050, and $140B in revenue that would support 700,000 jobs.[126] DOE is using mechanisms across the research, development, demonstration, and deployment (RDD&D) pipeline to achieve the Hydrogen Shot, such as the Hydrogen Shot Incubator Prize, FOAs, Consortia, Demos, H2Hubs, and Loan Guarantees.[127] These mechanisms, alongside other initiatives that DOE is using to reach the Hydrogen Program's priorities, are seen in Figure A31.

Figure A31
DOE's Clean Hydrogen Targets[128]



This diagram provides an overview of DOE's targets for clean hydrogen development across the value chain, electrolyzer and fuel cell technology, and justice and equity considerations. The Hydrogen Program is focused on four priority areas spanning hydrogen production, transport, storage, and end use and details initiatives currently underway that contribute to each area. Adapted from: DOE, 2022.

Another primary component of HFTO is the H2@Scale concept, which focuses on how hydrogen RDD&D projects can enable clean hydrogen pathways across the interconnected sectors of the energy system. Since 2018, nearly $112MM in funding has gone towards 56 projects addressing hydrogen activities across the value chain. Most recently, DOE announced $8MM for nine cooperative R&D agreements (CRADAs) that will use the Advanced Research on Integrated Energy Systems (ARIES) platform to determine how hydrogen will fit into future energy systems. Through the support of DOE's National Laboratories, H2@Scale has conducted workshops for a variety of potential hydrogen end uses and has also released three technical reports assessing resources for hydrogen production, hydrogen's technical and economic potential, and potential future demands for hydrogen in the United States.[129]

In addition, DOE's Loan Program Office is supporting bankable hydrogen projects across the country. The Loan Program Office (LPO) has more recently contributed to clean hydrogen projects as well. LPO primarily functions as a funding resource for emerging technologies and helps to bridge those technologies with bankability and full market acceptance.[130] The two clean hydrogen projects supported by LPO are described in Box A5: the Monolith Materials clean ammonia project and the Advanced Clean Energy Storage project.

Box A5

DOE Loan Programs Office Hydrogen Projects Target Bankable Demand

DOE's Loan Program Office (LPO) is equipped with over $40B in loans and loan guarantees, spread across multiple technology areas such as nuclear, fossil, and renewable energy.[131]

Recently, LPO has committed nearly $2B in loans to fund two major clean hydrogen projects (Figure A32). In December 2021, Monolith Materials received conditional approval for a $1.04B loan to complete a commercial "green" ammonia facility that produces clean hydrogen and carbon black via methane pyrolysis.[132] To produce clean hydrogen, Monolith procures renewable electricity through Renewable Energy Certificates (RECs).[133] Then, in June 2022, LPO finalized its first loan guarantee since 2014, to finance the largest clean hydrogen storage facility in the world with over $504MM. The storage facility, a large salt dome in Delta, Utah, will support the Advanced Clean Energy Storage (ACES) project, which plans to use 220 MW of electrolysis to produce hydrogen with renewables.[134] That hydrogen will be used as fuel for Intermountain Power Agency's (IPA) Intermountain Power Project (IPP). The project seeks to covert a coal plant to natural gas with blends of hydrogen up to 30 percent initially. By 2046, the ambition is to run the gas plant on 100 percent hydrogen.[135]

The two projects offer very different ways in which hydrogen is produced and consumed, yet they are backed by LPO for similar reasons – viable business models that transcend temporary policy support.[136] In the case of Monolith Materials, they are producing two valuable commodities – ammonia and carbon black. The ACES project is leveraging existing power purchasers in California who buy electricity from the coal plant in Utah. Having off-takers was integral to survive the technological valley(s) of death in funding such large-scale projects. [d] These projects offer important context about the importance of building

[d] "Valley of death" is a gap between academic research and industrial commercialization where investment is stifled, and, as a result, technologies do not reach maturity.

sustainable business models for large hydrogen projects or hubs when applying for federal money. Clean hydrogen remains expensive, and the technologies that leverage clean hydrogen often require heavy upfront capital expenditures.

Figure A32
LPO Announced Loan Guarantee Conditional Commitments for Two Clean Hydrogen Projects[137]

DOE's LPO has committed funding to two clean hydrogen projects to advance new technologies and industry job growth. Source: DOE, 2022.

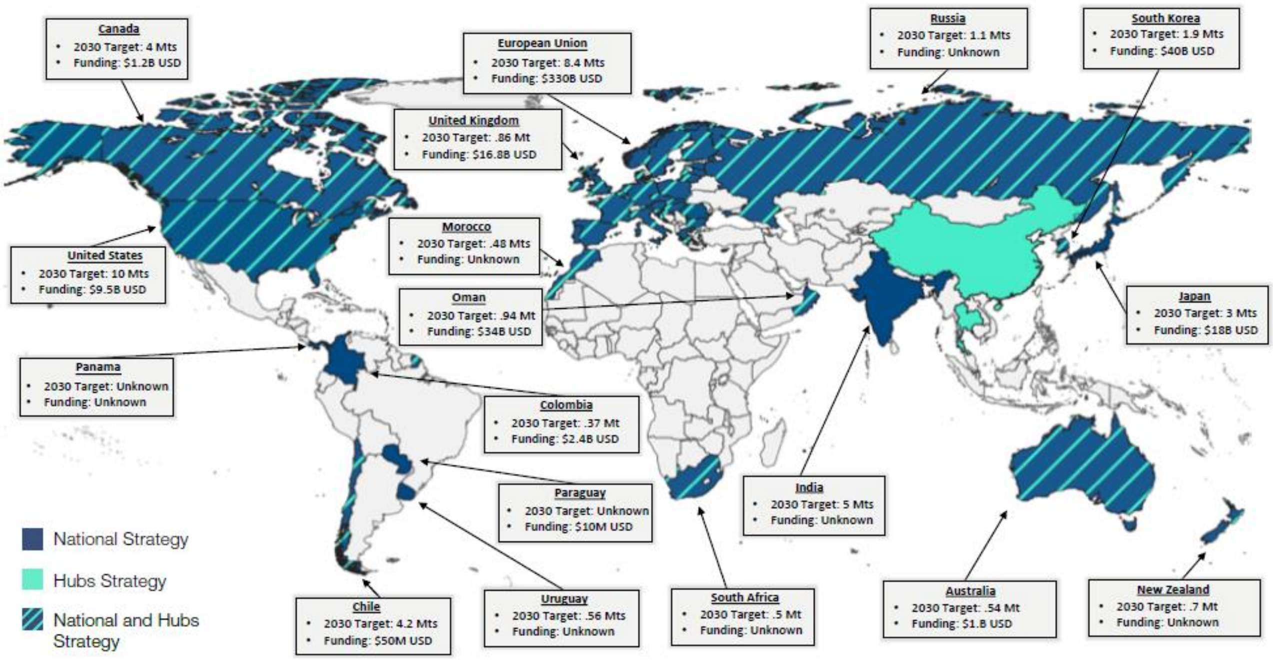
Appendix C. Global Clean Hydrogen Trends

Global climate commitments are spurring renewed interest in clean hydrogen. Most studies of the United States and global pathways to reach net-zero emissions include increasing amounts of clean hydrogen over time.[138] The International Energy Agency (IEA) calls hydrogen one of the six "pillars" for reaching global net-zero emissions by midcentury.[139]

Countries around the world are developing national hydrogen strategies to either boost economic development, reduce their emissions in line with climate goals, diversify energy supply, integrate renewables into their energy mix, or achieve some combination of these factors. A variety of sectoral priorities exist across national strategies, but many incorporate varying levels of hydrogen application in the following four areas: heating, industry, power, and transportation.

Global national hydrogen strategies represent roughly 65 Mt (35 Mt from China) of clean production. As of November 2021, there were at least 17 countries with hydrogen strategies, and 20 more national plans in development. The IEA found these countries have committed at least $37B in funding for hydrogen projects and additional $300B has been announced from the private sector.[140] As of July 2022, EFI's analysis found at least 33 countries with national hydrogen strategies or roadmaps that have identified at least $454B in total funding support required and are targeting nearly 54 Mt of new clean hydrogen supply by 2030 (Figure A33).

Figure A33
National Hydrogen Strategies and Regional Hubs



EFI reviewed national hydrogen strategies and hub strategies for at least 33 countries across the globe. The majority of those countries identified have both hydrogen and hub strategies, while some have one or the other. These strategies also detail hydrogen production targets by 2030 and the expected funding requirements to achieve these goals. Funding is measured in 2021 dollars. See Table A2 for data by country.

IEA also reported almost 400 clean hydrogen projects globally, most of which are in the early stages of development. If realized, these projects would produce 8.0 Mt of new zero-carbon hydrogen supply annually, compared to the current global market of 90 Mt.[141] According to IEA estimates, to reach net-zero, global hydrogen use will reach roughly 200 Mt by 2030 and 500 Mt by 2050.[142] This sum translates to a ramping of annual investment in clean hydrogen from roughly $337B in 2021 to $1.2 trillion (T) by 2030 to be on track for net-zero by 2050.[143] Hydrogen Council analysis from September 2022 identified 680 large-scale hydrogen project announcements that would add up to 7.3 Mt by 2025 and 26 Mt of clean hydrogen capacity by 2030.[144]

Released in September 2022, the United States' national hydrogen strategy focuses on sectors where deep decarbonization alternatives are limited (industry, heavy-duty transportation, and long-duration energy storage). The plan aims to foster development of a hydrogen market through hydrogen hubs and to decrease hydrogen costs. Such development could enable U.S. hydrogen production to reach 10 Mt, 20 Mt, and 50 Mt in 2030, 2040, and 2050, respectively, resulting in nationwide emissions reduction of 10 percent by 2050.[145] Initial funding to develop the U.S. hydrogen strategy comes from the

IIJA—$9.5B, and incentives brought about by the IRA are expected to leverage private sector investment.

Other national hydrogen strategies take different forms and involve different levels of commitment. There are countries on every continent (except for Antarctica) with national commitments to hydrogen. Global clean hydrogen commitments have been announced in Europe, Asia and Oceania, the Middle East, and South America. Governments have announced policy instruments, including carbon prices (e.g., EU's Emission Trading System and Carbon Border Adjustment Mechanism) (Box A6), auctions (e.g., Germany's H2Global funding program), mandates (e.g., India's mandates for the use of green hydrogen in industry [fertilizer, steel, and petrochemicals]), and volume requirements (e.g., more than 28 countries have hydrogen production targets for 2030), mostly focused on animating clean hydrogen production.[146,147] Many countries are developing international agreements to coordinate R&D programs, explore ways to harmonize standards, and encourage a global hydrogen trade. The United States, for instance, is working with other nations in the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) to harmonize methods of life cycle analysis for hydrogen production.[148] At this stage, most partnerships are bilateral with Memorandums of Understanding (MoU), developing collaboration on management, technology development, financing of research projects, and the potential for import-export value chains.[149]

Box A6

The EU Carbon Border Adjustment Mechanism (CBAM) and its Impact on Clean Hydrogen

A Carbon Border Adjustment Mechanism (CBAM) is a trade policy that places a tariff on imports to account for the carbon emissions of producing specific goods. This policy is meant to encourage the purchase of less carbon-intensive goods by increasing prices for more carbon-intensive goods. Because a CBAM is levied on goods traded among countries, it also provides an indirect pathway for emissions reductions across nations.[150] A CBAM is more effective when paired with a carbon price, as it addresses emissions leakages from carbon-intensive industries that may move offshore from the implementation of carbon pricing.[151]

The EU's CBAM proposal is one of the most significant to date, focusing on some of the most carbon-intensive industries and matching with the EU's Emissions Trading Scheme (ETS). Importantly, the CBAM could have a profound impact on the global trade of hydrogen by favoring its relative emissions reduction potential. The EU's initial proposal included iron and steel, cement, fertilizers, aluminum, and electricity as the primary sectors impacted by the CBAM, but coverage was recently expanded to include organic chemicals, hydrogen, and polymers.[152] By June 2025, the European Commission must adopt a delegated act with a timeline to gradually include all covered goods. Additionally, the Commission will need to assure accountability for downstream products and indirect emissions from electricity.[153]

A review of the existing national hydrogen strategies shows extensive focus on incentivizing hubs and green hydrogen production. Roughly three-quarters of these strategies include a "green" hydrogen production target (Table A2) and most focus heavily on regional hubs to drive market formation. Many include CO_2 intensity targets, technology production preferences (e.g., "green"), and clean hydrogen production volume targets.[154] Rapid progress has been made in clean hydrogen, including a doubling in global electrolyzer capacity over the last five years to more than 300 MW in 2021.[155] Europe is leading electrolyzer capacity deployment, with 40 percent of global installed capacity, and is set to remain the largest market in the near term on the back of the ambitious hydrogen strategies of the European Union and the United Kingdom.[156] The end-use sectors that feature the most in national hydrogen strategies are iron and steel production, chemical feedstock, and medium- and heavy-duty transportation.[157] There are, however, few end-use targets and where they exist they are relatively generic, long-term, or lack specific commitments.

Table A2: National Hydrogen Strategies around the World

Country	Release Date	Average Production Targets in Million Metric Tons (Mt) by 2030	Funding Sources	Public Investment USD Average[e]	Strategy Focus (Technology Neutral; Mobility; Green H2 Project; Industrial Decarbonization; Export Focus; Hub Focus)
Australia[158]	Nov-19	0.54	Public	$1,000MM (by 2030)[159]	Technology Neutral, Export Focus, Hub Focus
Austria[160,161]	Jun-22	0.17	Public & Private[162]	$5,300MM (by 2030)	Technology Neutral, Industrial Decarbonization, Hub Focus
Belgium[163,164]	Oct-21	0.03	Public[165]	$6,000MM (by 2030)	Green H2 Project, Mobility, Industrial Decarbonization, Hub Focus
Bulgaria[166,167]	Jun-20	0.06	Public	$1,400MM (by 2030)	Technology Neutral
Canada[168,169,170]	2020	4.00	Public	$1,200MM (by 2030)[171]	Technology Neutral, Export Focus, Mobility, Industrial Decarbonization, Hub Focus
Chile[172]	Nov-20	4.29	Public	$50MM (2021)	Green H2 Project, Export Focus, Mobility, Hub Focus
Colombia[173,174]	2021	0.37	Public	$2,400MM (until 2040)[175]	Technology Neutral, Export Focus, Mobility, Industrial Decarbonization
Czech Republic[176,177]	2021	0.10	Public	$1,700MM (by 2030)	Technology Neutral, Mobility, Industrial Decarbonization, Hub Focus
Denmark[178]	Dec-21	0.09	Public & Private	$1,700MM (by 2030)	Green H2 Project, Export Focus, Mobility, Industrial Decarbonization, Hub Focus
European Union[179,180]	Jul-20	8.43	Public & Private	$330,900MM (Total investment by 2050)	Green H2 Project, Mobility, Industrial Decarbonization, Hub Focus

[e] Currency exchange rates from August 17, 2022: 1 AUD = 0.69 USD, 1 EUR = 1.02 USD, 1 CAN = 0.77 USD

Finland[181,182]	Nov-20	0.13	Public & Private	$4,700MM (by 2030)	
France[183,184]	Sep-20	1.12	Public & Private	$16,500MM (by 2030)	
Germany[185,186]	Jun-20	0.86	Public & Private	$39,100MM (by 2030)	
Hungary[187,188]	May-21	0.03	Public	$2,400MM (by 2030)	
India[189,190]	Feb-21	5.00	n/a	$ n/a	
Italy[191,192]	Nov-20	0.86	Public & Private	$9,700MM	
Japan[193,194]	Sep-19	3.00	Public & Private	$18,000MM (by 2031)	
Morocco[195]	Aug-21	0.48	n/a	n/a	
Netherlands[196,197]	Apr-20	0.60	Public & Private	$9,800MM (by 2030)	
New Zealand[198]	Sep-19	0.70	n/a	n/a	
Norway[199]	Jun-20	n/a	Public	$19MM (2021)	
Oman[200]	2021-22	0.94	Public & Private	$34,000MM (by 2040)	
Panama[201]	Jan-22	n/a	n/a	n/a	
Paraguay[202,203]	Jun-21	n/a	Public	$10 MM	
Poland[204,205]	Nov-21	0.34	Public	$5,300MM (by 2030)	
Portugal[206,207]	Jul-20	0.30	Public & Private	$4,300MM (by 2030)	
Russia[208,209]	Oct-20	1.10	n/a	n/a	
Slovakia[210,211]	Jun-21	0.05	Public	$900MM	
South Africa[212]	Feb-22	0.50	n/a	n/a	
South Korea[213]	Jan-19	1.90	Public & Private	$40,300MM (by 2030)	
Spain[214,215]	Oct-20	5.34	Public & Private	$13,900MM (by 2030)	

Sweden[216,217]	Nov-21	0.86	Public & Private	$4,700MM (by 2030)	
United Kingdom[218,219]	Aug-21	0.86	Public	$16,800MM (by 2030)	
United States[220]	Sep-22	10	Public	$9.5B	
Uruguay[221, 222]	Jun-21	0.56	Public	n/a	
TOTAL		**53.6 Mt**		**$454.1B**[f]	

[f] The total number of public investments was calculated by subtracting the investments of individual EU countries by 2030 from total EU investments in hydrogen by 2050 and adding the remaining investments from other nations with national strategies. This approach was implemented to avoid double counting investments between European countries and the EU, as the latter funds several national projects. It is also important to note investments do not fall into a consistent timeframe and include projects from 2021-2050.

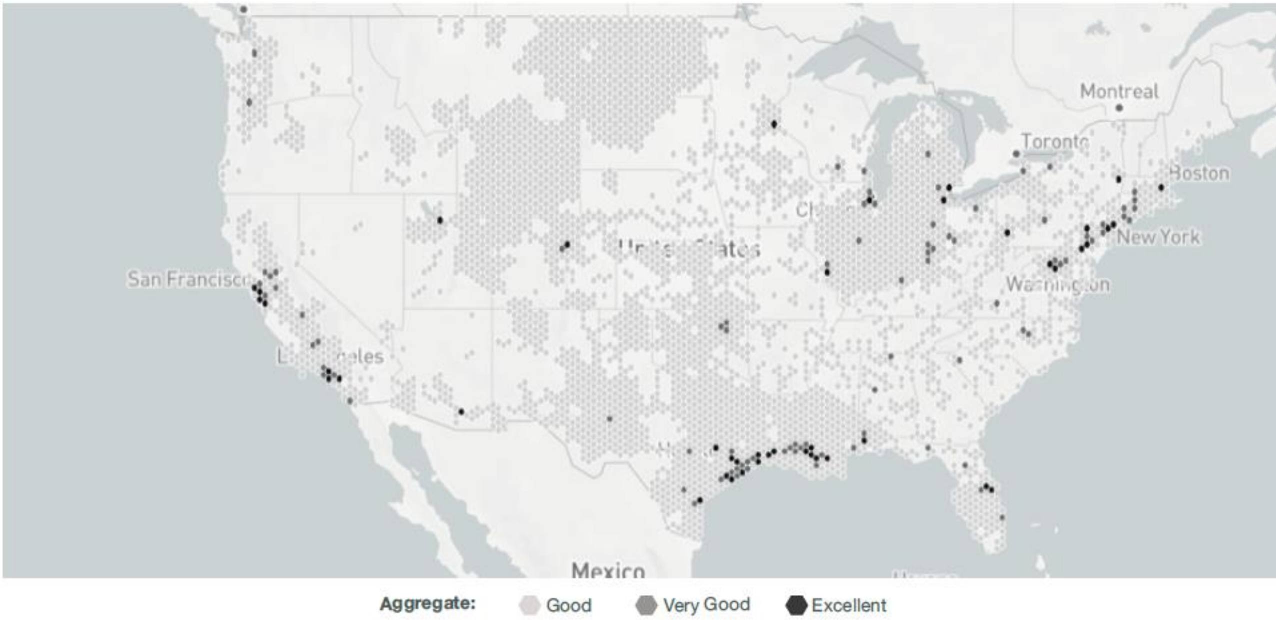
Appendix D. The Hydrogen Transition Framework (HyTF)

Regional clean hydrogen hubs should take a holistic approach to identify the ingredients to make projects successful and drive broader market formation. To assess the near-term potential of clean hydrogen market development, EFI developed a tool for profiling the diverse array of potential energy resources, workforce capabilities, economic and political interests, and demand sources across the country. These distinct elements—ingredients for regional hydrogen hub formation—can be used by policymakers, investors, and energy incumbents to evaluate the regional opportunities to unlock clean hydrogen potential.

EFI's Hydrogen Transition Framework (HyTF, pronounced "high-tiff") informs EFI's internal analysis on a variety of fronts, including environmental justice, the jobs transition, and hub formation. As a web tool for external users, HyTF can provide several important functions for hub applicants, developers, and H2Hubs reviewers at DOE. In the detailed planning phase, for example, conceptual designs for hubs will need to consolidate information on the production methods, hydrogen transportation and storage, demand centers, and institutions or other stakeholders that will collaborate to develop the hub. HyTF can provide this information in a single interface, acting much like an inventory of opportunities for H2Hubs. When putting together a workforce plan or market potential analysis, developers can also leverage HyTF to understand where labor supply or the capacity of a large power plant with potential to fuel switch are located. The latter could inform a financial or capacity expansion modeling exercise, as could the hydrogen production facilities or any other identified potential demand sectors. Techno-economic analyses could similarly be informed by HyTF, including the renewables or natural gas production potential of a region, carbon storage costs, demand potential, and water availability.

HyTF can also stimulate rapid demand uptake by identifying the human capital available to developers in an area. The interests and capabilities of a region are often overlooked yet are necessary elements for catalyzing hydrogen market formation. A novel finding of the HyTF tool is that the best regions for hydrogen hub formation will have a strong mixture of interests and/or capabilities to fully enable any resources or demand an area has to offer. Even in regions where there is limited clean hydrogen activity to date, such as the Carolinas, there are many capabilities and interests that could propel new investments for a future clean hydrogen supply chain. Figure A34 is a heatmap that demonstrates which areas have the most intersection between resources, demand, capabilities, and interests (defined in the next section). Notably, there are many darker colored regions signaling clean hydrogen market formation potential, yet no or limited hydrogen activity to date (see Figure 1 in the main report for current hydrogen activity in the United States).

Figure A34
HyTF Aggregate Layer Visualization Mode



The aggregate layer in HyTF shows all categories (resources, interests, demand, and capabilities) in one layer, cumulatively.

Categories and Elements of the Hydrogen Transition Framework (HyTF)

HyTF is a geospatial display built with information gathered from dozens of databases and modeling tools that provides insights about the heterogenous potential of clean hydrogen throughout the United States. HyTF aggregates regional attributes that can be leveraged for driving regional hydrogen hubs and broader hydrogen market formation. HyTF takes a holistic approach, combining data from the clean hydrogen value chain, hydrogen technologies, hydrogen-ready industries, and enabling infrastructures over 11,432 hex bins[g] across the country, to inform regional hydrogen hub developers. HyTF shows there are clean hydrogen opportunities in nearly every region of the United States and that hydrogen pairs well with existing U.S. industrial bases and workforce, offering a potential straightforward transition for workers and economic regions heavily dependent on fossil fuels.

[g] Hex bins are areas that are each approximately 400 square miles. Because of the unspecified dimensions or geographic scope of hydrogen hubs in the Bipartisan Infrastructure Bill, hex bins are the approximate size of a large metropolitan city. That is, a single hex could constitute its own hub. Just as likely, hubs will develop on the scale of states or regions. To remain flexible in the definition of 'close proximity', hex bins can be viewed in isolation or linked by adjacency and compatibility of elements.

HyTF categories are organized by Resources, Interests, Capabilities, and Demand (Table A3).

- **Existing Resources:** Natural conditions and established systems that currently take part in the hydrogen supply and demand value chain.
- **Enabling Resources:** Natural conditions and established systems that could support a hydrogen economy but have yet to be leveraged domestically.
- **Interests:** Private companies and governments with business activities and/or interest related to clean hydrogen development.
- **Capabilities:** Expertise and experience that can be used to innovate, educate, or provide necessary skills to the clean hydrogen economy.
- **Demand:** Current and potential end uses that will help drive the quantity of hydrogen supplied to the market domestically.

Table A3: EFI's Hydrogen Transition Framework (HyTF)

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

Resources *Natural conditions and established systems that could support a hydrogen economy*	**Demand** *Current and potential end uses that will help drive the quantity of hydrogen supplied to the market*	**Interests** *Demonstrated direct or indirect support for hydrogen from firms or policies*	**Capabilities** *Expertise and experience used to innovate, educate, or provide necessary skills to the hydrogen economy*
Existing • Fresh Water Access • Natural Gas Reservoirs • Hydrogen Pipelines • Salt Domes • Existing Hydrogen Production Capacity	*Near-Term Demand (Currently Commercialized)* • Refineries • Ammonia Plants • Methanol Plants • Limited Mobility Applications	*Private Sector* • Largest Investor-Owned Utilities • Other S&P 500 Companies	*Education Centers* • Universities by RD&D budget
Enabling • Saline Aquifers and Oil & Gas Reservoirs • CO_2 Pipelines • Natural gas pipelines • Roads, railways, waterways	*Medium-Term Demand (Commercialized 2025-2035)* • Data Centers • Steel Plants • Ports & Maritime Applications • Natural Gas Plants	*Policy* • Favorable State Climate Policies/Plans	*Skilled Labor* • Bureau of Labor Statistics regions with strongest adjacent hydrogen jobs/skills • Technical and Community Colleges

• Hydro, Solar, Wind, Biomass electricity generation installed capacity	• Energy Storage Potential • Medium and Heavy-Duty Mobility		
	Long-Term Demand (Commercialized After 2035) • Airports • Biofuels Production Potential • Cement Plants	*Public-Private Partnerships* • Government grants, direct payments, and loans for hydrogen technologies • Small Business Innovation Research Awards (SBIRs)	*Innovation Centers* • Patents for hydrogen technology • National Laboratories

Each of the categories in HyTF has distinct elements scored by relative importance to other elements in their category from highest to lowest, which is the basis for the 'Excellent', 'Very Good', and 'Good' descriptors in the HyTF legend. HyTF categories are informed by thorough literature review, interviews with stakeholders, and modeling exercises that have simultaneously informed the entire study. If a hex area does not score well enough in a category, but there is some level of clean hydrogen opportunity, that hex will still light up and describe the opportunity under the 'All' selection. EFI intends to update HyTF annually to ensure numbers remain as up to date as possible and may add other elements to the tool over time, if there is a need for certain information. Overall, the elements consist of 500,000 separate data points now publicly available and easily accessible. The sections below describe each HyTF category and their elements.

Existing Resources

Elements for clean hydrogen development exist in nearly every region of the United States. The country can leverage its technical resource potential to produce substantial amounts of clean hydrogen – 1B metric tons, according to one DOE study.[223] The United States maintains significant existing resources for clean hydrogen production—the resources, technologies, and systems in use by the hydrogen industry today. These resources include available water resources, natural gas potential, hydrogen pipelines, salt dome formations for long-duration storage, and current hydrogen production.[h] In HyTF, each of these elements is ranked in relation to one another so current hydrogen capability translates into stronger hydrogen production potential.

1- Freshwater Availability

Pure freshwater is an important input to nearly every energy system, regardless of production pathway or end use. The Available Water Remaining for the United States

[h] U.S. regions with high drought risks, such as the Southwest, were not excluded from HyTF but received slightly lower scores to reflect these concerns. Water access is determined using the Argonne National Laboratory's AWARE-US model, which characterizes water stress at a county level. Stress is determined by the impacts of marginal water consumption on overall access to water by the county population.

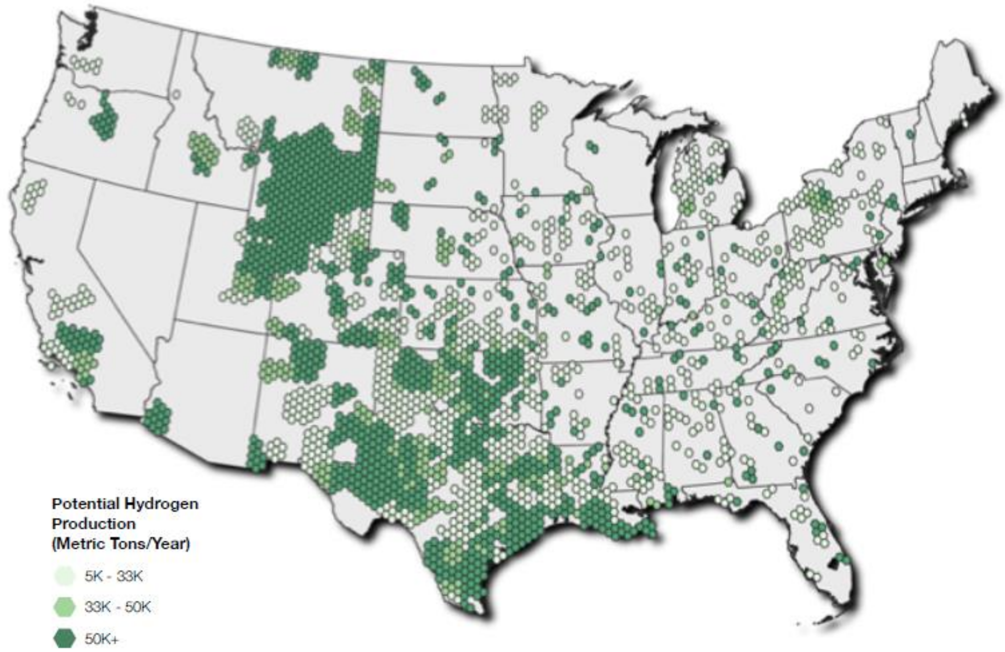
(AWARE-US) model, built on the AWARE global model, provides a granular analysis of water scarcity or stress at a county level. The AWARE model takes monthly data on the water scarcity footprint (WSF) of a county, which is a product of monthly water consumption and a monthly water stress capacity factor.

The national average annual WSF is 4.94 (m^3 equivalent). In HyTF, WSF is used as a cutoff for water availability. That is, counties are categorized as being above or below average for freshwater access. Seasonal variations may affect certain areas in larger ways, but on an annual basis, the areas identified as "water scarce" are the most likely to confront challenges of meeting water demand for energy requirements. In HyTF, areas with no freshwater scarcity have an average rank compared with other Existing Resources.

2- Natural Gas Potential

In HyTF, natural gas potential derives from availability of natural gas reserves. As a result, areas with stronger natural gas reserves receive a higher score than most other elements in the Existing Resources category. Natural gas potential is considered an existing resource because hydrogen is currently produced in the United States via SMR using natural gas as feedstock. However, the distribution of natural gas reserves throughout the contiguous United States and Alaska is highly variable. Some areas have particularly favorable access to natural gas– the Permian, Gulf Coast Mesozoic, and Appalachian Basins are the largest reserves in the country, each containing over 300T cubic feet of natural gas. A county in those regions could technically produce anywhere from 0 Mt to 3.4 Mt H_2 a year if it used 100 percent of its natural gas supplies for that purpose. Figure A35 shows the distribution of natural gas reserves across the country.

Figure A35
Potential to Produce Hydrogen from Natural Gas Reserves



NREL data maps the potential for natural gas reserves to produce hydrogen in a year. In HyTF, such information is converted to hex bins from county-level data. Producing more than 5,000 t of hydrogen a year means an area has above median-level reserves of natural gas; more than 33,000 t means an area is in the third quartile of natural gas reserves, and more than 50,000 t means an area has at least 1.5 times the third quartile (33,000 t) of natural gas reserves.

3- Hydrogen Pipelines

As discussed previously, only 25 hydrogen pipelines exist in the United States, spanning approximately 1,600 miles. Most are in the Gulf Coast and used to carry merchant or excess hydrogen to petrochemical users. Often, if a user has produced more hydrogen on site than is needed, they will sell it back to the pipeline operator for other users to purchase. Hydrogen pipelines were identified using the Pipeline and Hazardous Materials Safety Administration (PHMSA) database and manually recreated in geographic information system (GIS) software. In HyTF, areas with current hydrogen pipelines have an average rank compared with other Existing Resources.

4- Discovered Salt Domes

Salt domes are key enablers for large-scale and long-term hydrogen storage. Yet, there are few salt domes already in use in the United States for natural gas and hydrogen storage. They could become important resources for large long-term storage of hydrogen and may support several projects by allowing for multiple inputs and outputs simultaneously, working together in a Book-and-Claim system. Salt domes are important but rare, and as a result, most hex areas in HyTF containing salt domes appear as ‘Good’, ‘Very Good’, or ‘Excellent’ in Existing Resources.

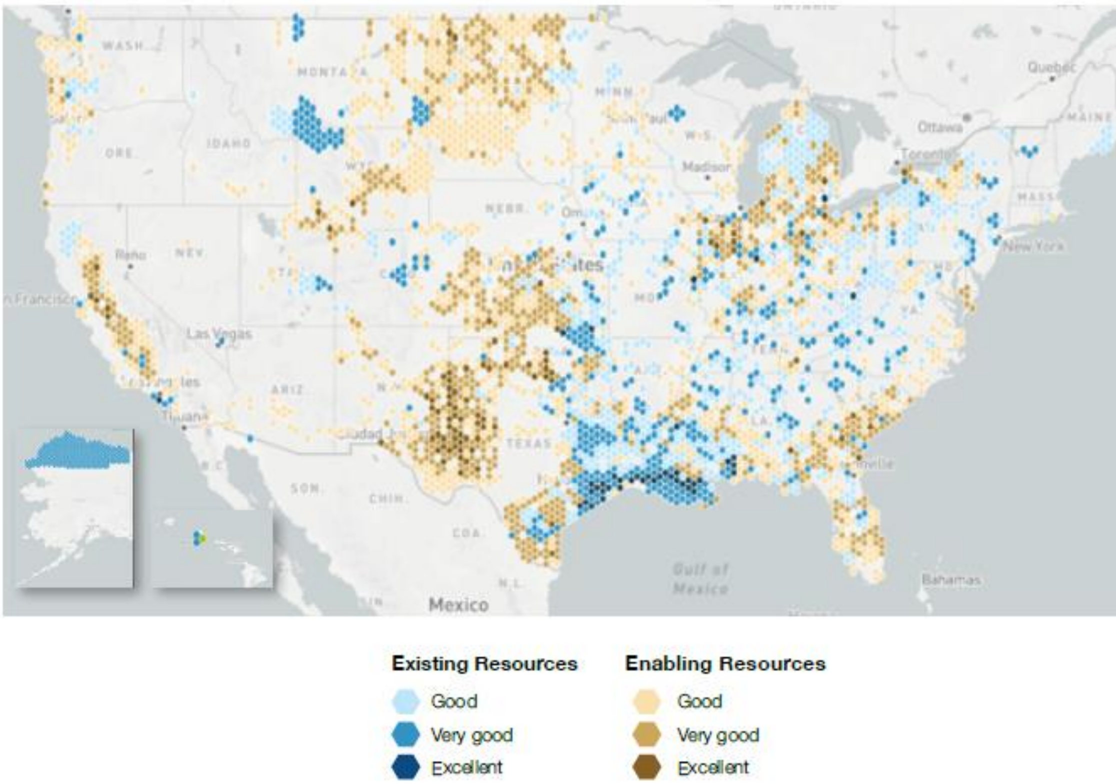
5- Current Hydrogen Production

Hydrogen producers receive the highest rank within the Existing Resources category of HyTF. As of 2021, 216 facilities are merchant, by-product, or captive plants producing hydrogen that almost all supply the petroleum refining industry. Some smaller facilities may also supply hydrogen for a variety of uses including chemicals, metals refining, food or electronics processing, glassmaking, and rocket fuel. Additional facilities (32 ammonia and 9 methanol plants), some of which are the largest hydrogen producers in the United States, are not accounted for in this category because they produce hydrogen at equilibrium – supply is perfectly equal to demand. In HyTF, these facilities feature in the Demand category.

Enabling Resources

In addition to the existing U.S. hydrogen resources, there are resources that can be used to enable clean hydrogen development that are important to consider when building regional hubs and making clean hydrogen investments. Such enabling resources include existing and enabling clean energy, gas pipelines for blending, and the roads, railways, and waterways that will allow for safely transporting hydrogen across the country. They also include CO_2 storage resources such as pipelines and reservoirs for permanent carbon storage if project developers are interested in producing hydrogen with SMR/ATR capture technology. As shown in Figure A36, most regions of the United States contain very strong existing or enabling resources that could seed a clean hydrogen economy.

Figure A36
Existing and Enabling Resources for Hydrogen Hubs and Projects



HyTF considers all existing and potential hydrogen resources and end uses, as well as interest in hydrogen and capabilities to support a hydrogen economy identified in Table A3. Regarding resources, regions with a significant share of one, or a combination of existing or enabling resources, are highlighted here, and classified by overall favorability for hydrogen hubs development. "Excellent" means at least one element in the category is exceptional or several elements are very strong or exceptional. If a region has a fraction of those resources, they may score "very good" or "good".[i] EFI will publish the full HyTF dataset online to complement this study.

1- Saline Aquifers and Oil & Gas Reservoirs: Carbon Storage Potential

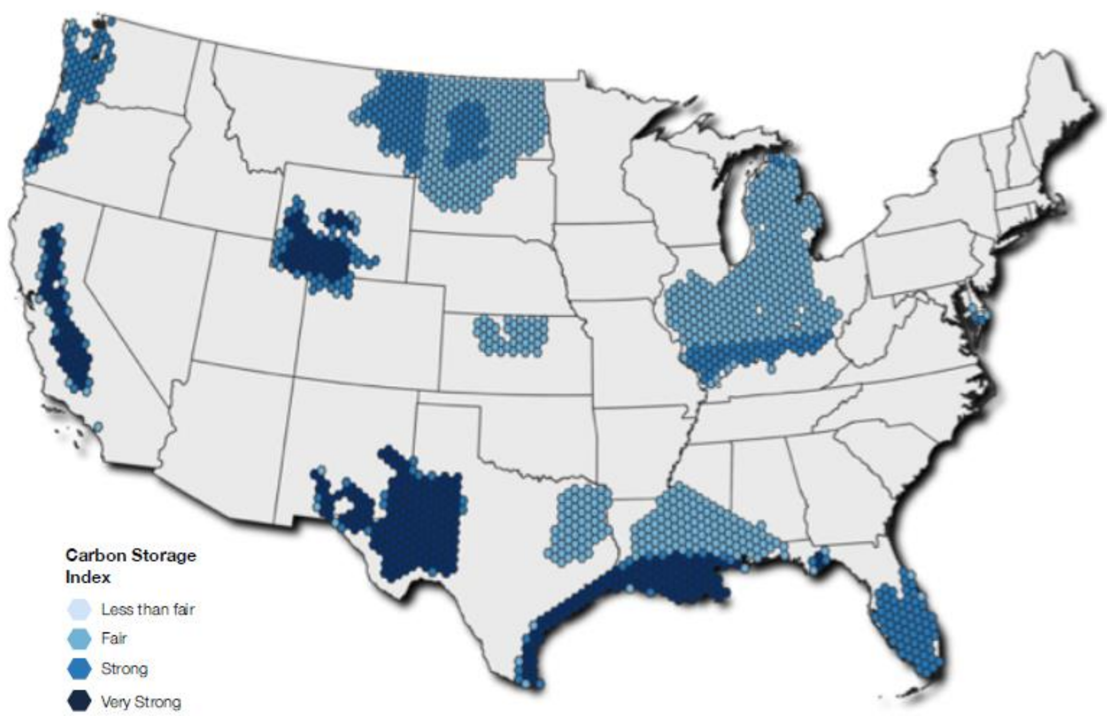
In the case of hydrogen production with CCS, saline aquifers and depleted oil and gas reservoirs must play a key role in the permanent storage of CO_2. As such, carbon storage ranks high among elements in the HyTF Enabling Resources category. Oil and gas reservoir data were obtained from NETL, while data pertaining to saline aquifers were acquired from Carbon Solutions – a company working on advanced modeling of metrics such as cost and capacity of aquifers. A carbon storage index was created using cost and capacity numbers, which derive from a model called SCO2T (Sequestration of CO_2 Tool) that uses machine

[i] The HyTF tool allows users to toggle different categories on and off, providing a more holistic look at hydrogen market formation than the report's static images.

learning to characterize the U.S. landscape. SCO2T works by linking sequestration engineering (e.g., injection rates, reservoir capacities, and plume dimensions) with techno-economics information to arrive at capacity and cost estimates. HyTF creates an index from these numbers by taking the capacity divided by the cost to understand which areas have the best combination of the two metrics. To help ensure best carbon storage sites, the modeling exercise also built exclusion areas where there are military zones, densely populated communities, Native American territories, or high risks of seismicity. Because the data is proprietary, exact numbers cannot be provided for given areas. However, capacities can range from 0.1 Mt to 964 Mt, and carbon storage costs range from $1 to $357.

HyTF considers the median carbon storage capacity and cost index as ‘Fair’, the third quartile as ‘Strong’, and the third quartile times 1.5 as ‘Very Strong’. For those indices with some carbon storage but less than the median, they are indicated as ‘Less than fair’. If an area has no storage, it is designated as N/A. Figure A37 shows the hex bins by carbon storage index.

Figure A37
Carbon Storage Capacity and Cost



The regions with the best mixture of low storage costs and high capacities are in Western Texas, the Gulf Coast, Wyoming, and Central California.

2- CO_2 Pipelines

Approximately 3,000 miles of CO_2 pipelines exist in the United States, concentrated in the regions of the country with heavy oil and gas production. CO_2 pipelines are almost entirely used for enhanced oil recovery (EOR), though they could support permanent CO_2 storage from hydrogen production plants in the future. Compared with other Enabling Resources, hex bins with CO_2 pipelines have an average rank in HyTF. Hydrogen pipelines were identified using the PHMSA database and manually recreated in GIS.[224]

3- Natural Gas Pipelines

There are approximately 3MM miles of natural gas pipelines in the United States, many of which currently can support small blends of hydrogen. However, technical challenges are present when moving blends above 20 percent in most pipelines, and thus the decarbonization opportunities may be minimal without major retrofits. Therefore, HyTF gives a low score to hex bins with natural gas pipelines, which is one of the lowest valued elements in the Enabling Resources category. Natural gas pipeline data were pulled from a public Homeland Infrastructure Foundation-Level Data (HIFLD) geospatial database.[225]

4- Roads, Waterways, and Rail

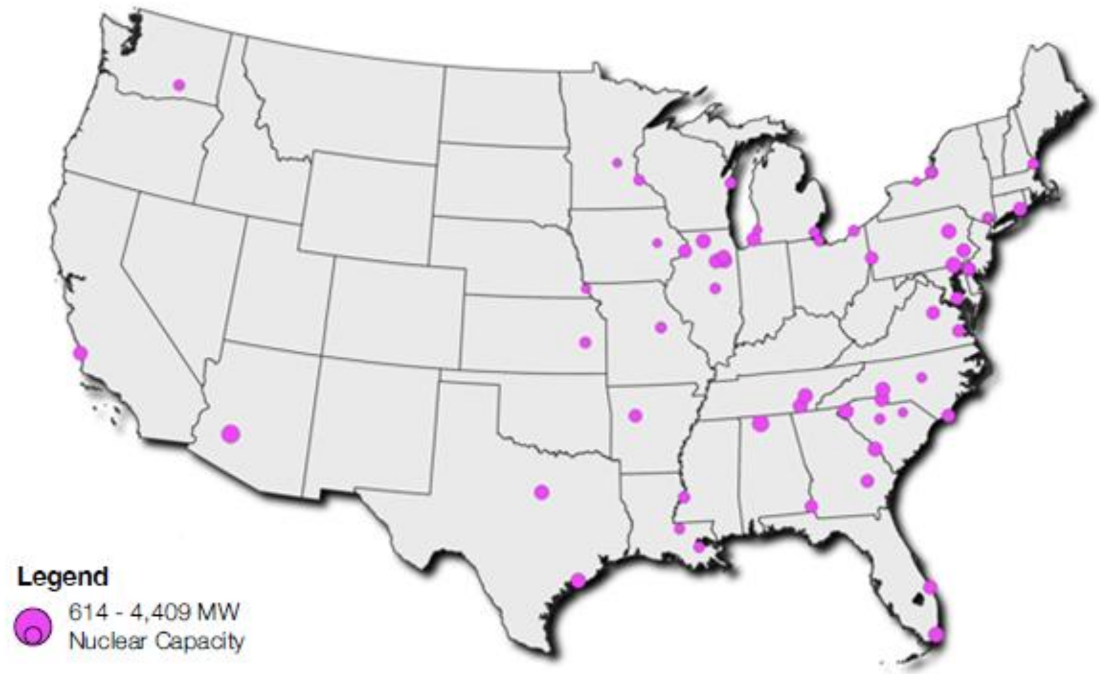
Transportation networks (major roads, waterways, and rail) to move hydrogen from point to point will be essential for the interconnectivity of hubs and the ultimate formation of a clean hydrogen market. Major highways and waterways were located using a HIFLD database. For rail, major intermodal freight facilities identified by the Department of Transportation (DOT) include ports, industrial centers, and other logistics hubs that facilitate the transport of freight in an intermodal container for use in rail, maritime shipping, trucking, or even air shipping. If a hex bin contains a major road, waterway, or intermodal freight facility, it receives a low score to reflect the ubiquity of these corridors or intermodal hubs, and because nearly all facilities involved in the hydrogen value chain will be somehow connected to these major corridors by other roadways. Hence, the Roads, Waterways, and Rail element is another of the lowest scored in HyTF's Enabling Resources category.[226,227]

5- Electricity Generation Installed Capacity

a. Nuclear Power Plants

IIJA mandates at least one H2Hub should have a nuclear production pathway – most likely high temperature electrolysis. Several projects are under development or being planned in the United States, as identified in EFI's hydrogen project database. High temperature heat or curtailed electricity are both feasible pathways for making hydrogen, and because of the capacity factor of nuclear plants relative to other clean energy options, hex areas with nuclear plants are ranked higher in HyTF than areas with existing variable renewables. Capacities of the plants were not factored into the score, nor were they factored in if a hex bin contained more than one plant. Figure A38 shows locations for all operational nuclear plants in the United States as of the end of 2022. Data was obtained from the World Resources Institute (WRI) global powerplant database.[228]

Figure A38
Operational Nuclear Power Plants in the United States



There are 92 operational nuclear power plants in the United States as of the end of 2022, producing approximately one fifth of the electricity in the country.

b. Existing Variable Renewable Power Plants

Wind and solar account for most of the electricity curtailment in the United States. Therefore, because avoiding renewables curtailment is a potential benefit of hydrogen as a storage medium, EFI sought to understand where significant levels of variable renewables reside in the United States. In HyTF, a hex bin with more than 20 MW of solar and/or wind combined is ranked up to the highest level of capacity. Compared with other elements in the Enabling Resources category, however, this score is relatively low to reflect the important, yet small, potential additions for future clean hydrogen production. HyTF describes the amount of capacity in MW in each hex (if that hex has >20 MW of capacity), but does not consider geothermal, hydro, or biomass, which are firm power resources. Data were obtained from the World Resources Institute (WRI) global powerplant database.

6- Renewable Energy Technical Potential

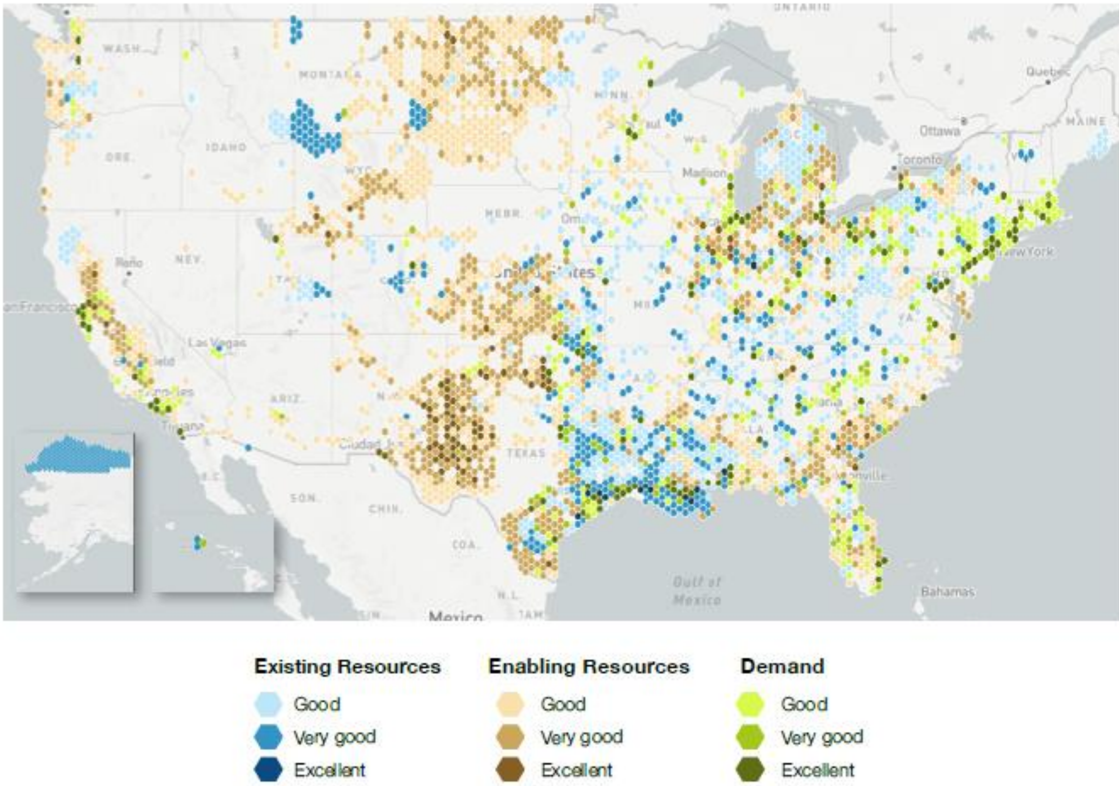
To produce green hydrogen at large-scale, a massive supply of electricity is required from clean energy sources. As such, compared to other elements in the HyTF Enabling Resources category, an area that presents great Renewable Energy Technical Potential is ranked among the highest. DOE's H2@Scale report provides data on renewable energy technical potential throughout the country, allowing for an assessment of which areas are relatively stronger for electrolytic hydrogen potential. [229] HyTF does not specify a technology, but considers wind, solar PV, CSP, biomass, and hydroelectricity as clean energy sources. Geothermal potential is not included in HyTF because DOE data is constrained to areas where county-level data was available. To reflect the relative strength of a given location in HyTF, areas with the potential to produce more than 1MM kg H_2/square kilometers (km^2)/yr score the highest, followed by areas that can produce between 1MM kg H_2/km^2/yr and 500,000 kg H_2/km^2/yr and between 500,000 kg H_2/km^2/yr and 100,000 kgH_2/km^2/yr.

Demand

In addition to existing and enabling resources, as well as interests and capabilities to seek out human capital, assessing the current and potential demand for hydrogen is important for developing market formation for regional hydrogen hub projects. Demand will be a function of technology readiness, market structures, business models, and other basic drivers. HyTF data includes near-, medium-, and long-term demand opportunities, some of which are driven by DOE's assessment of hydrogen-ready demand.[230] Near-term demand focuses on existing hydrogen use, while long-term demand expands to a variety of industries that could leverage hydrogen to decarbonize. Decarbonizing existing hydrogen production for refineries, ammonia, and methanol plants is a focal point of EFI's hydrogen strategy and can lower U.S. emissions by over 50 Mt of CO_2e per year (see Chapter 2 in the main report for more details). Decarbonizing these uses can also highly impact communities, as areas with strong current hydrogen demand and environmental justice concerns correlate. In HyTF, near-term demand elements are scored the highest, while medium and long-term demands receive average and lowest scores, respectively.

Beyond existing users, new applications for hydrogen can reach new consumers. Highly industrialized regions, particularly those with large steel plants, can use hydrogen to replace natural gas in emissions-intensive industrial processes such as iron reduction. The United States has dozens of facilities across the country that could explore this production pathway. Other areas of market potential are stationary power production, off-road operations at ports and airports (i.e., drayage trucks, yard trucks, top loaders, and ferry boats), on-road mobility, back-up power generation at data centers, grid stability, biofuels production, and cement manufacturing. Figure A39 highlights the array of demand potential across the country for clean hydrogen, particularly in heavily industrialized (e.g., Ohio River Valley), gas-dependent (e.g., Northeast), and grid-stressed regions (e.g., Florida). Many of those regions are complemented by the strong resources described above. Each element in the demand category is described below.

Figure A39
Map of U.S. Hydrogen Resources and Demand



Demand in HyTF is weighted temporally to differentiate the immediate decarbonization opportunities from new applications that may take decades to commercialize. Demand hex tiles may appear in the figure because of several end-use opportunities, one or two large existing users, or a combination of both. Heavily industrialized, gas reliant, and/or grid-stressed regions were likely to appear in the figure as strong areas for potential clean hydrogen demand.

Near-Term Demand (Currently Commercialized)

1- Refineries

Petroleum refining accounts for approximately 77 percent of hydrogen demand in the country, all of which is produced with fossil fuels. To calculate the hydrogen use by each refinery, EFI leveraged the methodology used in DOE's H2@Scale "Assessment of Potential Future Demands for Hydrogen in the United States" report. As discussed in Chapter 1 of the main report, the variance of crudes' sourness impacts the amount of hydrogen required to process a barrel of oil. Therefore, regional variance must be accounted for in an analysis of refinery hydrogen use.

EFI first used EIA's 2021 "Refinery Capacity Report" to locate refineries and calculate how many barrels of oil are produced per calendar day. Then, using DOE's facility-level analysis of refineries, EFI took the product of the crude oil capacity and ratio of hydrogen per barrel of crude shown in Table A4.[231] The ratio of hydrogen is dependent on the Petroleum Administration for Defense Districts (PADD) regions and is expected to steadily grow year-over-year as crudes become sourer over time. Finally, EFI performed a unit conversation to turn cubic feet of hydrogen into metric tons (t) of hydrogen. The resulting hydrogen demand from this exercise was 6.5 Mt for refineries in 2021, consistent with other studies to date. EFI also validated these numbers against proprietary IHS Markit data on captive and merchant hydrogen plants serving refineries to ensure accuracy. As an existing hydrogen market, hex areas with refinery hydrogen demand score as one of the highest relative to other Demand category elements.

Table A4: Ratio of Hydrogen per Barrel of Oil

	PADD1	PADD2	PADD3	PADD4	PADD5
H_2/crude (ft^3/bbl)	100	315	329	430	504

2- Ammonia Plants

Ammonia plants are the second largest source of hydrogen demand in the United States. All ammonia in the country is produced captively, resulting in no real existing market. To find the hydrogen production capacity per plant, EFI used the *Nutrien 2022 Fact Book* to identify the 32 existing ammonia plants in the country and their respective production capacities. In total, ammonia plants produced 17.9 Mt in 2021.[232] USGS's "Mineral Commodity Summaries 2022" specifies each of those plants has approximately an 84 percent operating capacity.[233] Using a hydrogen ratio of approximately 18 percent for every unit of ammonia produced at this operating capacity, existing ammonia plants were responsible for producing 2.7 Mt of hydrogen. As an existing hydrogen market, hex areas with ammonia hydrogen demand score as one of the highest relative to other Demand category elements.

3- Methanol Plants

There are nine operational methanol plants in the United States, which consume a large share of the total hydrogen demand in the country – 1.6 Mt annually. EIA compiled data on the methanol production capacity of each plant, and using a hydrogen/methanol ratio of 16 percent, EFI found an estimated hydrogen production capacity for each plant. As an existing hydrogen market, hex areas with methanol hydrogen demand score as one of the highest relative to other Demand category elements.

Medium-Term Demand (Commercialized 2025-2035)

1- Datacenters

Stationary fuel cells can be used as a storage medium for backup power to replace highly emitting diesel generators unable to meet stringent EPA regulations. An area of interest for these stationary fuel cells is at datacenters, where they can provide backup power options, while maintaining reliability, to facilities expected to operate at nearly all times. Microsoft, Amazon, and Facebook are some of the companies that could profit from such applications. With some datacenters requiring up to 100 MW of electricity capacity, and a proof-of-concept complete at Microsoft, there is large potential for datacenters to leverage clean hydrogen without switching the primary power source. Even if backup fuel cells do not initially use clean hydrogen, they can still run using cheaper fossil-derived hydrogen or even natural gas.

Using a database of U.S. datacenters, EFI identified the location of all large-scale facilities in the United States. As a technology with medium-term potential (commercialization in the next 10 to 15 years), HyTF gives datacenters an average score relative to other elements in the Demand category.

2- Steel Facilities

There are 77 steelmaking facilities across the United States, identified by the Global Energy Monitor along a variety of factors including location, capacity, and technology. EFI estimated the total capacity of annual steel production (in metric tons) by hex area. As a technology with medium-term potential (commercialization in the next 10 to 15 years), HyTF gives steel facilities an average score relative to other elements in the Demand category.

3- Ports and Maritime Applications

The Pacific Northwest National Laboratory used emissions data to estimate potential hydrogen demand for ports – more than 500,000 t of hydrogen annually. A smaller port may use around 50 t H_2/day while a larger port could need up to 465 t H_2/day. Most of the near-term hydrogen demand in ports would come from drayage trucking, though yard tractors, container handlers, cranes, and straddle carriers could follow in the coming decades.[234] Maritime hydrogen demand projections are not known due to massive barriers to decarbonizing the industry. Hydrogen has many applications on board a boat or ship, yet it is unclear whether pure hydrogen, LOHCs, ammonia, or other options present the best economics or properties to accommodate demand.

Currently, there is no commercial market for port or maritime hydrogen applications in the United States. However, many pilot projects and proof-of-concept designs are underway across the country. As of 2019, EPA's H2 Fuel Cells at Ports Initiative found 22 fuel cell demonstration and deployment projects, which include seven drayage trucking, five power generation at the port, four yard tractors or top loaders, four hydrogen refueling stations, one portable light tower, and one ferry boat project.[235] As an end use with medium-term potential (commercialization in the next 10 to 15 years), ports and maritime applications receive an average score relative to other elements in the Demand category.

4- Natural Gas Power Plants

There are thousands of natural gas power plants scattered across the United States, which could switch to hydrogen depending on the cost and duration of retrofits. In some cases, natural gas power plants can already use small blends of hydrogen with natural gas, and there are opportunities, albeit costly, to shift to 100 percent hydrogen. Even when costs are not considered, the amount of clean hydrogen needed to transition an average-sized plant to 100 percent hydrogen is not yet viable, considering it would require approximately one percent of the total hydrogen production in the United States to date.

Using WRI's global power plant database, EFI identified the capacity in megawatts of each natural gas power plant. Then, using GIS, the total capacity of natural gas power plants was found in each hex bin. As a technology with medium-term potential (commercialization in the next 10 to 15 years), HyTF gives natural gas power plants an average score relative to other elements in the Demand category.

5- Grid Storage

From a technical standpoint, hydrogen can act as a storage medium in ways batteries cannot – storing energy for weeks or months at a time to overcome seasonal weather and temperature changes. NREL calculated the United States has the technical potential to produce nearly 15 Mt of hydrogen, which could displace natural gas or coal generation. In reality, hydrogen will play a limited but important role in load-balancing grids and avoiding renewable energy curtailment. Still, by understanding the technical potential of hydrogen for grid storage at a county level, it becomes possible to relatively compare different parts of the country and identify areas most likely to rely on stationary fuel cells powered by hydrogen.

Using NREL modeling outputs from the Regional Energy Deployment System (ReEDs) model, DOE found an estimated storage potential for hydrogen based on electricity generated with natural gas in a scenario with high penetration of variable renewables (i.e., solar and wind). In such a scenario, natural gas is used sparingly at expensive rates and is highly emissions intensive. By instead producing clean hydrogen to be stored for use during peak load hours at costs equivalent to running a peaker fossil plant, an electric grid can limit renewable energy curtailment. In HyTF, as an end use with medium-term potential (commercialization in the next 10 to 15 years), grid storage scores on average relative to other elements in the Demand category.

6- Medium- and Heavy-Duty On-Road Mobility

EFI research has not found evidence a large-scale light-duty FCEV market will materialize in the United States. There may be, however, opportunity for limited medium- and heavy-duty vehicle (MDV and HDV) applications, depending on the region. Based on the market penetration rate of 35 percent for fuel cell vehicles in 2050, DOE estimates around 4.2MM MDVs and 2MM HDVs will be adopted. Fulfilling such demand would require 5.2 Mt of hydrogen annually. Using a MA3T vehicle choice model, DOE subsequently projects adoption at a county level based on the percentage of ZEV penetration that are FCEVs.[236] As an end use with medium-term potential (commercialization in the next 10 to 15 years), HyTF gives medium- and heavy-duty on-road mobility an average score relative to other elements in the Demand category.

Long-Term Demand (Commercialized After 2035)

1- Airports and Aviation

No proven business cases currently exist for aviation applications of hydrogen in the United States, and no fueling stations are available at any airports. Airports have run studies to prove the concept of hydrogen integration, though issues with hydrogen supply, terminal space, and infrastructure needs all prevented further analysis. Additionally, many opportunities for hydrogen integration in ground operations have already turned to battery electric technologies.[237] For airplanes in particular, the focus is mainly on sustainable aviation fuels (SAFs). If in the future hydrogen can fuel aviation technologies, the demand potential for airports and aviation is large. However, commercialization of such vessels is unlikely by 2050. Therefore, in this sector, demand is restrained to ground transportation, fueling, and hauling applications. Because of the limited potential for airports and aviation, HyTF assigns this element a low score relative to other elements in the Demand category.

2- Biofuels Production

Biofuels are currently viewed as one of the primary options for replacing energy-dense fuels in heavy transportation applications, such as maritime and aviation. Since the production of biofuels, such as cellulosic ethanol, requires a carbon-intensive fermentation process, alternative technologies involving hydrogen, such as hydroprocessing or hydrotreating biofuels, are under development.[238] One process, known as catalytic pyrolysis, develops bio-oil more efficiently because hydrogen chemically reacts with biomass, thus not requiring additional energy use while creating higher energy yields compared to traditional biofuel production processes.[239]

SAFs have the greatest use for hydrogen in biofuel production. NREL estimates a small portion of SAFs will be produced from hydrotreating fats, oil, and greases into diesel drop-in fuels, while the majority will be produced using catalytic pyrolysis of lignocellulosic biomass. NREL projected an annual serviceable consumption potential of 8.7 Mt of hydrogen will derive from the two processes. To distribute that potential geospatially, NREL found the distribution of available biomass based on the “Billion Tons Survey” DOE published in 2016, which makes assumptions about the location of biofuels production within a given state. In this case, biofuels are distributed to areas with refineries, ammonia plants, metals refining, and hydrogen production because of the available infrastructure to support a biofuel plant.[240] Because the SAF industry is still nascent (commercialization after 2040), and there is a high degree of uncertainty in the geographic distribution of biofuel plants, HyTF scores biofuels production low relative to other elements in the Demand category.

3- Cement Plants

The cement industry is the third largest energy consumer across the global industrial sector and responsible for approximately seven percent of overall global emissions. Cement production results in direct and indirect GHG emissions. The former occurs from the chemical decomposition of limestone, known as calcination. The latter takes place when fossil fuels are used to generate high-temperature process heat to produce clinker, the precursor to cement, which is produced from mixing decomposed limestone with raw materials at high temperatures. Currently, coal is the most common fuel used to generate heat for clinker production. With existing technologies, coal with CCS has the lowest cost increase per ton of clinker manufactured, followed by hydrogen produced from SMRs with CCS. Also, hydrogen fuel-switching is restricted to process heating, resulting in only a 30 percent reduction in total cement facility emissions.[241]

HyTF identified 91 cement plants and estimated clinker production for each based on state-level clinker production data and the proportional emissions of each plant in that state.[242,243] Because fuel-switching to hydrogen cannot completely decarbonize cement production, and using hydrogen to decarbonize process heat in cement production is seen as a long-term solution (commercialization after 2040), HyTF scores cement plants low relative to other elements in the Demand category.

Interests

A successful regional hydrogen hub cannot rely only on resources to develop a market. Human capital plays an integral role in whether a region can develop the proper governance, business models, and community engagement plans to fulfill the basic requirements established in the FOA for H2Hubs. Interests, that is, the private companies and governments with business activities and/or interests related to clean hydrogen development, can act as important catalysts to stimulate supply and demand. In HyTF, interests are classified under the private sector, public sector, or at the intersection of the two. Under the private sector, HyTF considers large investor-owned utilities and S&P 500 companies with clean hydrogen activity. The public sector refers to state governments with favorable climate policies. The intersection of the two looks at public-private partnerships: government grants, loans, and direct payments, as well as Small Business Innovation Rewards (SBIRs) pertaining to hydrogen. All these elements are described below.

1- Investor-Owned Utilities

Utilities have a large interest in hydrogen along their value chain, including for energy storage, pipeline blending and residential heating, nuclear applications, and curtailment of renewables. An analysis of investor-owned utilities found at least 25 major utilities with ongoing or planned hydrogen activity. Those utilities' service territories are taken into HyTF's hex areas to represent their interest in hydrogen development. Municipal utilities and utilities with small market capitalization were not considered in the analysis. In discussions with relevant industry stakeholders, EFI found utilities are among the most important businesses propelling clean hydrogen activity in the United States. Thus, service areas of a large investor-owned utility with hydrogen interest or activity score above average relative to other elements in the Interests category of HyTF. Utility activity is further described in the Readme document, found on the HyTF webpage.

2- S&P 500 Companies with Hydrogen Interest

The S&P 500 is an index that tracks the performance of about 500 of the largest publicly traded U.S. companies. It is used to define the dominant industries in the U.S. economy.[244]

As such, the S&P 500 index contains many of the largest private companies in the United States that would have a major impact on a clean hydrogen economy if they pursued hydrogen projects and partnerships. An analysis of all S&P 500 companies found approximately 78 of these organizations have publicly announced activities or interest in clean hydrogen. All these companies fall under the S&P Global Industry Classification Standard (GICS) for industrial, energy, or utilities sectors. In HyTF, each company's weight component of the full S&P 500 index was used to normalize the private sector impact relative to other components in this category. As a result, HyTF scores S&P 500 companies with hydrogen activities above average relative to the rest of the Interests category.

3- State Climate Policy

EFI's workshop report "The Potential for Clean Hydrogen in the Carolinas" noted long-term policy support is a requisite of hydrogen market growth.[245] The juxtaposition of states with strong and weak climate policy highlights the importance of state governments in meeting emissions reduction objectives. HyTF uses Climate Xchange's geospatial data to assess the strength of a state's climate policy.[246] Strong state policy is scored the highest relative to other elements in the Interests category because of the role it plays in setting targets, holding stakeholders accountable, and stimulating growth in clean energy sectors, such as hydrogen. When hex areas in HyTF cross state lines, the state that takes up the greatest percentage of that hex's area determines its climate policy.

4- Federal Government Grants, Direct Payments, and Loans

Financial assistance from the federal government can stimulate R&D, help bridge the investor's "valley of death," and support the growth of a nascent but important industry. Hydrogen projects have received funding since 1980 across all aspects of the value chain, according to USASpending.gov. Using keywords "hydrogen," "electrolysis," and "fuel cell," HyTF identified over 1,800 projects relevant to hydrogen technology. Over 300 projects were screened out from the database for various features (e.g., projects with $0 in funding). HyTF turns point data into cumulative dollar amounts (2021$) for a given hex area and shows that total amount in the interest pop-up window.[247] Because very little federal money has been spent on hydrogen to date, HyTF scores this element between low and average depending on the cumulative funding in a given hex area.

5- Small Business Innovation Research (SBIR) Awards

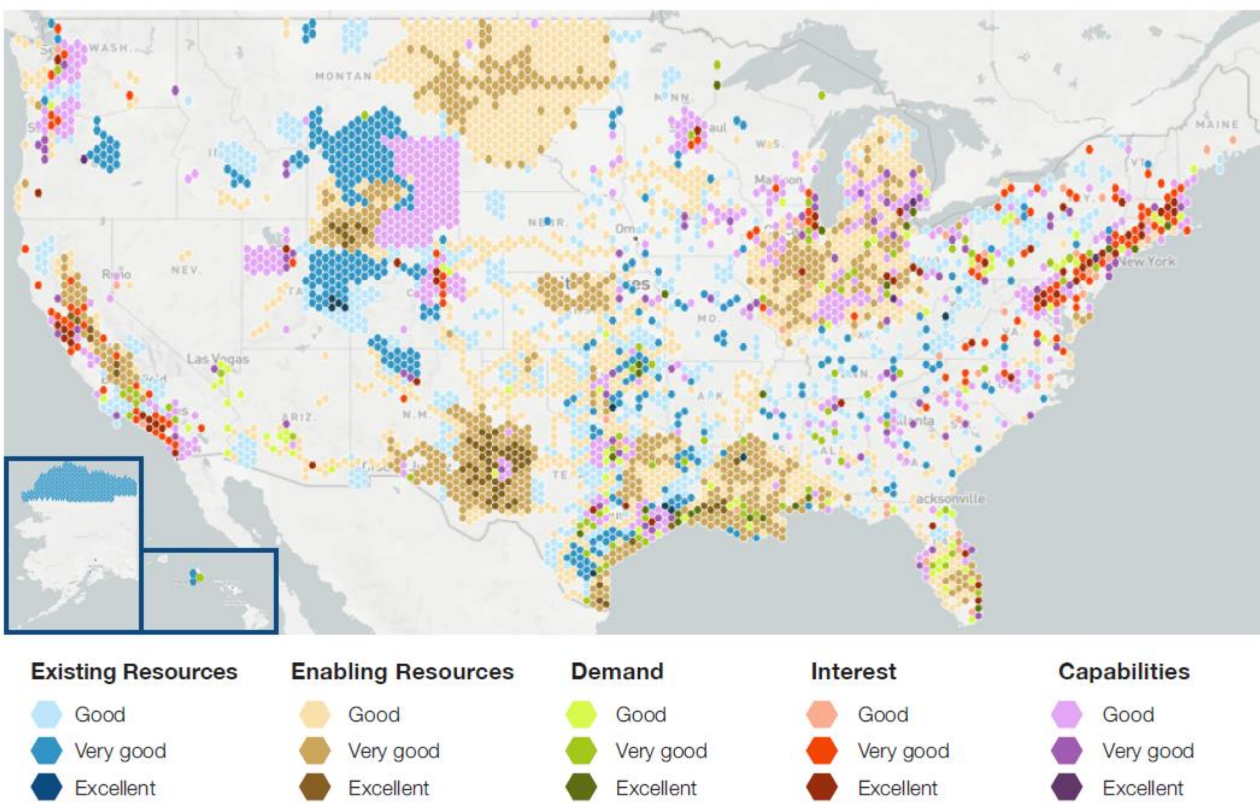
The SBIR and Small Business Technology Transfer (STTR) programs are initiatives that encourage small businesses to engage in federal R&D and help different technologies reach commercialization. Importantly, this competitive program builds up the technological potential of small businesses and provides an incentive for companies to benefit from R&D. For STTRs, small businesses also partner with non-profit research institutions that primarily bridge the basic science stage to commercialization.[248] In HyTF, the location of these programs represents areas of hydrogen entrepreneurship and innovation. HyTF identified 2,045 SBIRs and STTRs with the title keywords of "hydrogen," "fuel cell," and "electrolysis" from 2000 to 2021.[249] Compared to other areas in this category, HyTF scores this element below average because SBIR and STTR projects are small in scale and relatively little federal R&D has focused on the commercialization of clean hydrogen technologies to date.

Capabilities

Similar to interests, this category of HyTF seeks out important human capital that can be leveraged to catalyze resources or demand potential in an area. Capabilities are defined by HyTF as the enabling systems that could support hydrogen investments. As such, the Capabilities category encompasses the expertise and experience that can be used to innovate, educate, or provide necessary skills to the clean hydrogen economy. It includes universities, technical and community colleges, a labor pool capable of transitioning to a hydrogen economy, a track record of hydrogen technology patents, and the 17 national laboratories around the country. EFI's workshop report "The Potential for Clean Hydrogen in the Carolinas" found centers of innovation and a skilled labor force are important enablers of a clean hydrogen hub.[250] That is, if an area has strong resources, demand, and capabilities, there is great potential for a hydrogen hub to materialize. The Capabilities elements of HyTF are described below and Figure A40 combines all the categories in HyTF.

Figure A40

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



HyTF favors regions with large research and innovation systems, such as national laboratories or universities with large R&D budgets or existing hydrogen programs. HyTF also favors regions with skilled labor or institutions that contribute to a technical workforce (e.g., community colleges). Southern and Northern California, metropolitan Chicago, and the Northeast Atlantic coast are especially highlighted in HyTF because of the combination of physical and human capital required to unlock the resource and demand potential of a region interested in hydrogen hubs development.

1- Education Centers

a. Tier One Research Universities

The Carnegie Classification of Institutions of Higher Education deems 146 schools as having "very high research activity in 2021".[251] These universities, sometimes known as R1 Universities, are designated as such if they achieve the following requirements: award at least 20 research/scholarship doctoral degrees in the given year; spend at least $5MM in total research (as reported through the National Science Foundation Higher Education Research and Development Survey (HERD); and score high in a Research Activity Index calculation. HyTF uses the HERD survey to identify R&D expenditure data for each school and geolocate them accordingly.[252] Schools were considered if some funding went to at least one of the following scientific areas with potential hydrogen applications: geosciences, atmospheric sciences, ocean sciences, physical sciences, social sciences, and engineering. HyTF does not consider higher education schools with a focus on health sciences or medical, pharmaceuticals, cosmetics, hair, military, optometry, or dental training.

Tier One University R&D is scored anywhere from above average to very high relative to other elements in the Capabilities category, depending on the total relevant R&D dollars in a hex area. Schools with energy research programs do not receive additional weight within capabilities, but they are identified in the HyTF user interface as potential institutions for clean hydrogen funding to flow through.

b. Other Research Universities

Other universities include the list of remaining universities on the HERD survey – those research schools not designated as R1. These schools are included in the Capabilities category because of their importance on two fronts – additional research capabilities and their contributions to an educated and skilled workforce. The "other universities" list contains 426 schools.[253] They receive relatively low scores compared to other elements in the Capabilities category, recognizing they do not have the capital or funds of R1 universities.

2- Skilled Labor

a. Bureau of Labor Statistics Regions with Strongest Adjacent Hydrogen Jobs/Skills

The classification of a relatively skilled or non-skilled area in the United States is an innovative feature of HyTF, which combines DOE's "Hydrogen and Fuel Cells" career map with the North American Industry Classification System (NAICS) data from the Bureau of Labor Statistics (BLS) at the metropolitan and nonmetropolitan area levels. DOE's career map profiles many hydrogen and fuel cell careers, or potential careers, including advanced (i.e., engineering manager, finance manager, attorney, regulatory expert, economist, site/plant manager, asset manager, budget analyst, communication manager, and professors), mid-level (i.e., chemical engineer, material scientist, environmental scientist, software engineer, civil engineer, research engineer, environmental engineer, electrical engineer, mechanical engineer, project manager, safety and occupational health specialist, computational scientist, buyer, industrial engineer, power systems/transmission engineer, sales engineer, power marketer, logistician, public affairs specialist, editor, and writer), and entry-level (i.e., electrician, instrumentation and electronics technician, advanced manufacturing technician, assembler and fabricator, computer numerical control operator, plant operator, industrial equipment mechanic, legal assistant, salesperson, trade worker, construction worker, transportation worker, and educational aid).[254] Box A7 describes the U.S. potential to transition the existing workforce to clean hydrogen.

Box A7
Hydrogen-Ready Jobs and Industries

The transition to net-zero emissions will depend on an unprecedented transition of the U.S. workforce and will require considerable job growth. According to one study, to support a net-zero transition, jobs in clean energy production alone will need to grow by 15 percent by 2030.[255]

In this regard, the U.S. energy workforce continues to adapt to the changing energy system. Over the last two years, the U.S. energy sector grew by roughly three percent and four percent respectively.[256] While the United States experienced major shifts in electricity generation from coal to renewables and natural gas, U.S. energy sector employment continued to grow, employing more than 7.8MM workers in 2021, with more than 3MM jobs in net-zero aligned areas. [257, j]

To enable the job growth needed by the clean transition, it is critical to support decarbonization pathways, such as hydrogen, that leverage numerous vulnerable workers. According to DOE, clean hydrogen depends on most of the same skillsets found in U.S. industrial and fossil-fuel sectors.[258] Petroleum extraction, for example, employs civil, electrical, and process engineers—roles that can perform the necessary skills across hydrogen R&D, facility operations, and professional services. Other roles in policy and regulatory analysis, legal, construction, sales, and computer science will also be important to support the growth in clean hydrogen that could come from sectors impacted by the clean transition. This will be especially important in certain U.S. regions that are more at risk (see below for more information). The three-state region of Ohio, Pennsylvania, and West Virginia (the Ohio River Valley) supports a large share of U.S. heavy industry, including 22 percent of U.S. steel production.[259] The combined total economic output from manufacturing sectors that could use hydrogen in the three Ohio River Valley states was almost $120B in 2019, according to a study conducted by EFI and the AFL-CIO.[260]

To enable the job growth needed by the clean energy transition, it is important to support decarbonization pathways, such as hydrogen, that leverage labor force participants vulnerable to the energy transition. EFI identified six industries particularly vulnerable to the energy transition – coal mining, oil and gas extraction, pipeline transportation, natural gas distribution, petroleum and coal products manufacturing, and electric

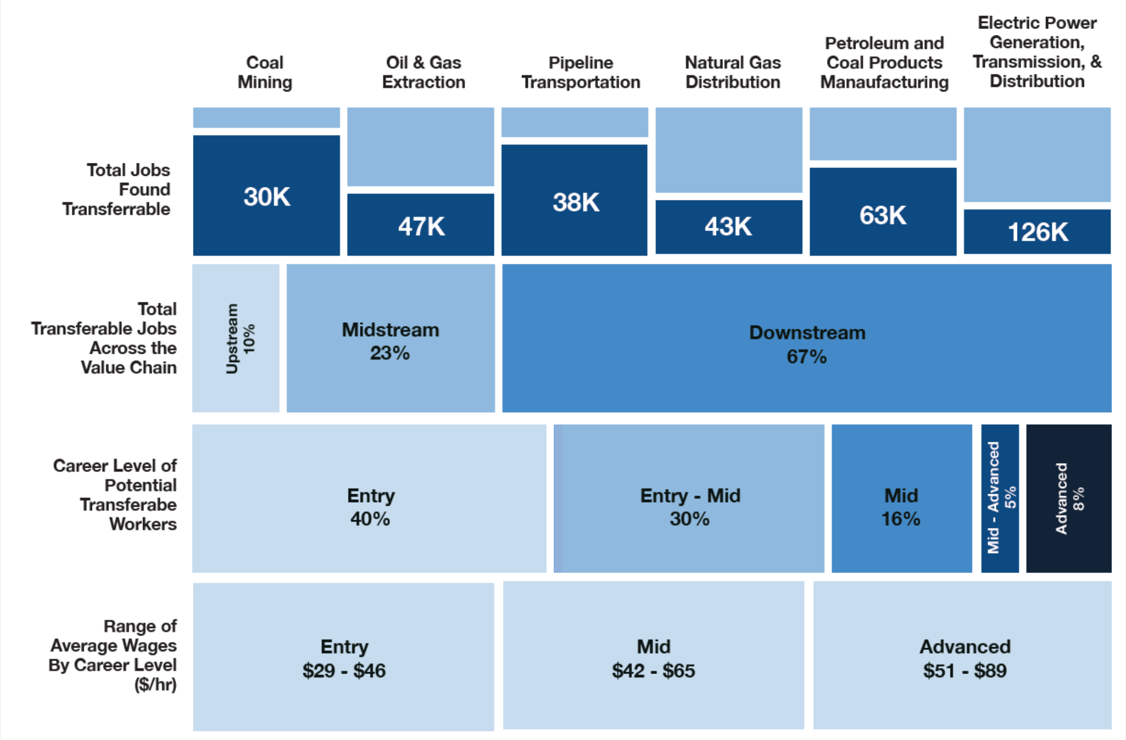
[j] Jobs in net-zero emissions-aligned areas are defined as jobs related to: renewable energy; grid technologies and storage; traditional transmission and distribution; nuclear energy; a subset of energy efficiency; biofuels; and plug-in hybrid, fully electric, and hydrogen fuel cell vehicles and components.

power, generation, transmission, and distribution. Combined, these sectors employ nearly 800,000 workers along the value chain, from wellhead drillers to communication specialists.

In the next decade, if the United States is to meet their economy-wide Nationally Determined Contribution (NDC) target with aggressive decarbonization policies, hundreds of thousands of jobs could phase out in such fossil-intensive industries. Some fossil-producing regions, such as the Ohio River Valley or the shore regions of Texas, Louisiana, and Mississippi (the Gulf Coast), are home to many of these jobs. For example, West Virginia has approximately 13,000 coal mining jobs, or 34 percent of all coal mining jobs in the United States.

Fortunately, new jobs in a well-functioning hydrogen economy leverage many of the skills workers in at-risk sectors possess. Engineers, scientists, sales specialists, lawyers, analysts, managers, and production workers possess specific degrees, knowledge, and abilities that will drive the creation of a robust clean hydrogen market. Over 44 percent of the workforce in at-risk sectors are well-suited to take on new jobs in hydrogen. The identified sectors are based upon DOE's EERE office findings of specific skills and background needed to support a hydrogen economy. In fact, an even greater percentage of the at-risk industry jobs will possess transferable skills to a hydrogen economy, as new roles and needs are realized over time. Figure A41 shows at-risk industries that employ jobs with transferable skills to working with hydrogen and fuel cells, the type of job an individual might look to under the umbrella of hydrogen, and the average expected wages of a worker in that line of work. Promisingly, in especially vulnerable sectors such as coal mining, more than four out of five jobs are occupations with highly transferable skills to hydrogen jobs.

Figure A41
Opportunity for Hydrogen Industries to Leverage Skilled Workers in At-Risk Sectors



NAICS codes from BLS were used to inform this figure. In some cases, missing data prevented an entirely comprehensive analysis of each sector. However, each NAICS code included is based on an equivalent occupation highlighted by DOE EERE as a job that will be needed in a growing hydrogen economy. The EERE hydrogen jobs work further determined the career levels of each occupation analyzed.

A Role for Hydrogen in Fossil-Dependent Regional Communities

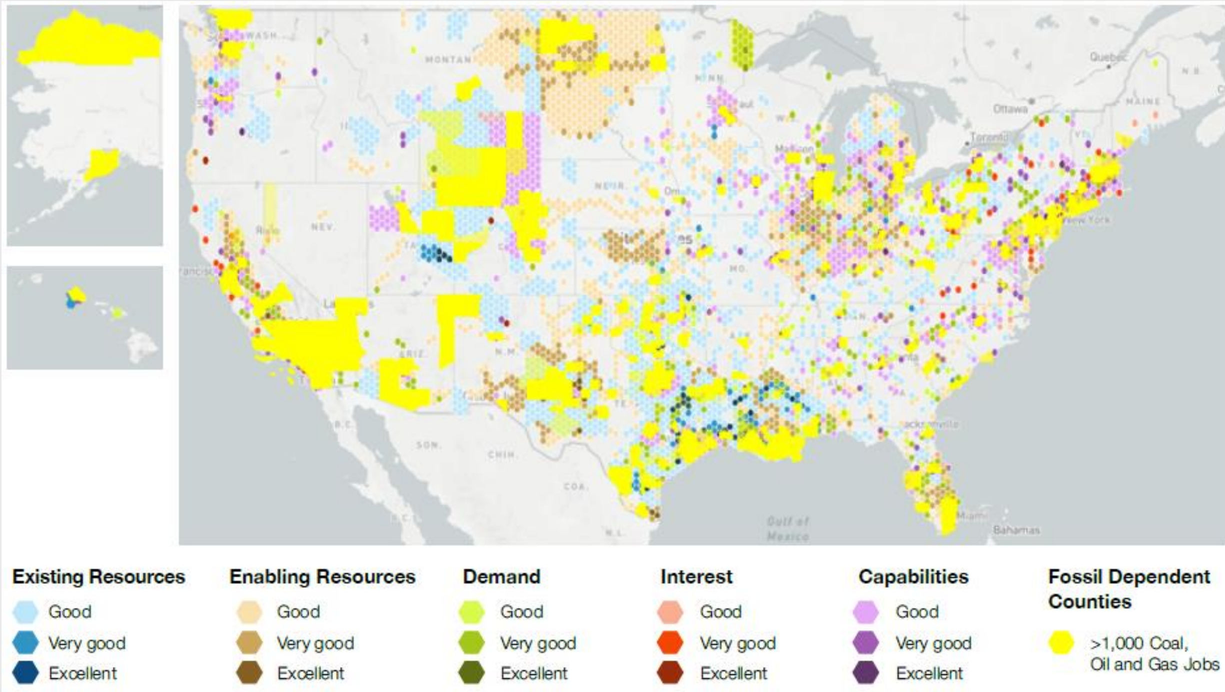
Communities that depend heavily on fossil fuels face huge challenges during the transition to net-zero emissions. While the transition to net-zero emissions will involve unprecedented economic and social changes, the type, magnitude, and regional impacts of these changes depend heavily on the specific paths and destinations of deep decarbonization. However, communities across the United States where jobs, income, and tax revenues depend on carbon-intensive industries, such as fossil fuel extraction and auto manufacturing, may be most affected by the clean transition. According to the Biden administration, "an equitable transition to a clean economy requires more than efforts to reduce emissions."[261]

There are acute risks in communities with large concentrations of heavy industries. While policy can be used to intervene, not every fossil job will translate to a clean energy job, and certain regions may not be well suited for large-scale clean investments. There are many U.S. jobs in the automotive industry, including powertrain design and development, that may not translate to electric vehicle manufacturing, due to the different components and parts. The U.S. powertrain sector—which employs 140,000 workers—is highly concentrated, with roughly 70 percent of workers in Michigan, Ohio, and Indiana.[262] Moreover, there are certain regions where fossil fuel employment is as high as 30 to 50 percent of all employment. The coal extraction industry is located primarily in Appalachia and the Mountain West, with 90 percent of coal production coming from 50 counties.[263]

Clean hydrogen investments in fossil-dependent regional economies can boost local industries and locations most affected by the energy transition.[264] The opportunities for a hydrogen economy to mitigate or alleviate job loss in at-risk communities are promising (Figure A42). Jobs that are ubiquitous throughout the fossil industry require skills that may be called upon to build and grow hydrogen hubs across the United States. Engineers, metal workers (e.g., welders), chemists, scientists, industrial equipment operators, construction workers, sales and project leads, financial managers, to name a handful, are all positions that the hydrogen economy will need to tap into.[k]

[k] An extension of Figure A41, these jobs are derived from BLS jobs data that correspond to a list of sectors compiled by DOE that identifies transferable jobs to the clean hydrogen workforce. A complete list of NAICS sectors used in this report is presented in Table A5.

Figure A42
Hydrogen Opportunities in Fossil Fuel-Dependent Communities



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

Fortunately, the diversity of skilled labor that the hydrogen value chain requires benefits a wide spectrum of geographies and demographics. For example, in nonmetropolitan Eastern Wyoming a large proportion of workers are in construction, industrial equipment operating, and metals fabrication relative to other areas. Therefore, despite a sparse population, the region is equipped with a sizeable labor force that could plug into the infrastructure development and maintenance of a hydrogen hub. Conversely, in the Durham-Chapel Hill area of North Carolina, the high proportion of the workforce in software engineering, project and financial management, and legal support, could contribute to a robust hydrogen innovation and governance plan in that region. Both areas are prime examples of a highly capable labor force that can provide immense capabilities to various segments of the hydrogen value chain through different skills.

Each career listed has a NAICS-adjacent job code from the BLS. While not a perfect one-for-one, for every metropolitan and nonmetropolitan census area, EFI evaluated the proportion of people in hydrogen-adjacent sectors per 1,000 people.[265] This way, urban and rural areas, which have a vastly different make-up of workers, are equally likely to be considered “skilled” as it pertains to hydrogen jobs. The jobs considered hydrogen-adjacent are shown in Table A5. Fair, strong, or very strong labor areas receive an average to above-average score relative to other elements in the Capabilities category because of the importance of finding workers that need minimal training to successfully transition to hydrogen jobs.

Table A5: Hydrogen-Adjacent Jobs[266]

Jobs	NAICS Code
Operations Research Analyst	152031
Budget Analyst	132031
Public Relations Specialist	273031
Chemical Engineers	172041
Environmental Engineer	172081
Computer Programmer	151251
Software Developer	151252
Software Assurance	151253
Electrical Engineers	172071
Electronics Engineer	172072
Civil Engineer	172051
Industrial Engineer	172112
Health Safety Engineer	172111
Mechanical Engineer	172141
Lawyers	231011
Legal Assistants	232011
Engineering Managers	119041
Financial Managers	113031
Project Manager	131082
Logistician	131081
Buyers	131020

Sales Managers	112022
Sales Rep Tech and Science	414011
Sales Engineers	419031
Material Scientists	192032
Power Plant Operators	518013
Geologic Engineers	172171
Nuclear Engineers	172161
Chemist	192031
Construction Managers	119021
Construction Equipment Operators	472073
Electricians	472111
Occupational Health and Safety	195012
Crane and Tower Operators	532071
Dredge Operators	537031
Hoist and Winch Operators	537021
Industrial Truck Drivers	537051
Extruding Metals	514021
Furnace, Kiln, and Oven Operators	519051
Surveyors	171022
Sheet Metal Workers	472211
Structural Iron and Steel Workers	472221
Solar Photovoltaic Installers	472231
Wind Service Technicians	499081
Industrial Machine Mechanics	499041
Power Line Installers	499051

Welding	514121
Assemblers and Fabricators	512090

b. Technical and Community Colleges

HyTF identified 1,040 technical, trade, and community colleges with student populations greater than 1,000 and at least one sciences program.[267] Community and technical colleges offer a wide range of opportunities, especially for financially disadvantaged students. Each community college is scored relatively low compared to other elements in the capabilities category, but hex areas with multiple community colleges can score very high. For example, one hex area has 16 community colleges, and results in the hex lighting up as “Excellent” among other reasons. The affordable education provided to a diverse pool of students is an important aspect of developing a labor force ready to contribute to this new energy commodity market.

3- Hydrogen Patents

Locating areas where hydrogen technology innovation occurs enables one to understand if a region has the capabilities to develop a hub. Using the U.S. Patents and Trademarks Office (USPTO) Patents View, HyTF draws geospatial data for each patent based on the location of the patent assignee and the keywords “hydrogen,” “fuel cell,” and “electrolysis.” Additionally, the Cooperative Patent Class was specified as “Y02E,” which designates all patents related to the “reduction of GHGs, energy generation, or transmission and distribution.”[268] The nearly 2,000 patents in HyTF extend back to 1976 and each receive a relatively low score for a single patent. Cumulative patents, however, may result in hex area lighting up as “Excellent.” For instance, one area in HyTF includes over 190 patents fitting the above description.

4- National Laboratories

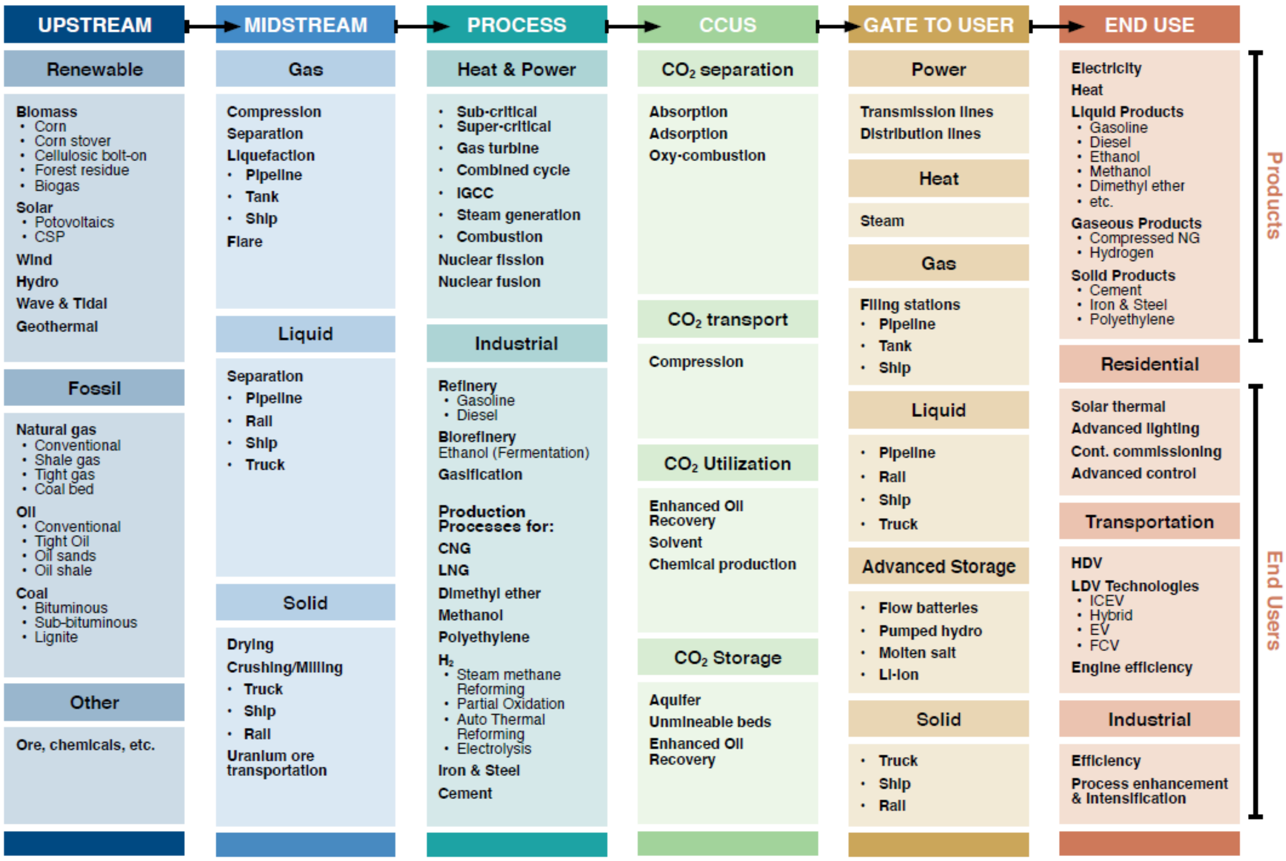
HyTF provides the location of all 17 DOE national laboratories. The laboratories are important for this framework because researchers are developing new energy technologies, advancing the frontier of scientific discovery, protecting national security, incubating new industries, and fostering the next generation of scientists and engineers. Many have activities directly influencing hydrogen R&D worldwide. To ensure they appear in HyTF, they score the highest among elements in the Capabilities category. Because of the nature of the locations for the national laboratories, there might not be a lot of other activity to draw upon. Still, with only 17 labs scattered across the country, a region with a national laboratory has an advantage for the innovation plan of a hub design.

Appendix E: Accurate Estimation of Decarbonization Potential of Energy Choices via Sustainable Energy Systems Analysis Modelling Environment (SESAME)

To assess the level of decarbonization achieved through the energy transition, one needs to study the carbon footprint of the energy system as a whole. An assessment of plausible country-specific transition pathways should be guided with a set of quantitative methods and assessment tools. Such tools cover multi-sector dynamics of transitions and consider economy-wide and sectoral life cycle analyses of numerous options, while highlighting trade-offs to provide decision-making insights to government stakeholders. To that end, a first-of-a-kind modeling framework was developed: Sustainable Energy Systems Analysis Modelling Environment (SESAME).[269,270,271,272,273] SESAME is an interactive tool for exploring the impacts of all relevant technological, operational, temporal, and geospatial characteristics of the evolving energy system. SESAME focuses on the accurate estimation of life cycle GHG emissions, techno-economic assessment, and the scalability and feasibility of emerging pathways.

The versatility and flexibility of SESAME stem from its modular structure, comprising a matrix of modules grouped by six life cycle steps, as shown in Figure A43. SESAME is a multi-platform tool that includes more than 1,000 individual energy pathways that combine fossil resources (coal, natural gas, crude oil from different sources and with different compositions), renewable energy sources (solar, wind, hydropower, biomass), major processes (power plant, refinery, chemical processing, etc.), and major end uses (transportation, electricity, industrial products). The flexible architecture of SESAME is designed to integrate available tools and techniques.

Figure A43
Modular Representation of the Energy System as Defined in SESAME



The SESAME model is a flexible multi-platform tool that includes more than 1,000 individual energy pathways in a matrix of modules grouped by six life cycle steps that combine fossil resources (coal, natural gas, crude oil from different sources and with different compositions), renewable energy sources (solar, wind, hydropower, biomass), major processes (power plant, refinery, chemical processing, etc.), and major end uses (transportation, electricity, industrial products).

A core aspect of this scenario analysis framework is the ability to assess key systems interactions and couplings. The emissions impact of many technologies cannot be analyzed within a single sector of the economy. For example, the emissions impact of electric vehicle growth depends on both the transportation and power sectors. For another example, the emissions impact of growth in fuel cell vehicles and hydrogen production depends on the transportation, power, and industrial sectors. SESAME models inter-sector interactions, and thus allows maximizing the emissions removals resulting from new technologies.

Life Cycle Analysis Methodology, System Boundaries, and Functional Units

To accurately represent the energy system, SESAME was developed as a pathway-level and system-level life cycle analysis (LCA) tool following the ISO 14040 and 14044 standards.[274,275] SESAME is designed to conduct attributional LCA for all the pathways and systems that can be defined via the modular architecture of the tool. For the power system, SESAME can model and project GHG emissions as a consequence of renewables penetration of the grid.

System boundaries have been specified for the LCA of all the products of focus in SESAME. The system boundaries encompass all the life cycle steps (cradle-to-grave), which are: upstream; midstream; process; CCUS as an optional step; gate to user; and end use.

Depending on the nature and function of the product, the functional unit can vary. For example, for biofuels, the functional unit could be one megajoule (MJ) of biofuel (calculated based on lower heating value) or one mile driven by a car fueled by 100 percent biofuel. For power, the functional unit could be one MWh (consumed by a car or a residential facility) or one mile driven by an electric vehicle.

Modeling Framework

SESAME's programming architecture is implemented in Python by integration with Aspen Plus process simulation software for some advanced pathways using the methodology presented by Gençer and Agrawal and Gençer et al.[276,277] This approach allows complementing life cycle analysis and techno-economic assessment with process simulation capabilities to capture the performance and emission variations arising from technological, operational, and geospatial factors (by calculating energy and mass balance). The developed architecture provides a platform to implement simulations of process units with high emission rates, critical for the system design. Data Sets, Python, and Aspen Plus are used to feed input assumptions to the Python core script. As needed, the tool can be equipped with more programming platforms and connected to various existing tools.

A novel aspect of this analytical framework is the ability to assess key systems interactions and couplings, allowing transition pathway options to be compared holistically and on the same basis. Moreover, SESAME's modular design can be modified as the complex energy system evolves. Integrating process simulations allows for exploring the impact of operational and topological changes to the process. For the initial set of simulations, scaled-up processes consistent with industrial operation standards have been used. However, the platform allows users to integrate process simulations at different scales, including lab-scale processes, and to perform a full assessment of these processes in different pathways and systems. This feature can be used to understand the GHG emissions reduction potential of a novel process relative to conventional ones, or to analyze a modification in process integration, such as introduction of green hydrogen into an industrial facility.

The modular approach is composed of four main compartments at the very highest-level: User Input, Control Panel, Life Cycle Step Modules, and Output. Users select from default options to initiate the computation. The control panel module is the core of the tool that takes users' inputs and communicates with relevant life step modules to send and receive information. The results from each life step module are adjusted and combined in accordance with the user's selections. Finally, the results are reported as output in the desired form and units in accordance with the functional unit of the pathway/system selected. For the pathways with energy products such as electricity and fuel, the output is per unit energy based. For chemicals pathways, results are presented per unit mass. For transportation pathways, the results are presented per distance driven, and for heavy duty transportation, the results are presented per distance-load driven. All the results can be presented scaled instead of per unit, and various units can be selected.

Low Carbon Hydrogen Supply Chain Module

The low carbon hydrogen supply chain module is a multi-nodal system that optimizes for power and hydrogen production, transmission, and storage. It takes a macroeconomic modeler's perspective, optimizing for social welfare by minimizing the overall costs. Perfect foresight is adopted using power generation data.

For each node, capacities of renewable generation from solar and wind, electrolyzers, ATR and SMR plants, and hydrogen and electricity storage are optimized. Power generation is used for electrolyzers and compressors for hydrogen storage and transmission. The relative share of wind and solar resources to install is optimized depending on the regions in which this production is located.

Transmission is optimized for both electricity and hydrogen. This model also performs a life cycle analysis, which is accounted for in the objective function via a carbon tax or production tax credit. It includes emissions for all infrastructure installed, which are assumed to linearly scale with increasing capacity. It notably includes carbon emissions not captured by CCS from ATR and SMR. Hydrogen storage is assumed to be provided by salt caverns.

Renewable generation capacity factor (CF) profiles are sourced using the ZEPHYR (Zero-emissions Electricity system Planning with HourlY operational Resolution) repository.[278,279] ZEPHYR accesses historical wind and irradiance data from the NREL Wind Integration National Dataset (WIND) Toolkit, and the NREL National Solar Radiation Database (NSRDB), and calculates power output, assuming all PV units have single-axis tracking systems and 1.3 DC-to-AC inverter ratios, and wind turbines have a hub height of 100m.[280,281] A collection of representative capacity factor curves was manually sourced for each region, over a range of years (2007-2013).

The objective function aims to minimize the annualized costs of the system, which comprises capital and operational expenditures of assets, fuel, and emissions costs. A set of electrical production infrastructure includes solar photovoltaics (PV), wind turbines, inverters, and electrical storage (Li-Ion batteries). The set of hydrogen production/storage infrastructure includes electrolyzers, ATR and SMR plants, storage, and compressors.

SESAME Hydrogen Model Use Cases

1- Granular representation of hydrogen system

Granular representation involves accurately characterizing hydrogen demand and supply networks for different regions. On the demand-side, various end-use applications are considered and temporal profiles are used.

2- The interconnected regions

The in-region production of hydrogen might not be sufficient to meet the growing low carbon hydrogen demand. To address this challenge, three key connections can be evaluated: low carbon hydrogen imports, low carbon electricity imports for hydrogen production, and natural gas import with the associated export of the CO_2 captured.

3- The optimal hydrogen transport options

Determining optimal low carbon hydrogen supply configurations includes considering different transport modes from regions of interests. Transport modes include long distance pipelines, liquefied hydrogen, and promising hydrogen carriers such as ammonia.

4- The role of emerging technologies

Even though the hydrogen ecosystem is quite mature, there is still room for technology improvements and new technologies across the value chain. The role of such technology options and improvements is explored to reflect their potential. Specific examples for thermal processes include methane pyrolysis, which has been presented as one of the game-changing technologies for natural gas-based hydrogen production.

5- Scenario analysis

Developed analytical capabilities are used to explore minimum-cost hydrogen supply chain design options for different scenarios and timeframes. The cost and emission analysis provides insights into various international hydrogen trading options.

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