The Landscape of Clean Hydrogen

An Outlook for Industrial Hubs in the United States

May 2023

CARBON SOLUTIONS

I³ Industrial Innovation Initiative

a partnership between Great Plains Institute and World Resources Institute

A report by Carbon Solutions in association with the Industrial Innovation Initiative.

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About Carbon Solutions

Carbon Solutions applies proprietary research and development, software, and team expertise to address energy challenges, including carbon capture and storage, geothermal energy, wind energy, biofuels, energy storage, and the hydrogen economy. Carbon Solutions aims to accelerate low-carbon energy and beneficial infrastructure development in the US.

The Carbon Solutions vision is focused on three integrated pillars: research and development that advances low-carbon energy science, software development that generates unique tools and data, and services that apply our research and development and software to address emerging energy challenges.

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About I^3

The Industrial Innovation Initiative (I^3) is an ambitious coalition that builds upon years of stakeholder engagement by its co-conveners, Great Plains Institute and World Resources Institute, collaborating with government officials and subject-matter experts to advance decarbonization solutions important to the industrial sector.

This report was created to provide informational value to I^3 members; however, it was not drafted with member input and does not reflect the expressed opinions of participating organizations.

I^3 Mission

To advance solutions key to decarbonizing the industrial sector by midcentury through policy development and implementation; technology demonstration and adoption; and demand-side market development at state, regional, and federal levels.

Learn more: industrialinnovation.org

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Executive Summary

Hydrogen is an energy carrier, fuel, and chemical feedstock that can enable decarbonization across multiple sectors of the US economy. The US Department of Energy's (DOE) H2Hubs program is set to support the growth of clean hydrogen over the coming decades, jump-starting clean hydrogen projects at regional hubs across the country. Hydrogen production must quickly scale beyond these initial hubs to reach the DOE's targets of 10 million metric tons of clean hydrogen by 2030, 20 million metric tons by 2040, and 50 million metric tons by 2050.

This report examines regional opportunities for clean hydrogen hubs and considers the immense scale of new hydrogen production, carbon capture retrofits, and electrolysis capacity needed to meet national climate goals. This information can help build a better understanding of the key criteria for impactful hydrogen hubs, allowing for the best potential in driving decarbonization.

Key findings of the report include the following:

- **There are numerous diverse applications for clean hydrogen,** including as a chemical feedstock in refining, petrochemicals, ammonia and fertilizer; in new applications including energy-efficient steelmaking and low-carbon transportation fuels; and as an energy source or electric grid balancing resource.
- **Prioritizing the use of hydrogen in hard-to-electrify sectors will be essential to maximizing climate benefits.** In sectors such as heavy industry and transportation, where emissions are anticipated to persist or increase by midcentury without additional policy, hydrogen will be an important enabler of decarbonization.
- **DOE's goals represent hydrogen production at five times today's current capacity.** These goals can be met from a variety of hydrogen production methods as long as they achieve low lifecycle carbon intensity thresholds set by the 2022 Inflation Reduction Act's Clean Hydrogen Production Tax Credit. This includes electrolysis and natural gas-based hydrogen with carbon capture, among others.
- **Hydrogen hubs are an opportunity to co-locate production with new and existing markets,** leveraging the unique assets of each region to allow for growth to regional scale and maximize emissions reduction.
- **It will be beneficial to establish hydrogen hubs with large production targets,** such as 100 thousand tons to 1 million tons of hydrogen per year. Otherwise, it will take many more hubs at DOE's minimum production thresholds to meet roadmap goals and midcentury targets.
- Electrolysis accounts for less than one percent of hydrogen production. **Electrolysis will need to scale immensely to achieve multi-gigawatt scale in the next decade,** eventually matching the same order of magnitude as current fossil-based hydrogen production and beyond.
- Hydrogen produced via electrolysis requires a significant amount of clean electricity. **This additional load impact will need to be accounted for in electric grid planning,** with an emphasis on additional renewable generation capacity where possible.
- **Hydrogen not only provides GHG benefits but can also reduce air quality pollutants** by displacing fossil fuel use in industry and transportation. This can especially benefit disadvantaged communities co-located with polluting facilities and high-traffic areas.
- **Meeting DOE's clean hydrogen goals could avoid 245 to 366 million metric tons of emissions** from conventional hydrogen and fossil fuels, with further reductions enabled by a variety of other applications.

Executive Summary

Regional hubs can be critical drivers of innovation in the race to scale hydrogen production to reach DOE's climate goals and meet our nation's growing energy demands. In examining high-impact opportunities for hydrogen production and use in a variety of industrial and transportation subsectors, promising regional use cases for clean hydrogen emerge across the US. For example:

- The Gulf and Midcontinent's many refineries, chemical producers, and other industrial facilities could achieve major emissions benefits by displacing current hydrogen production and use with clean hydrogen.
- The Upper Midwest is well-positioned to develop clean hydrogen-based ammonia for use in fertilizer, providing a domestic resource for agricultural communities.
- Iron and steelmaking could be decarbonized using clean hydrogen. The iron range of the Upper Midwest could participate in a developing market for direct reduced iron (DRI) made using clean hydrogen. Active supply chains and distribution infrastructure could support new hydrogen and DRI-based steel production in the Gulf and Great Lakes.
- High rates of renewable energy produced in California, the Southwest, and Midwest could power hydrogen electrolysis facilities, which could be used for electric grid balancing and energy storage.

Strategic opportunities for clean hydrogen production and use by region

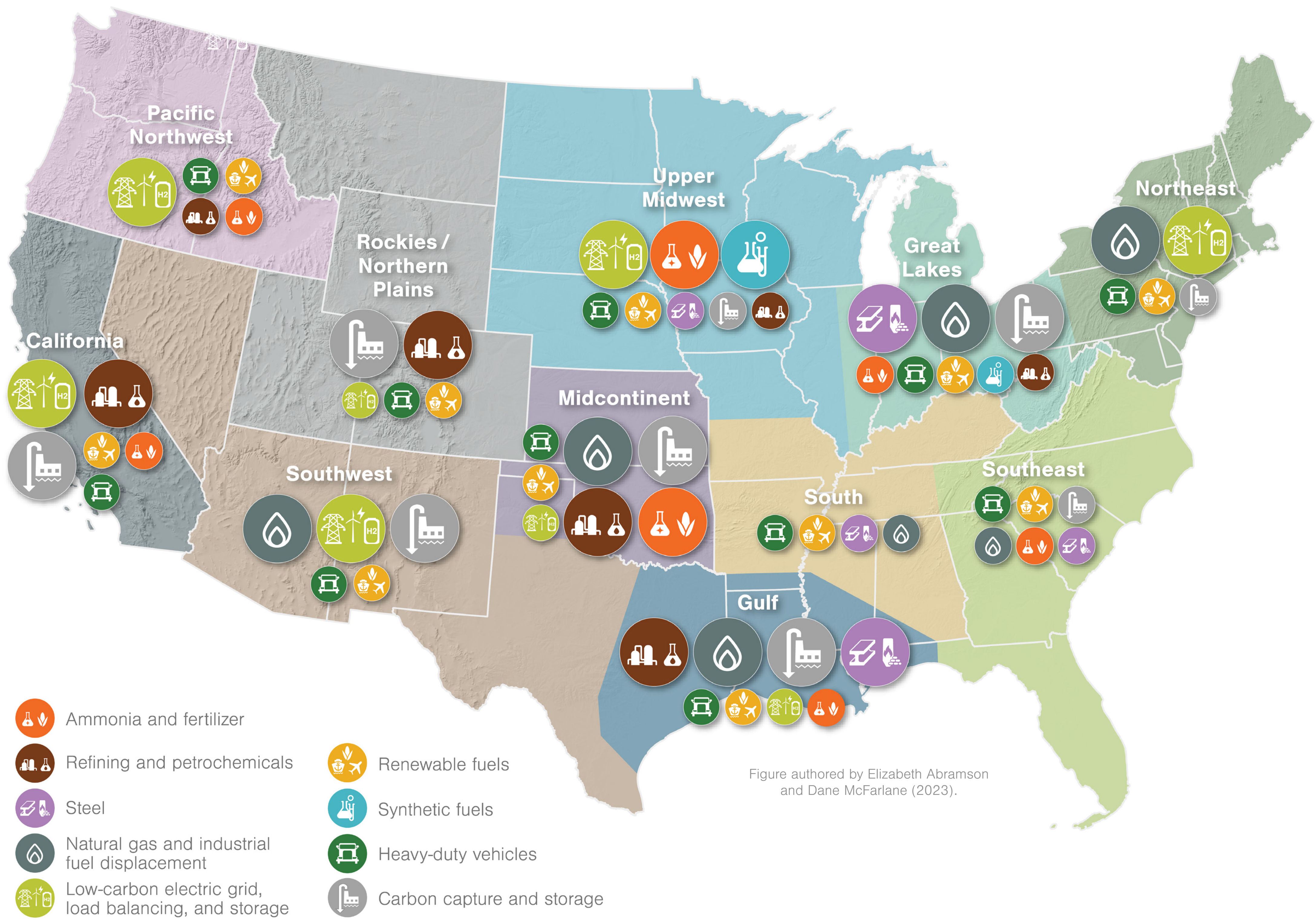


Figure authored by Elizabeth Abramson and Dane McFarlane (2023).

The Landscape of Clean Hydrogen | Section 1

The Role of Clean Hydrogen in Achieving US Midcentury Climate Goals

Hydrogen: A central tool for economy-wide decarbonization

As the US moves toward achieving its goals to reduce greenhouse gas (GHG) emissions by 50 percent compared to 2005 levels by 2030, and to net zero by 2050, clean hydrogen has emerged as a critical resource for decarbonizing energy-intensive sectors of the economy.

Hydrogen can provide decarbonization benefits through several primary applications:

- Hydrogen's role as a carbon-free combustion fuel for high-grade heat makes it valuable in industrial applications, where the production of materials and goods often requires high-temperature heat that is currently provided by the burning of fossil fuels and is difficult to electrify.
- Clean hydrogen can also provide emissions reductions in industrial facilities where conventional hydrogen is currently used as a chemical feedstock, such as in **ammonia** and **nitrogen fertilizer** production, and **petroleum refining.**
- Hydrogen can be used as a material feedstock that helps decarbonize the supply chain through innovative processes in industrial sectors like **steelmaking** and **biofuels** production.
- Several developing markets that will enable the US to achieve net-zero emissions can use hydrogen to produce a range of **synthetic fuels, aviation fuel**, and various forms of energy storage while enabling the complementary deployment of renewable electricity, carbon capture, and next-generation biofuels.

US production and use of hydrogen

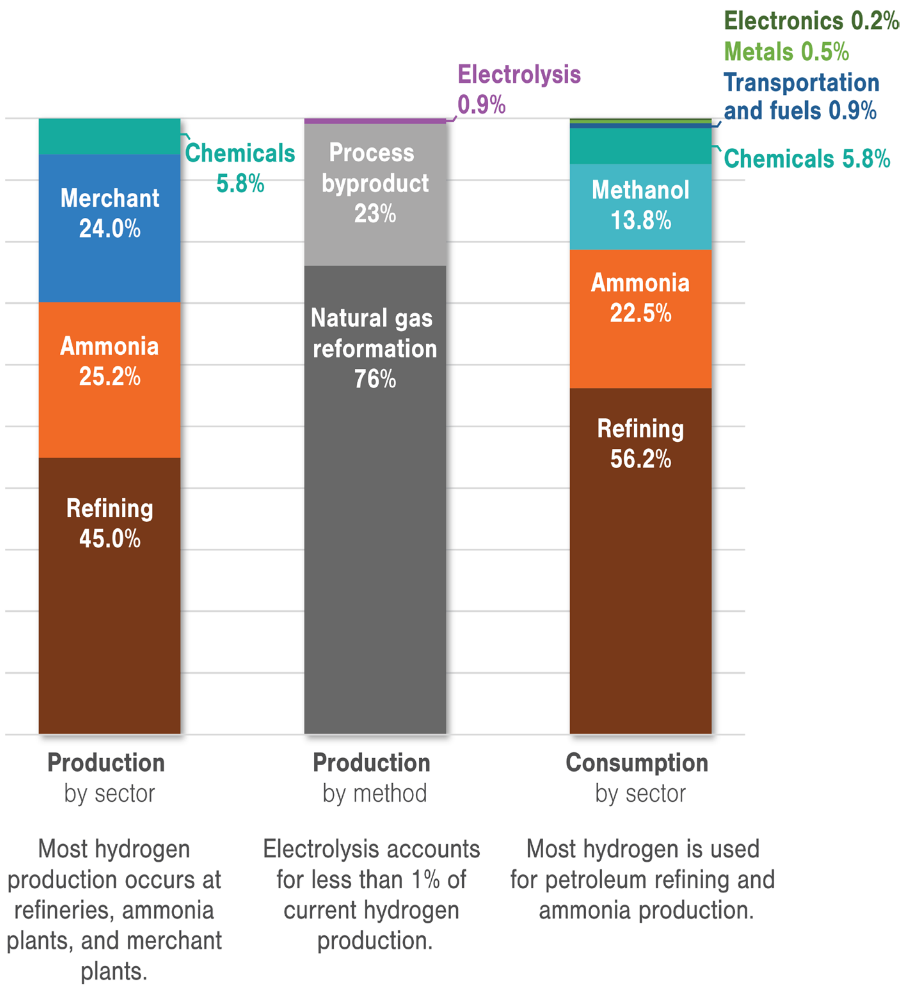


Figure authored by Elizabeth Abramson (2023) based on *The U.S. Hydrogen Demand Action Plan* (Energy Futures Initiative, February 2023); S&P Global Commodity Insights, *Directory of Chemical Producers*.

Current hydrogen production and use

Today, the US produces approximately 10 million metric tons (Mt) of hydrogen per year using dedicated production equipment for applications in ammonia and nitrogen fertilizer production, petroleum refining, and chemicals and petrochemicals manufacturing.[1] **About 95 percent of US hydrogen (excluding process bybroduct) is produced through a natural gas-based process called steam methane reforming (SMR),** which results in GHG emissions through the combustion of fuel, use of electricity, and the chemical release of carbon dioxide (CO_2).[2] The SMR process is often considered a prime candidate for economically feasible retrofit of carbon capture equipment due to its release of high-purity CO_2.

Hydrogen can also be produced in dedicated electrolyzers, which use electricity to split water into oxygen and hydrogen. **If electrolysis is powered by clean electricity, the result is clean hydrogen with very low or zero carbon intensity.** While many hydrogen electrolyzers exist throughout the US, their hydrogen production capacity is quite small relative to that of industrial SMR units. With an average electrical capacity of 441 kilowatts (kW), today's typical electrolyzer can produce 74 metric tons of hydrogen per year at expected energy-to-hydrogen yields and operation rates for low-temperature electrolysis.[3]

Hydrogen: A central tool for economy-wide decarbonization

Existing US hydrogen production facilities are shown at right. These facilities include refineries, ammonia production plants, and chemical manufacturing plants, where hydrogen is typically produced for use on site, as well as merchant hydrogen plants, where hydrogen is produced for sale to off-site users. Existing US electrolyzers are also shown.

New electrolysis projects have been announced with electrical capacities of 120 megawatts (MW), much larger than the historic average, capable of producing up to 20 thousand metric tons of hydrogen per year.[4] While carbon capture can be used to decarbonize hydrogen production at SMR-based facilities, electrolysis is often seen as the long-term future of clean hydrogen production due to a simpler engineering process and its reliance on water and clean electricity rather than fossil fuels. Electrolysis also provides a nearly complete reduction in on-site GHG and criteria air pollutants compared to SMR, and a complete reduction in upstream energy carbon intensity if electricity is supplied by new builds of renewable energy.[5]

A 120 MW electrolysis project is a notable improvement over existing electrolyzers but is still quite small and often costly in capital expense and energy costs compared to SMR-based production. **Advancements in electrolyzer capacity, cost, efficiency, and yield will be needed to enable clean hydrogen production at scale.**

Current hydrogen production in the United States

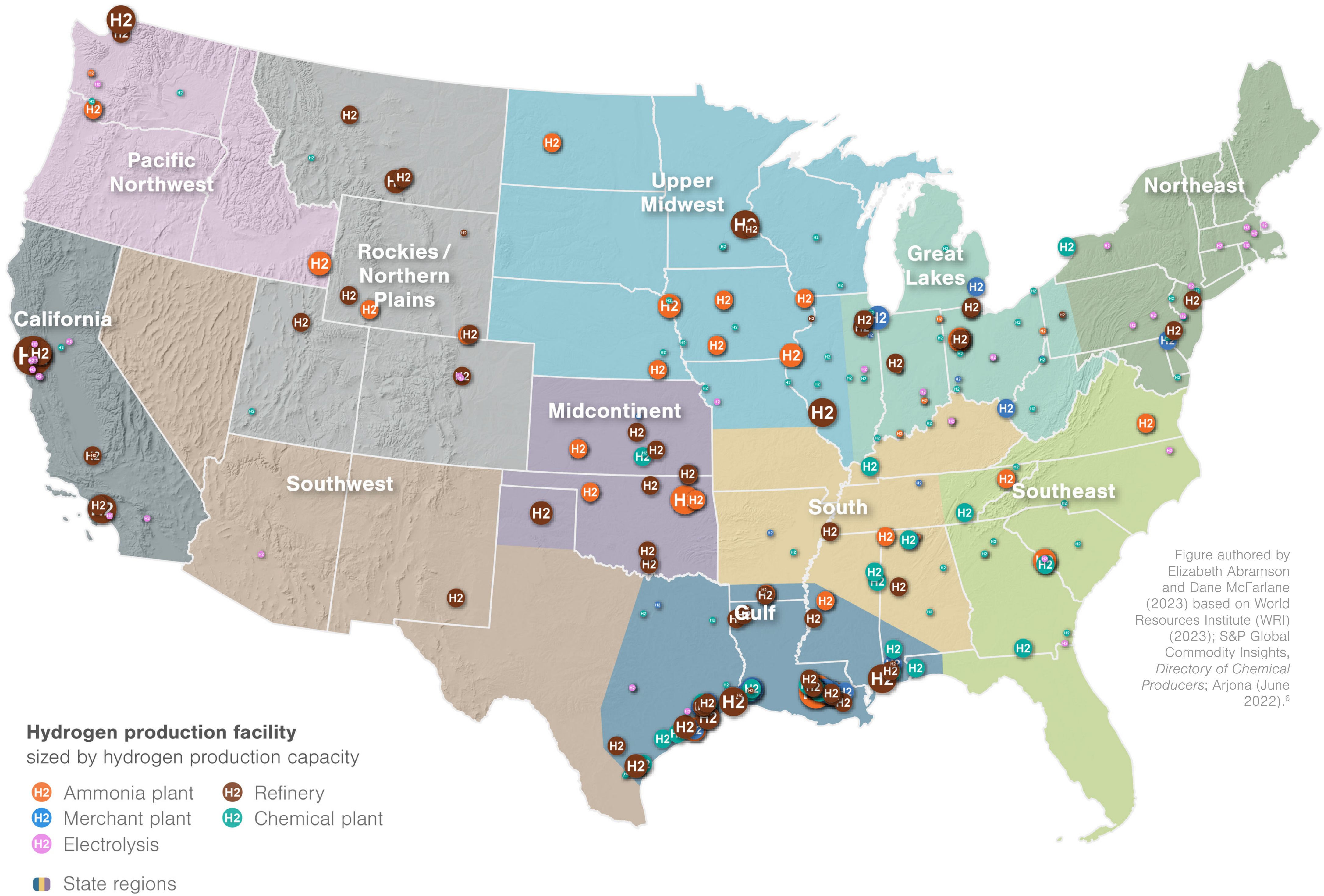


Figure authored by Elizabeth Abramson and Dane McFarlane (2023) based on World Resources Institute (WRI) (2023); S&P Global Commodity Insights, *Directory of Chemical Producers*; Arjona (June 2022).[6]

Hydrogen: A central tool for economy-wide decarbonization

Scaling up hydrogen production

The DOE *National Clean Hydrogen Strategy and Roadmap* establishes a series of goals for the nation's clean hydrogen production capacity. These include an annual production capacity of 10 Mt of clean hydrogen by 2030, 20 Mt in 2040, and 50 Mt in 2050.

These targets represent a massive scale-up of clean hydrogen production, especially considering that today's roughly 10 Mt of US hydrogen could only count toward DOE targets by retrofitting with carbon capture and storage (CCS) equipment or transitioning to other clean production pathways.

The DOE's H2Hubs program, established under the Bipartisan Infrastructure Law in 2021, is set to fund six to ten hub locations demonstrating the full hydrogen value chain in 2023, with award negotiations continuing into 2024. **The H2Hubs program has an important role to play in jumpstarting national progress toward achieving the DOE's clean hydrogen goals.** Beyond the hydrogen produced at core hub facilities, the program will be critical in developing supportive industrial ecosystems to catalyze additional regional clean hydrogen activity. Further, the selected hubs will demonstrate a variety of clean hydrogen production and application use cases to inform clean hydrogen project development across the country.

The scale of change needed to achieve clean DOE clean hydrogen goals

The US currently has around 10 million metric tons of dedicated hydrogen production, nearly all using emissions-intensive pathways, namely steam methane reforming (SMR).

The DOE has a goal of scaling *clean* hydrogen production to 10 Mt by 2030, 20 Mt by 2030, and 50Mt by 2050. Transitioning current hydrogen production to clean pathways is an important step toward reaching these goals.

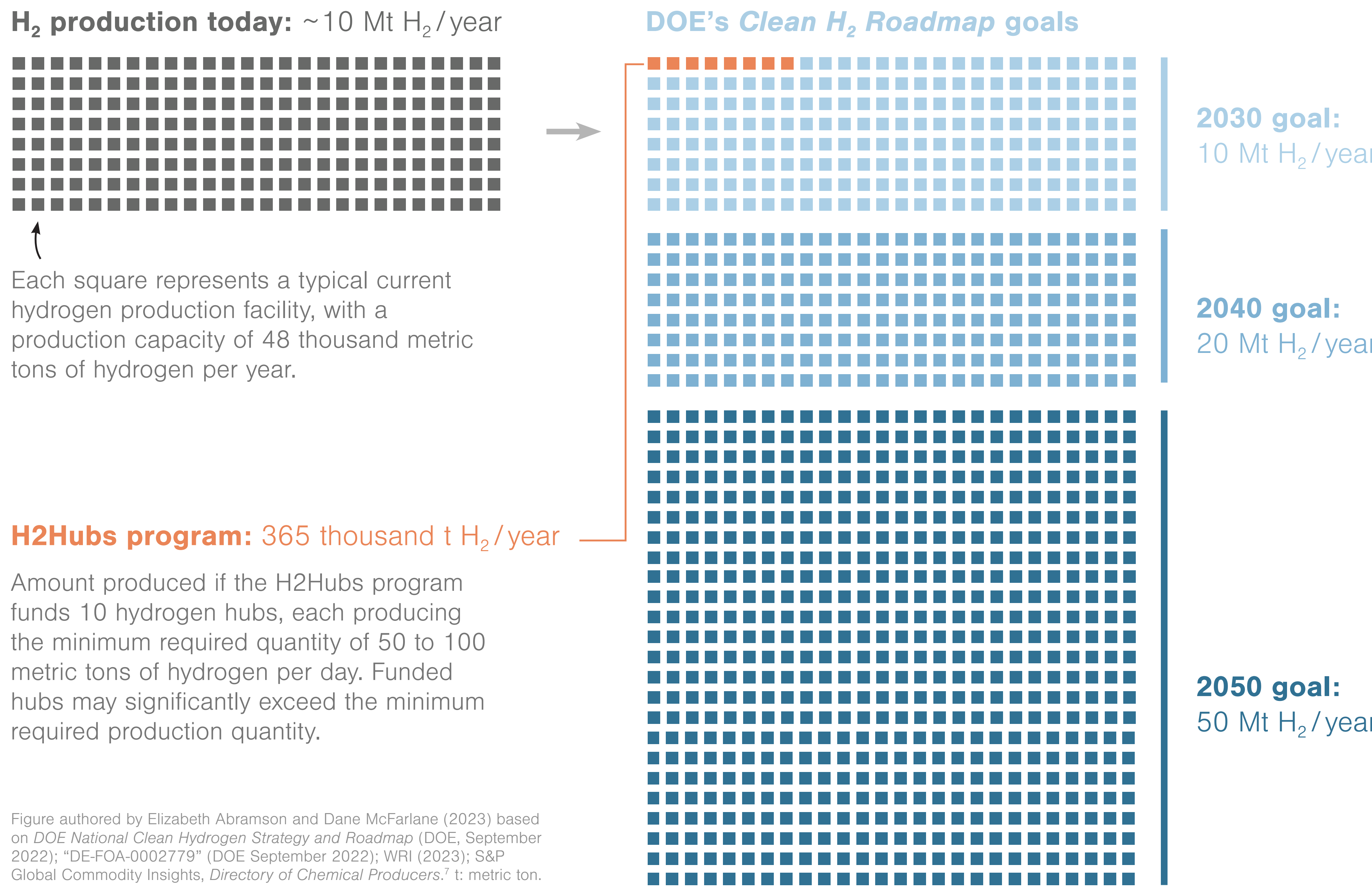


Figure authored by Elizabeth Abramson and Dane McFarlane (2023) based on *DOE National Clean Hydrogen Strategy and Roadmap* (DOE, September 2022); "DE-FOA-0002779" (DOE September 2022); WRI (2023); S&P Global Commodity Insights, *Directory of Chemical Producers*.[7] t: metric ton.

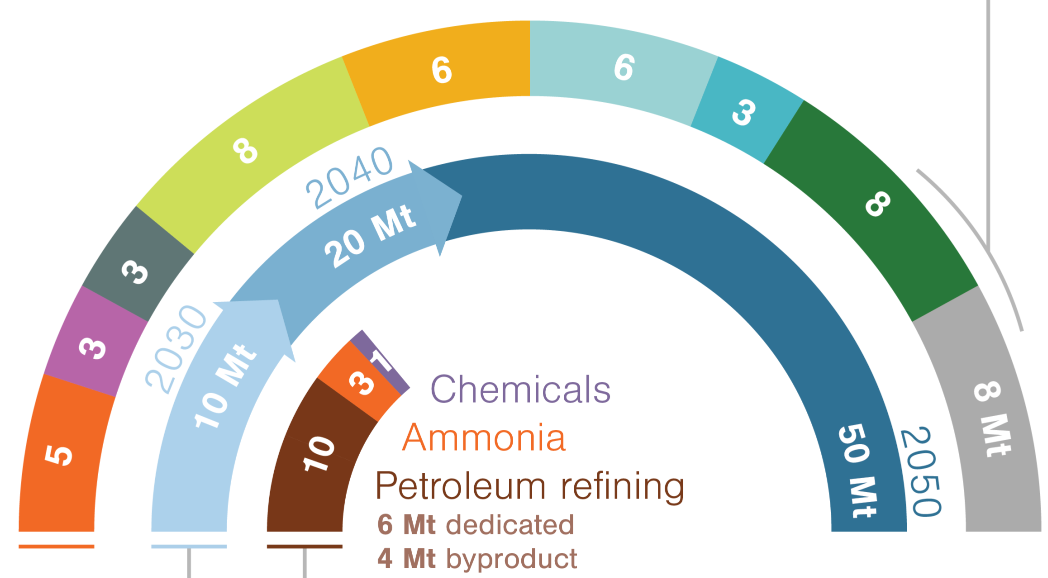
Hydrogen: A central tool for economy-wide decarbonization

While today hydrogen is primarily used in petroleum refining, ammonia production, and chemicals production, **the DOE has identified several new demand sectors with collective projected demand for 50 Mt of clean hydrogen in 2050.** These demand sectors are shown in the outermost ring of the graph at right. For clean hydrogen to successfully scale to necessary levels, markets for clean hydrogen utilization in sectors such as these must grow alongside increases in production.

Fully decarbonizing the nation's economy to achieve net-zero emissions by midcentury may require even more hydrogen production than the DOE's goal of 50 Mt in 2050. Modeling conducted as part of Princeton University's *Net-Zero America* study charted at least five potential pathways for the nation to achieve net-zero emissions by 2050, all of which require extensive use of clean hydrogen to displace fossil fuels, act as an energy storage medium, and contribute to the production of synthetic fuels or biofuels.[9]

Depending on the amount of electrification achieved across sectors, the cost of renewable energy and fuels, and the level of renewable energy penetration in the electric grid, **Princeton's modeling projects that between 58.3 Mt and 135.8 Mt of hydrogen will need to be produced per year by 2050 to achieve net-zero emissions.** In addition to hydrogen produced via electrolysis, several Princeton scenarios rely on hydrogen produced through SMR, autothermal reforming, or methods involving biomass and bioenergy, all of which would require pairing with carbon capture and storage to achieve low carbon intensity. The role of hydrogen in Princeton's Net-Zero scenarios is explored in greater detail on pages 35 and 36.

US hydrogen production, targets, and potential demand



Potential Clean H_2 Demand
DOE Clean H_2 Strategy and Roadmap
50 Mt H_2 by 2050
- Ammonia
- Iron reduction & steelmaking
- Injection to NG infrastructure
- Energy storage
- Biofuels
- Power-to-liquid fuels
- Synthetic methanol
- Fuel cell vehicles: medium & heavy-duty
- Other

DOE Clean H_2 Production Goals
50 Mt H_2 by 2050

Current H_2 consumption
10 Mt dedicated
4 Mt byproduct

Figure authored by Elizabeth Abramson and Dane McFarlane (2023) based on *DOE National Clean Hydrogen Strategy and Roadmap* (DOE, September 2022); WRI (2023); S&P Global Commodity Insights, *Directory of Chemical Producers*.[8]

The DOE has identified demand for 50 Mt of hydrogen across several key sectors by 2050. Even more hydrogen production and use may be needed to reach net zero.

Hydrogen: A central tool for economy-wide decarbonization

Locating hydrogen hubs

Opportunities exist throughout the US for hydrogen production and use to reduce emissions across multiple sectors. New hydrogen hubs may most effectively target regions with significant levels of current hydrogen production and use, as well as areas with a high concentration of industries that have the potential to use hydrogen for future decarbonization.

Some applications of hydrogen, such as in the development of synthetic fuels, aviation fuel, and energy storage, are less geographically concentrated. It is difficult to specifically predict where these applications will develop. When deployed responsibly with community and labor input, the DOE H2Hubs program can provide high-wage jobs, help alleviate environmental burdens, and provide new benefits to disadvantaged communities. Applying DOE's Justice40 principles to the siting and development of hydrogen hubs will help ensure that communities across the country equitably benefit from the major investments needed to scale hydrogen production and use.

Study approach

To assess the regional dynamics of siting hydrogen hubs, this report studies the geographic distribution of current hydrogen production and use as well as the distribution of high-value applications in industries that may increasingly use hydrogen in the future. The report also considers the implied need for new hydrogen electrolysis facilities to meet the DOE's midcentury hydrogen production goals, and to align with net-zero scenarios such as those published by Princeton University.

To assess the emissions reduction potential provided by the large-scale application of clean hydrogen, this report compares the carbon intensity of current hydrogen production methods to the carbon intensity thresholds required for clean hydrogen in the Inflation Reduction Act's (IRA) Production Tax Credit (PTC). This report also compares the carbon intensities of fossil fuels to that of clean hydrogen. This analysis estimates the possible emissions reductions that could be achieved in industries with potential to transition their fuel sources from fossil fuels to clean hydrogen. Finally, this report examines potential emission reductions that could be achieved with innovative applications of hydrogen in new industries and fuel types. Per-ton emissions reductions from replacing several conventional fuels with clean hydrogen are shown in the figure at right and are explored in depth later in the report.

Energy applications

Hydrogen can be used as an electric grid balancing resource or energy storage medium. As seasonal and variable energy generation increases, excess clean electricity from the grid can be used to produce hydrogen, which can be used to displace carbon-intensive fuels or conventional hydrogen, or used as short- to long-duration energy storage.

In the near and medium term, hydrogen can be co-fired with natural gas in existing equipment to provide high-grade heat in industrial applications. In the long term, high-capacity fuel cells could produce electricity, releasing the energy effectively stored in hydrogen that is released when hydrogen travels across a fuel cell's membrane to bond with oxygen.

Emissions reductions from displacing conventional fuels with clean hydrogen

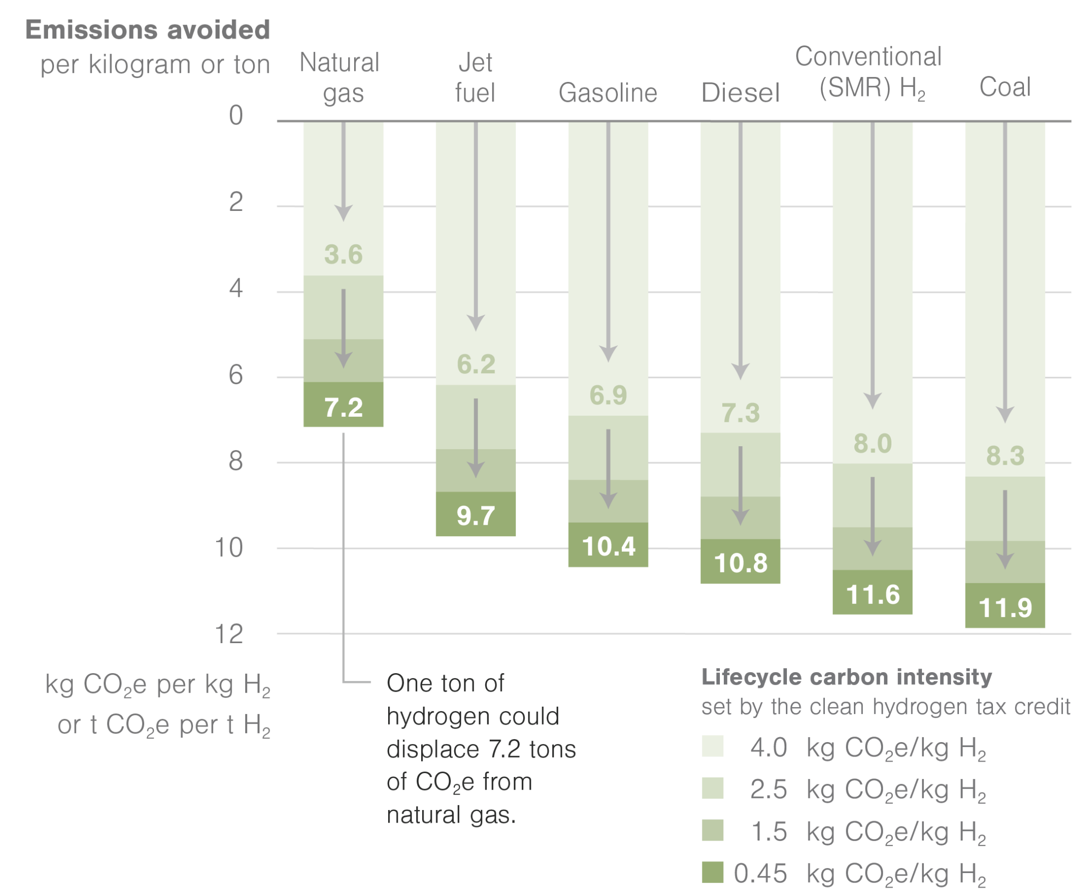


Figure authored by Elizabeth Abramson, Dane McFarlane, and Amy Jordan (2023) based on GREET Model (ANL, 2022); CA-GREET3.0 (California Air Resources Board, August 2018).[10]

Diverse applications for clean hydrogen

Already used as a feedstock in petroleum refining, petrochemicals, ammonia, and fertilizer applications, clean hydrogen has a wide variety of potential applications that will help the US meet its climate goals.

Figure authored by Elizabeth Abramson and Dane McFarlane (2023) based on *DOE National Clean Hydrogen Strategy and Roadmap* (DOE, September 2022).[11]

Strategic uses of clean hydrogen will expand over time

Ammonia & fertilizer

Ammonia and nitrogen fertilizer production is the second largest hydrogen market today.

Ammonia demand is expected to rise 43% to 19.5 Mt/year in 2050.[12]

Growing demand for fertilizer means growing demand for hydrogen.

Refining & petrochemicals

As today's largest hydrogen market, most US hydrogen is currently produced from SMR at petroleum refineries and used in on-site operations.

Using cleaner hydrogen production pathways at refineries can produce major GHG reductions.

Heavy-duty vehicles

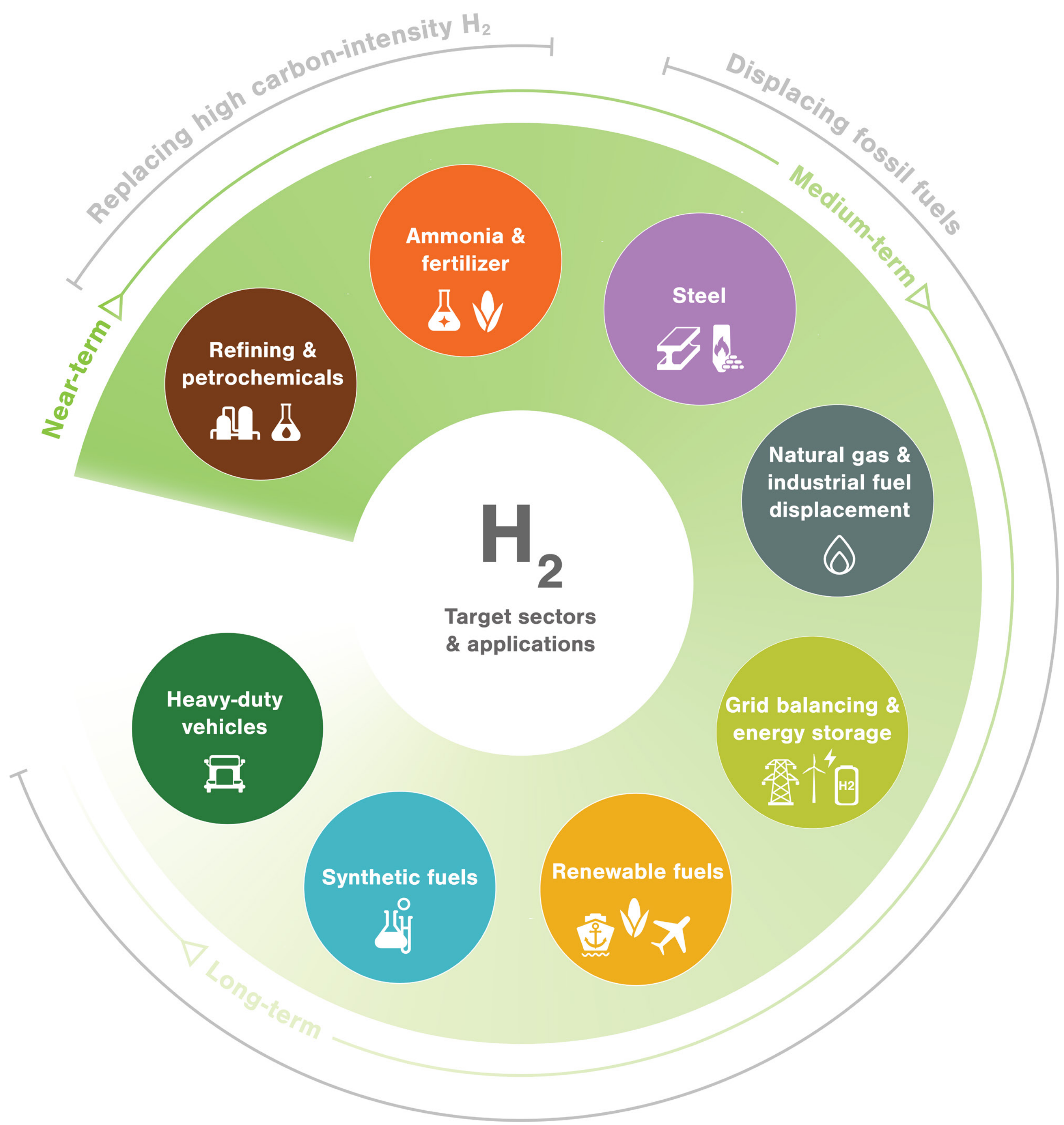
Hydrogen fuel cell vehicles could provide greater energy density for heavy-duty applications where battery vehicles may not be sufficient.

Hydrogen fuel cells are well-suited to power medium- and heavy-duty vehicles.

Synthetic fuels

Hydrogen can be used along with captured high-purity CO_2 to create low-carbon fuels such as Fischer-Tropsch products or methanol.

Synthetic fuels produced with hydrogen can displace traditional fossil fuels.



Steel

Hydrogen can displace natural gas or coal as a source of heat and act as a feedstock in steel production.

Hydrogen can be used to produce direct reduced iron (DRI), which can be melted to produce steel. Transitioning to DRI-based steel production can increase hydrogen demand.

Natural gas used to produce the carbon monoxide used in DRI production can also be blended or replaced with hydrogen.

Natural gas & industrial fuel displacement

Hydrogen can displace natural gas as a fuel for industrial applications.

Hydrogen can be used for high-grade industrial heat applications currently served by natural gas and other fuels and can be safely integrated into natural gas systems.

Grid balancing & energy storage

Hydrogen can provide long-duration energy storage required to support an increasingly renewable-powered electric grid.

Excess renewable electricity can be used to create hydrogen using electrolysis. Stored hydrogen can then be used to support the electrical grid over a short term (e.g., peaking capacity) or long term (e.g., seasonal usage and energy time shifting).

Renewable fuels

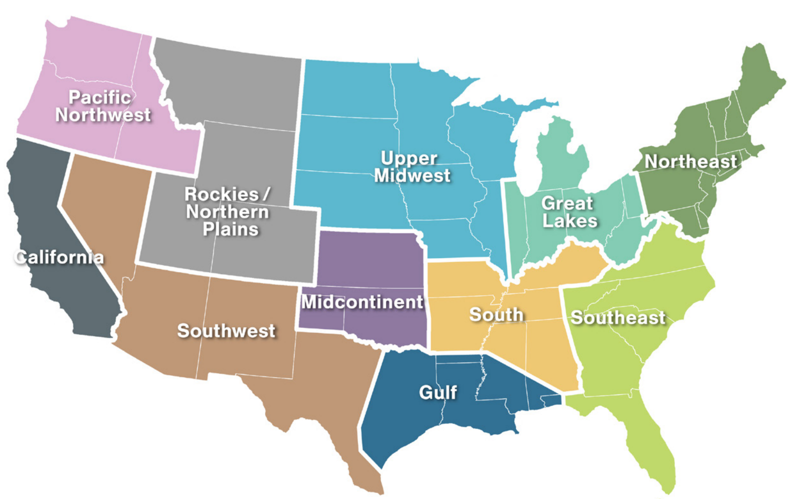
Renewable fuels produced with hydrogen can power heavy duty transport, aviation, and maritime shipping.

Hydrogen can be used as a feedstock for production and upgrading of fuels such as renewable diesel or fats, oils, and grease (FOG) derived biofuel. These fuels can be used for freight, aviation, and maritime shipping.

Regional opportunities for clean hydrogen hubs

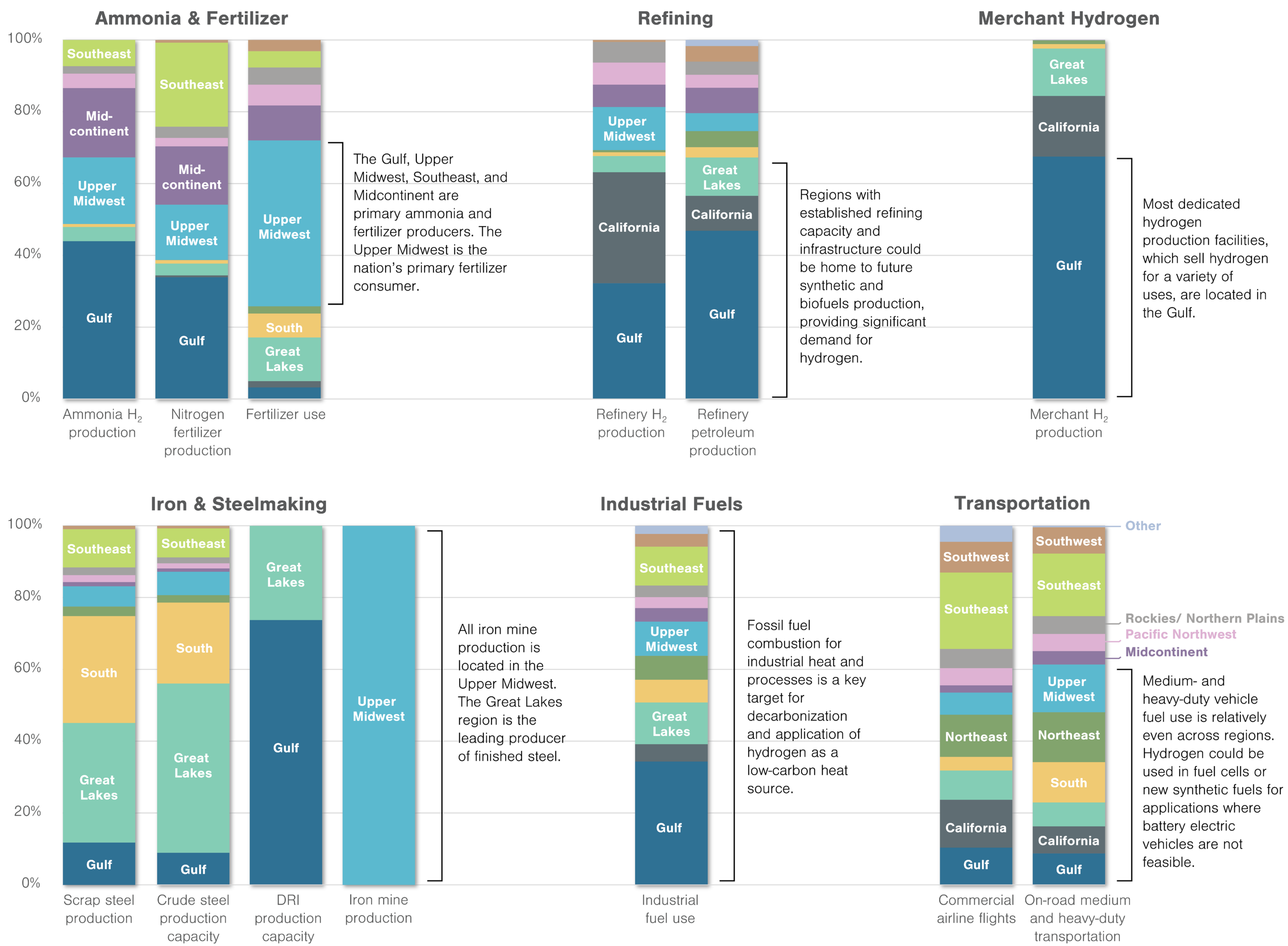
With the DOE set to fund six to ten clean hydrogen hubs starting in 2023, there are opportunities throughout the US to kickstart the use of hydrogen as a climate solution both in sectors with existing uses of hydrogen and in brand new application areas. **This report outlines existing activity and potential for clean hydrogen production and application across 11 US regions.**

Each region has a unique industrial profile, presenting various advantages for hydrogen hub development. The charts at right give a high-level overview of the share of activity and production in hydrogen application sectors such as ammonia and fertilizer, petroleum refining, hydrogen production, iron and steelmaking, industrial fuel use, and transportation.



Figures authored by Elizabeth Abramson and Dane McFarlane (2023) based on WRI (2023); S&P Global Commodity Insights, *Directory of Chemical Producers*; Cao et al. (2017); Updated database tool by Amy Jordan based on "Industry Energy Data Book" (NREL, accessed January 2023) and McMillan et al., (2019); "Global Steel Plant Tracker" (Global Energy Monitor, 2022); Mineral Commodity Summaries: Iron Ore (US Geological Survey, January 2023); Mineral Commodity Summaries: Iron and Steel Scrap (US Geological Survey, January 2022); "2021 Data Summary Spreadsheets" (EPA, accessed March 2023); Refinery Capacity 2022 (EIA, January 2022); 2020 Highway Performance Monitoring System (National Transportation Atlas Database, February 2023); "OPSNET > Airport Operations" (FAA, accessed March 2023).[13]

Sectoral activity and hydrogen production by region



Regional opportunities for clean hydrogen hubs

Strategic opportunities for clean hydrogen production and use

Pacific Northwest
- Geothermal and hydroelectric resources for electrolysis
- Opportunity to produce ammonia for local agricultural market
- CO_2 storage opportunity through mineralization
- Aviation, marine, and freight transport can use synthetic fuels and SAF

Rockies / Northern Plains
- Existing H_2 production
- Low-cost geologic CO_2 storage opportuntiies
- Abundant wind and solar for electrolysis
- Nearby regional markets for clean ammonia

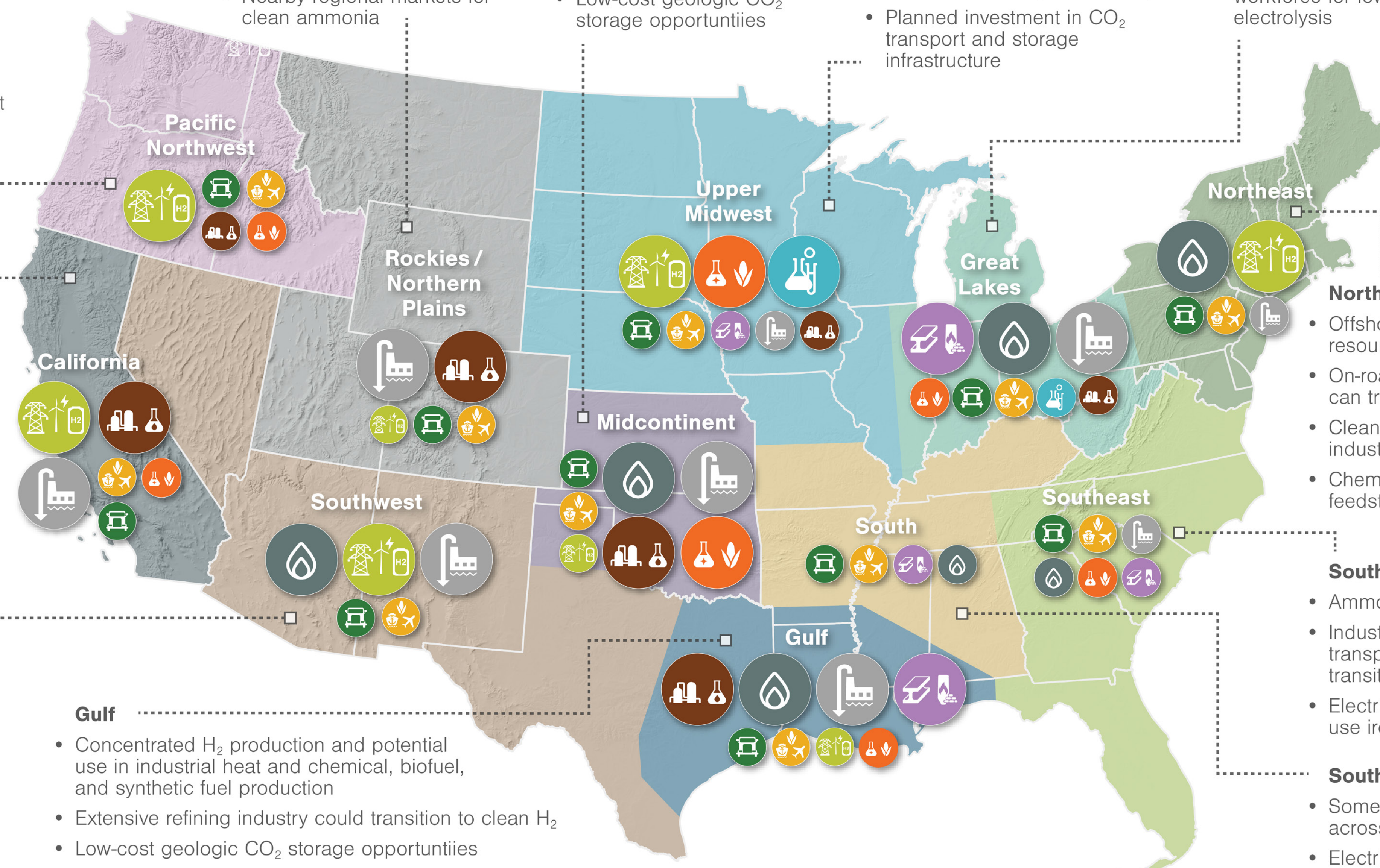
Midcontinent
- High concentration of current H_2 production
- Major fertilizer producer
- Abundant clean grid electricity
- Low-cost geologic CO_2 storage opportuntiies

Upper Midwest
- Largest regional concentration of ammonia production for agricultural use
- Iron ore mining for H_2-powered steel production
- Abundant clean grid electricity
- Planned investment in CO_2 transport and storage infrastructure

Great Lakes
- National steel production hub
- Existing H_2 production
- Low-cost geologic CO_2 storage opportuntiies
- Nuclear fleet and experienced workforce for low-carbon electrolysis

Opportunities to jump-start clean hydrogen production and use are informed by each region's industrial and energy landscape.

In-depth regional summaries are provided on pages 63 to 68.



California
- Sizable refinery and merchant H_2 production
- Refining industry can transition to clean H_2
- Opportunity to produce ammonia for large in-state agricultural market
- High renewable generation capacity for electrolysis

Southwest
- Abundant renewable energy capacity
- Access to trucking routes and crucial refueling access in remote areas
- Large nuclear capacity for low-carbon electrolysis
- Carbon storage and natural gas operations in the Permian Basin area

Gulf
- Concentrated H_2 production and potential use in industrial heat and chemical, biofuel, and synthetic fuel production
- Extensive refining industry could transition to clean H_2
- Low-cost geologic CO_2 storage opportuntiies
- Major fertilizer producer
- Wind and solar resources for electrolysis
- Iron ore imports for DRI

Northeast
- Offshore wind and renewable resources for electrolysis
- On-road transportation can transition to clean fuel
- Clean H_2 fuel for high industrial heat generation
- Chemical production via H_2 feedstocks

Southeast
- Ammonia fertilizer producer
- Industrial and on-road transportation fuel use can transition to clean H_2
- Electric arc steel production can use iron made with clean H_2

South
- Some current H_2 production across multiple sectors
- Electric arc steel production can use iron made with clean H_2
- Clean H_2 fuel for high industrial heat generation

Ammonia and fertilizer
Refining and petrochemicals
Steel
Natural gas and industrial fuel displacement
Low-carbon electric grid, load balancing, and storage
Renewable fuels
Synthetic fuels
Heavy-duty vehicles
Carbon capture and storage

Figure authored by Elizabeth Abramson and Dane McFarlane (2023).

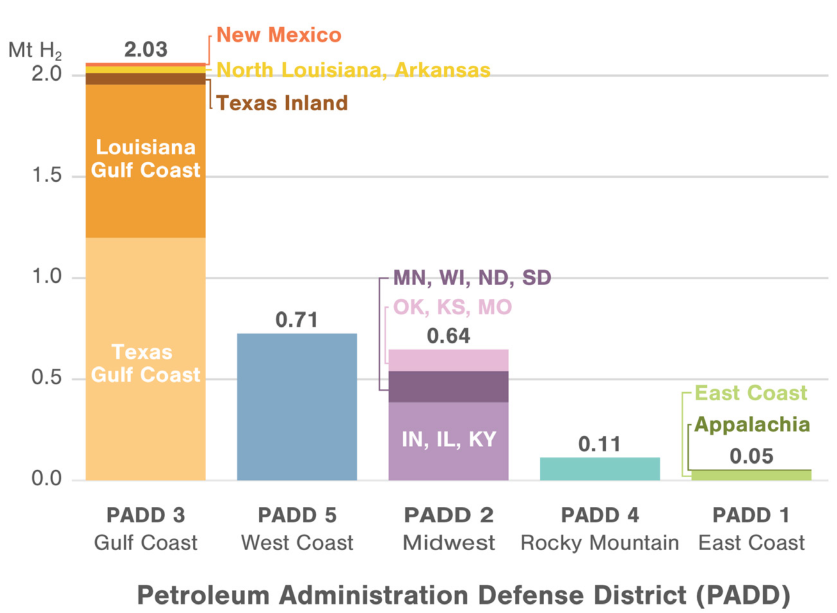
The Landscape of Clean Hydrogen | Section 2

Industrial and Transportation Sector Spotlights for Clean Hydrogen Application

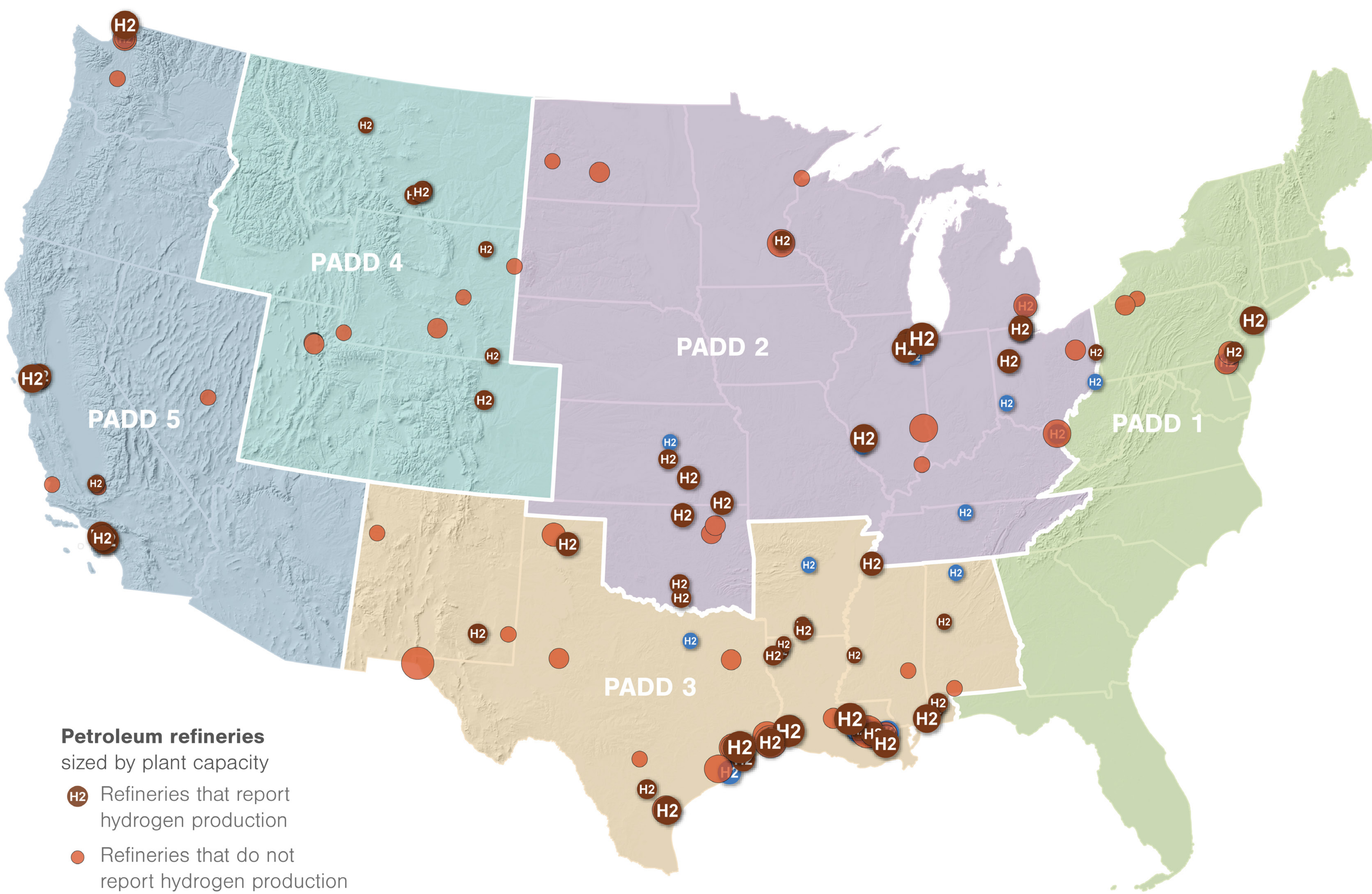
Clean H_2 opportunity: **Refineries**

Petroleum refineries turn crude oil into transportation fuels, energy products, and other chemical products. While battery electric vehicles are seen as the future of the passenger vehicle market, many studies indicate sustained demand for petroleum products over the next few decades in aviation, marine shipping, and heavy-duty freight. Hydrogen is both a useful chemical feedstock for petroleum refining and petrochemical production and a byproduct of these processes. **Clean hydrogen could help reduce the carbon impact of sustained demand for petroleum products.** Hydrogen can also act as a chemical feedstock for sustainable aviation fuel, drop-in renewable fuels, and synthetic fuels produced at refineries that convert to producing clean fuels. With concentrated activity in the refining sector, the Gulf could be a major market for clean hydrogen or a center for new renewable fuel production.

Refinery and blender net hydrogen input, 2021



Hydrogen production at petroleum refineries



Petroleum refineries
sized by plant capacity

- Refineries that report hydrogen production
- Refineries that do not report hydrogen production

Hydrogen production facility
sized by hydrogen production capacity

- Merchant plant

Figures authored by Elizabeth Abramson and Dane McFarlane (2023) based on S&P Global Commodity Insights, *Directory of Chemical Producers*; "2021 Data Summary Spreadsheets" (EPA, accessed March 2023); *Refinery Capacity 2022* (EIA, January 2022).[14] Note: This map uses petroleum administration defense districts in order to interpret refinery production data shown in the corresponding bar chart. These districts differ from the regions used throughout the rest of this report.

Clean H_2 opportunity: **Refineries**

The role of hydrogen at refineries

Unrefined petroleum, also known as crude oil, is composed of hydrocarbons (mixtures of carbon and hydrogen) along with other elements such as nitrogen, oxygen, sulfur, and metals. Refineries use hydrogen and catalysts to remove these other elements from the crude oil through processes including hydrotreating, hydrocracking, and hydrodesulfurization, transforming the crude oil into useful fuels and other products. Failure to remove these compounds can lead to excess air pollutants, corrosion, and unwanted chemical products.

Because hydrogen is integral to fuel production, **the refining sector is the largest current market for hydrogen.** There are currently 142 petroleum refineries in the US that report to the EPA's Greenhouse Gas Reporting Program, with the majority located along the Gulf Coast.[15] Cumulatively, they consume about 10 Mt of hydrogen per year from both dedicated hydrogen production and byproduct hydrogen from other refining processes.[16]

Refineries often have a dedicated SMR on-site or are co-located with a merchant plant operated by a third party. Dedicated and merchant production of hydrogen accounts for approximately 6 Mt of hydrogen, with dedicated production comprising approximately 8 percent of refining's total emissions in 2021 (14 $MtCO_2e$). The remaining hydrogen is recovered as a byproduct through additional processes that remove hydrogen from primary refinery products such as napthenes and aromatics.

Transitioning to clean hydrogen

Switching to clean hydrogen in line with the clean hydrogen PTC could reduce dedicated production emissions at refineries by 66 to 96 percent at the highest and lowest PTC tiers, respectively.[17] Though it is theoretically simple to replace conventional hydrogen with clean hydrogen, as the molecules are the same, switching to clean hydrogen can present logistical challenges for refineries. Refineries have unique equipment processing configurations tailored to specific crude oils or product specification constraints. These configurations are also highly optimized, operating at high efficiencies and capacity factors to maximize profit margins. Transitioning to clean hydrogen might require reengineering certain processes, particularly for refineries that produce dedicated hydrogen.

The refining industry outlook

To meet US climate goals, fossil fuel production and use must be reduced to the greatest extent possible. Large fossil fuel companies in the US have begun consolidating their fleet of refineries in recent decades, with a 20 percent decline in the number of operating facilities between 2000 and 2022.[18] However, while the long-term role of conventional refining remains uncertain, leading projections anticipate up to an 80 percent demand reduction in total hydrocarbon use if net-zero decarbonization goals are met by 2050.[19] However, even as refineries close or consolidate, **hydrogen demand at refineries may increase even as total utilization falls due to increases in lower quality, heavy crude oil, and the diesel-to-gasoline production ratio.**[20]

In the wake of current policies and demand signals, some refineries may transition to producing clean fuels that use hydrogen as a refining agent or feedstock. Biofuels derived from biomass or plant- and animal-based oils can use similar refining processes as conventional petroleum-based fuel, including upgrading with hydrogen. Alternatively, synthetic fuels (discussed on pages 22 to 25) are derived from combining clean hydrogen with captured CO_2. Hubs selected based on refinery offtakers must demonstrate the capability to transition to producing clean fuels or survive industry consolidations.

A note on byproduct hydrogen

While most commonly produced in dedicated SMR units, hydrogen is also a byproduct of petroleum refining and chemicals production. Lifecycle accounting typically allocates emissions to primary products rather than byproducts. Byproduct hydrogen may also decline as industry and transportation electrify and decarbonize. This report focuses on opportunities for dedicated hydrogen production, through electrolysis and methane-based processes with carbon capture, rather than byproduct production.

Clean H_2 opportunity: **Ammonia**

Ammonia- and nitrogen-based fertilizers are of critical importance in US agricultural production. Ammonia allows crops to utilize more nitrogen, a vital nutrient for growth, in their root networks. Synthetic fertilizers thereby support higher crop yields and increasing food demand for growing global populations.

The US has over three dozen facilities that produce a nationwide total of 15 to 17 Mt of ammonia annually.[22] **Ammonia, produced by combining atmospheric nitrogen with hydrogen in what is known as the Haber-Bosch process, utilizes around 3 Mt of hydrogen per year, making ammonia production the second-highest hydrogen consumer of any industrial sector, after petroleum refining.[23]** The *DOE Clean Hydrogen Strategy and Roadmap* estimates that demand for hydrogen in the ammonia sector will grow to around 5 Mt by 2050. As such, ammonia is a leading market for future hydrogen demand.

Most carbon emissions attributed to commercial-scale ammonia plants originate from hydrogen production via SMR units.[24] **Clean hydrogen, then, would be able to reduce virtually all of the ammonia sector's CO_2 emissions.** Moreover, ammonia produced without natural gas could avoid additional methane leakage emissions, which ammonia with carbon capture would still have to mitigate.

Nitrogen fertilizer use and hydrogen production for ammonia

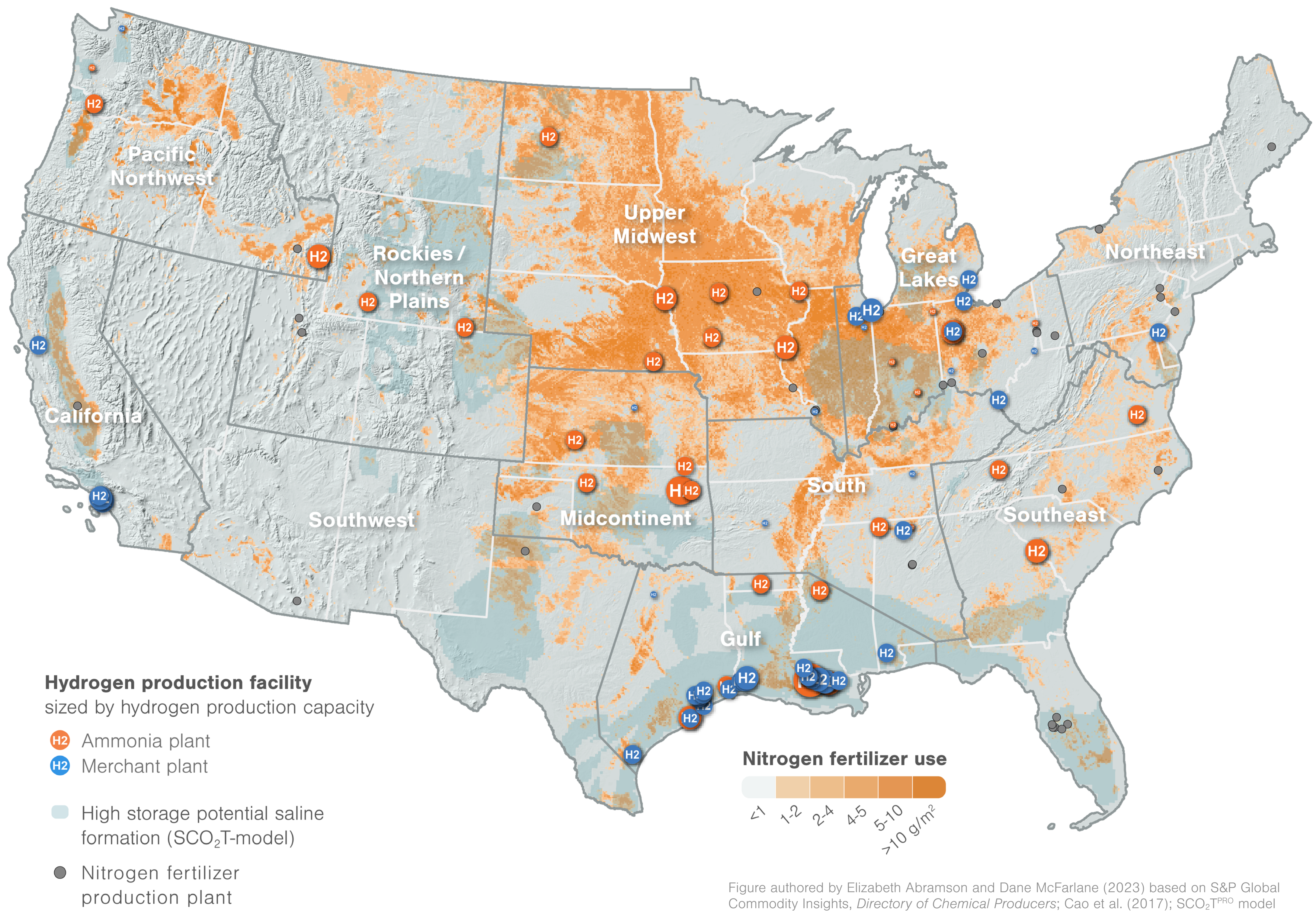


Figure authored by Elizabeth Abramson and Dane McFarlane (2023) based on S&P Global Commodity Insights, *Directory of Chemical Producers*; Cao et al. (2017); SCO_2T^{PRO} model (Carbon Solutions 2022).[21] Note: offshore saline formations are not shown on this map.

Clean H_2 opportunity: **Ammonia**

The most widely used ammonia-based fertilizers are urea/urea ammonium nitrate, anhydrous ammonia, ammonium nitrate, ammonium phosphates, and ammonium sulfate.[25] Ammonia plants often produce some of these fertilizers on-site or export ammonia to co-located fertilizer plants.

Common ammonia and nitrogen-based fertilizers:

Ammonia	$N\mathbf{H}_3$
Urea	$CO(N\mathbf{H}_2)_2$
Ammonium Nitrate	$N\mathbf{H}_4NO_3$
Ammonium Sulfate	$(N\mathbf{H}_4)_2SO_4$
Ammonium Phosphate	$(N\mathbf{H}_4)_3\mathbf{H}PO_4$

Regional opportunities for clean hydrogen in ammonia production

The Gulf Coast, Upper Midwest and Illinois, and California have favorable characteristics and prerequisite conditions for hydrogen-based ammonia production.

While agricultural production occurs throughout the country, nitrogen fertilizer use is particularly concentrated in the Upper Midwest, along with the Midcontinent and Great Lakes regions, making these regions major potential clean hydrogen offtakers.

The Gulf Coast is home to a large portion of the nation's ammonia production, including the largest ammonia plant in the world. That plant, located in Donaldsonville, Louisiana, recently announced plans to produce 1.7 Mt of ammonia via SMR with carbon capture. The project would capture and sequester nearly 2 $MtCO_2$ in a yet-to-be-determined site. The Donaldsonville facility also plans to install a small pilot plant using electrolysis and renewable energy for additional ammonia production. The Gulf contains abundant saline pore space for CO_2 sequestration along with extensive industrial infrastructure and workforce expertise, creating supportive conditions for hydrogen production paired with carbon capture.

The Upper Midwest contains many ammonia plants serving extensive demand for fertilizer across the Corn Belt and surrounding agricultural land. Additionally, this region hosts ample renewable resources and nuclear energy that could power clean electrolysis.

California is another prospective candidate for electrolysis-based hydrogen production given its substantial agricultural market, the absence of existing ammonia production, extensive renewable capacity, and access to shipping lanes.

Clean H_2 opportunity: **Iron and steel**

Clean hydrogen can be used as a low- or zero-carbon energy source and reducing agent to decarbonize steelmaking, a major contributor to US economic activity and industrial GHG emissions. The US and global economy are set to maintain significant demand for steel through midcentury as a result of economic development, construction of new infrastructure, and material demand for new clean energy projects.[27]

Steelmaking is an energy-intensive process that currently consumes large quantities of fossil fuels like natural gas and coal coke. Most primary (iron-ore based) steel production in the US currently uses carbon-intensive manufacturing equipment such as blast furnaces, while secondary (recycled scrap-based) steelmaking uses electric arc furnaces (EAFs), which are more efficient and less emissions-intensive.[28] **Hydrogen can be used as both an energy source and chemical reactant to produce direct reduced iron (DRI),** a form of processed iron ore that can be melted in an EAF to produce finished steel. **Using hydrogen-based DRI in an EAF further reduces emissions from steelmaking** as compared to blast furnace processes.

Activities within the US iron and steel sector

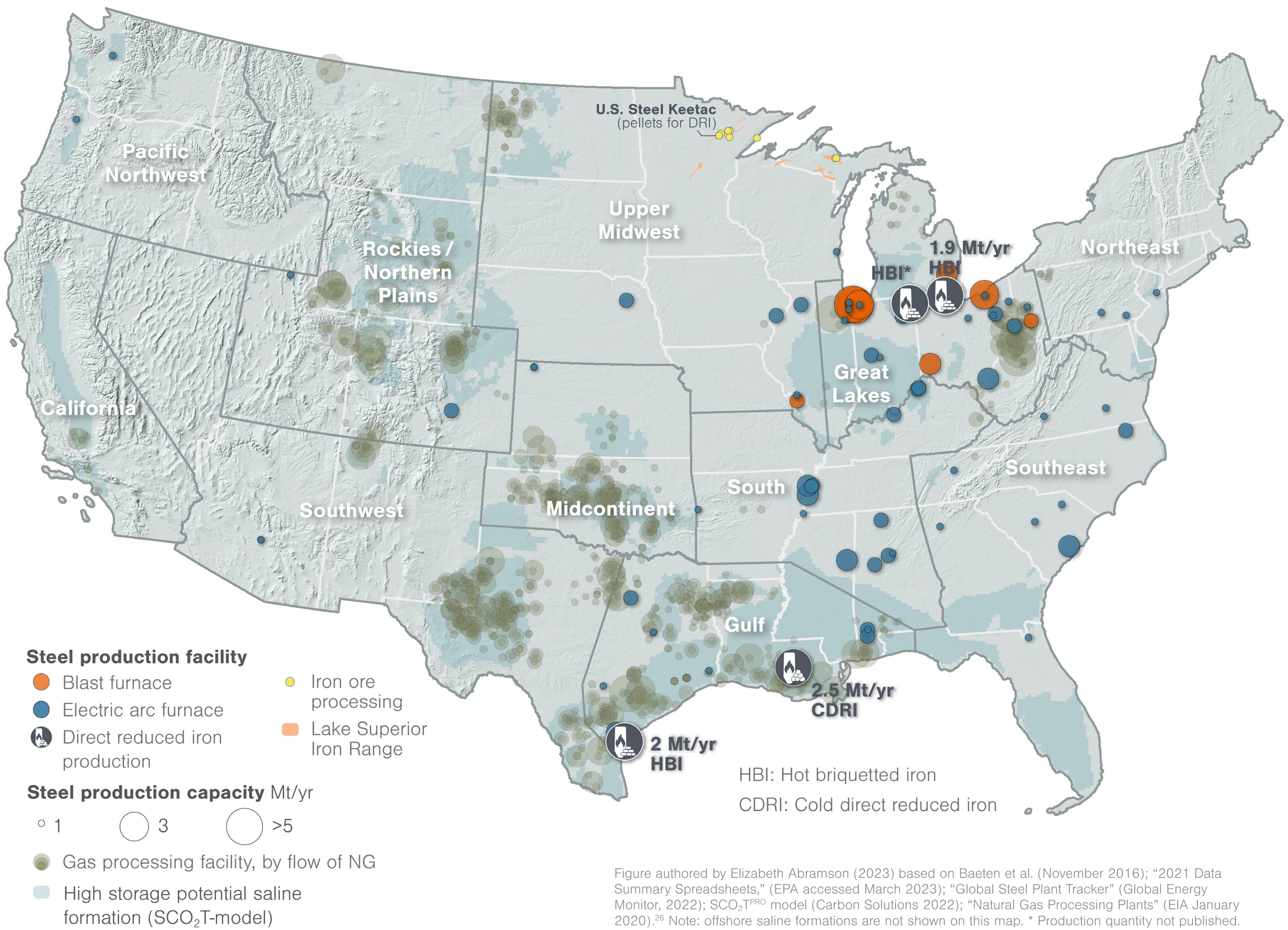


Figure authored by Elizabeth Abramson (2023) based on Baeten et al. (November 2016); "2021 Data Summary Spreadsheets," (EPA accessed March 2023); "Global Steel Plant Tracker" (Global Energy Monitor, 2022); SCO_2T^{PRO} model (Carbon Solutions 2022); "Natural Gas Processing Plants" (EIA January 2020).[26] Note: offshore saline formations are not shown on this map. * Production quantity not published.

Clean H_2 opportunity: **Iron and steel**

The US steelmaking landscape

In recent years, the US has seen a decrease in primary blast furnace/basic oxygen furnace-based steelmaking and an increase in secondary, scrap-based steel production using electric arc furnaces.[29] New electric arc furnace technologies have also recently been deployed that can make many of the same primary steel products traditionally made by a blast furnace/basic oxygen furnace. These electric arc furnace technologies require high quality iron inputs, namely direct reduced iron (DRI), which can be produced using clean hydrogen.

Primary steel production begins with mining iron ore and removing oxygen and other impurities from the ore. Domestic iron ore mining in the US is almost exclusively limited to northern Minnesota and Michigan in the Mesabi and Marquette ranges, where around 45 Mt of ore are mined per year.[30] In 2022, the US imported around 3.2 Mt of iron ore, mostly from Brazil (2.2 Mt) and Canada (0.88 Mt), and exported around 9.4 Mt of iron ore.[31]

In primary steelmaking, coal is heated in the absence of oxygen, a process known as pyrolysis, to make coke, which is nearly pure carbon. This coke is then fed into a blast furnace along with the iron ore, scrap steel, and other inputs to be melted together, producing iron. The resulting iron, along with some steel scrap, is next fed into a basic oxygen furnace, where lime, oxygen, and other additives are used to remove any remaining impurities and adjust the properties of the final steel product. In secondary steelmaking, electric arc furnaces use electricity to melt steel scrap and iron feedstocks to produce new steel products.

Iron and steel scrap are important inputs for both primary and secondary steelmaking. The US has a high rate of steel recycling, at around 85 percent, which resulted in the production of 52 Mt of recycled steel scrap in 2021.[32] In 2021, the US exported 13 Mt and imported 4.8 Mt of iron and steel scrap for a net export of about 8 Mt of scrap.[33] In the 2022, 11 integrated steel mills, which use blast furnaces for primary steelmaking, produced 23 Mt of steel in the US. 101 mini mills, which use EAFs for secondary steelmaking, produced 59 Mt of steel.[34] Integrated mills in the US are located mainly in the Great Lakes region, close to the country's iron ore reserves, while mini mills are dispersed around the country.

Low-carbon steelmaking with hydrogen

Hydrogen-based steelmaking is often seen as a leading technology to decarbonize the steel industry. Hydrogen can be used in low- or zero-carbon steelmaking by displacing natural gas or coal coke to act as a reducing agent that removes oxygen and impurities from solid state iron ore, producing DRI. The DRI can then be melted in an electric arc furnace to produce steel. Hydrogen could also be used as an energy source to preheat reacting gases in the DRI process, displacing natural gas.

While EAFs are typically less emissions-intensive than blast furnaces, using clean hydrogen-based DRI in an EAF further reduces emissions.[35] In one study, an EAF using DRI produced with 35 percent hydrogen blending reduced CO_2 emissions by nearly two thirds relative to blast furnace steelmaking.[36] **Deeper decarbonization benefits can be achieved as the percentage of hydrogen blended in for DRI production increases.[37]**

The US has four existing DRI plants. The Gulf region is home to two natural gas DRI plants, while the Great Lakes region is home to one natural gas DRI plant and one coal DRI plant. Together, these plants produce around 6.4 Mt of DRI per year.[38] With extensive existing steel production, the Great Lakes region could anchor a national transition to hydrogen-based steelmaking. As a major hydrogen producer, and home to existing steel production including DRI, the Gulf also has unique advantages in advancing the transition to clean steel. Robust gas processing activity in these regions can also ensure a supply of natural gas to supplement hydrogen as a reducing agent for DRI.

Deep decarbonization can be achieved in the steel sector by transitioning to clean hydrogen-based direct reduction of iron.

Clean H_2 opportunity: **Biofuels, aviation fuel, and drop-in fuel production**

Clean hydrogen is an enabling feedstock in the production of biofuels such as sustainable aviation fuels (SAF) and drop-in renewable fuels. These fuels can help cut emissions from hard-to-decarbonize modes of transport that typically rely on combustion engines, such as aviation, marine shipping, and freight transport. Existing biofuel operations, such as ethanol plants, can be a source of CO_2 from relatively low-cost carbon capture, which can be combined with hydrogen to create low-carbon synthetic fuels and chemicals.

Biofuel production is highly concentrated in agricultural regions such as the Upper Midwest and Great Lakes. Petroleum refining occurs throughout the US, but is concentrated in regions such as the Gulf, Great Lakes, Midcontinent, Rockies and Northern Plains, and California. **These locations could act as markets, or off-takers, for clean hydrogen in making new types of biofuels or synthetic fuels for use in aviation, marine, and heavy-duty vehicle applications.**

However, many biofuels may not truly provide a climate benefit over fossil fuels. Continued or accelerated scaling of biomass crops to generate biofuels could displace food production on prime farmland and trigger cropland expansion and conversion of native ecosystems. This land use change decreases land carbon sequestration and produces emissions, compounding global concerns about ecosystem damage and strain on food systems associated with increasing reliance on biofuels.

Biofuel operations as potential markets for clean hydrogen to create renewable and synthetic fuel

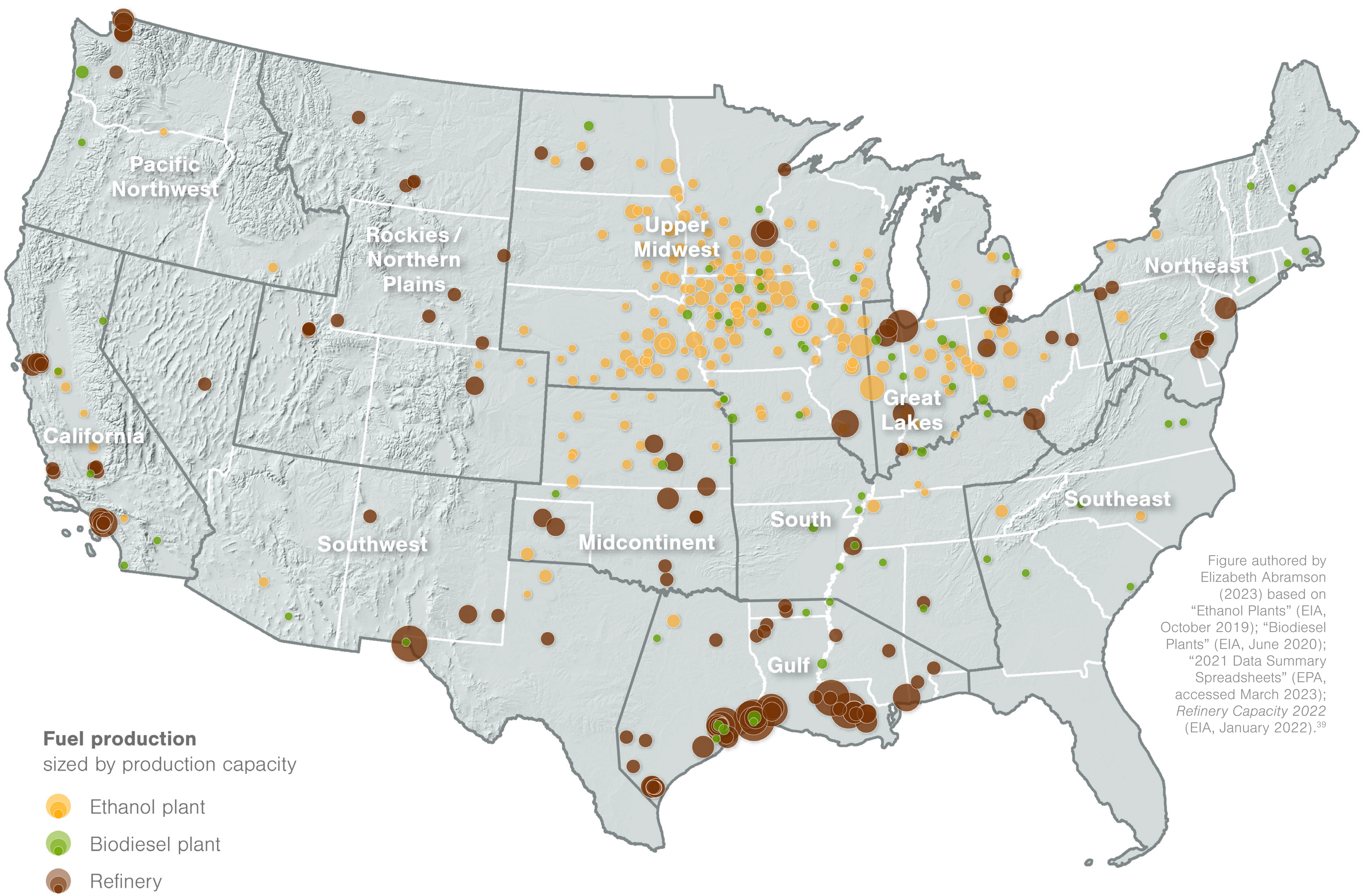


Figure authored by Elizabeth Abramson (2023) based on "Ethanol Plants" (EIA, October 2019); "Biodiesel Plants" (EIA, June 2020); "2021 Data Summary Spreadsheets" (EPA, accessed March 2023); *Refinery Capacity 2022* (EIA, January 2022).[39]

Clean H_2 opportunity: **Biofuels, aviation fuel, and drop-in fuel production**

Petroleum fuels like gasoline, diesel, and jet fuel, rely on molecules of hydrogen and carbon, collectively called hydrocarbons, to generate energy. Renewable fuels such as renewable diesel, SAF, and renewable gasoline, can produce hydrocarbons from a range of biomass sources including cellulosic materials (e.g., crop residues and woody biomass) and lipids (e.g., fats and greases). These renewable fuels are chemically identical to their fossil-based analogs and require little to no blending with petroleum fuels before usage in conventional combustion engines or turbines. As these fuels can be directly "dropped in" to existing engines and infrastructure, they are often referred to as drop-in fuels. Using clean hydrogen as a feedstock in renewable fuels production can minimize the fuel's lifecycle carbon intensity.

Renewable gasoline and diesel

Renewable gasoline and renewable diesel can be synthesized in a process often referred to as power-to-liquids, using electricity to combine hydrogen and CO_2. These renewable drop-in fuels are chemically identical to their fossil-based analogs and can be produced by combining hydrogen gas with CO and or CO_2 to form long-chain hydrocarbons using the Fischer-Tropsch Process. If this process is completed using low-carbon feedstocks and power generation, then these fuels will also have a low lifecycle carbon intensity. Near-term power-to liquid (PtL) fuels will likely take advantage of easily capturable CO_2 from point sources (e.g., ethanol, cement, and ammonia facilities) and eventually expand to use atmospheric CO_2 sourced from direct air capture.

Biomass and other carbon-rich feedstocks can be used to produce renewable diesel and gasoline through a range of biochemical and thermochemical processes such as hydrotreating, catalytic conversion or biological upgrading of sugars, gasification, pyrolysis, and hydrothermal processing.[40] The overall process of producing renewable fuels is similar to conventional refining in that renewable fuel synthesis converts low-value hydrocarbon structures unsuitable for internal combustion engines into ready-to-use compounds.

Renewable fuel facilities commonly co-produce multiple fuel types, such as diesel and SAF, to maximize total output.[41] Like their crude oil-based analogs, renewable feedstocks used to make fuels are composed of various hydrocarbons, allowing manufacturers to separate out the specific compounds desired. Separating out differently weighted hydrocarbons, or fractions, allows renewable fuel manufacturers to produce multiple fuel types simultaneously.

US renewable diesel production capacity has grown rapidly in recent years. In January 2022, there were 11 renewable fuel plants in the US producing 1.75 billion gallons of drop-in fuels.[42] By the end of 2022, total renewable diesel production capacity increased to 2.6 billion gallons.[43] This expansion represents a nearly threefold production increase from 2020.[44] Capacity is expected to continue expanding, reaching an estimated 5.9 billion gallons per year in 2025.[45] The US imported 262.7 million gallons of renewable diesel in 2022, primarily from Singapore.[46]

Methanol

Hydrogen and CO_2 can be reacted to form methanol, an important potential feedstock for synthetic drop-in fuels and other renewable fuels. Methanol can be "upgraded" through combination with other hydrocarbons to create renewable gasoline, diesel, jet fuel, and natural gas that are chemically identical to their fossil-based equivalents.

Methanol is also an efficient hydrogen carrier. Hydrogen is a highly voluminous gas whose compression or liquification requires large amounts of energy and extensive safety precautions to prevent undesired combustion. In contrast, methanol does not need to be liquefied or compressed and can be easily transported in its liquid form at room temperature. Methanol also has a higher energy density than compressed hydrogen, meaning the amount of energy that could be generated from a tank of the same volume of methanol is higher than what could be generated from an equal size tank of compressed hydrogen. Hydrogen can be separated out from methanol as needed, or methanol can be used alone as a fuel or feedstock for other processes.

Methanol is currently produced using hydrogen from SMR in a process that combines natural gas and steam at high heat to form a synthesis gas, or syngas, rich in CO, CO_2, and hydrogen. The hydrogen is then selectively reacted with the CO to form methanol (CH_3OH). While the reaction of syngas to produce methanol is a relatively energetically efficient pathway, pure hydrogen gas can also be reacted with pure CO_2 to make methanol without intermediate syngas. Using low-carbon hydrogen alongside CO_2 captured from anthropogenic sources to make methanol with low-carbon electricity is a viable alternative to the carbon-intensive methods used today.

Sustainable Aviation Fuel

Aviation is unlikely to be decarbonized by electrification or hydrogen fuel cells, and hydrogen propulsion in aviation is unlikely to be commercially deployed until 2035 at the earliest.[47] Decarbonization in this sector may depend on the production of SAF from biofuels, synthetic fuels, and low to zero-carbon hydrogen.

In the near term, hydrogen will be important in the development of SAF, which has similar characteristics to conventional jet fuel but a lower lifecycle carbon intensity. SAF can be produced from a variety of feedstocks, including biological (e.g., waste cooking oils, animal fats, agricultural residue, algae), and nonbiological sources (e.g., PtL fuels or synthetic fuels).[48] As a drop-in fuel, SAF is compatible with existing aircraft engines and fueling infrastructure, and thus is well-suited for near-term deployment. The use of SAF may achieve other environmental co-benefits, including reductions in contrail formation and improvements to air quality.[49]

The GHG Society of Testing and Materials has certified nine production pathways for SAF suitable for commercial applications when blended up to 50 percent with conventional jet fuel. SAF produced through the PtL process can reduce lifecycle emissions by up to 100 percent compared to fossil jet fuel.[50] By one estimate, PtL could account for as much as 42 percent of the SAF market by 2050, though this will depend on technology maturity and available quantities of hydrogen and low-carbon electricity for production.[51] The DOE estimates that 6 Mt of hydrogen would be required to produce 4 billion gallons of PtL fuels by 2050.[52]

State and federal policy support for SAF

The US currently produces 4.5 million gallons of SAF on an annual basis.[53] In 2021, the DOE, the US Department of Transportation, and the US Department of Agriculture launched a Sustainable Aviation Fuels Grand Challenge with a near-term goal of producing 3 billion gallons of SAF by 2030 and 35 billion gallons by 2050.[54] This effort will help ensure that an adequate supply of SAF develops alongside a reliable market. An accompanying roadmap released in September 2022 includes strategies to meet 100 percent of aviation fuel demand by 2050.[55]

The IRA took additional steps to support the production of SAF on a commercial scale, with Congress authorizing a new Alternative Fuel and Low-Emission Aviation Technology program funded at $296 million over five years to help address barriers related to SAF production, transportation, blending, and storage, complemented by a two-year SAF Blenders Tax Credit to help incentivize production. The blenders credit starts at $1.25 per gallon for SAF achieving 50 percent or greater lifecycle emissions reduction, with an additional $0.01 per gallon credit available for each additional percentage point of emissions reduction over 50 percent. Once the blenders tax credit expires, SAF is eligible for a Clean Fuel Production Credit through the end of 2027, with the credit amount ranging from $0.35 to $1.75 per gallon.

State policies and programs can also play a role in encouraging domestic production and use, with the California Low Carbon Fuels Standard and the federal Renewable Fuel Standard offering opt-in features for SAF. These programs help provide additional revenue for producers while emerging opportunities may exist to incentivize domestic use, such as a new purchase credit for SAF sold to or used by air carriers in the state of Illinois.[56]

DOE and Argonne National Laboratory's *H2@ Scale* report projects that the hydrogen demand for renewable fuels, synthetic chemicals, and biofuels is expected to reach 22.6 Mt annually by 2050. This quantity assumes that there are ample biofuel

Clean H_2 opportunity: **Biofuels, aviation fuel, and drop-in fuel production**

feedstocks and that 100 $MtCO_2$ are captured from economical sources (e.g., ethanol fermentation) or legacy industrial sectors (e.g., refining and ammonia). *H2@Scale* considers renewable fuels and synthetic chemicals to be analogous, as the common chemical bases can be used to synthesize drop-in fuels or chemicals. Expectations of hydrogen demand vary depending on the prevalence of electrification in transportation and industry.

Industry movements to expand SAF

From 2021 to 2022, the number of announced offtake agreements for SAF nearly doubled.[57] In the US, members of Airlines of America pledged to assist the federal government in making 3 billion gallons of SAF available to US aircraft by 2030, and a number of global airlines have an SAF use target of 10 percent by 2030.[58] Cooperation at the international level can also play a critical role in developing a cost-competitive market, with members of the First Movers Coalition committing to utilizing SAF to replace 5 percent of conventional jet fuel demand by 2030.[59] Recently, United Airlines also launched a venture fund to support start-ups focused on SAF research and production.

Environment and emissions considerations

Estimating the full impact of biofuel production requires consideration of several integrated factors. There is growing evidence that the use of croplands for biofuels increases GHG emissions through land use changes.[60] It can also intensify agricultural production via increased fertilizer and energy use, resulting in increased emissions and threats to water quality.[61] The US Department of Agriculture reports that ethanol production now accounts for 45 percent of corn use, an expansion of 8.7 percent, or 2.8 million hectares (6.9 million acres), from the enactment of the renewable fuel standard in 2008 through 2016.[62] These changes increased annual nationwide fertilizer use by 3 to 8 percent and increased water quality degradants by 3 to 5 percent.[63]

Clean H_2 opportunity: **Transportation applications**

Replacing carbon-intensive transportation fuels with low- or zero-carbon renewable fuels will be critical to decarbonizing the transportation sector. Production and use of such renewable fuels must ramp up in tandem to ensure that there is sufficient supply of clean fuels to match demand.

Hydrogen-based drop-in renewable fuels can be used by a variety of hard-to-decarbonize transportation sectors, from marine and rail shipping to air travel and long-haul freight trucking. Large airports, a major intended offtaker of renewable fuels, namely SAF, are distributed throughout the country, but especially concentrated in the Northeast and Great Lakes. Truck stops along the national highway system could also act as delivery sites for renewable fuel.

Additionally, while battery electric vehicles are a practical application in the light-duty passenger vehicle market, hydrogen fuel cells provide a complementary alternative to traditional combustion engines for medium- and heavy-duty transportation. **Developing a national network of hydrogen refueling stations could support the transition of medium- and heavy-duty vehicles to run on clean hydrogen power.** The following pages explore the advantages and market context of hydrogen fuel cell electric vehicles (FCEVs) in medium- and heavy-duty applications.

Aviation and heavy-duty truck fueling locations as potential delivery sites for hydrogen-based renewable and synthetic fuels

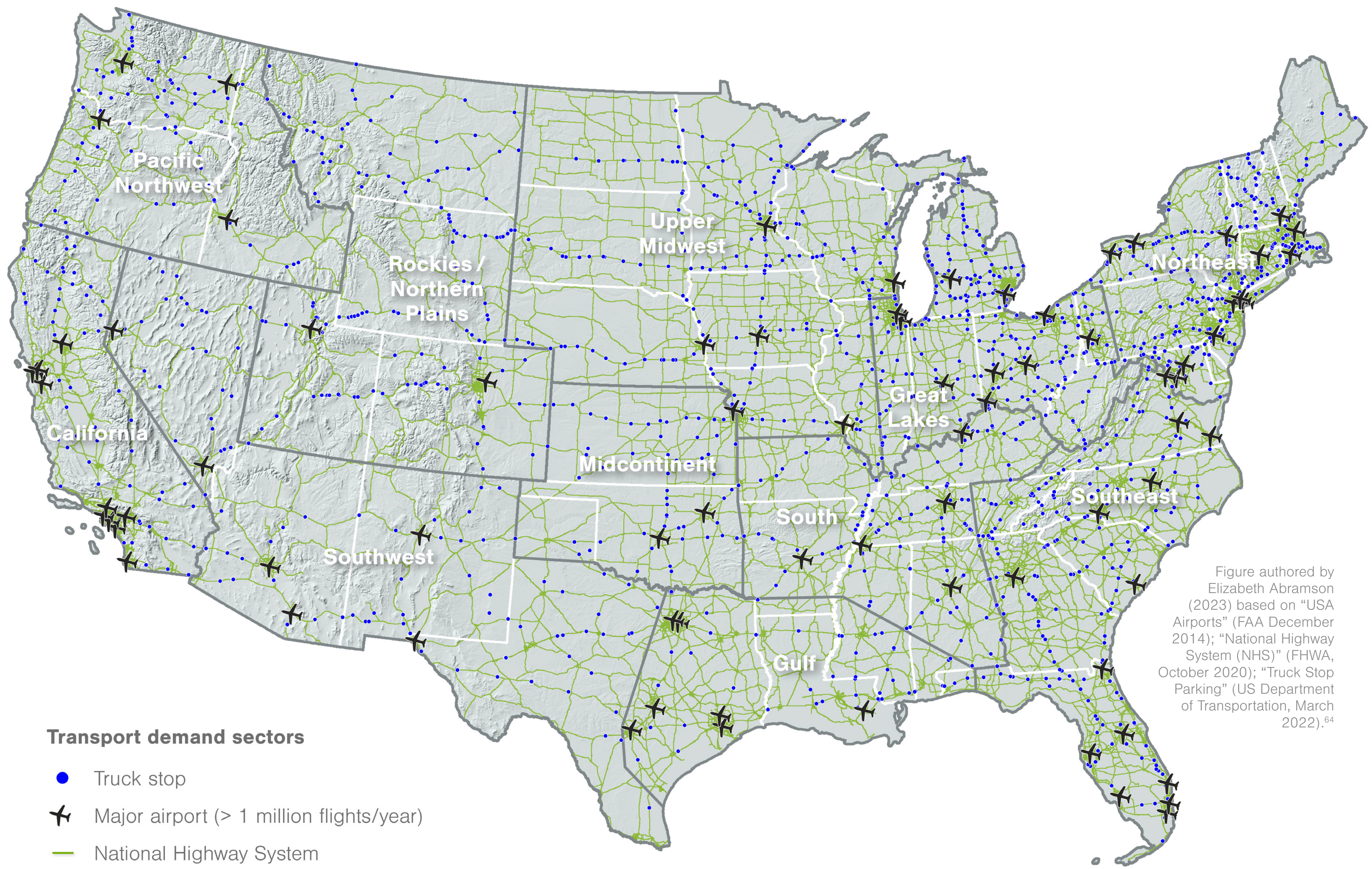


Figure authored by Elizabeth Abramson (2023) based on "USA Airports" (FAA December 2014); "National Highway System (NHS)" (FHWA, October 2020); "Truck Stop Parking" (US Department of Transportation, March 2022).[64]

Clean H_2 opportunity: **Transportation applications**

Advantages of hydrogen fuel cells

In a hydrogen FCEV, oxygen is combined with hydrogen to create electricity, producing no CO_2 emissions or particulate matter at the point of use. In addition to a zero-emission tailpipe, hydrogen FCEVs offer several advantages for the medium- and heavy-duty market. First, **hydrogen fuel cells are lighter than lithium batteries with an equivalent energy content.**[65] This is an important consideration in long-haul trucking for freight companies, where cargo capacity has a direct correlation to revenue. **FCEVs also refuel as quickly as diesel tanks and have up to twice the range of battery electric vehicles.**[66] Daimler, one of the world's largest commercial vehicle manufacturers, is developing a fuel cell-powered long-haul truck capable of traveling 600 miles before refueling.[67] FCEVs also have a higher capital investment, which makes them a better fit for commercial use than for individual or household purchases, with a study by the US Department of Energy's NREL showing hydrogen FCEVs trending toward cost-competitiveness for long-haul trucks by 2035.[68]

In 2022, there were 54 retail hydrogen refueling stations in the US, all located in California.[69] In contrast, there are 51,945 stations across the US for battery electric vehicle charging.[70] The coordinated build-out of hydrogen fueling infrastructure at scale will be crucial to enable the adoption of medium- and heavy-duty FCEVs in long-haul transportation.

Policy and program support for hydrogen fuel cell vehicles

In 2015, the Fixing America's Surface Transportation (FAST) Act required the US Department of Transportation's Federal Highway Administration (FHWA) to identify national alternative vehicle fueling corridors across the US.[71] In 2021, the BIL amended the FAST Act to establish a regular cadence for updating and redesignating corridors. The BIL also provided funding for a new Charging and Fueling Infrastructure Program to further deploy hydrogen infrastructure along designated corridors.

Since 2015, FHWA has issued six rounds of requests for alternative fueling corridor nominations. Two locations on the National Highway System have been identified as hydrogen corridor-ready, with at least 30 other designations pending.[72] The FHWA considers highways "corridor-ready" when they contain public hydrogen refueling stations located no greater than 150 miles apart, and no more than five miles from interstate exits or highway intersections.[73] Corridors that receive this designation utilize shared signage and join a network of state agencies, utilities, alternative fuel providers, and car manufacturers collaborating to build out a shared national infrastructure for hydrogen refueling.

In 2023, DOE announced $7.4 million in funding for seven projects across 23 states to develop medium- and heavy-duty electric vehicle charging and hydrogen corridor infrastructure plans. The announcement will fund two projects to develop hydrogen infrastructure along the I-10 corridor from Los Angeles, California, to Houston, Texas, and the I-80 corridor across Illinois, Indiana and Ohio.[74]

Hydrogen fuel cells produce zero emissions and offer long ranges and quick refueling times for medium- and heavy-duty vehicles.

The DOE is supporting hydrogen fuel cell development and use in medium- and heavy-duty applications through several ongoing initiatives. In 2009 DOE launched the SuperTruck Initiative, a partnership with industry to expand zero-emission truck technology. The Initiative has undergone three rounds of funding, with the most recent focusing on reducing costs and improving durability in hydrogen and battery electric trucks. Through the initiative, DOE is partnering with the major automobile manufacturers Ford and General Motors on FCEV truck development.[75] DOE's long-standing 21st Century Truck Partnership similarly brings together industry, federal agencies, and national labs to support research and development on fuel cell applications for heavy-duty trucking.[76] In 2022, DOE launched the Million Mile Fuel Cell Truck Consortium to further support fuel cell adoption in the heavy-duty vehicle market.[77]

Clean H_2 opportunity: **Transportation applications**

Beyond the transformational clean hydrogen production tax credit, the IRA included several federal incentives to expand the use of hydrogen and fuel cell projects. The IRA extends the credit sunset for the Alternative Fuel Refueling Property Credit to 2033, supporting the build-out of hydrogen refueling infrastructure by providing a credit for 30 percent of the cost of alternative refueling property up to $100,000. The IRA also provided a new Qualified Commercial Clean Vehicle credit up to $40,000 available for FCEVs through 2023.[78] Many states also provide incentives for hydrogen fuel cells, or rules regarding zero-emission fleets and Advanced Clean Trucks.[79] The DOE's Office of Energy Efficiency and Renewable Energy maintains a database detailing many of the existing laws and incentives pertaining to alternative fuels and vehicles at the state level.[80]

Clean H_2 opportunity: **Synthetic chemicals and hydrocarbons**

The chemical manufacturing industry produces thousands of unique products, which are often used to make other chemical compounds. Hydrogen is currently used in this sector to synthesize and process chemicals such as methanol. Generally, hydrogen is combined with another feedstock, often CO and CO_2-rich synthesis gas, to form light hydrocarbons, which can be further combined to form longer chain hydrocarbon species or bonded with other chemical feedstocks to make specific compounds.

Economic considerations for clean hydrogen in chemicals manufacturing

Adoption of low-carbon hydrogen for chemical synthesis will depend largely on lowering the cost of clean hydrogen production. To be competitive in chemicals manufacturing, clean hydrogen costs must be below roughly $2 per kilogram (kg).[81] While the current cost of hydrogen production via SMR with carbon capture falls within this threshold, current costs of electrolysis range from roughly $5 to $7 per kg.[82]

Synthetic hydrocarbon production will be dependent on the supply of both low-carbon hydrogen and captured CO_2 from high-purity streams and economically feasible capture costs. The DOE's *National Clean Hydrogen Strategy and Roadmap* and the *H2@Scale* report identified strategic opportunities to utilize 44 $MtCO_2$ from ethanol facilities and nearly 60 $MtCO_2$ from other feasible sources to provide alternatives to fossil fuel-based feedstocks for chemical manufacturing.[83]

High priority targets for clean hydrogen in chemicals manufacturing

Methanol, ethylene, and BTX (benzene, toluene, and xylene) are high priority targets for decarbonization within the chemical manufacturing sector.[84] Production of these three products, along with ammonia, accounts for nearly three-quarters of the chemical manufacturing sector's energy use and CO_2 emissions.[85] Some parts of this process, including low- and medium-temperature process heat and steam generation, may be decarbonized through electrification and low-carbon energy generation, while others will need to be addressed by using renewable feedstocks, low-carbon hydrogen feedstocks, and hydrogen-fired process heat to achieve the high temperatures required.

Methanol is currently used as a feedstock for many commodity chemicals, such as those found in paints and adhesives, and can be used for organic synthesis, the chemical production of organic compounds, using robust industrial chemical processes. As mentioned previously, methanol can also be used as a hydrogen carrier to mitigate the difficulties of storing and transporting hydrogen in gaseous or liquid forms.

Ethylene is an important intermediary in the production of plastics and consumer chemicals (e.g., detergents, surfactants, antifreeze). Synthesis of ethylene using low-carbon hydrogen and captured CO_2 can reduce the carbon intensity of many consumer products by displacing fossil fuel feedstocks. Ethylene (C_2H_4) is currently produced by reacting ethane (C_2H_6) at high temperatures and pressures with steam over a catalyst bed. This same process can be accomplished by producing synthetic ethane using the PtL process previously described. Low- to zero-carbon ethylene would decarbonize many aspects of the plastics and polymers manufacturing process without compromising the quality of materials produced.

Clean hydrogen can replace conventional hydrogen as a feedstock in chemicals manufacturing, reducing the carbon intensity of many consumer products.

The Landscape of Clean Hydrogen | Section 3

The US Hydrogen Landscape: Current Production and Goals

Hydrogen production pathways

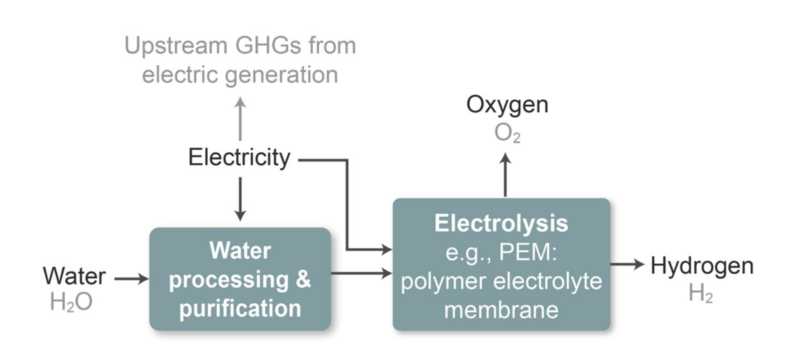
The most common modern methods of hydrogen production include steam methane reforming (SMR), autothermal reforming (ATR), and electrolysis. Due to their reliance on fossil fuels, both **SMR and ATR production require carbon capture equipment to produce hydrogen with low lifecycle carbon intensities. Meanwhile, electrolysis can be powered primarily with zero-carbon electricity from renewables or nuclear power to produce hydrogen with minimal lifecycle emissions.**

While facilities vary in their specific configurations, the following process diagrams depict the primary components, emissions sources, and points of CO_2 capture in SMR, ATR, and electrolysis-based hydrogen production.

Electrolysis

This process diagram shows the major components of a polymer electrolyte membrane electrolysis system. Because this process results primarily in the formation of oxygen and hydrogen, it does not involve the capture of CO_2.

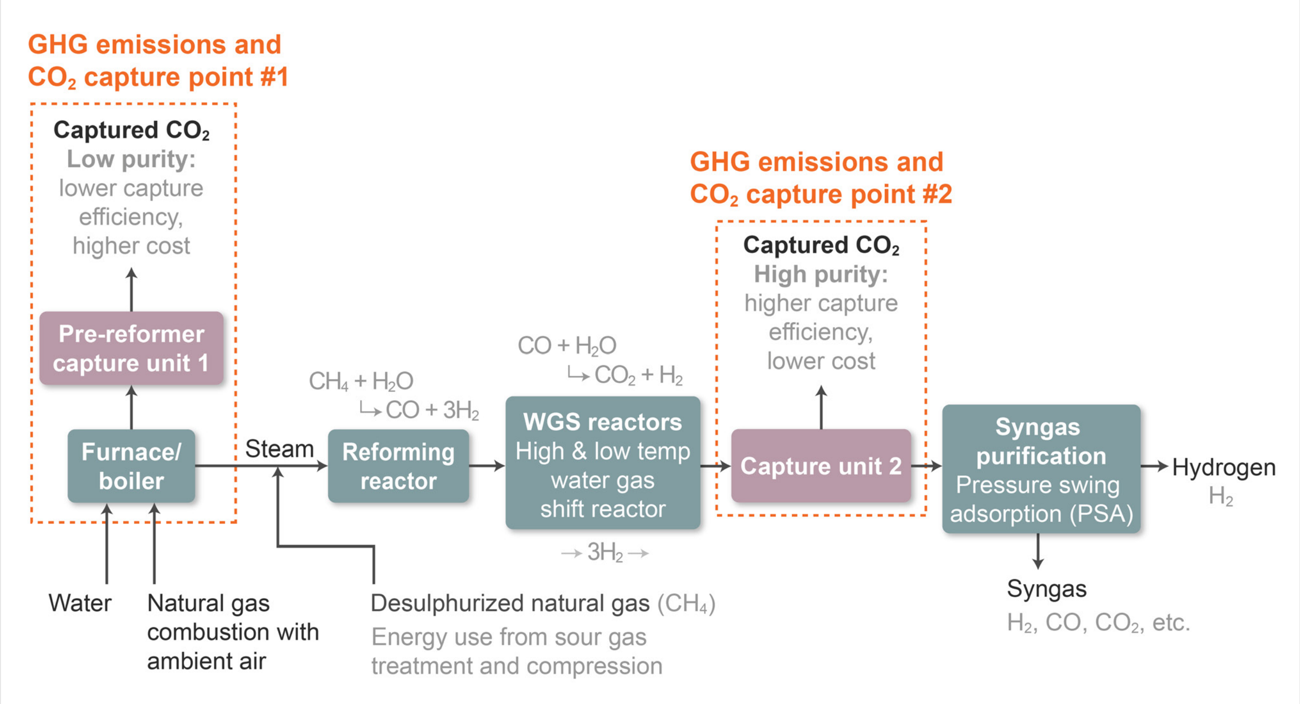
Process diagram: Hydrogen electrolysis



Steam methane reforming

This process diagram shows the major components of a steam methane reforming unit coupled with pressure swing adsorption. CO_2 can be captured from the reformer furnace emissions or the purification unit tail gases. Generally, a capture unit installed before the purification unit will account for about 60 percent of capturable CO_2. A second capture unit for the reformer furnace flue gases accounts for the remaining 40 percent of feasibly capturable CO_2.

Process diagram: SMR with carbon capture

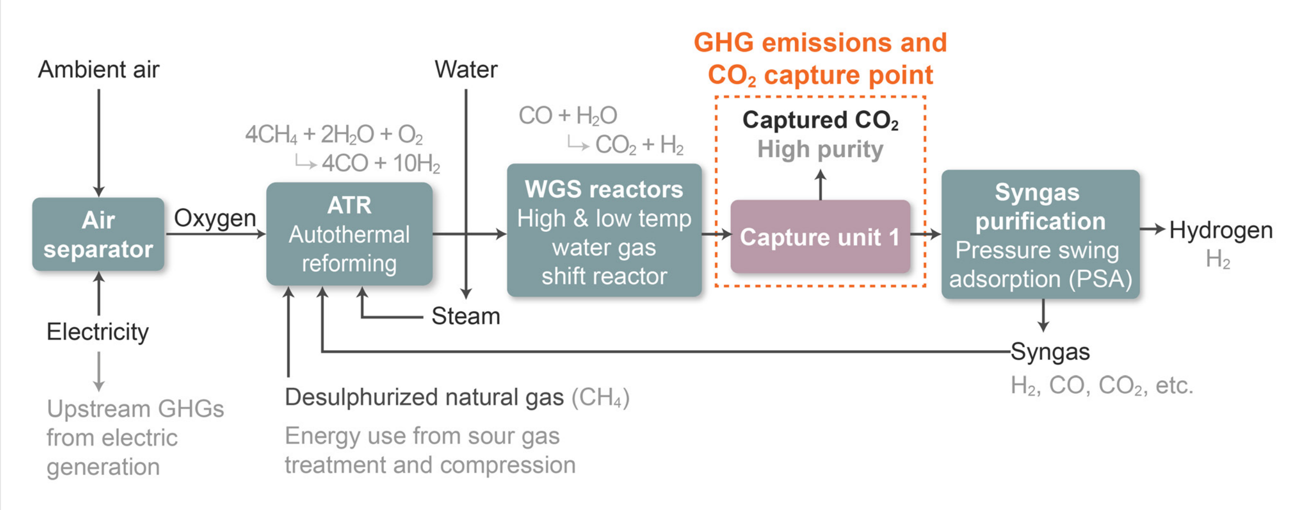


Autothermal reforming

This process diagram shows the major components of an autothermal reforming unit. ATR operates at almost double the temperature of SMR and heat exchangers can be used in lieu of external boilers. CO_2 can be captured from the purification unit tail gases.

Figures authored by Elizabeth Abramson, Daniel Rodriguez, and Dane McFarlane (2023) based on Mayyas et al. (August 2019); Oni et al. (February 2022).[86]

Process diagram: ATR with carbon capture



Hydrogen production pathways

Lifecycle carbon intensity

The relative carbon intensities of various pathways are shown in the graph at right, with ATR or SMR with CCS achieving low carbon intensities nearing that of electrolysis powered by carbon-free electricity sources. The graph compares these to the carbon intensity thresholds for clean hydrogen as defined by the federal clean hydrogen PTC, which is discussed later in this report. Within a single production pathway, emissions can also vary widely depending on plant design, process efficiency, fuel use, and upstream conditions. Further GHG reductions can likely be achieved through increased energy efficiency, engineering innovation, higher CO_2 capture configurations, and greater use of renewable energy.

Carbon capture considerations for SMR-based and ATR-based hydrogen production

Economically feasible capture rates range from around 85 to 90 percent for SMR, while capture rates for ATR can be greater than 90 percent.[87] Some sources propose that it is feasible for ATR to achieve capture rates greater than 95 percent.[88] The potential for higher capture rates originates from ATR involving only a single stream of CO_2 from syngas purification. While SMR involves syngas purification as well, it also utilizes a preheater or furnace, generally powered by natural gas combustion. The relatively dilute CO_2 concentration of natural gas furnace emissions results in lower efficiency carbon capture. ATR's higher capture potential is also due to its injection of pure oxygen into the reforming reactor, while SMR's use of ambient air in the reformer results in a lower molar concentration of CO_2, reducing the effectiveness of carbon capture.[89]

While ATR generally has a higher capture rate than SMR, this does not guarantee a lower carbon intensity due to a variety of factors. ATR operates at much higher temperatures and pressures, and requires larger quantities of methane feedstock and significant electrical energy. Both SMR and ATR processes require electrical inputs to power facility operations, but ATR's use of an air separator unit increases its electrical demand substantially.[90] One publication found that ATR required almost three times more electricity than SMR, resulting in a higher carbon intensity for ATR despite a lower level of underlying process emissions.[91] This means that in the near term, while its process emissions are lower and potential capture rates are higher than SMR, ATR remains a more energy-intensive process. ATR's carbon intensity can improve as the electric grid decarbonizes in the coming decades, or through the use of current renewable generation or power purchasing agreements.

Published lifecycle intensities for hydrogen production methods

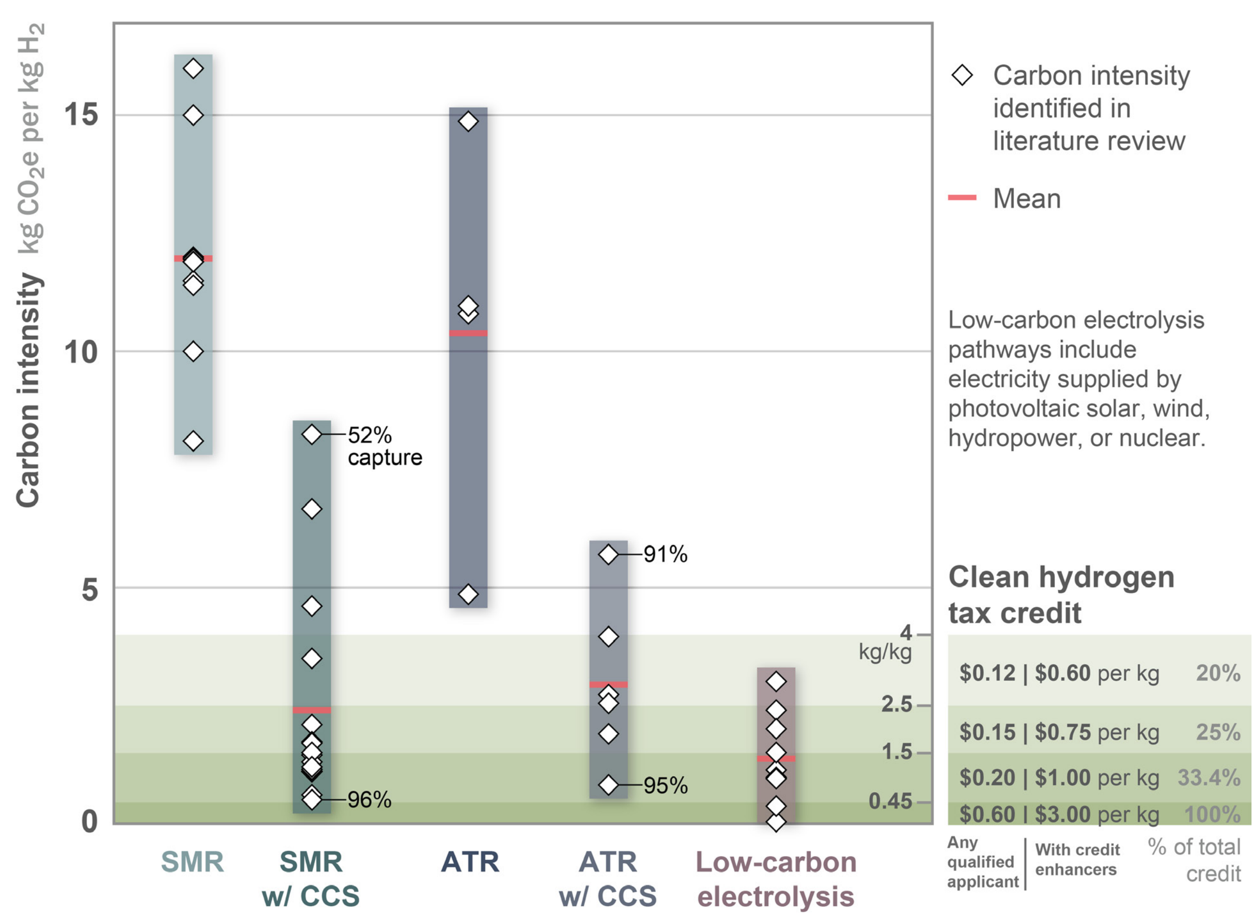


Figure authored by Elizabeth Abramson, Daniel Rodriguez, and Dane McFarlane (2023) based on Ajanovic et al. (July 2022); Bhandari et al. (December 2014); Feasibility study into blue hydrogen (CE Deflt, July 2018); Cetinyaka et al. (February 2012); Dufour et al. (January 2012); Hamje et al. (2014); Petterson et al. (June 2022); Rostrup-Nielsen et al. (August 2022); Salkuyeh et al. (June 2017); Lewis et al. (April 2022); Oni et al. (February 2022); Siddiqui et al. (March 2019); Spath et al. (February 2001); Spath et al. (February 2004); Suleman et al. (June 2015).[92]

Carbon capture and storage can enable hydrogen produced via SMR or ATR to achieve a low lifecycle carbon intensity.

Hydrogen production pathways

Permanent carbon storage for clean hydrogen with carbon capture

Hydrogen production at regional clean hydrogen hubs will likely occur through a mix of building new large capacity electrolysis facilities, retrofitting carbon capture equipment onto existing SMR-based production equipment, and building new integrated SMR with carbon capture projects. To ensure effectiveness in both cost and emissions reductions, **carbon capture projects must identify permanent storage locations or end-uses.**

This map shows current hydrogen production operations across the US. Nearly all high-capacity hydrogen production facilities shown on this map involve the fossil fuel-based steam methane reforming process to make hydrogen. To decarbonize existing SMR operations, carbon capture equipment must capture CO_2 from high concentration process emissions and/or stationary combustion of fossil fuel, and deliver this CO_2 to permanent geologic storage formations. The dark green areas on this map indicate geologic formations where current data from the SCO_2T model indicate high potential for technically and economically feasible carbon storage.

Facilities that are not located within the vicinity of these storage formations may need to consider conversion to electrolysis or long-distance CO_2 transport to decarbonize their hydrogen production.

Potential permanent carbon storage formations and current hydrogen production

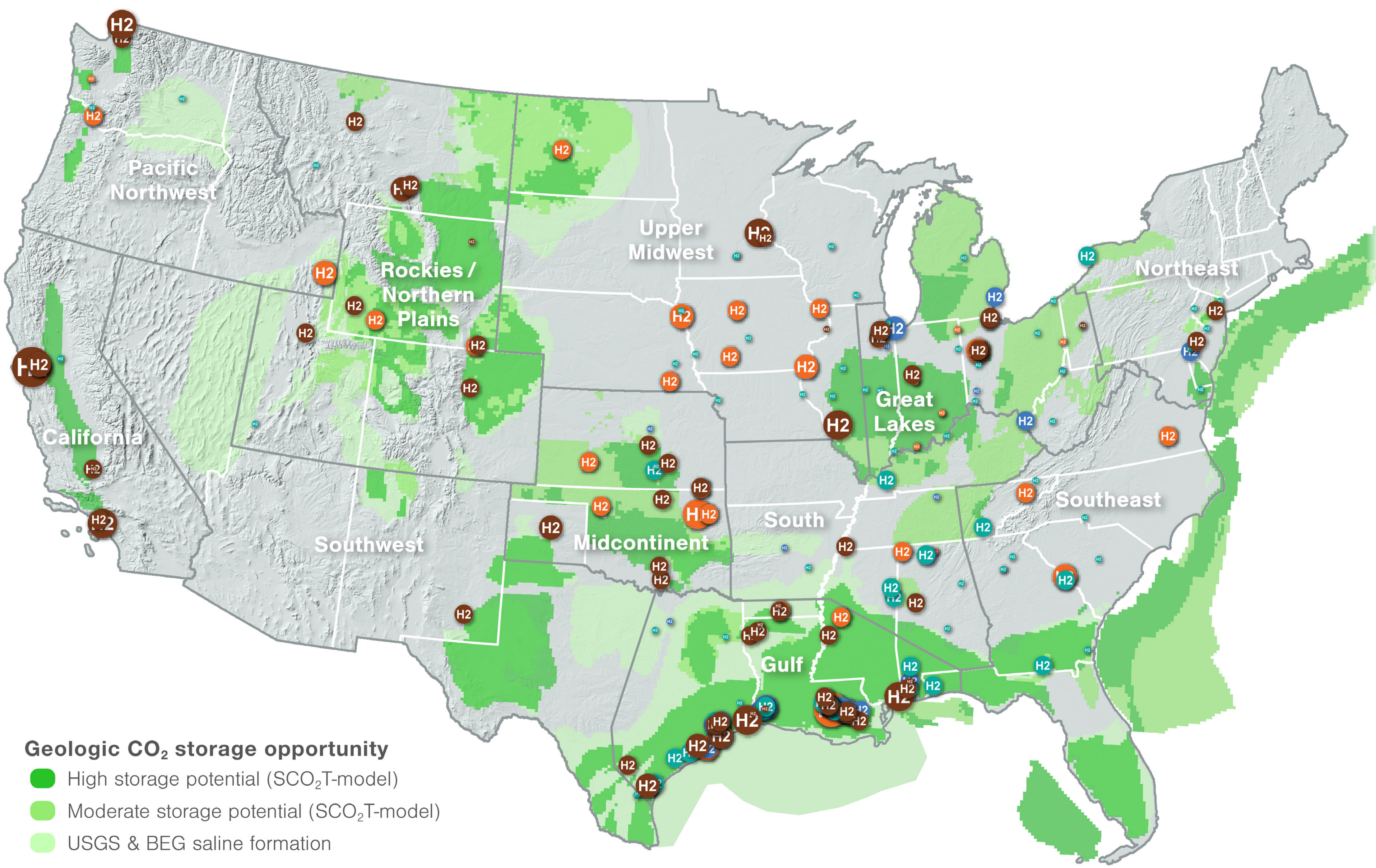


Figure authored by Elizabeth Abramson and Dane McFarlane (2023) based on SCO_2T^{PRO} model (Carbon Solutions 2022); Warwick et al. (October 2012); Carr et al. (Gulf Coast Carbon Center); S&P Global Commodity Insights, *Directory of Chemical Producers*; Arjona (June 2022).[93] Note: USGS data is shown for onshore areas while BEG data is shown for the offshore Gulf Coast area.

The scale of hydrogen production today

The US typically produces an estimated 10 Mt of hydrogen per year from dedicated facilities across the ammonia, refining, and chemicals sectors (excluding byproduct production).[94] **This report identified a total hydrogen production capacity of at least 12.4 Mt per year at almost 300 facilities,** with individual production capacity varying widely.[95] These facilities are shown in the diagram at right, which also compares industrial SMR production to the existing capacity of electrolysis facilities in the US.

The DOE's *National Clean Hydrogen Strategy and Roadmap* aims to achieve multi-gigawatt (GW) national production capacity of hydrogen via electrolysis in the late 2020s.[96] According to DOE data, **there are only 7 electrolyzers in existence in the US with a capacity of 1 megawatt (MW) or above.**[97] The largest of these has an electrical capacity of 5 MW (0.005 GW). **The DOE also reports a handful of proposals around the country for electrolyzers with an electrical capacity of up to 120 MW.**[98] Only 10 or so of these would need to be built to achieve 1 GW electrolysis capacity. If operating at nearly full time, a 1 GW production capacity would yield about 150 thousand metric tons of hydrogen per year, representing about 1.5 percent of the current US market of roughly 10 Mt per year.[99]

Current methane-based hydrogen production far exceeds electrolysis capacity

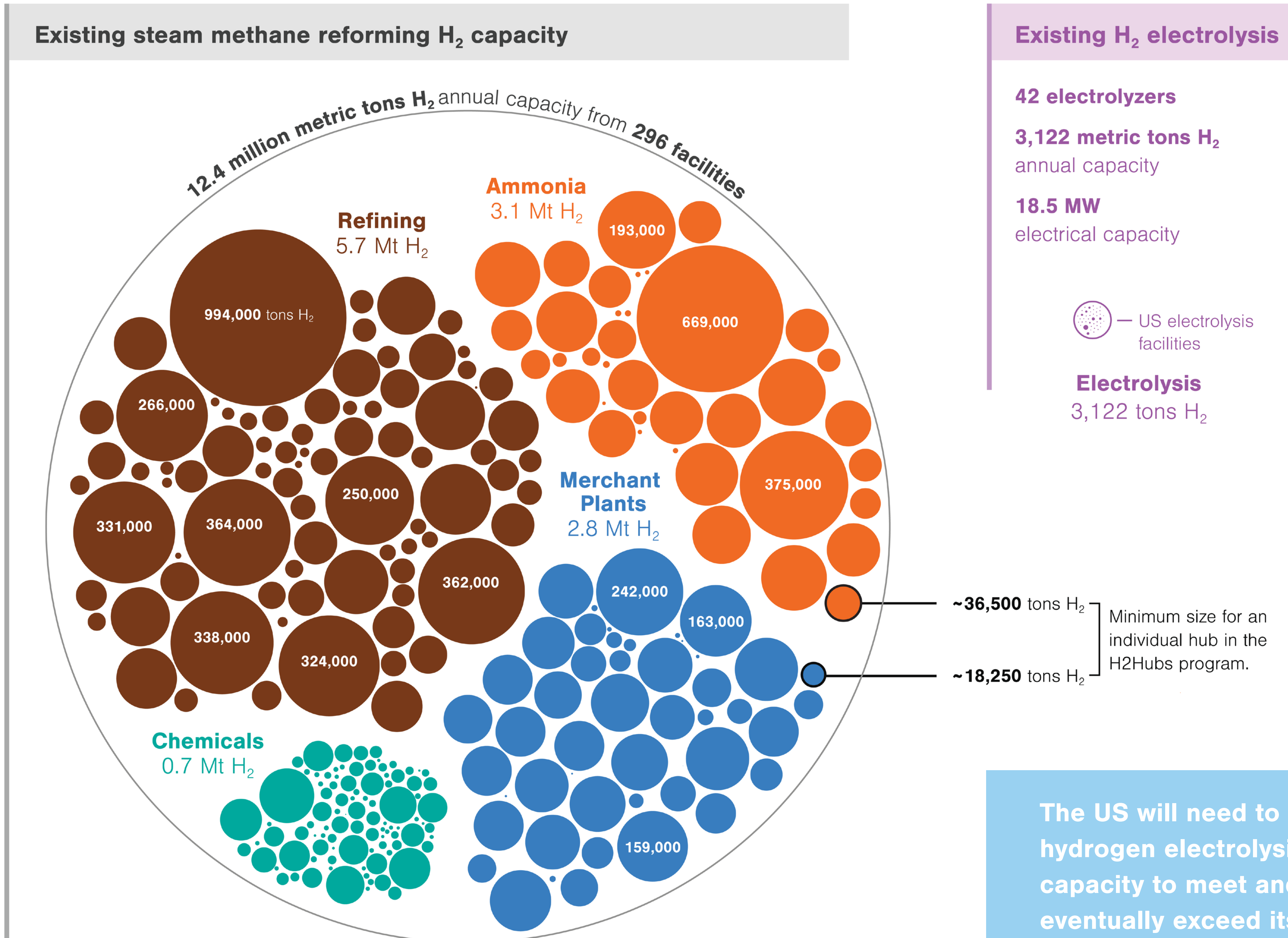


Figure authored by Elizabeth Abramson (2023) based on WRI (2023); S&P Global Commodity Insights, *Directory of Chemical Producers*; Arjona (June 2022); "DE-FOA-0002779" (DOE September 2022).[100]

The US will need to scale hydrogen electrolysis capacity to meet and eventually exceed its existing fossil-based hydrogen production.

Clean hydrogen goals, potential demand, and net-zero pathways

The DOE has set ambitious targets for the US to achieve 50 Mt of clean hydrogen production and use by 2050. In their *National Clean Hydrogen Strategy and Roadmap*, the DOE presents theoretical uses for that volume of hydrogen across chemicals and synthetic fuels, ammonia fertilizer production, iron reduction and steelmaking, energy storage, biofuels, and other applications. A previous study by the DOE and Argonne National Lab outlined more than 70 Mt of potential economic demand for hydrogen across similar sectors.[101]

These volumes for midcentury are based on the DOE's initial goals for clean hydrogen and expected economic competitiveness of its production against traditional fossil fuels and other alternative fuels. **While the DOE's hydrogen-specific goals will help the US meet its climate goals by midcentury, they do not guarantee full achievement of economy-wide net-zero emissions goals by 2050.** Modeling efforts such as Princeton's *Net-Zero America* study and Evolved Energy Research's (EER's) *Annual Decarbonization Perspective* have published numerous pathways for the US to achieve its goals and make the reductions necessary to limit global temperature change to 1.5 to 2°C.[102] A select number of those pathways, which require the use of anywhere from 58 Mt to 136 Mt of hydrogen in 2050, are shown for comparison on this and the following page.

National 2050 clean hydrogen goals and potential demand scenarios

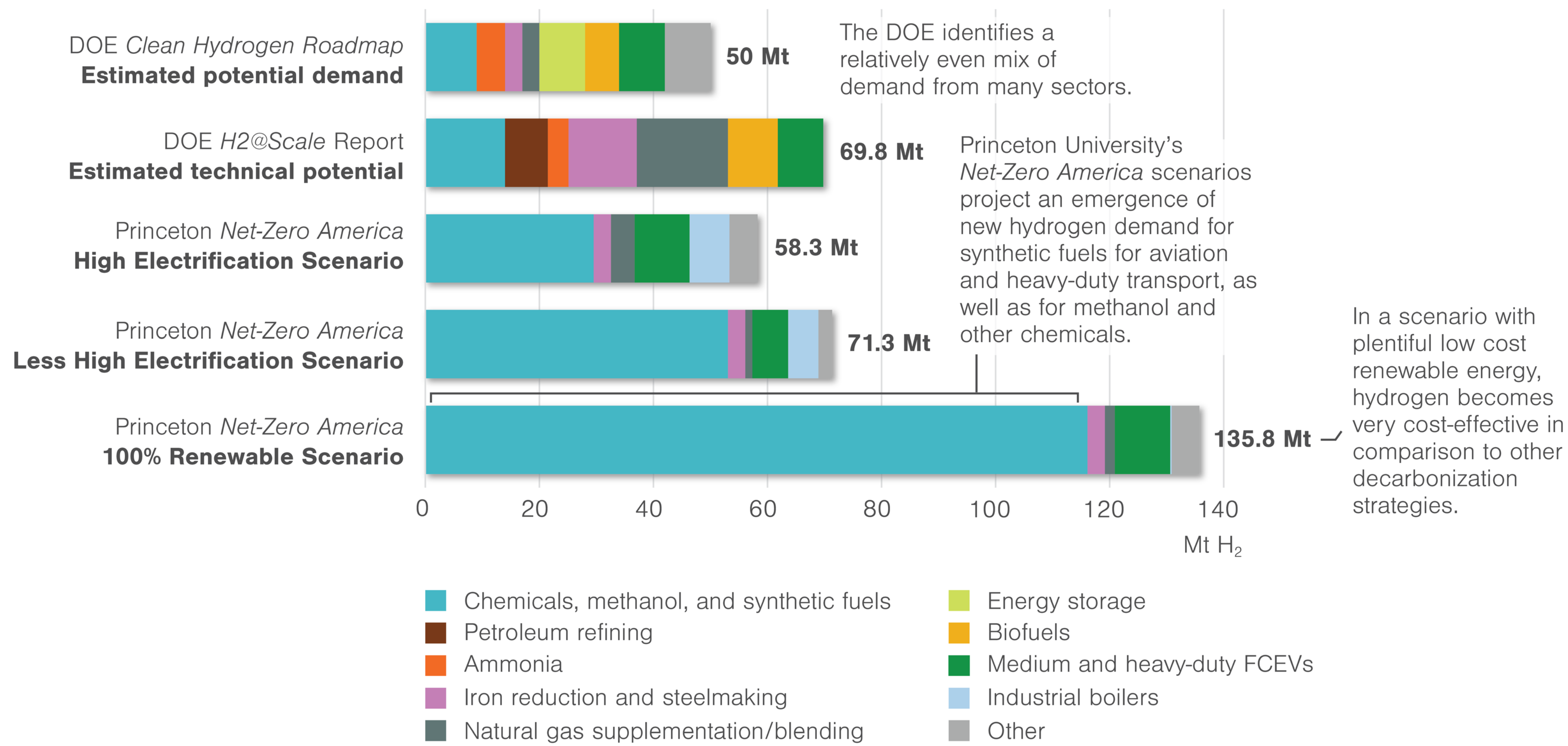


Figure authored by Elizabeth Abramson (2023) based on *DOE National Clean Hydrogen Strategy and Roadmap* (DOE, September 2022); Ruth et al. (October 2020); *Net-Zero America* (Princeton University, October 2021).[103] Note: applications for light-duty fuel cell vehicles were omitted due to growing opportunities for light-duty battery electric vehicles.

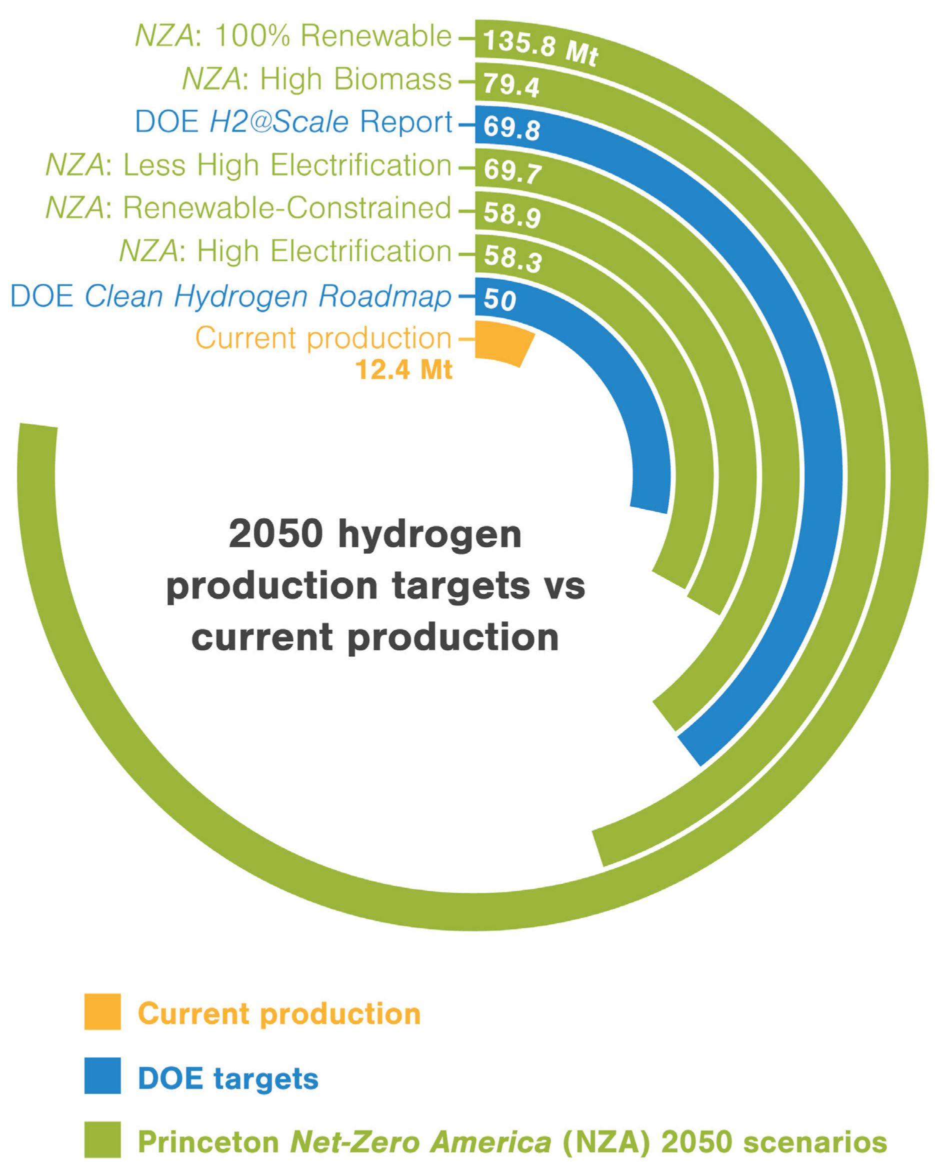
The DOE's hydrogen production goals will contribute to emissions reduction across many sectors but do not guarantee achievement of national net-zero targets.

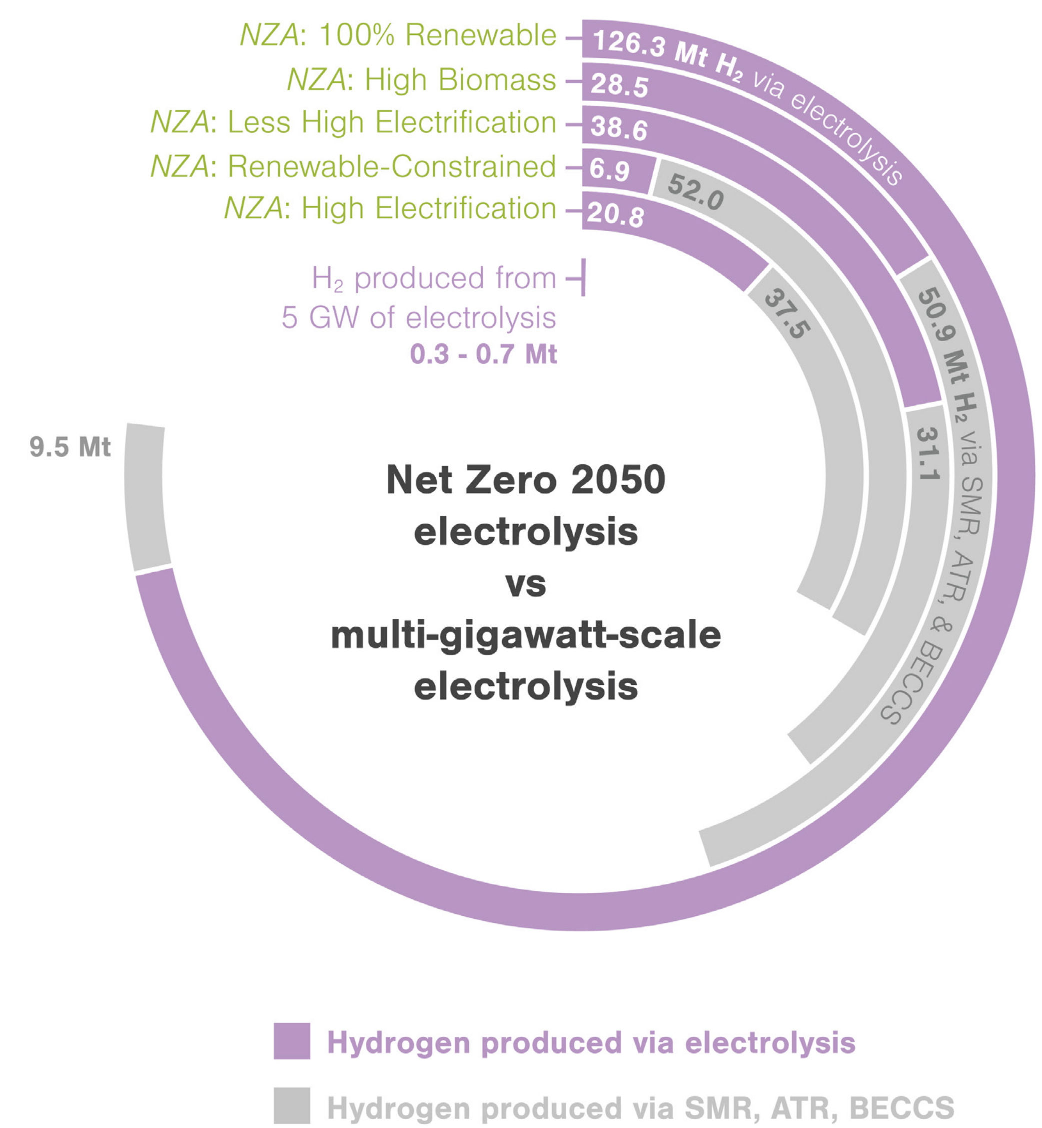
The DOE's national targets for hydrogen production establish a goal to essentially match current US hydrogen production capacity with 10 Mt of clean hydrogen by 2030. The DOE hopes to double and then quintuple this amount to 20 Mt by 2040 and 50 Mt by 2050. Meanwhile, Princeton University's *Net-Zero America* study estimates that **achieving net-zero emissions may require 5 to 13 times as much hydrogen as is used today.**

Nearly all hydrogen produced today is made from natural gas through SMR. With a simpler engineering process and reliance on water and clean electricity instead of fossil fuels, electrolysis is expected to be a central means of producing clean hydrogen to meet national targets. As shown in the rightmost graph, Princeton's *Net-Zero* scenarios require up to 126 Mt of annual hydrogen production through electrolysis.

In addition to electrolysis, Princeton's *Net-Zero* scenarios are inclusive of bioenergy with carbon capture and storage (BECCS) pathways, which involve the gasification of biomass. In addition to producing hydrogen, the CO_2 produced from biomass gasification can be used for synthetic applications like transportation fuel or can be sequestered to achieve net negative emissions. Converting 100 million tons of corn stover to hydrogen could produce approximately 10 million tons of hydrogen and achieve 160 million tons of CO_2 removal.[104]

Total hydrogen production and expected share for electrolysis by scenario





Figures authored by Elizabeth Abramson (2023) based on *DOE National Clean Hydrogen Strategy and Roadmap* (DOE, September 2022); Ruth et al. (October 2020); *Net-Zero America* (Princeton University, October 2021); S&P Global Commodity Insights, *Directory of Chemical Producers*; Hodges et al. (March 2022); Revankar (2019); Ayers (September 2017); Roy et al. (November 2006); Mayyas et al. (August 2019).[105]

Achieving net zero may require up to 13 times as much hydrogen as is currently used today, with hydrogen largely produced via electrolysis.

The Landscape of Clean Hydrogen | Section 4

Achieving Scale in US Clean Hydrogen Production

The US hydrogen policy landscape

Hydrogen will play an essential role in the transition to a net-zero emissions economy in the US. **With flexible production pathways and an expansive set of end uses, hydrogen is one part of a larger portfolio of energy technologies supporting the Biden Administration's climate goals.** President Biden issued Executive Order 14008 in January 2021, establishing domestic targets to achieve a net-zero emissions power sector by 2035 and net-zero emissions economy by 2050.[106] In April 2021, the US elevated this ambition by submitting a nationally determined contribution to the Paris Agreement under the United Nations Framework Convention on Climate Change to reduce emissions at least 50 percent below 2005 levels by 2030.[107] In November 2021, the US published a long-term strategy in line with limiting global temperature increase to 1.5°C, formalizing the goal of achieving net-zero emissions by 2050.[108]

Overview of the federal policy landscape

The past two years have marked an inflection point in federal policy support and funding for clean hydrogen. Recognizing the importance of matching cost-effective clean hydrogen production with regional demand, Congress passed two major pieces of legislation to support a large-scale commercial ecosystem for clean hydrogen.

Inflation Reduction Act

In August 2022, Congress enacted the IRA including a 10-year clean hydrogen PTC under Section 45V, designed to defray the upfront and operating costs associated with hydrogen production. Clean hydrogen produced with a carbon intensity of less than 0.45 kg CO_2e per kg H_2 is eligible for the full credit value of up to \$3 per kg H_2, provided prevailing wage requirements are met. Hydrogen produced with a carbon intensity greater than 4 kg CO_2e per kg H_2 is not eligible for the credit. The credit is technology-neutral and awarded based on carbon intensity, such that the lower the carbon intensity of the hydrogen produced, the greater the credit value.

As an alternative to the clean hydrogen production tax credit, taxpayers may elect to utilize the Section 48 investment tax credit (ITC) for clean hydrogen production facilities, receiving a credit of up to 30 percent depending on the carbon intensity of the production process.

Bipartisan Infrastructure Law

In November 2021, Congress enacted the Bipartisan Infrastructure Law (BIL) including the landmark Regional Clean Hydrogen Hubs Program, or H2Hubs, expanding the use of clean hydrogen in the industrial sector and beyond. **The H2Hubs Program will invest \$8 billion over a five-year period** encompassing fiscal years 2022 through 2026, with funding authorized to the newly created Office of Clean Energy Demonstrations at DOE, with the goal of demonstrating the viability of the entire hydrogen value chain.

Hydrogen hubs can support a national clean hydrogen ecosystem that leverages regional assets, infrastructure, and investments to promote manufacturing and markets for clean hydrogen. As centers of supply and demand, hubs will be critical to delivering economies of scale while generating opportunities for job growth and community engagement. Building self-sustaining networks of production, processing, and use will maximize the potential for decarbonization, economic benefit, and equitable outcomes of clean hydrogen at scale.

Each clean hydrogen hub will be selected by DOE based on a mix of criteria, including:[109]

- **Feedstock diversity.** Of the six to ten hubs, three must meet specific feedstock requirements. At least one hub must demonstrate the production of clean hydrogen from fossil fuels, at least one will focus on hydrogen from renewable energy, and at least one will target hydrogen from nuclear energy.

The US hydrogen policy landscape

- **End-use diversity.** The hubs must demonstrate a variety of different end uses for clean hydrogen. With at least one hub desired in the electric power generation sector, the industrial sector, the residential and commercial heating sector, and the transportation sector, the funding will help demonstrate hydrogen's utility across sectors.
- **Geographic diversity.** Each regional clean hydrogen hub will be located in a different region of the US and make use of energy resources abundant in that region.
- **Natural gas-producing regions.** At least two regional clean hydrogen hubs will be chosen to the maximum extent possible for their proximity to the nation's greatest natural gas resources.
- **Training and employment.** Priority will also be given to regional clean hydrogen hubs that are likely to create opportunities for skilled training and long-term employment for the greatest number of residents in the given region.
- H2Hubs will also be evaluated on the degree to which they **"demonstrably aid the achievement" of a Clean Hydrogen Production Standard** targeting 4 kg CO_2e per kg H_2 produced. The standard will help reduce lifecycle GHG emissions and criteria pollutants compared to conventional technologies and processes.

DOE has developed a four-phase structure for the program, with go/no-go decisions also occurring between or within phases:[110]

- **Phase 1** will encompass initial planning and analysis activities to ensure that the overall H2Hub concept is technologically and financially viable, with input from relevant local stakeholders.
- **Phase 2** will finalize engineering designs and business development, site access, labor agreements, permitting, offtake agreements, and community engagement activities.
- **Phase 3** will begin installation, integration, and construction activities.
- **Phase 4** will enable full operations including data collection to analyze the H2Hub's operations, performance, and financial viability.

The initial funding opportunity issued in September 2022 encompasses Phase 1 activities and envisions selecting six to ten H2Hubs for a combined total of up to $6 billion to $7 billion in federal funding, reserving the remaining $1 billion to $2 billion for future launches or activities. Each hub is required to provide a 50 percent non-federal cost share, with a preference for projects requesting federal funding between $500 million and $1 billion. DOE anticipates that the core hydrogen production facility for each hub would have a nameplate capacity of at least 50 to 100 metric tons of daily clean hydrogen production.[111] In this initial phase of funding, these minimum levels could amount to an estimated 110 thousand to 219 thousand metric tons of clean hydrogen production annually from six hubs, or 182 thousand to 365 thousand metric tons of clean hydrogen production annually from 10 hubs. DOE will favor hubs that exceed the minimum amount of daily production stated in the Funding Opportunity Announcement, dependent on facility equipment and feedstock inputs. Each project is also required to have a Community Benefits Plan that specifically addresses community and labor engagement, workforce investment, diversity, equity, inclusion and accessibility, and Justice40 Initiative criteria.

For the first phase of the hubs application process, the Office of Clean Energy Demonstrations requested concept papers from potential applicants in November 2022. The program received a total of 79 submissions across all technology pathways and every region of the US, encouraging 33 to submit a full proposal by the April 7, 2023, deadline.[112] Pre-selection interviews for awards will occur throughout the summer of 2023, followed by selection notifications in the fall of 2023. Award negotiations will take place during the winter of 2023 into 2024.

The BIL also requires the completion of a *National Clean Hydrogen Strategy and Roadmap*, to be updated every three years. In September 2022, DOE released an initial draft of the *Roadmap* responding to the legislative language set forth in section 40314 of the BIL. The *Roadmap* identifies hydrogen's potential to reduce US emissions approximately 10 percent by 2050 relative to 2005 and identified strategic opportunities for 10 Mt of clean hydrogen production annually by 2030, 20 Mt by 2040, and 50 Mt by 2050.

Other provisions of the BIL include $1 billion for a Clean Hydrogen Electrolysis Program to reduce costs of hydrogen produced from clean electricity, the goal of which is to enable $2 per kg of clean hydrogen from electrolysis by 2026; and $500 million for Clean Hydrogen Manufacturing and Recycling Initiatives to support equipment manufacturing and strong domestic supply chains.

The BIL and IRA lay the groundwork for achieving the Biden Administration's comprehensive approach to the widespread deployment of commercial-scale hydrogen. **Reaching cost-effective hydrogen production by 2030 will be important as DOE expects clean hydrogen production to increase to as much as five times the current 10 Mt produced in the US annually.**[113] H2Hubs will also be a crucial complement to DOE's Hydrogen Shot goal, which aims to reduce the cost of clean hydrogen by 80 percent to $1 per kg in one decade.[114] Taken together, these investments will form the foundation of a national clean hydrogen network that, supported by the Biden Administration's Justice40 Initiative, will help ensure communities benefit from a burgeoning US clean hydrogen economy.[115]

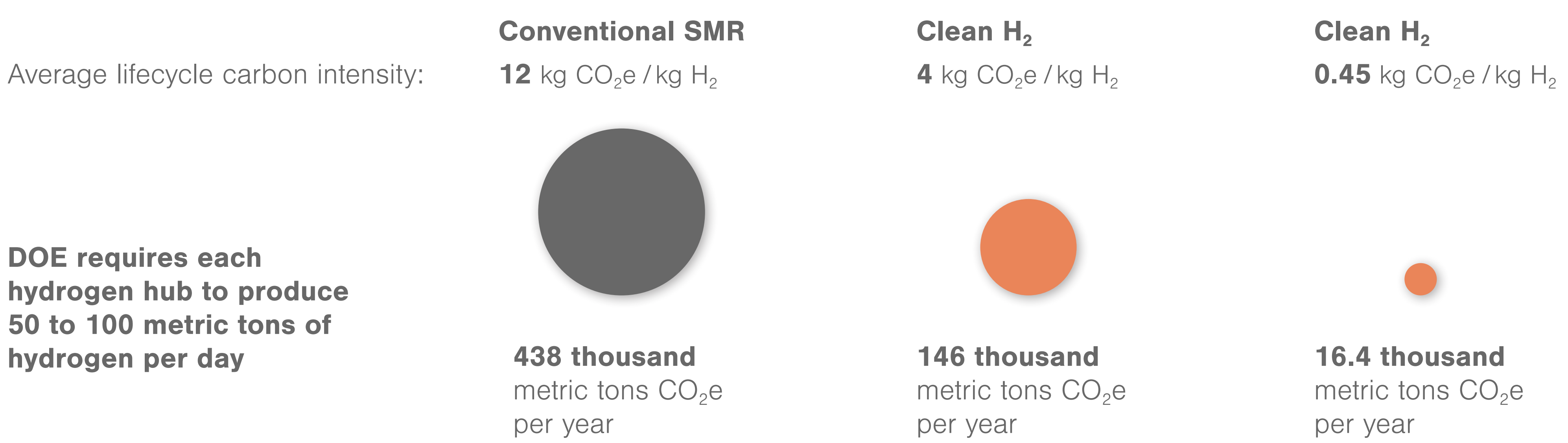
Clean hydrogen hubs as a starting point for national goals

DOE's H2Hubs Program establishes a minimum nameplate production capacity range of 50 to 100 metric tons of hydrogen per day at each hub. This capacity could produce around 18 thousand to 37 thousand metric tons of hydrogen each year per hub. For comparison, industrial scale SMR-based hydrogen production facilities frequently have capacities of over 100 thousand metric tons per year.[116] The H2Hubs award selection process will likely favor proposals with significantly higher production capacities than the minimum threshold.

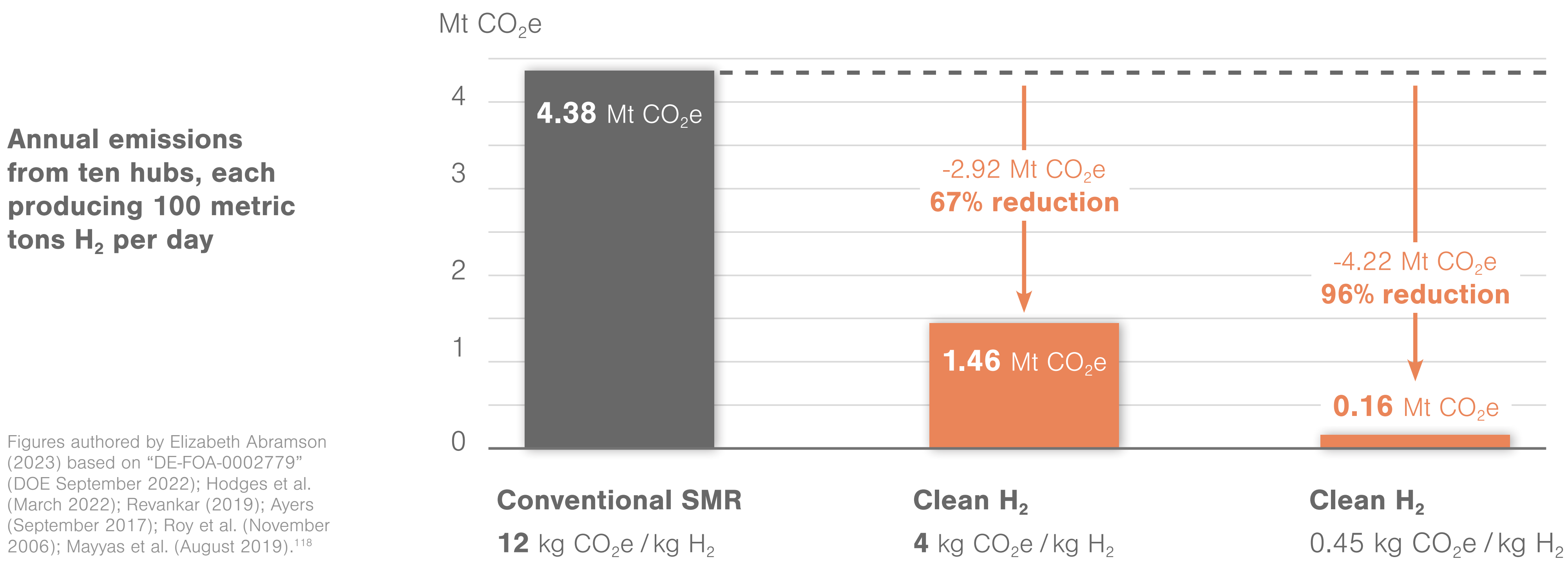
Hubs can provide emissions reductions through alignment with the clean hydrogen PTC. Producing 37 thousand metric tons of hydrogen through conventional SMR with an average lifecycle carbon intensity of 12 kg CO_2e per kg H_2 would emit approximately 438 thousand metric tons of GHGs each year.[117] Producing the same amount of hydrogen with a pathway achieving the first PTC threshold of 4 kg CO_2e per kg H_2 would emit 146 thousand metric tons of GHGs (a 67 percent reduction from conventional SMR). Achieving the most stringent PTC threshold of 0.45 kg CO_2e per kg H_2 would emit only 16.4 thousand metric tons per year (a 96 percent reduction from conventional SMR).

Thus, **each hydrogen hub would emit between 292 thousand and 422 thousand metric tons of GHGs less than the equivalent hydrogen production via SMR.** Six to ten hubs would emit 1.75 million to 4.2 million metric tons of GHGs less than equivalent SMR-based production annually.

Annual emissions from producing 100 metric tons of hydrogen per day



Annual emissions reduction from ten clean hydrogen hubs compared to conventional SMR



Figures authored by Elizabeth Abramson (2023) based on "DE-FOA-0002779" (DOE September 2022); Hodges et al. (March 2022); Revankar (2019); Ayers (September 2017); Roy et al. (November 2006); Mayyas et al. (August 2019).[118]

Clean hydrogen hubs as a starting point for national goals

At the H2Hubs minimum production thresholds, many more hubs will need to be established, or existing and future hubs will need to grow significantly, to achieve DOE's 10 Mt, 20 Mt, and 50 Mt clean hydrogen goals for 2030, 2040, and 2050 respectively.

Initial clean hydrogen hubs can establish a foothold in regional markets to jump-start clean hydrogen production and demand. **It is crucial for established hubs to continue to grow in production while identifying nearby off-takers and decarbonization opportunities to achieve regional scale.**

The diagram at right compares the combined minimum production capacity of 10 clean hydrogen hubs (represented as one dot) against DOE's production goals for 2030, 2040, and 2050. At these minimum levels, many hubs would be needed to reach DOE's *Roadmap* targets. As shown on the right half of this diagram, **scaling up facility capacity would necessitate fewer individual project locations to reach DOE production goals.**

Hydrogen hubs: From 100 tons per day to 50 million tons per year

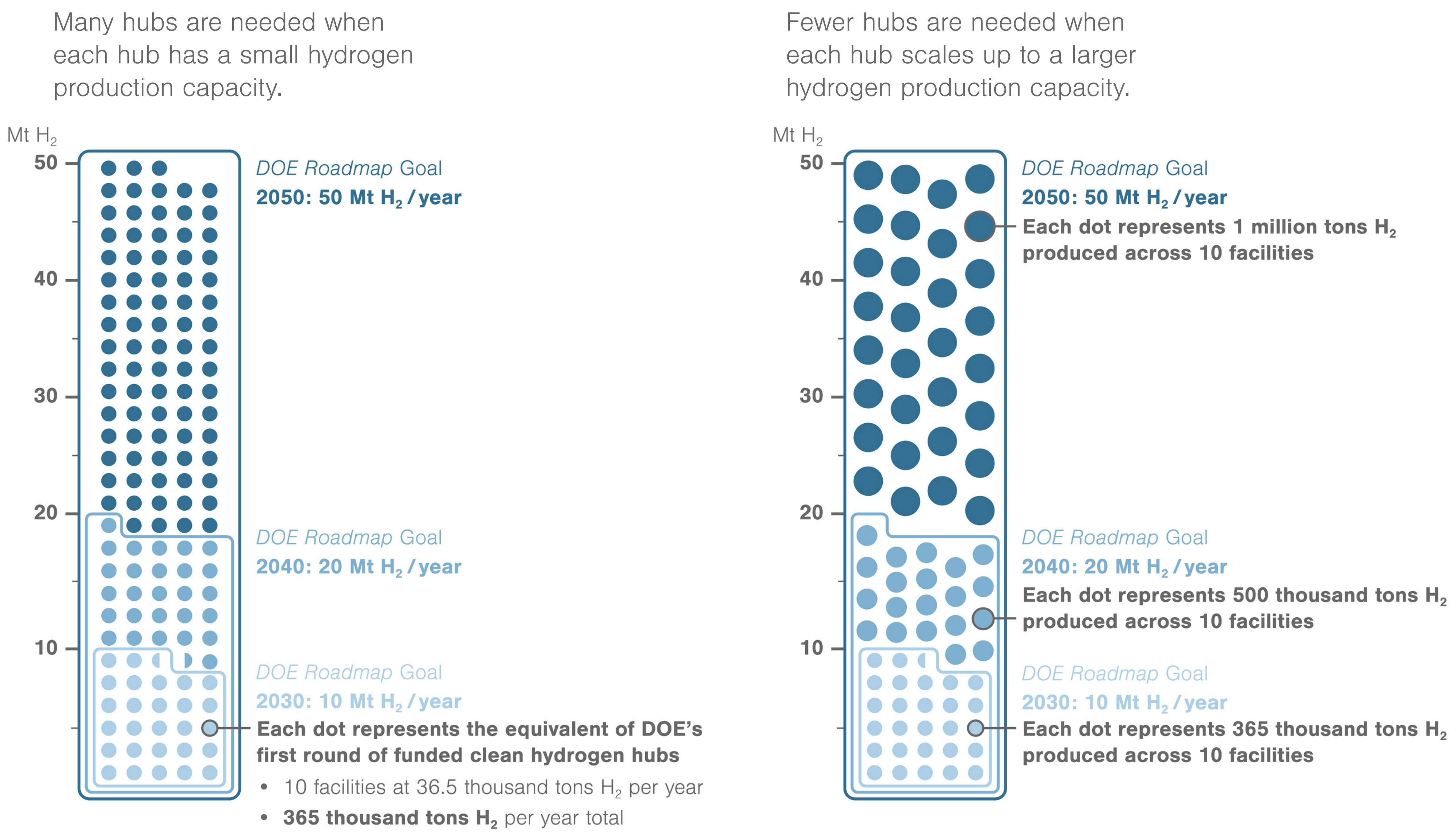


Figure authored by Elizabeth Abramson and Dane McFarlane (2023) based on *DOE National Clean Hydrogen Strategy and Roadmap* (DOE, September 2022); "DE-FOA-0002779" (DOE September 2022).[119]

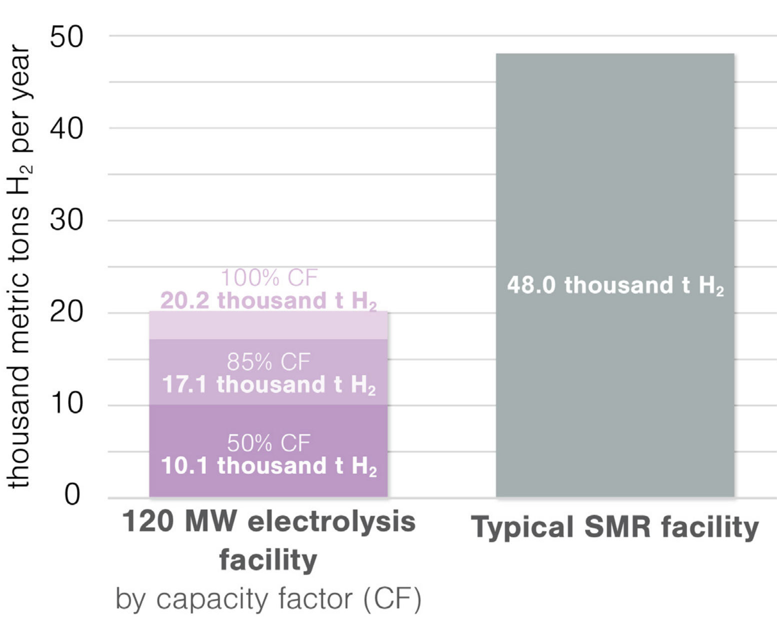
Scaling up clean hydrogen production capacity at each hub would reduce the number of individual project locations needed.

Electrolysis: Creating hydrogen from water with clean electricity

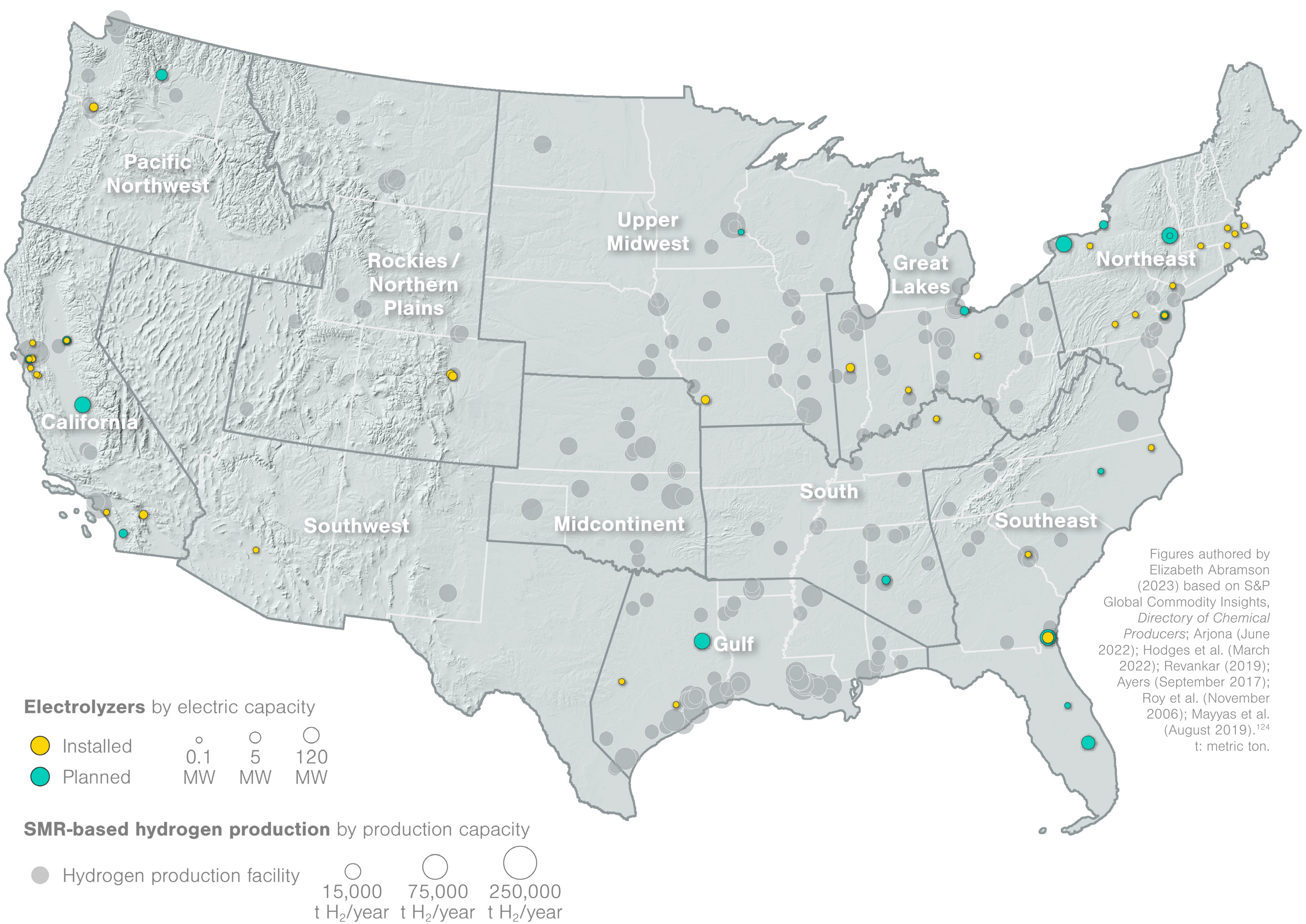
Electrolysis produces hydrogen and oxygen from water through the application of electricity across a material membrane. When supplied with carbon-free or renewable electricity, electrolytic hydrogen can achieve a very low or virtually zero carbon intensity.

The 42 known electrolyzers in the US make up a small fraction of national hydrogen production.[120] These facilities range in electrical capacity from 120 kW to 5 MW for a total capacity of 18 MW, which could produce about three thousand metric tons of hydrogen per year if operating at full time capacity.[121] Four new announced projects with a capacity of 120 MW could each produce up to 20.2 thousand metric tons of hydrogen per year if operated full time.[122] In comparison, a typical SMR-based production facility produces 48 thousand metric tons of hydrogen per year.[123]

120 MW electrolysis vs typical SMR



Location of existing US hydrogen electrolysis



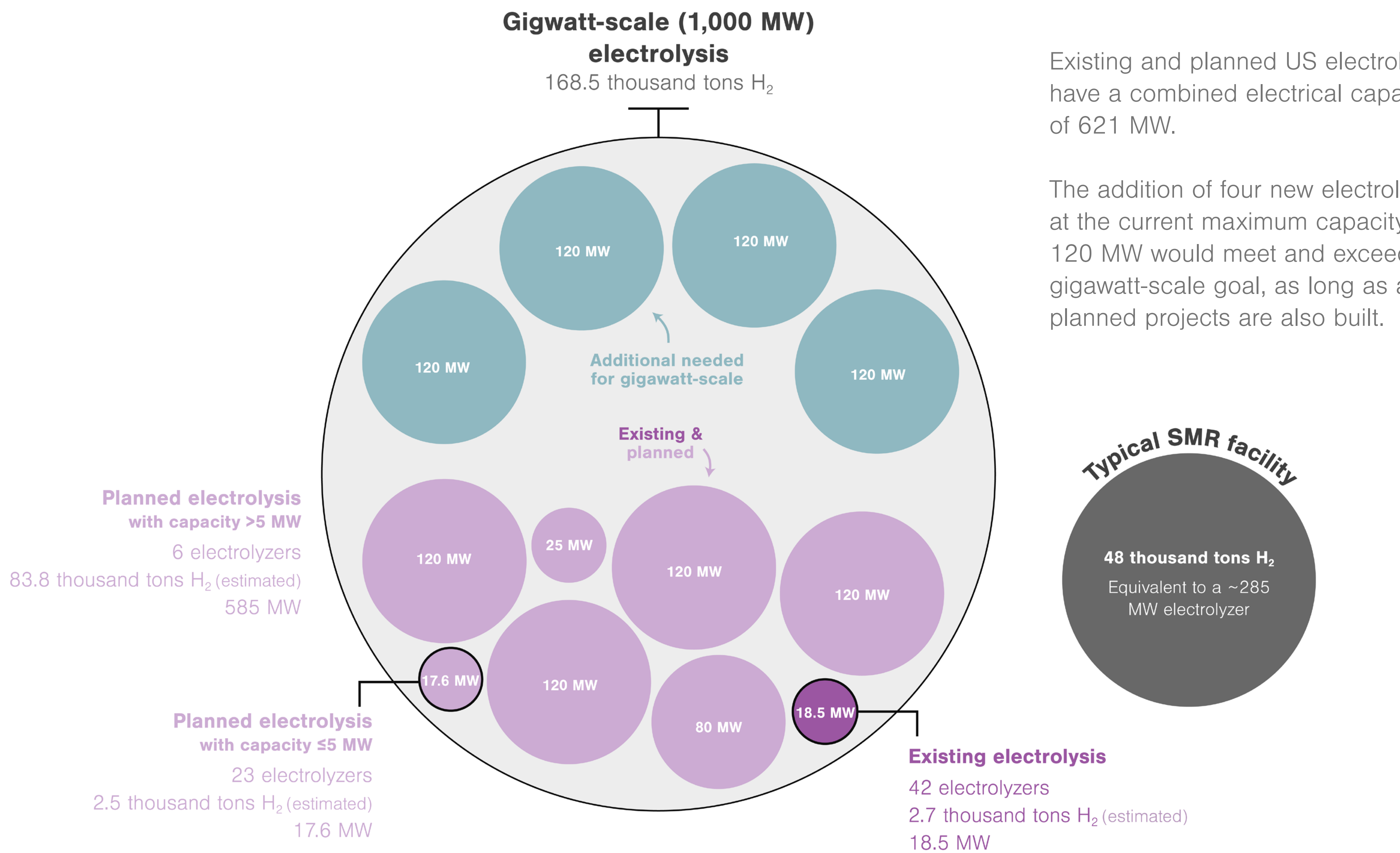
Figures authored by Elizabeth Abramson (2023) based on S&P Global Commodity Insights, *Directory of Chemical Producers*; Arjona (June 2022); Hodges et al. (March 2022); Revankar (2019); Ayers (September 2017); Roy et al. (November 2006); Mayyas et al. (August 2019).[124]
t: metric ton.

Achieving gigawatt-scale electrolysis and beyond

Included in the goals laid out in the DOE's *National Clean Hydrogen Strategy and Roadmap* is an aspiration to achieve multi-gigawatt-scale electrolysis capacity in the US in the next decade. As mentioned on the previous page, data published by the DOE reports 42 known electrolyzers installed across the US with a combined electrical capacity of about 18 MW (0.018 GW). The database also reports at least 29 new planned or announced electrolysis projects. 23 of these have capacities below 5 MW each, totaling about 17.6 MW in additional capacity. Six more projects are planning for much larger capacity: one project targeting 25 MW; another targeting 80 MW; and four projects targeting 120 MW each. **If all of these projects become operational, the US could have a total electrolysis capacity of about 621 MW, almost two-thirds of the way toward the first gigawatt capacity milestone.**

At current production yields for low-temperature electrolysis and typical capacity factors, 1 GW of electrolysis production would yield about 143 thousand to 169 thousand metric tons of hydrogen each year.[126] Technological advancement or the use of high-temperature or alkaline electrolysis would achieve yield increases relative to low-temperature electrolysis. As such, **single digit gigawatt scale production would need to be only the beginning of US electrolysis capacity development.**

Additional electrolysis capacity needed to achieve gigawatt-scale electrolysis (at 100% capacity factor)



Existing and planned US electrolyzers have a combined electrical capacity of 621 MW.

The addition of four new electrolyzers at the current maximum capacity of 120 MW would meet and exceed the gigawatt-scale goal, as long as all planned projects are also built.

US electrolysis capacity

18.5 MW installed 3.1 thousand metric tons H_2

602.6 MW planned 101.5 thousand metric tons H_2

Additional needed to achieve 1 GW

380 MW 64.0 thousand metric tons H_2

Figure authored by Elizabeth Abramson and Dane McFarlane (2023) based on WRI (2023); S&P Global Commodity Insights, *Directory of Chemical Producers*; Arjona (June 2022); Hodges et al. (March 2022); Revankar (2019); Ayers (September 2017); Roy et al. (November 2006); Mayyas et al. (August 2019).[127]

Achieving gigawatt-scale electrolysis and beyond

The use of electrolysis for hydrogen production will need to scale immensely through the construction of many facilities, improved electric efficiency and hydrogen yields, and increased per-facility production capacities. The table at right highlights the relationship between electrolyzer capacity and hydrogen production.

At current yields, **1 GW of electrolysis would produce about 143 thousand metric tons of hydrogen annually** when operating 85 percent of the year (85% capacity factor). For context, 1 GW is equivalent to the capacity of roughly 333 utility-scale wind turbines (3 MW each).[128] **10 GW of electrolysis at an 85% capacity factor could produce over 1.4 Mt of clean hydrogen and start to achieve the order of magnitude needed to contribute to US production goals.** However, electrolysis projects that act as load-balancing resources to reduce the curtailment of renewable electric generation may operate at a much lower capacity factor, reducing yields for this same electrolytic capacity.

Producing 10 Mt of hydrogen could require around 70 GW of electrolysis, with 20 Mt and 40 Mt requiring 140 and 280 GW, respectively. Princeton University's *Net-Zero America* study 100% Renewable scenario projects a demand for 126 Mt of hydrogen via electrolysis, which would require over 880 GW of capacity at current typical yields.

Electrolysis-based hydrogen production at 85% capacity factor required to meet midcentury targets

Production capacity	H_2 produced via electrolysis Mt H_2	Required electrolysis capacity GW	Required combination of electrolysis capacity: 120 MW # of facilities	500 MW # of facilities	1 GW # of facilities
1 GW	0.14	1	3	1	0
10 GW	1.4	10	28	7	3
10 Mt hydrogen	10	69.8	194	47	23
20 Mt hydrogen	20	139.7	388	93	47
40 Mt hydrogen (e.g., 50 Mt H_2 production goal in 2050 with 10 Mt from SMR + CCS)	40	279	776	186	93
126 Mt hydrogen Princeton NZA 100% Renewable	126.3	882	2,449	588	294

Source: Carbon Solutions analysis based on Hodges et al. (March 2022); Revankar (2019); Ayers (September 2017); Roy et al. (November 2006); Mayyas et al. (August 2019); *Net-Zero America* (Princeton University, October 2021).[129] Note: the table assumes an equal split between 120 MW, 500 MW, and 1 GW facilities, with facilities operating at an 85 percent capacity factor (CF).

Achieving DOE's hydrogen production targets or Princeton's *Net-Zero* scenarios could require hundreds to thousands of electrolysis facilities.

Grid balancing and energy storage

Widespread development of multi-gigawatt-scale hydrogen electrolysis represents a potential grid-balancing resource that could enable higher rates of renewable electricity generation and reduce the need for fossil fuel-based peaking power plants. The growing share of electric generation provided by renewable sources like wind and solar can present a technical challenge due to the intermittency of renewable resources. Excess electricity produced when wind and solar resources are most abundant can result in negative wholesale electricity prices.[130] This can be avoided through curtailment, which essentially turns renewable generation off even if it is available, increased transmission capacity, and energy storage. Dispatchable electrolysis production could be ramped up to provide additional load to the grid during times of high renewable availability, preventing curtailment and negative prices.[131]

When wind and solar resources are low, utilities often rely on fossil fuel electric generation, such as from natural gas peaking plants, to quickly ramp up to meet electric demand. These peaking plants can have much higher costs and GHG intensities than other generation sources.[132] Hydrogen electrolysis facilities could ramp down production during times of peak load, reducing strain on the electric grid and diminishing the need for fossil-fuel based electric generation.[133]

Running electrolysis at varying rates reduces the amount of hydrogen created compared to a facility's full production capacity and could have an impact on the cost performance of capital investment. A 120 MW electrolyzer running at a full-time rate (100 percent capacity factor) could produce approximately 20 thousand metric tons of hydrogen per year at current typical yields. Running the same electrolyzer to match typical capacity factors for renewable sources, such as at 33 percent of the time, would only yield about seven thousand metric tons of hydrogen per year. On a 1 GW scale, this means the difference between 166 million tons and 58 million tons of hydrogen produced using the same equipment. Higher capacity factors generally help spread out capital investment and operating costs over larger volumes of product. Recent studies suggest that it may be most economically efficient to run electrolysis between 33 and 65 percent of the time to take advantage of lower electricity prices during windows of high solar and wind generation. The capital cost benefit of increasing production beyond that range is effectively offset by higher electricity prices increasing operating costs.[134]

Hydrogen produced from a 120 MW electrolyzer, by capacity factor

While an electrolyzer can produce the greatest amount of hydrogen by running at a full-time rate (100% CF), the variability of renewable electricity generation may make it more economically efficient to run at a lower capacity factor, matching the capacity factors of renewable sources like wind and solar.

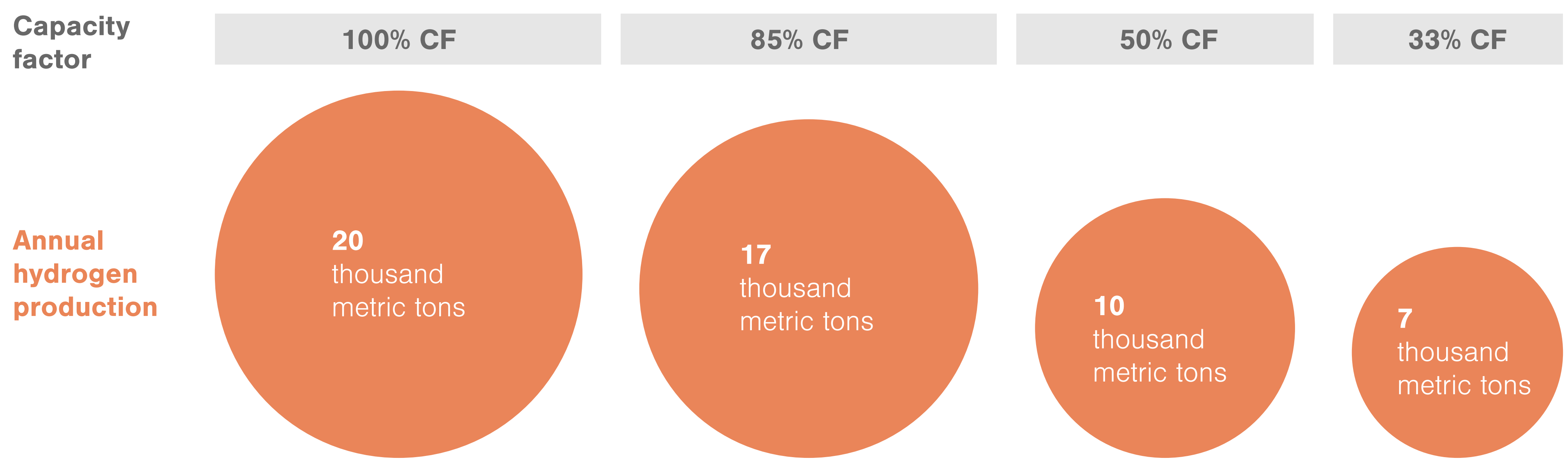


Figure authored by Elizabeth Abramson and Dane McFarlane (2023) based on Hodges et al. (March 2022); Revankar (2019); Ayers (September 2017); Roy et al. (November 2006); Mayyas et al. (August 2019).[135]

Clean electricity for hydrogen electrolysis

Hydrogen production via electrolysis requires significant quantities of electricity and, for high temperature processes, heat. The impact of new load from hydrogen electrolysis will need to be accounted for in electric grid planning, through purchasing agreements for renewable electricity, onsite generation, and real-time tracking of electric carbon intensity in order for electrolysis facilities to produce clean hydrogen.

Nearly 60 percent of today's grid-connected electricity generation comes from fossil fuels, resulting in an average grid intensity of 388.74 kg CO_2e per MWh.[136] A typical low-temperature electrolysis facility would need to run on electricity with a carbon intensity lower than 81 kg CO_2e per MWh to achieve the first clean hydrogen threshold of 4 kg CO_2e per kg H_2.[137] Achieving the lowest threshold of 0.45 kg CO_2e per kg H_2 would require electricity with a very low carbon intensity of 9 kg CO_2e per MWh or less. This would require virtually all electricity supplied to the facility to be renewable or zero-carbon. High-temperature electrolysis facilities could run at higher hydrogen yields and energy efficiencies, and thus have less stringent standards for clean electricity on a mass basis (per kg hydrogen produced), but would need a clean source of thermal energy, such as nuclear power plants.

Required electric generation carbon intensity at clean H_2 PTC levels

H_2 carbon intensity kg CO_2e/kg H_2	**Electric carbon intensity** kg CO_2e/MWh
0.45	9.15
1.5	30.49
2.5	50.82
4.0	81.31

Source: Carbon Solutions analysis using rate of 52 kWh/kg H_2, based on current range of hydrogen mass yield for LTE electric conversion and scaling factor for total lifecycle energy use.[138]

Ensuring a supply of low- or zero-carbon electricity for electrolysis facilities is essential to producing clean hydrogen. The variability of renewable electricity generation from sources such as wind and solar makes it crucial to match hydrogen electrolysis operations with areas where low-carbon electricity is available. To maximize the amount of hydrogen produced each year, an electrolyzer would need to operate at a high capacity factor through the use of energy storage or low-carbon grid electricity in times when direct renewable electricity is not available.

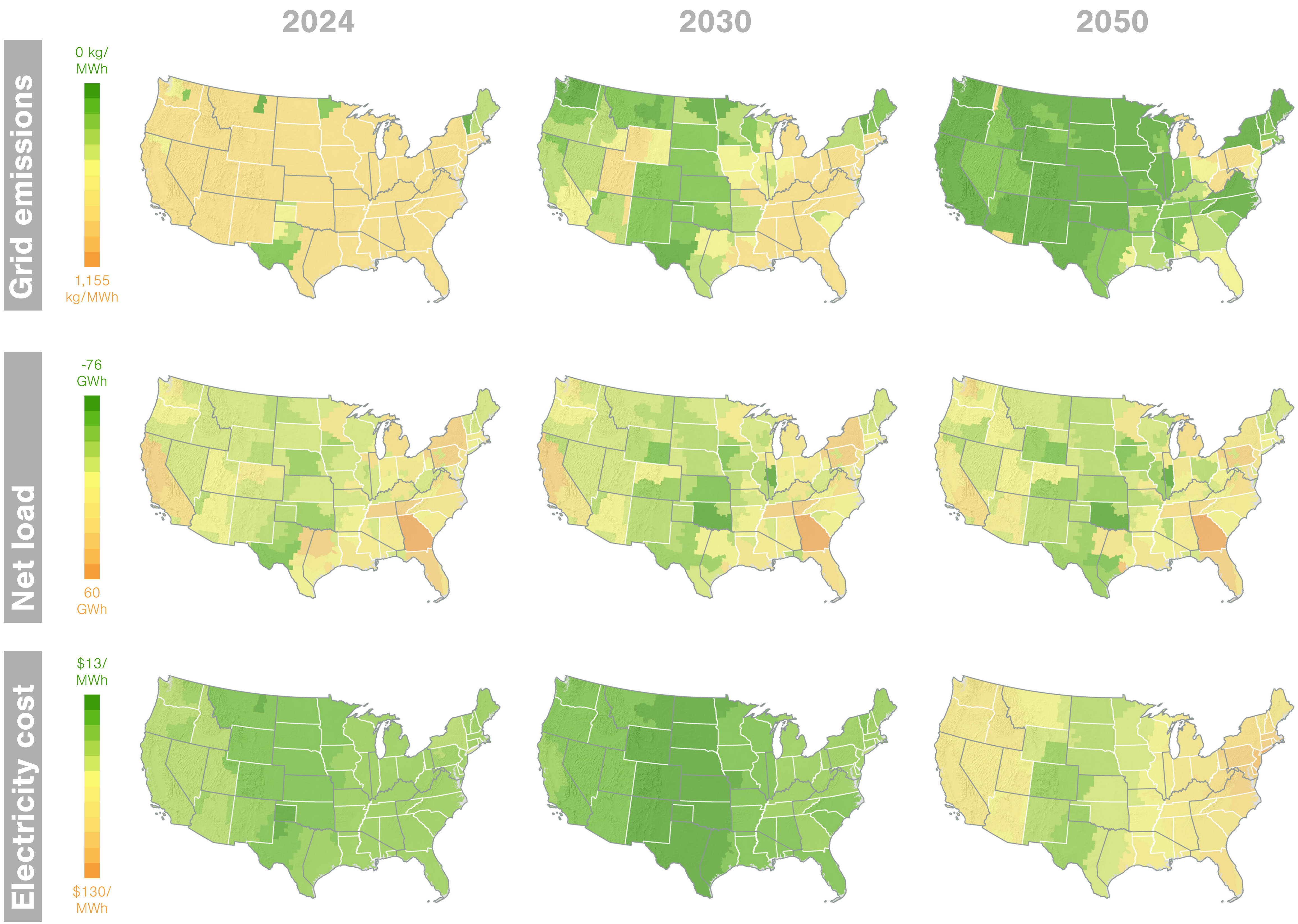
Even with power purchasing agreements that allocate renewable energy for the electric load of new projects, it is important to consider the impact of new marginal load on dispatchable generation resources across the electric grid. **The indirect effect of causing increased or sustained demand for existing or new fossil fuel electric generation would be counter-productive to national and global climate goals for electric system decarbonization.** Thus, it may be advisable for clean hydrogen electrolysis projects to ensure that power purchasing agreements specify a requirement for the allocation of newly built renewable or zero-carbon electricity, or engage in on-site generation of zero-carbon electricity.

Electrolysis uses large amounts of electricity. To avoid adverse impacts on the electric grid, electrolysis projects must ensure a dedicated supply of low- or zero-carbon electricity to power facility operations.

Clean electricity for hydrogen electrolysis

Grid-connected electrolysis facilities can achieve a low lifecycle carbon intensity for hydrogen in areas of the country with high levels of renewable generation and thus low average emission intensity or marginal emission rates for electric generation. Even in these areas, indirect impacts of new electrolytic loads on fossil-based marginal electric generation must be considered.

Electrolysis facilities above 120 MW in electrical capacity present significant new electric load, making it important to locate projects without a congested grid. Project finances and low-cost hydrogen will also depend on energy prices faced by the facility. For a general sense of electric grid suitability for new loads, this page presents a series of maps based on the National Renewable Energy Laboratory's Regional Energy Deployment System (NREL ReEDS) projected grid emission intensity, net load, and electricity cost over time.



Figures authored by Elizabeth Abramson and Dane McFarlane (2023) based on NREL ReEDS Cambium 2022 Mid-case (2023); NREL ReEDS Cambium 2021 Low Renewable Energy Cost (2023); NREL ReEDS Cambium 2021 Mid-case 95 by 2050 (2023).[139] ReEDS modeled electricity costs are based on capacity expansion, capital investment, and availability of low-cost generation in each specific scenario.

The Landscape of Clean Hydrogen | Section 5

US Emissions Trends and Reduction Potential with Clean Hydrogen

The role of hydrogen in reaching net-zero US emissions

US emissions are projected to decline overall between the present day and 2050, with large uncertainties in predictions based on the impact of current and future policy decisions and market forces.[140] However, forecasts suggest that **the US will not meet its climate goals by 2030 or 2050 without additional emissions-reducing strategies.[141]** Hydrogen can play a critical role in helping the US achieve its climate goals.

Emissions reduction study approach

In this section, current and future GHG trends are analyzed to see where hydrogen could make a meaningful difference in reducing emissions. Focus is placed on the industrial and transportation sectors, where emissions are expected to persist in the coming decades due to rising demand and subsectors that are difficult to decarbonize through traditional means.

Hydrogen's emissions reduction potential in these sectors is calculated by comparing the lifecycle carbon intensities for common currently used fuels to those of clean hydrogen aligned with the clean hydrogen PTC. Using the DOE's estimated hydrogen demand in industrial sectors like ammonia and steel and in fuels such as synthetic fuels and biofuels, **an estimated 245 to 366 $MtCO_2e$ in emissions could be avoided annually through the use of clean hydrogen in industry and transportation by 2050.**

National GHG emission trends

US emissions from industry, transportation, and commercial and residential energy use have been relatively steady since 1990, while emissions from the electric power sector have declined steadily since a peak in the mid-2000s.[142] The US Energy Information Administration (EIA) provides projections for CO_2 emissions through 2050, with the 2023 *Annual Energy Outlook* including the effects of the IRA.[143] Without the IRA, GHG emissions estimates range around 9 to 20 percent higher in 2030, depending on the analysis.[144]

When including the IRA in modeling, EIA projections still do not anticipate that the US will meet its nationally determined contribution to the Paris Agreement of a 50 percent reduction in total emissions below 2005 levels by 2030.[145] Analysis by the Rhodium Group projects a 32 to 42 percent emissions reduction by 2030 relative to 2005.[146]

In EIA's reference case projections, which include the impacts of the IRA, the largest decline in emissions by 2050 comes from the electric power sector, particularly as coal-fired power plants are replaced with renewable energy. Transportation, currently the highest CO_2-emitting sector, sees a modest decline in projected emissions by 2040 before a reversal due to demand growth outweighing efficiency improvements. Overall, the transportation sector shows a decline of around 19 percent from 2005 levels by 2050.

Without further policy, industrial emissions are projected to rise due to growing demand for energy and hydrocarbon feedstocks, with emissions ending up nine percent higher in 2050 than 2005 levels. **Ramping up hydrogen production and use can help decarbonize industrial and transportation processes where emissions are expected to persist without further action.**

Historical and projected US emissions

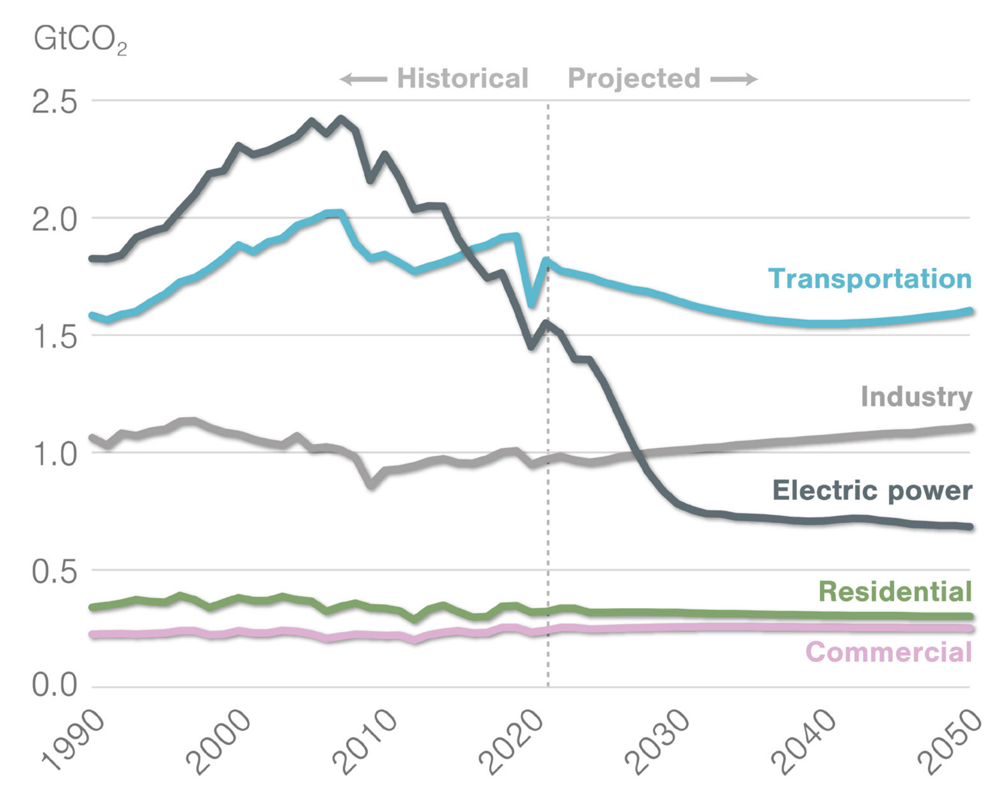


Figure authored by Elizabeth Abramson and Amy Jordan (2023) based on "Total Energy" (EIA, accessed March 2023); "Annual Energy Outlook 2023" (EIA, accessed March 2023).[147]

Clean hydrogen's uses in fuel-switching, fuel cells, and feedstocks

Fuels

Clean hydrogen can be combusted directly in retrofitted or dedicated hydrogen-burning equipment or blended with natural gas to produce high-grade heat for industrial processes. When hydrogen is combusted with pure oxygen, the product is water.

Combustion of hydrogen for energy and heat:

$$2H_2 + O_2 \rightarrow 2H_2O$$

However, by far the most common use case is combustion of hydrogen in ambient air (which contains nitrogen). This results in the formation of nitrogen oxide compounds (NOx), though other pollutants common to fossil fuel combustion are greatly reduced, as discussed in detail on pages 59 to 61.

Hydrogen can also be used as a feedstock to generate synthetic drop-in fuels including renewable diesel and gasoline. As discussed on pages 23 and 24, some of these synthetic fuels are classified as power-to-liquid (PtL) fuels, where hydrogen and CO_2 are combined to generate other hydrocarbons. PtL fuels are a major demand sector in the DOE's *Roadmap* and could be used to displace conventional diesel.

DOE also identified biofuels generated using clean hydrogen as tools for displacement of fossil fuels. Biofuels generated with clean hydrogen could displace conventional diesel, or, in the form of sustainable aviation fuel, they could displace jet fuel.

Methanol and ammonia, while commonly used as feedstocks for chemicals and fertilizer, could also be used as fuels. When made with clean hydrogen, these hydrogen "carriers" could supplant or blend with fuels in maritime shipping and other forms of transportation to reduce sector emissions.[148]

While combusting hydrogen does not produce CO_2, combusting other drop-in fuels produced using clean hydrogen (with the exception of ammonia) would still generate CO_2. However, CO_2 emissions from biofuel combustion are typically excluded from emission totals as they are offset by carbon uptake during the growing period of the biomass feedstock.[149] Likewise, CO_2 used to generate PtL fuels may come from captured sources, making its combustion carbon-neutral, though the fuel would still have lifecycle emissions associated with its upstream production. Using clean hydrogen minimizes the lifecycle emissions from these drop-in fuels.

Fuel cells

Fuel cells produce electricity from hydrogen in a system similar to a battery, with a cathode and an anode and a catalyst to separate electrons from protons in the hydrogen atoms. **The only byproducts of fuel cells are heat and water; there are no combustion emissions of CO_2, NOx, or other pollutants.** The potential applications of fuel cells in industry and transportation are extensive. They may be designed for vehicles (FCEVs), as described on pages 26 to 27, used to generate industrial heat, or sized to large capacities for service in energy storage applications.

Opportunities for hydrogen to displace conventional fuels

Conventional hydrogen	→	Clean hydrogen
Natural gas & other fossil fuels	→	Clean hydrogen
Diesel	→	Power-to-liquids & biofuels
Jet fuel	→	Sustainable aviation fuels
Diesel & gasoline	→	Fuel cells

Feedstocks

In addition to its role in low-carbon fuels, clean hydrogen can be used as a feedstock in ammonia and chemical manufacturing, refining, and steel production. In this case, emissions reductions come from replacing conventional SMR-based hydrogen with clean hydrogen produced via renewable electrolysis or SMR plus carbon capture.

Hydrogen lifecycle emissions in context

Comparing the combustion emission factors of common fuels

The combustion of hydrogen delivers high grade thermal energy while producing water instead of carbon and other GHGs, resulting in a direct combustion emission factor of 0 g CO_2e per megajoule (MJ). The bar chart at right compares this to average GHG emission factors from a variety of fossil or other common fuels used in both the industrial and transportation sectors.

These emission factors mean that fossil fuel displacement by hydrogen results in reduced on-site carbon emissions. However, the true impact of hydrogen use depends on full lifecycle carbon intensity, including upstream production.

For most fuels, combustion contributes the largest portion of lifecycle GHG emissions (compared to upstream contributions to generating the fuel). For hydrogen, the opposite is true: combustion emissions of GHGs are zero to minimal, while the full lifecycle contribution to planet-warming emissions comes from the upstream methods used to produce it. Decarbonizing hydrogen production leads to a near-zero GHG emitting fuel.

GHG emission factors for combustion of common fuels

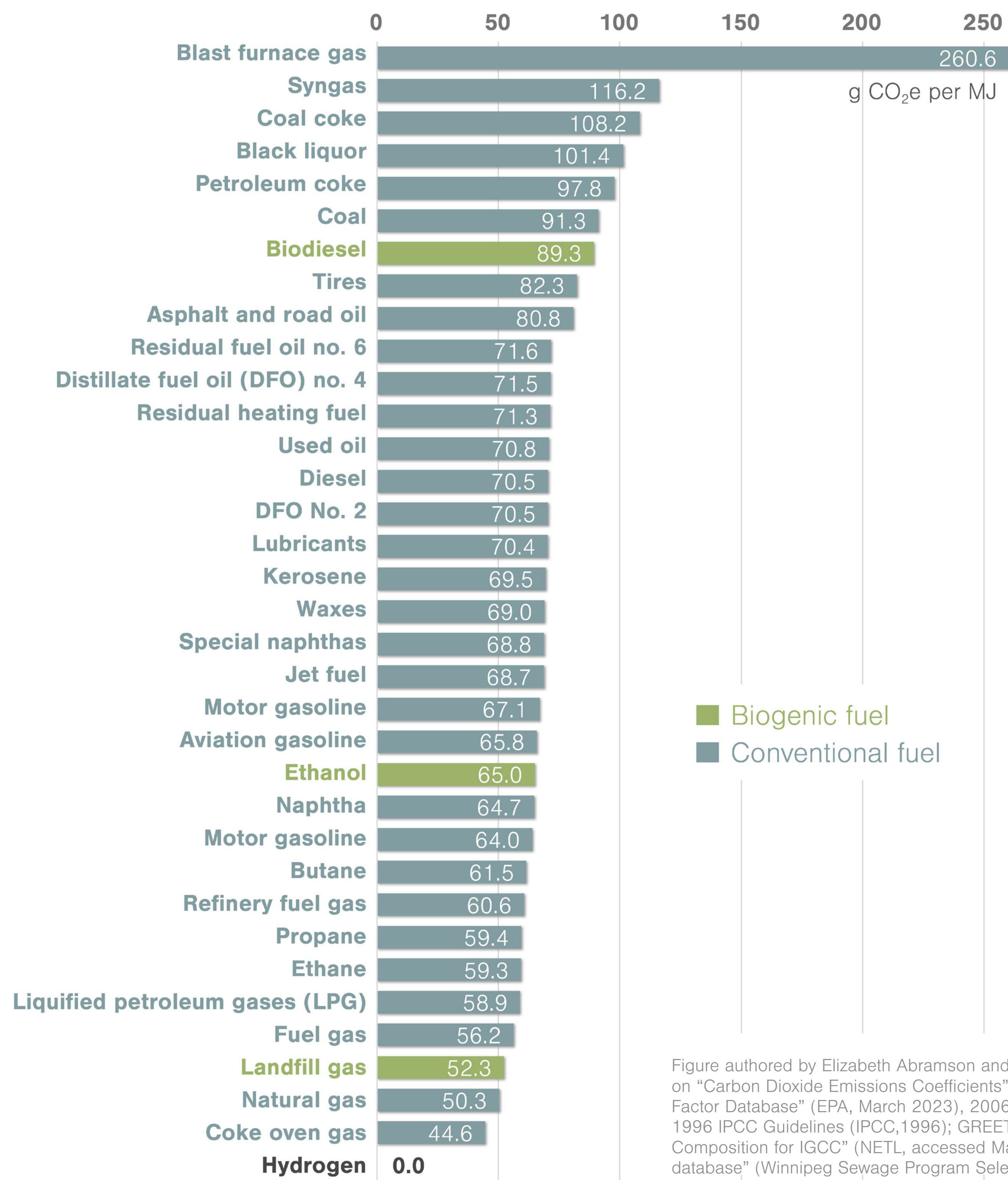


Figure authored by Elizabeth Abramson and Daniel Rodriguez (2023) based on "Carbon Dioxide Emissions Coefficients" (EIA, October 2022); "Emission Factor Database" (EPA, March 2023), 2006 IPCC Guidelines (IPCC, 2006); 1996 IPCC Guidelines (IPCC,1996); GREET Model (ANL, 2022); "8.5. Syngas Composition for IGCC" (NETL, accessed March 2023); "CO_2 emission factors database" (Winnipeg Sewage Program Selection Report, December 2011).[150]

Hydrogen does not emit GHGs when combusted. All of hydrogen's lifecycle emissions come from upstream production and product distribution.

Hydrogen lifecycle emissions in context

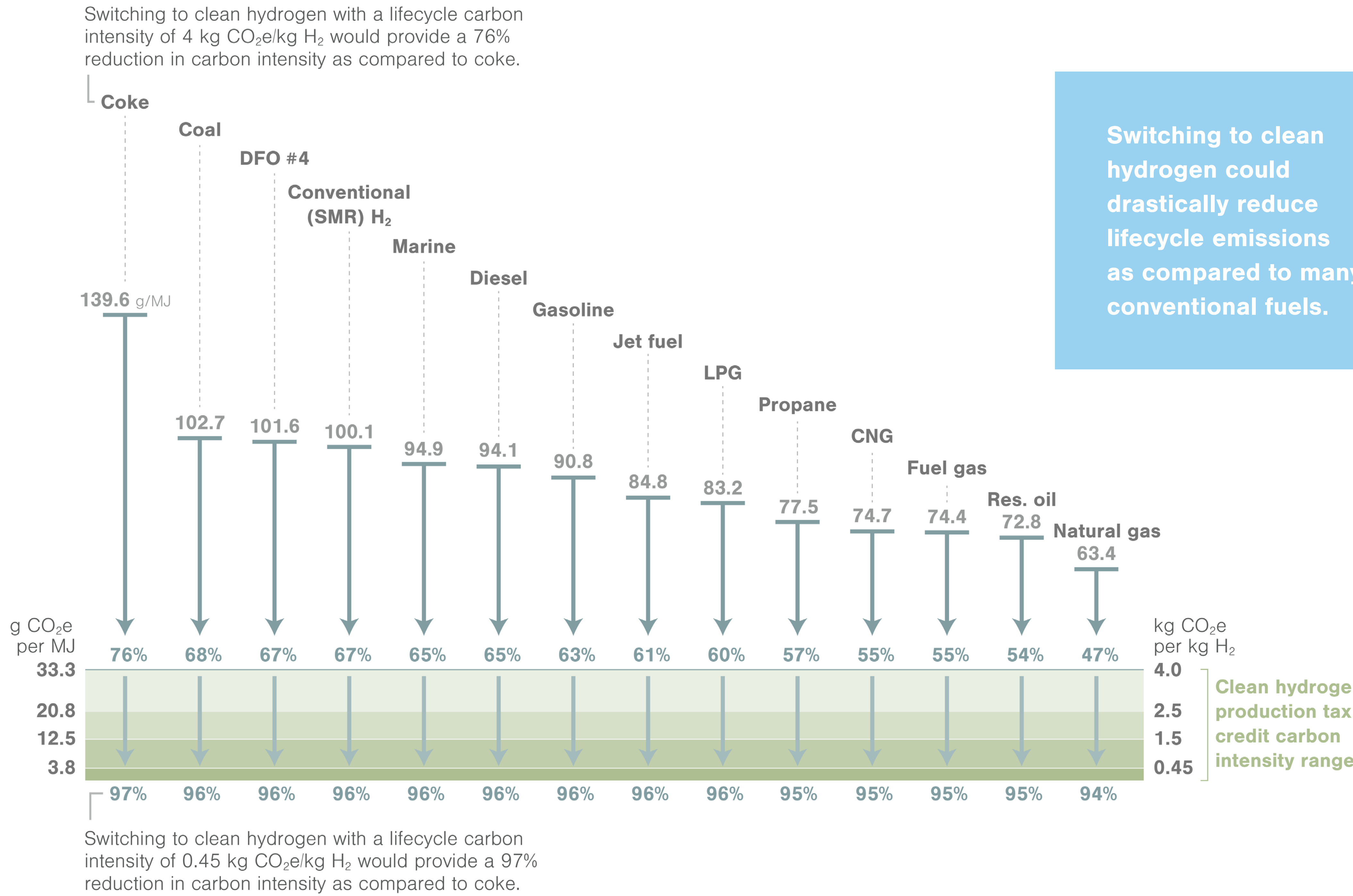
Comparing the lifecycle carbon intensities of common fuels

To fully understand the emissions reduction potential of displacing conventional fossil fuels with hydrogen, it is important to examine the full lifecycle emissions associated with the production and combustion of each fuel.

While hydrogen produces zero combustion emissions regardless of how it is produced, its lifecycle carbon intensity varies widely depending on its production method. As shown on the chart at right, hydrogen produced via conventional SMR has a lifecycle carbon intensity of 100.1 g per MJ. In contrast, the clean hydrogen PTC sets carbon intensity limits ranging from 33.3 down to 3.8 g per MJ.

Switching to clean hydrogen can provide drastic lifecycle emissions reductions for all of the common fuels shown at right, with emissions reductions increasing if a fuel is replaced with clean hydrogen aligning with the most stringent PTC tiers. For example, coal coke has an emissions intensity of 139.6 g per MJ. Switching from coke to clean hydrogen with a lifecycle carbon intensity of 4.0 kg CO_2e per kg H_2 (PTC tier 1) would reduce emissions by 76 percent. Switching to clean hydrogen with a lifecycle carbon intensity of 0.45 kg CO_2e per kg H_2 (PTC tier 4) would reduce emissions by 97 percent.

Lifecycle emissions intensity reduction from switching to clean hydrogen



Switching to clean hydrogen could drastically reduce lifecycle emissions as compared to many conventional fuels.

Figure authored by Elizabeth Abramson, Daniel Rodriguez, and Dane McFarlane (2023) based on GREET Model (ANL, 2022); CA-GREET3.0 (California Air Resources Board, August 2018); Wu et al. (May 2018).[151] Note: fossil fuel lifecycle carbon intensity values represent general averages taken from the GREET lifecycle model for illustrative purposes. The low heating value for hydrogen of 1 kg H_2 = 120 MJ was used to calculate emissions per megajoule. Actual fuel lifecycle carbon intensities depend on the specific feedstock and production pathways used. CNG: compressed natural gas; LPG: liquefied petroleum gases; Res. oil: residual fuel oil; DFO: distillate fuel oil.

Reducing industrial emissions with clean hydrogen

Emissions in the industrial sector

The industrial sector is responsible for many goods that sustain everyday life, from buildings and bridges to detergents and fertilizers. **Today, 24 percent of US greenhouse gas emissions are a direct result of industrial processes.**[153]

Direct emissions are a result of activity occurring at an industrial facility. Around three-quarters of direct emissions originate from the combustion of fossil fuels for heat or power ("stationary combustion"), with the remaining quarter released during the chemical or physical transformation of raw materials into a finished product ("process emissions"). Industrial processes also require electricity, which contributes indirectly to total emissions from the sector. With electricity use included, industry is the highest-emitting sector of the US economy, and industrial energy demand is only anticipated to grow by midcentury.[154]

A diverse set of strategies will be required to meaningfully reduce industrial GHG emissions by midcentury given the variety and complexity of processes and emission sources across subsectors. Options for mitigating industrial sector emissions include electrification and energy efficiency measures, switching to clean fuels and feedstocks, and carbon management.

This graph shows industrial GHG emissions from the stationary combustion of fossil fuels and from process emissions. For example, process emissions are particularly high compared to stationary combustion in the cement industry due to the chemical reactions involved in manufacture of the final product. Carbon management will be crucial for sectors where a large portion of emissions results from the inherent chemical transformation of the product.

US industrial emissions by sector and type, 2022

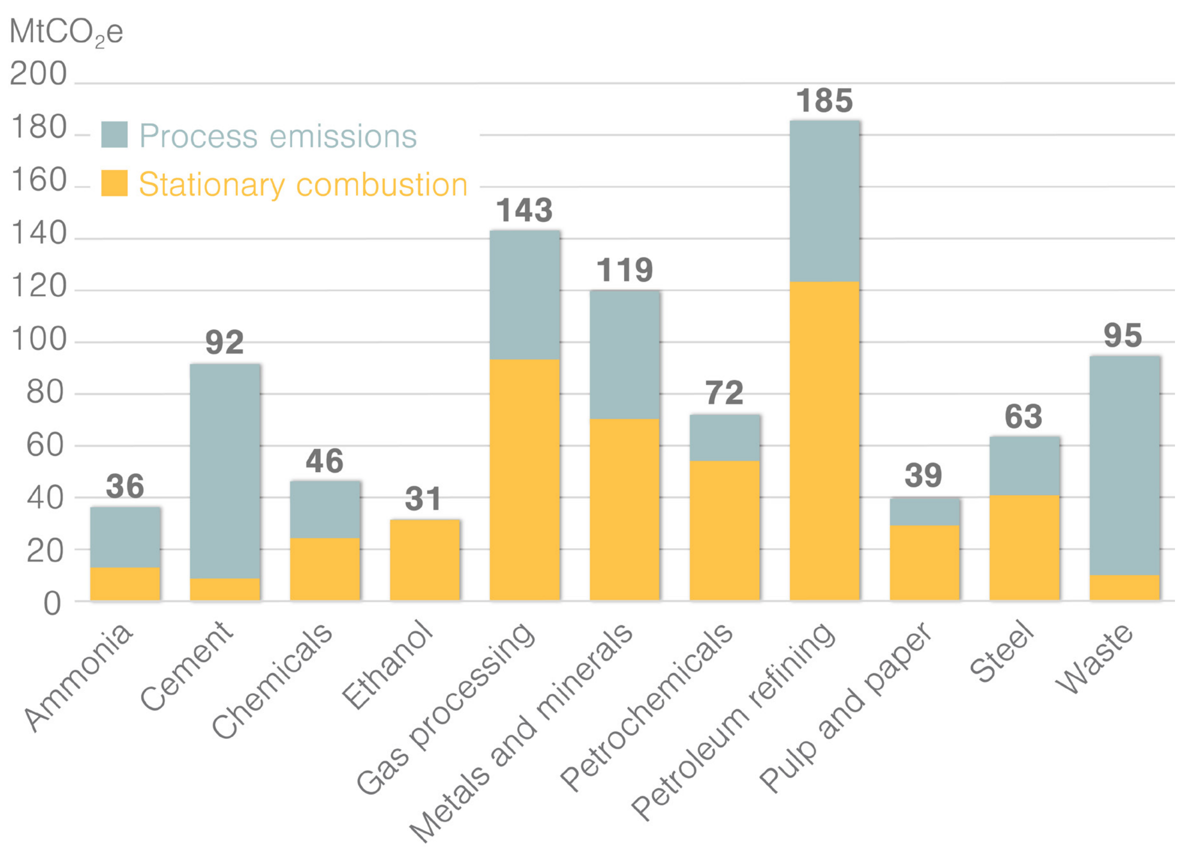


Figure authored by Elizabeth Abramson and Amy Jordan (2023) based on "2021 Data Summary Spreadsheets" (EPA, accessed March 2023).[152]

Hydrogen can reduce stationary combustion emissions when used as a fuel and can reduce process emissions by acting as a chemical or material feedstock in sectors like ammonia, steelmaking, petroleum refining, and petrochemicals or chemicals.

Hydrogen can reduce stationary combustion or process emissions when used as a fuel or feedstock in certain industrial processes.

Reducing industrial emissions with clean hydrogen

Types of fossil fuel consumption in the industrial sector

Top sources of fossil fuel combustion in the US industrial sector include petroleum refining, gas processing, metals and steelmaking, ammonia production, ethanol production, and chemicals manufacturing. The bar chart at right summarizes the top fuels used by the industrial sector.

Natural gas is the predominant fuel used in most industrial subsectors. With a lifecycle carbon intensity of 63.4 g CO_2e per MJ energy produced, natural gas has long been considered a relatively clean fuel compared to coal, diesel, and many other common fuels. Clean hydrogen with a lifecycle carbon intensity aligning with the clean hydrogen PTC thresholds provides a 47 to 94 percent reduction in emissions relative to natural gas for the same amount of energy production. Hydrogen can also produce the high temperature heat required for many industrial processes.

Fuel gas, which is used extensively in petroleum refining and petrochemical production, is a byproduct fuel with combustion and lifecycle carbon emissions factors slightly greater than those of natural gas. Switching from fuel gas to clean hydrogen would result in a 55 to 95 percent reduction in GHG emissions across the four clean hydrogen PTC tiers.

The pulp and paper industry makes heavy use of byproduct wood and wood residuals as fuels, which are unlikely to be replaced by hydrogen.

Electrification is an important strategy for low-temperature heat processes at industrial facilities that burn fossil fuels in equipment such as boilers and process heaters. **Where industrial processes require high-temperature heat, electrification is more difficult and costly to achieve. In these situations, switching from traditional fossil fuels to low-carbon fuels such as clean hydrogen is more feasible for decarbonization.**

US industrial fuel use by sector and fuel, 2021

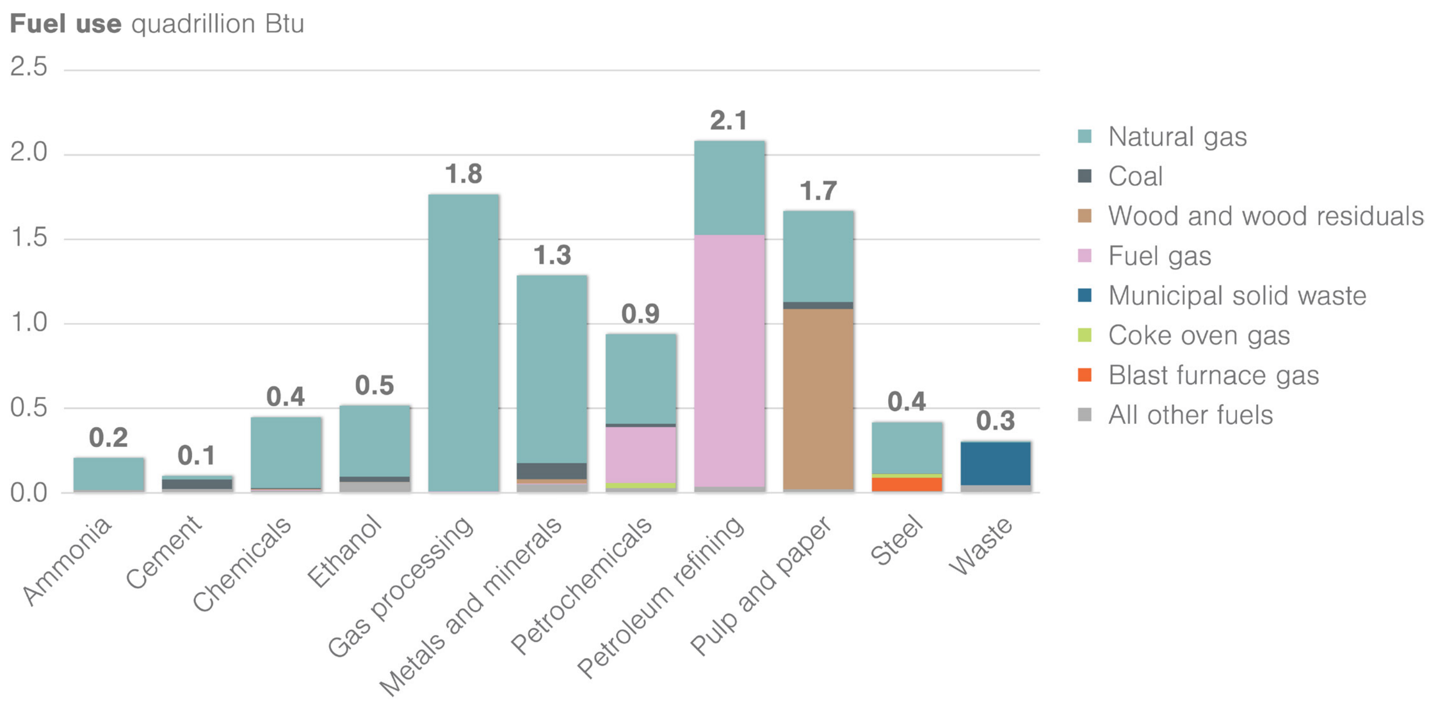


Figure authored by Elizabeth Abramson and Amy Jordan (2023) based on "Greenhouse Gas Model" (EPA, accessed February 2023); "Emissions by Unit and Fuel Type" (EPA, accessed November 2022; "Industry Energy Data Book" (NREL, accessed January 2023).[155]

Hydrogen can provide an alternative to electrification in industrial processes requiring high-temperature heat.

Reducing industrial emissions with clean hydrogen

Displacing fossil fuel consumption in the industrial sector

Process heat is the largest driver of energy consumption within the US industrial sector, with fossil fuel combustion accounting for over 90 percent of the energy consumed.[156] In 2021, industrial users consumed 9.7 quadrillion Btu of fuel, with the majority of that coming from natural gas.[157] Using a typical energy content for hydrogen of 120 MJ per kg, an equivalent amount of energy to this total fuel use could be produced by combusting 85 million metric tons of hydrogen.

Clean hydrogen's low lifecycle carbon intensity can reduce GHGs when used as a source of heat and power to displace fossil fuels. New use of hydrogen combustion for process heat would likely be most effectively applied to units and processes that require large volumes of high temperature heat, such as those used in petroleum refining, steelmaking, and chemicals production.

US industrial fuel use by sector

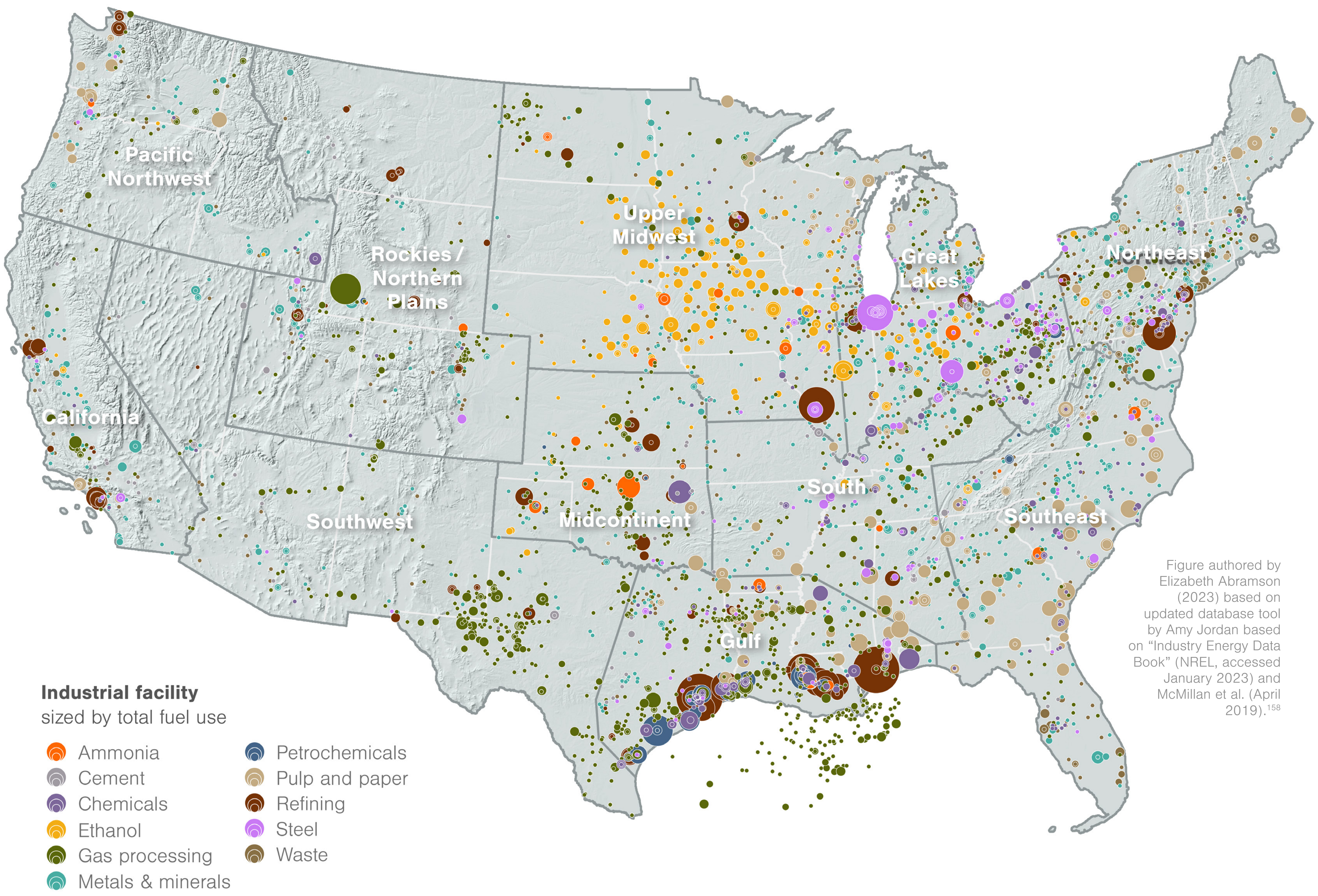


Figure authored by Elizabeth Abramson (2023) based on updated database tool by Amy Jordan based on "Industry Energy Data Book" (NREL, accessed January 2023) and McMillan et al. (April 2019).[158]

Reducing transportation emissions with clean hydrogen

Trends in transportation fuel consumption

Transportation accounts for 27 percent of direct US greenhouse gas emissions and is where most petroleum fuels are consumed within the US economy today.[159] Light-duty vehicles are responsible for more than half of the sector's emissions, with the remaining emissions attributed to medium- and heavy-duty vehicles, aviation, and a small percentage to pipelines, maritime transport, and rail.[160]

Emissions from transportation are decentralized and difficult to capture. In addition to GHG emissions, vehicles emit other pollutants that can impact human health, including particulate matter, VOCs, benzene, formaldehyde, carbon monoxide, and NOx.[161]

Decarbonizing transportation

Decarbonization of the transportation sector will depend on multiple strategies in each subsector. While many passenger light-duty vehicles are expected to be replaced by battery electric vehicles in the coming decades, hydrogen-powered vehicle technologies have several advantages for decarbonizing long-range transportation (e.g., trucking) and applications in other sectors that cannot easily be refueled on their commercial routes (e.g., marine shipping and aviation).

As described previously, decarbonization options for the transportation sector include FCEVs, fuel-switching with drop-in fuels, or directly using hydrogen in specialized internal combustion engines. Burning hydrogen directly produces NOx emissions, but none of the other pollutants listed above. Options for NOx reduction strategies for hydrogen combustion are discussed in detail later in this chapter.

Hydrogen leakage is another concern for transportation and other applications.[162] Although hydrogen is neither toxic nor a GHG by itself, it has indirect global warming potential due to its effect on atmospheric concentrations of methane.[163]

US transportation-related emissions by mode of transport, 2019

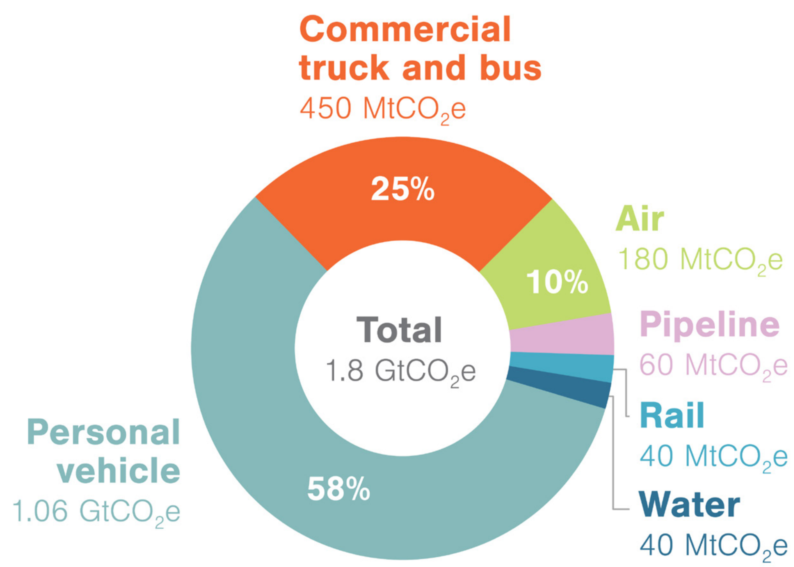


Figure authored by Elizabeth Abramson (2023) based on "Emissions of Carbon Dioxide in the Transportation Sector" (Congressional Budget Office, December 2022).[164]

The cost-driven projections of demand for hydrogen use in industry, transportation, and the electric sector provided by DOE's *National Clean Hydrogen Strategy and Roadmap* help estimate the emissions displacement potential of clean hydrogen.[165] In industry, existing and emerging hydrogen demands are found in feedstocks as well as fuels. The emissions avoided by using clean hydrogen depend on the fuel or feedstock displaced and the assumed heating or energy value of hydrogen.

The graph at right summarizes sector-by-sector estimates of emissions reduction potential enabled by transitioning from a conventional fuel source to clean hydrogen at the four PTC carbon intensity tiers.

The DOE estimates that in 2050 the ammonia industry could generate demand for around 5 Mt of hydrogen per year for fertilizer and other chemicals. Using clean hydrogen instead of conventional hydrogen to meet this demand could result in an emissions reduction of 40 to 57.8 $MtCO_2e$ per year.

Likewise, the DOE estimates that using hydrogen for 10 to 20 percent of steelmaking by 2050 could consume around 3 Mt of hydrogen per year. This could avoid up to 34.7 Mt $MtCO_2e$ per year if clean hydrogen is used instead of conventional hydrogen.

The DOE projects that the use of hydrogen to replace or blend with natural gas in existing high-grade industrial heat applications could use 3 Mt of hydrogen annually by 2050. With a lifecycle carbon intensity reduction from 63.4 g CO_2e per MJ to between 3.8 and 33.3 g CO_2e per MJ across the four clean hydrogen PTC tiers, blending or replacement of natural gas could avoid 10.8 to 21.5 $MtCO_2e$ in emissions per year.

The DOE *Roadmap* anticipates up to 8 Mt of hydrogen demand per year for medium- and heavy-duty vehicles, 6 Mt per year each for biofuels and PtL fuels, and 3 Mt for synthetic methanol. Emissions reductions are calculated assuming the displacement of diesel (94.1 g CO_2e per MJ) for the same energy content of clean hydrogen. Although these fuels generate CO_2 emissions, the emissions are either considered biogenic (in the case of biofuels) or are carbon-neutral due to the use of captured CO_2 in the production of the fuel (in the case of PtL fuels). Where fuel cell vehicles are used for medium and heavy-duty transport, there are no GHG emissions except for the lifecycle emissions from the production of clean hydrogen.

In total, using clean hydrogen to meet the DOE's projected 2050 hydrogen demand across all sectors shown at right could result in between 245 and 366 $MtCO_2e$ in avoided emissions through the displacement of conventional hydrogen, diesel, and natural gas. Additional emissions reductions could be achieved through hydrogen's contributions in energy storage and other applications.

High-level estimates of emission reduction potential from clean H_2

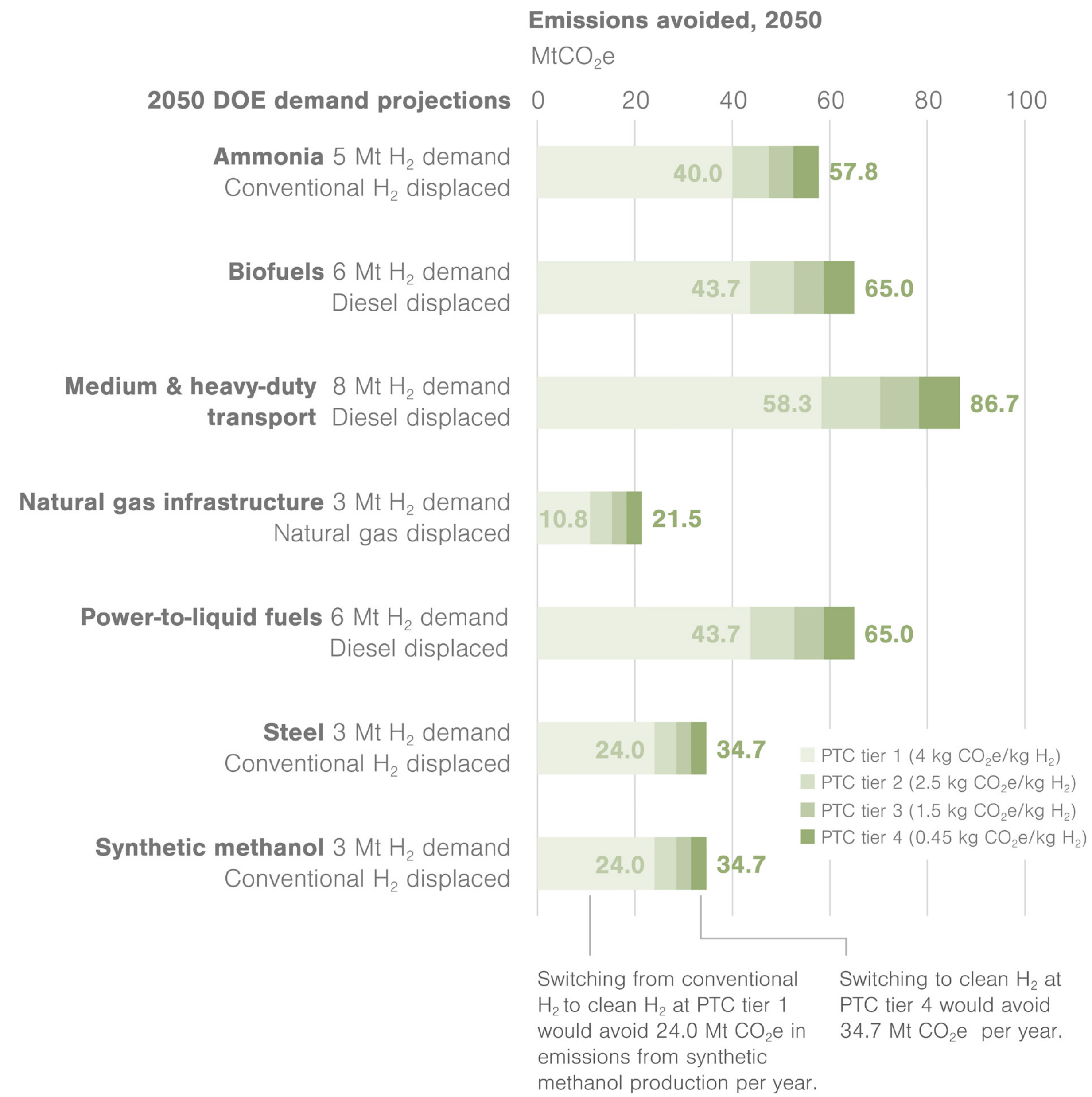


Figure authored by Elizabeth Abramson and Amy Jordan (2023) based on *Clean Hydrogen Roadmap* (DOE September 2022); *The Hydrogen Economy* (National Academies of Sciences, Engineering, and Medicine, 2004); "H2 Tools" (Pacific Northwest National Laboratory, accessed March 2023); Lewis et al., (April 2022).[166]

Air quality considerations and opportunities

Introduction to criteria pollutants

A variety of pollutants can impact air quality and public health, including a group of chemicals known as criteria air pollutants. Referred to in this report simply as criteria pollutants, these include six chemicals: nitrogen dioxide (NO_2), a component of nitrogen oxides (NOx); particulate matter (PM); sulfur dioxide (SO_2), a component of sulfur oxides (SOx); ground-level ozone (O_3); carbon monoxide (CO); and lead. As stated in the Clean Air Act, these pollutants negatively impact public health and the environment.

Most anthropogenic emissions of SO_2, NO_2, and PM are the product of fossil fuel combustion.[167] SO_2 is a respiratory irritant that is produced when sulfur or sulfur-containing compounds, such as coal, are combusted.[168] NO_2, another respiratory irritant, is generally formed when fuels are burned at high temperatures, leading to a reaction of oxygen and atmospheric nitrogen. Chronic exposure to NO_2 and other nitrogen oxides may contribute to the development of respiratory disease and increase susceptibility to respiratory infection.[169] PM is composed of a wide range of chemicals, including those made from NOx and SOx. The many components of PM can be products of incomplete combustion (e.g., black carbon or soot), nitrate and sulfates produced from NOx and SOx, or they can have natural sources (e.g., pollens, mold spores, oceanic aerosols, dust, etc.).[170] Particulate matter smaller than 10 microns, referred to as PM_{10}, has particularly harmful health effects. PM_{10} is an irritant to mucus membranes in the body and can cause increased risk of fatal cardiovascular disease, respiratory disease, and lung cancer.[171] The remaining criteria pollutants include CO (a byproduct of carbonaceous fuel combustion), lead (a byproduct of leaded fuels or metal and ore processing), and O_3 (a secondary pollutant that forms in the atmosphere). These three criteria pollutants have likewise been shown to cause negative impacts to neurologic, respiratory and pulmonary, and cardiac health.[172]

Emissions of criteria pollutants are a major concern for the transportation, power, and industrial sectors. **Adoption of hydrogen and other decarbonization strategies can mitigate most criteria pollutant emissions.** Many criteria pollutants, such as CO and PM, cannot form without carbon-based fuels.[173] Other criteria pollutants, such as SO_2 and lead, cannot form without fuel impurities or additives, such as elemental sulfur in coal or leaded vehicle fuels.[174] However, while hydrogen combustion does not directly produce any criteria pollutants, the high temperature of the resulting flame can lead to NOx formation upon contact with nitrogen in the air. **Specialized equipment configurations and pollution control devices can mitigate NOx emissions from hydrogen combustion.**

Criteria pollutant emissions from combusting common fuels, by combustion unit type

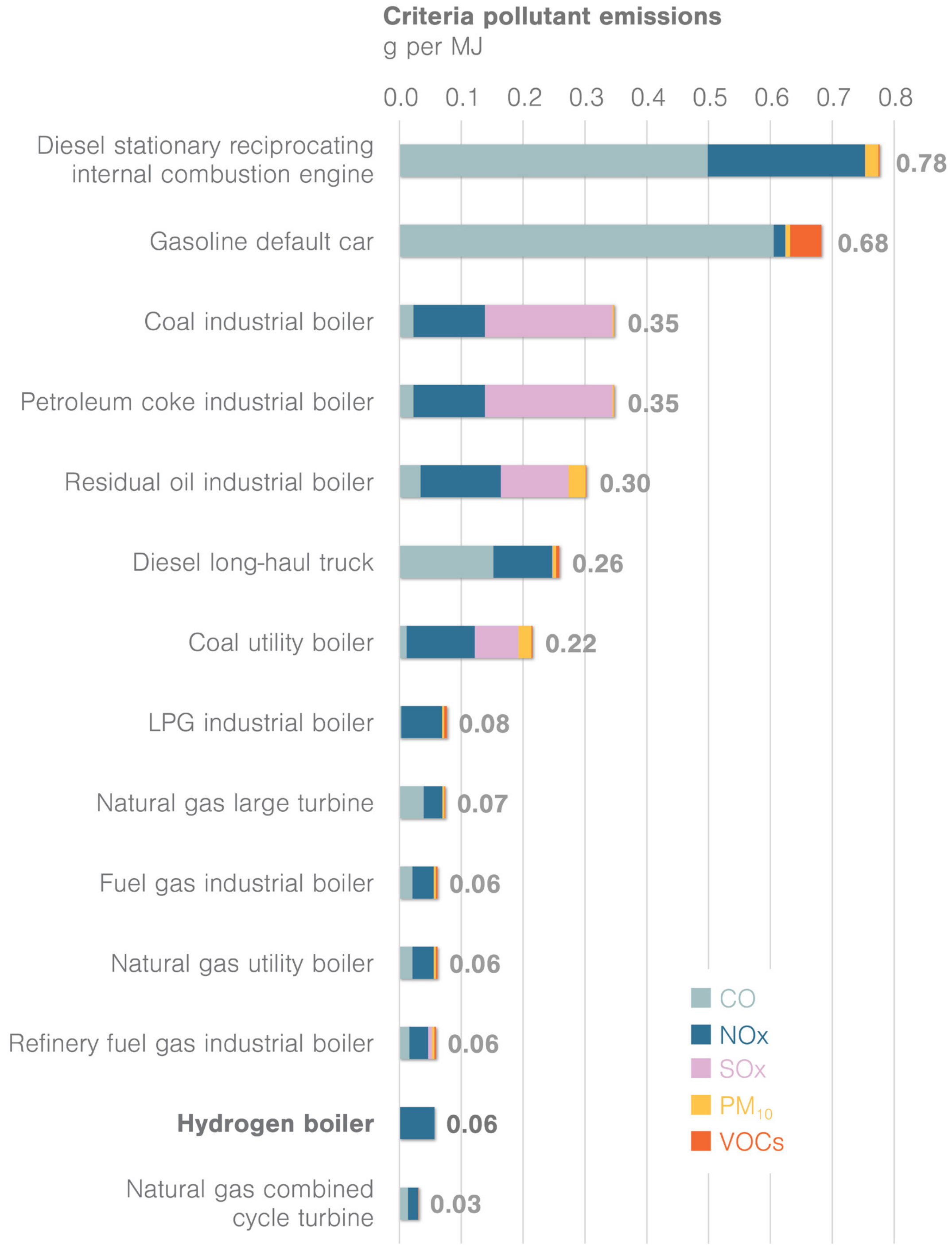


Figure authored by Elizabeth Abramson, Amy Jordan, and Daniel Rodriguez (2023) based on GREET Model (ANL, 2022).[175]

Air quality considerations and opportunities

Reducing NOx emissions from hydrogen

NOx refers collectively to NO and NO_2, two of the most common nitrogen oxides. These pollutants can form when high flame temperatures from hydrogen combustion split apart atmospheric nitrogen (N_2) in ambient air. NOx emissions from hydrogen vary widely depending on the temperature and combustion configuration. NOx emissions from a hydrogen boiler average 0.06 g per MJ.[176]

While combustion equipment is often designed to maximize the thermal energy and temperature from a given fuel, including hydrogen, adjustments can be made to spread the combustion zone within a heating vessel to reduce flame intensity. Methods for lowering the combustion flame temperature include pre-combusting hydrogen before the main combustion chamber, extending the flame length by preventing fuel and air mixing within the chamber, and lowering the oxygen content within the chamber.[177] Alternatively, **hydrogen can be fired in a pure oxygen environment (so-called "oxy-fuel" combustion), which completely eliminates all NOx emissions,** as there is no nitrogen gas within the combustion chamber. **Hydrogen fuel cells, which do not use combustion at all, do not produce NOx or other criteria pollutants.**

NOx produced from combustion of hydrogen gas can also be reduced by the installation of pollution control equipment. Robust pollution control equipment is already used at many industrial and power facilities. These technologies include selective catalytic reduction, non-selective catalytic reduction, and selective non-catalytic reduction equipment. Each of these splits NOx into its constituent parts, resulting in nitrogen gas (N_2) and oxygen gas (O_2), the two most common gases in our atmosphere, and releases them harmlessly. Economic, chemical, and engineering factors determine the most effective pollution control technology for a given facility.

Blending clean hydrogen with natural gas to produce high-grade process heat can reduce the carbon intensity of fuel combustion and processes at industrial facilities with minimal equipment modifications. However, hydrogen blending at certain percentages can lead to the formation of more NOx than combusting natural gas or hydrogen alone. There are complex effects of certain combustion conditions that determine the blends of hydrogen and natural gas that lead to the greatest NOx formation. Under some conditions (preheating to 585°C, low oxygen content), NOx formation is highest for natural gas blends with low concentrations of hydrogen (10 to 30 percent).[178] Under other conditions (no preheating, low oxygen content), the greatest NOx formation occurs at around 70 percent hydrogen blend, although the total NOx produced is less than half of the scenario with preheating.[179] A low-NOx scenario for natural gas blending must be ensured to reduce criteria pollution relative to conventional fossil fuel combustion.

Air quality considerations and opportunities

Air quality benefits of hydrogen

Air quality is an important determinant of human health, with excess air pollution leading to increases in emergency medical intervention needed in affected communities.[180] **Many polluting facilities are located within or near federally designated disadvantaged communities.**[181] **These communities often face multiple intersecting social, economic, and environmental burdens.** Additionally, criteria pollutant emissions from transportation vehicles burden areas with higher densities of population and traffic.

While there is some formation of NOx from hydrogen combustion (which can be mitigated using pollution control equipment), there are essentially no emissions of other criteria pollutants and hazardous air pollutant species. **The reduction in pollutants from fossil fuel displacement by hydrogen can improve public health** and result in positive economic opportunities associated with improved health outcomes in disadvantaged communities and for the general population.

A number of strategies can be used to ensure that the establishment of hydrogen hubs will lead to improved air quality for local communities. When clean hydrogen is generated using electrolysis paired with renewable energy, criteria pollutants are substantially reduced by avoiding fossil fuel consumption (compared to production of hydrogen by SMR), and emissions are also avoided by using renewable energy rather than fossil fuels for electricity generation. If SMR with carbon capture is used to produce hydrogen in a hub, criteria pollutant reduction may occur as a co-benefit of carbon capture system pretreatment of flue gases before CO_2 removal.[182] This pretreatment will remove the majority of pollutants from the flue gases, notably criteria air pollutant species such as NO_2 and SO_2.

When NOx-reducing strategies are employed at the site of hydrogen consumption, the air quality benefits continue to accrue. These strategies include the use of non-polluting fuel cell technology, pollution controls to capture NOx from hydrogen boilers in industrial settings, optimized combustion configurations to drive NOx emissions below those of fossil fuels per amount of energy produced, as well as monitoring and adjustment of the percentages of hydrogen used when blended with traditional fuels in high heat applications.

The Landscape of Clean Hydrogen | Section 6

Regional Opportunity Summaries

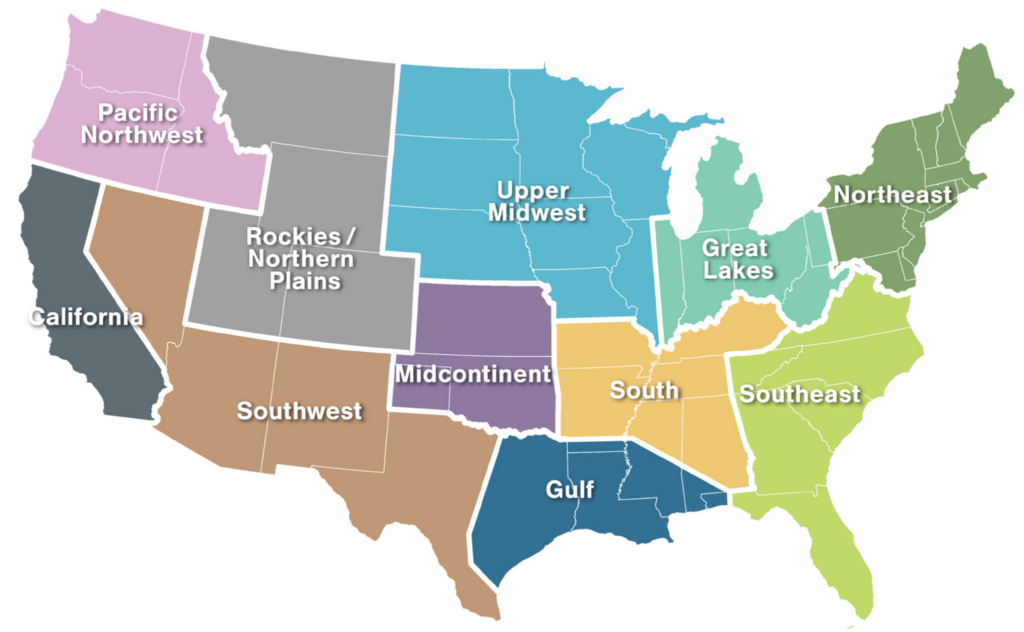
Regional opportunities for clean hydrogen hubs

The regional clean hydrogen landscape

This section highlights opportunities to jumpstart the production and use of clean hydrogen across 11 US regions. Each region's industrial and energy profile presents unique advantages for clean hydrogen hub development. With widespread emissions reductions needed to meet national climate goals, every region can realize decarbonization benefits from clean hydrogen.

On the following pages, regional strengths in several key sectors are highlighted using the icons below, with icons sized to reflect the region's strength in a given sector within the national context.

- Ammonia & fertilizer
- Refining & petrochemicals
- Steel
- Natural gas & industrial fuel displacement
- Low-carbon electric grid, load balancing, & storage
- Renewable fuels
- Synthetic fuels
- Heavy-duty vehicles
- Carbon capture & storage



Emissions reductions are needed across the country to meet national climate goals. Every US region can realize decarbonization benefits from clean hydrogen.

Estimated dedicated hydrogen production, by region

Region	Merchant t H_2/year	Refineries t H_2/year	Chemicals t H_2/year	Ammonia t H_2/year	Electrolysis t H_2/year	Total t H_2/year
California	500k	1.7m	Less than 50k	-	Less than 50k	2.2m
Great Lakes	450k	200k	Less than 50k	100k	Less than 50k	800k
Gulf Coast	1.8m	1.9m	600k	1.4m	Less than 50k	5.75m
Midcontinent	Less than 50k	350k	Less than 50k	600k	-	950k
Northeast	Less than 50k	Less than 50k	Less than 50k	-	Less than 50k	100k
Pacific Northwest	Less than 50k	350k	Less than 50k	150k	Less than 50k	450k
Rockies	-	300k	Less than 50k	50k	Less than 50k	400k
South	Less than 50k	50k	Less than 50k	Less than 50k	Less than 50k	150k
Southeast	-	-	Less than 50k	250k	Less than 50k	300k
Southwest	-	Less than 50k	-	-	Less than 50k	Less than 50k
Upper Midwest	Less than 50k	650k	Less than 50k	600k	Less than 50k	1.3m

Source: Carbon Solutions analysis based on S&P Global Commodity Insights, *Directory of Chemical Producers*; Arjona (June 2022).[183] Note: production totals are rounded to the nearest 50,000. k: thousand. m: million.

Regional opportunities for clean hydrogen hubs

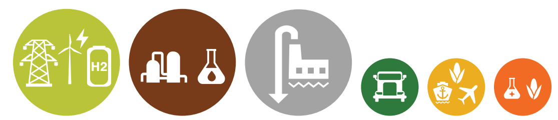
Gulf

Louisiana, Texas, Alabama, Mississippi, Arkansas

The Gulf's many hydrogen-producing facilities include 27 merchant plants, 33 refineries, and 10 ammonia plants. With an experienced workforce in related industries and a network of hydrogen pipelines connecting merchant plants to adjacent refineries and chemical plants, the Gulf is well-positioned to lead a national clean hydrogen transition.

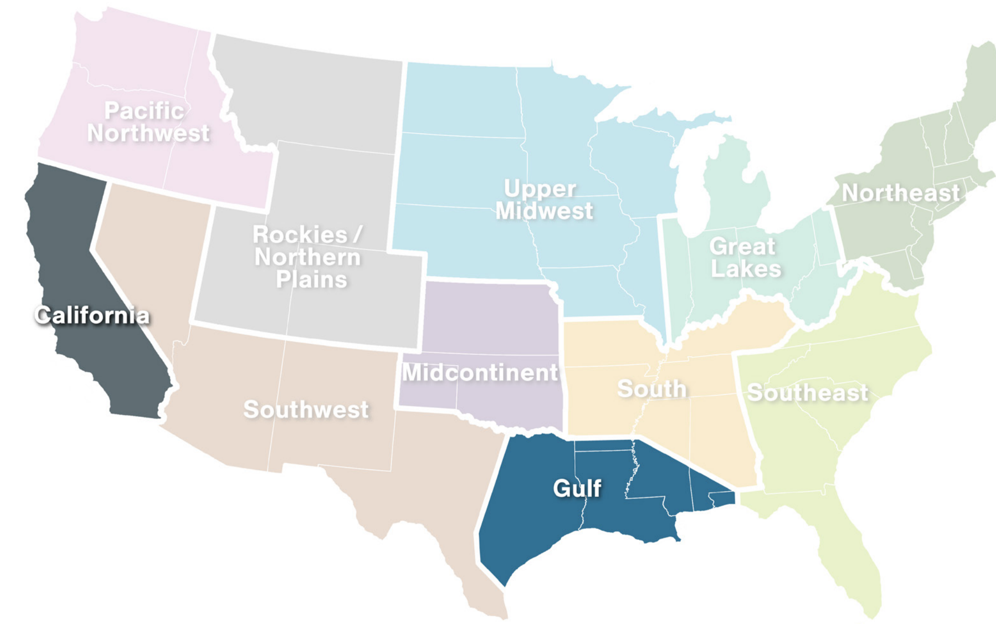
SMR-based hydrogen production coupled with carbon capture can use existing CO_2 transport and storage infrastructure along the Gulf Coast. The presence of heavy industry, particularly in Louisiana, makes hydrogen use for industrial heat, chemical production, and biofuel and synthetic fuel production likely applications for the medium term. Access to oceanic trade routes and the Mississippi River give the Gulf strategic access to domestic and international hydrogen-related markets. For example, iron ore imports shipped down the Mississippi River or from Brazil can be used in existing and future DRI plants for clean steel. The Gulf's natural gas supply can supplement clean hydrogen in DRI production. While natural gas is the leading regional energy source today, the Gulf has significant wind and solar resources that could be used to power electrolysis-based hydrogen production.

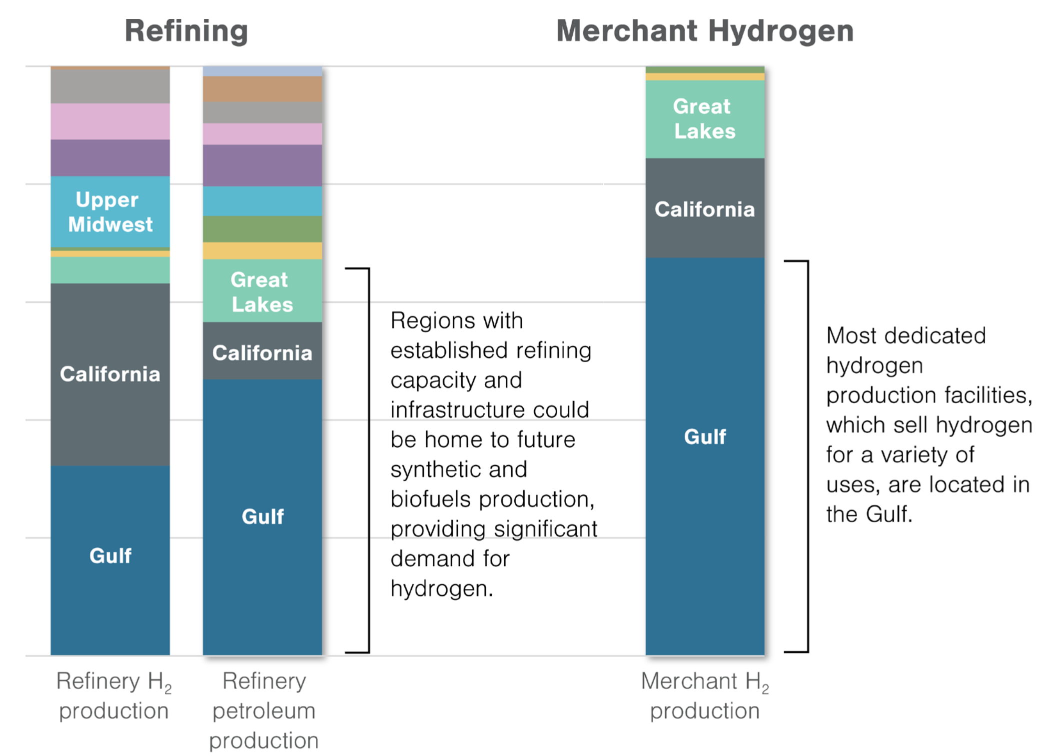
California



Most of California's hydrogen production is attributed to 11 refineries and five merchant hydrogen plants. The state's many refineries can engage in both the production and use of clean hydrogen. California has one of the highest renewable energy generation capacities in the US, meaning renewable-powered electrolysis holds great potential in the state. As a major national center for agricultural production, California could produce clean hydrogen-based ammonia for a large in-state market.

California is particularly well-positioned to expand the use of hydrogen in fueling, as all US hydrogen refueling stations are located in the state. California is already investing in research and development of transportation and refueling infrastructure for hydrogen fuel cell vehicles to help reach the state's carbon neutrality goals. Home to the country's largest port, California could utilize clean hydrogen-based marine fuels to decarbonize shipping off the Pacific Coast.

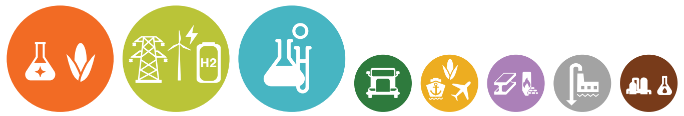




Regional opportunities for clean hydrogen hubs

Upper Midwest

North Dakota, South Dakota, Minnesota, Wisconsin, Iowa, Western Illinois

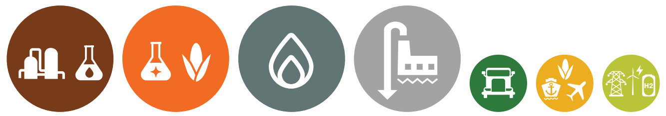


The Upper Midwest hosts 24 hydrogen-producing facilities, with most production attributed to seven ammonia plants and four refineries. The Upper Midwest plays a critical role in supplying ammonia-based fertilizers to support regional agricultural output, making ammonia production a major near-term market for clean hydrogen in the region.

The Upper Midwest's substantial wind power resources could be harnessed to produce hydrogen via electrolysis either with the installation of additional capacity or with existing generation that would otherwise be curtailed. Proximity to the nation's iron ore reserves and shipping lanes via the Mississippi River and Great Lakes also makes the region a leading contender for hydrogen-based steel production in the long term. In addition, abundant ethanol plants producing highly concentrated CO_2 streams have led to investment in CO_2 transport and storage projects, which could facilitate regional clean hydrogen production coupled with CCS. Captured CO_2 from ethanol plants could also be used in the production of synthetic fuels that rely on the pairing of carbon and hydrogen.

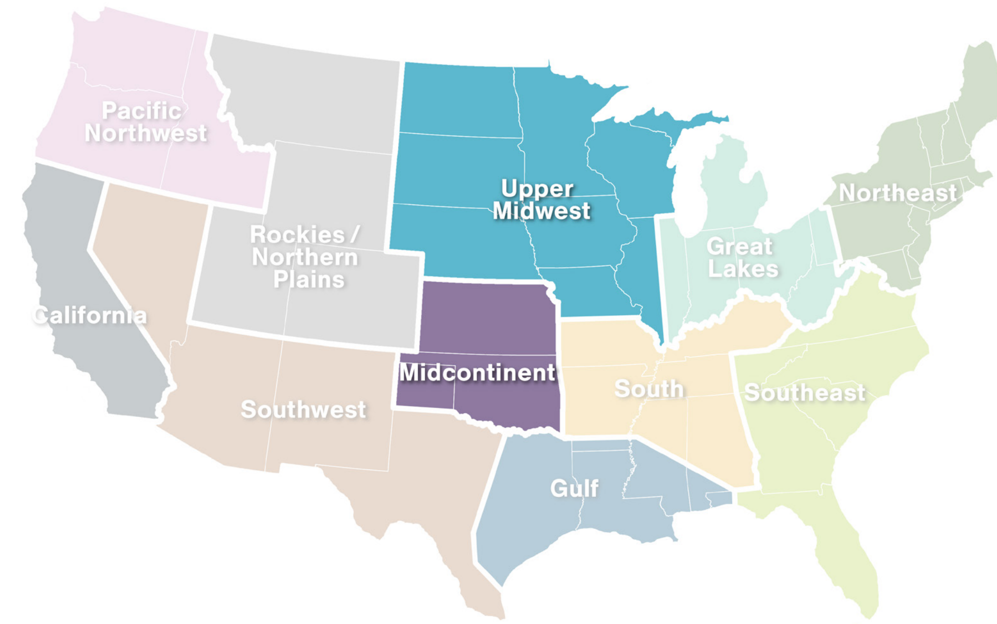
Midcontinent

Kansas, Oklahoma, Texas Panhandle

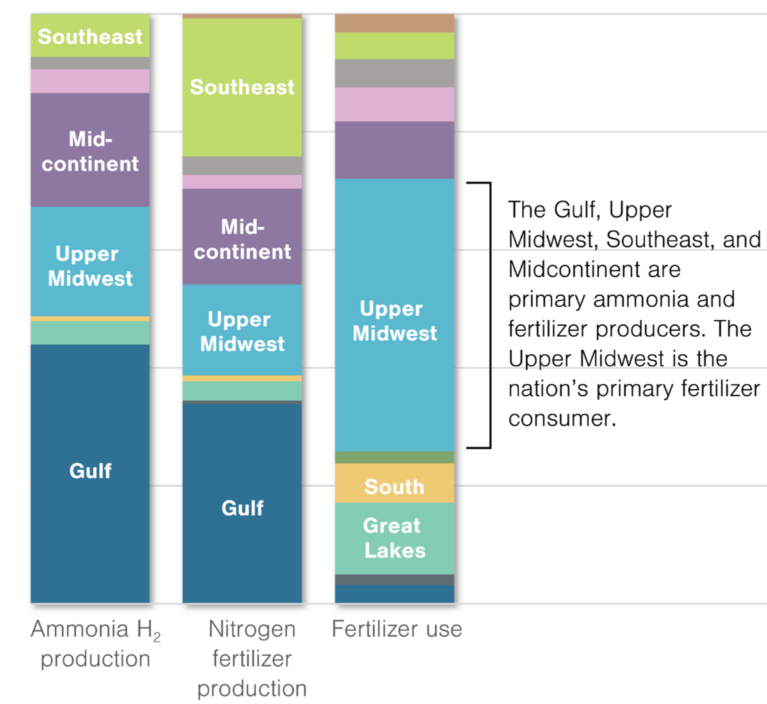


Seven refineries and five ammonia plants are responsible for the bulk of the Midcontinent region's hydrogen production. The region's sizable refining sector presents a near-term opportunity to both produce and use clean hydrogen. With access to agricultural markets spanning the Midcontinent, Upper Midwest, and Great Lakes, the Midcontinent is a major supplier and user of ammonia-based fertilizer, paving the way for the Midcontinent to lead the nation in clean hydrogen-based ammonia production.

The Midcontinent region also has some of the highest onshore wind energy potential in the US, complemented by significant solar energy. This abundance of renewable energy could be used to produce clean hydrogen through electrolysis. Additionally, the region is home to significant natural gas production, which, when paired with the Midcontinent's plentiful CO_2 storage potential, allows the opportunity for clean hydrogen production via SMR with carbon capture.



Ammonia & Fertilizer



Regional opportunities for clean hydrogen hubs

Great Lakes

Western Pennsylvania, Ohio, Michigan, Indiana, Eastern Illinois

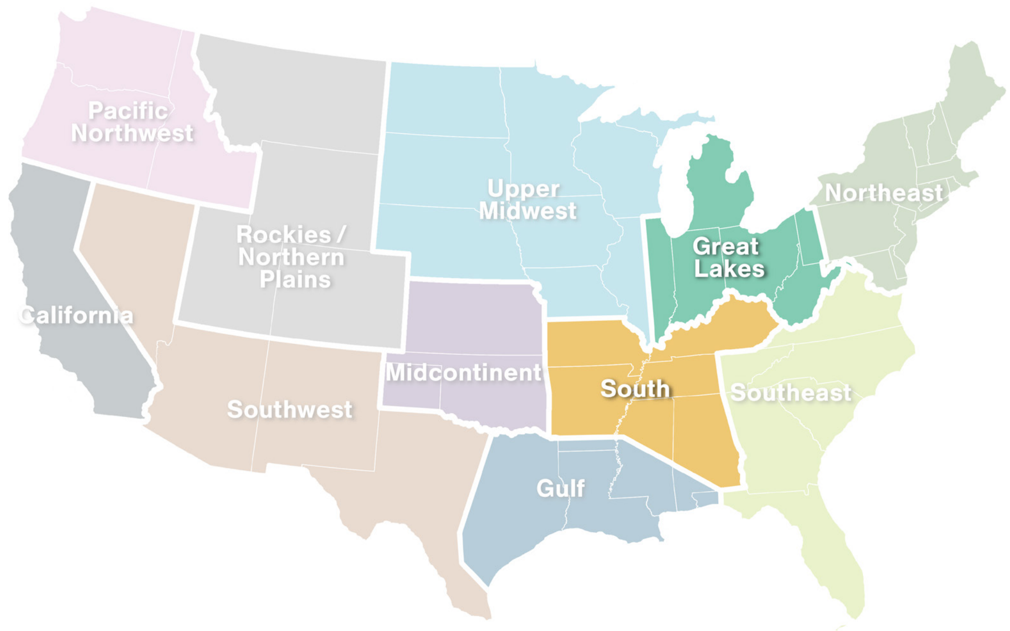
The Great Lakes region hosts nine merchant plants that produce the bulk of its hydrogen, supplemented by hydrogen from 10 refineries, 13 chemical plants, and seven ammonia plants. Historically, the region has produced the majority of US primary steel due to its proximity to iron ore reserves. The region has also benefited from access to coal in the Appalachian region, which is a main input for traditional steel production. This region contains two of the nation's four existing DRI facilities and could become a leading national market for DRI produced with clean hydrogen, enabling steel sector decarbonization. Regional natural gas reserves could be used to supplement clean hydrogen in the DRI production process. Natural gas could also be used to produce clean hydrogen via SMR coupled with carbon capture to provide a supply of clean hydrogen for steelmaking, utilizing the region's suitable CO_2 storage geology for local carbon storage.

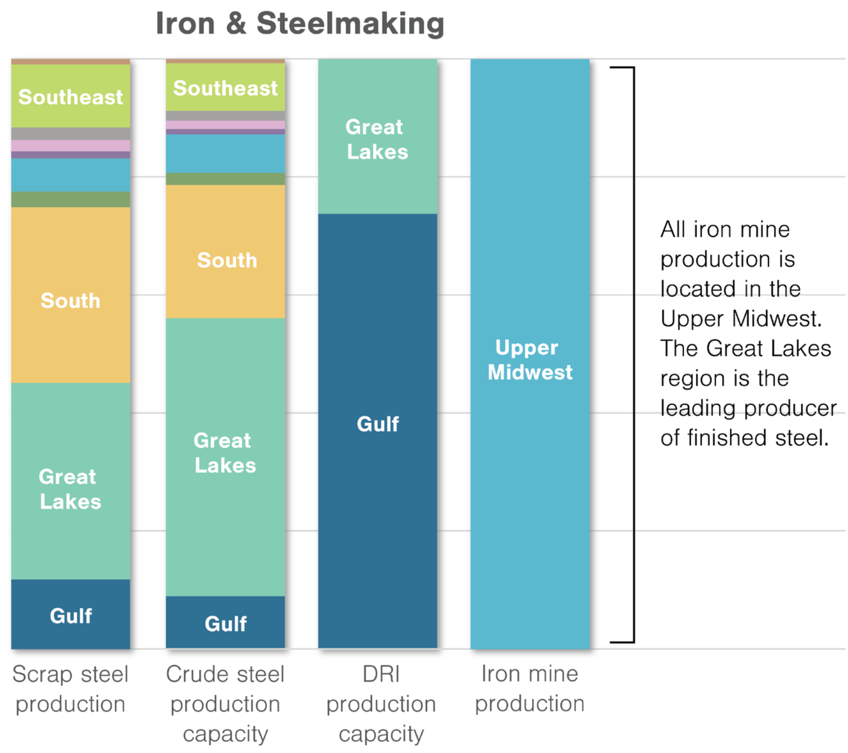
In the medium term, electrolysis could harness the region's nuclear power generation capacity. Low-cost CO_2 capture from the region's ethanol plants could also be used for carbon and hydrogen-based synthetic fuel production.

South

Kentucky, Mississippi, Alabama, Tennessee, Missouri

The South is home to hydrogen production at 12 chemical plants, four merchant plants, two refineries, and two ammonia plants. While much of the region's hydrogen opportunity space overlaps with the Southeast and Gulf Coast regions, the South does not have the same concentration of industrial facilities as its neighboring regions. Nonetheless, it could share some of the advantages of these regions with overlapping production, end users, and connective infrastructure. With several large electric arc steel production facilities, the South can provide an important market for iron made with clean hydrogen. The region's demand for high-grade heat in the industrial sector and low-carbon fuels in the transportation sector present additional markets for clean hydrogen application.





Regional opportunities for clean hydrogen hubs

Southeast

Georgia, North Carolina, South Carolina, Tennessee

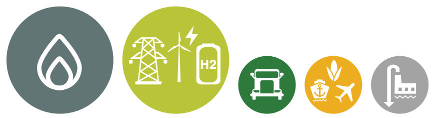
The Southeast primarily produces hydrogen at three ammonia plants, with most of that production attributed to one large ammonia plant in Georgia. This ammonia is used for the fertilizer that supports the area's agricultural output. Ammonia production represents a near-term market for clean hydrogen in the Southeast.

Electric arc steel production facilities across the Southeast can provide a market for iron made with clean hydrogen. The region also has some of the highest industrial heat use and annual miles traveled in the transport sector, representing substantial medium-term targets for clean hydrogen in fueling.

Although the region's electricity is largely generated by natural gas, the Southeast hosts several nuclear power plants and has substantial solar energy resources, which could be harnessed to produce hydrogen via electrolysis. With favorable geology for CO_2 storage, the Southeast could also support SMR-based hydrogen production coupled with carbon capture and local storage.

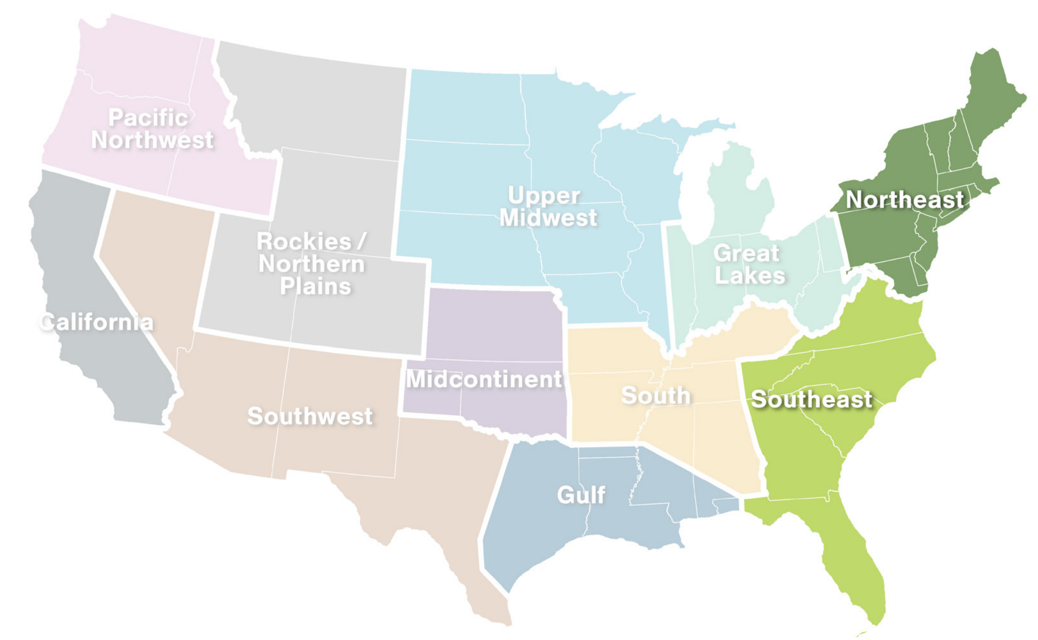
Northeast

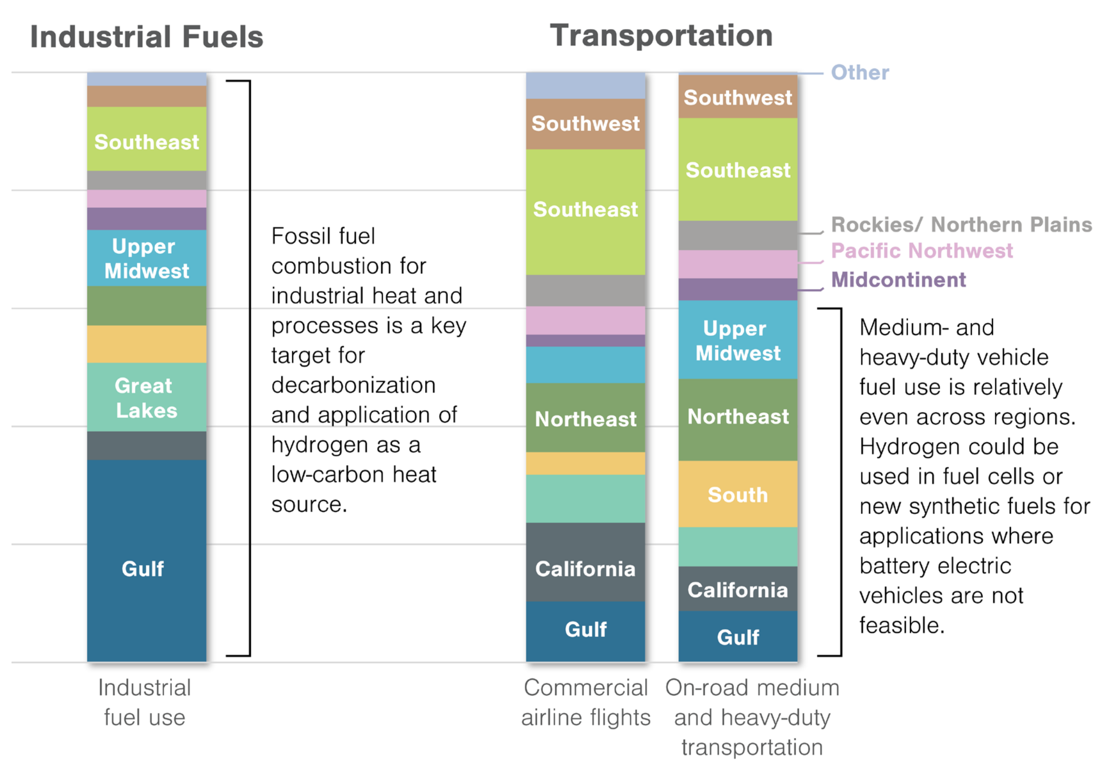
Pennsylvania, New York, New Jersey, Maryland



The Northeast hosts 20 hydrogen production facilities, with most of its hydrogen produced at one merchant plant and three refineries. With a large share of national medium- and heavy-duty vehicle traffic, particularly along heavily trafficked roads like Interstate 95, hydrogen-based fuels or FCEVs present important tools for decarbonization in the Northeast. Clean hydrogen can also provide emissions reductions as a source of high-temperature heat to displace fossil fuels in the region's numerous industrial facilities.

In addition, chemical plants along the region's industrial corridor could facilitate long-term production of novel chemicals and fuels using hydrogen as a feedstock. The Northeast is also host to a significant amount of nuclear energy as well as offshore wind potential that would enable clean hydrogen production via electrolysis. Offshore CO_2 storage capacity also presents potential local opportunity for clean hydrogen production via SMR paired with carbon capture.





Regional opportunities for clean hydrogen hubs

Rockies

Colorado, Utah, Idaho, Wyoming, Montana, Nebraska

The Rocky Mountain region can attribute much of its hydrogen production to nine refineries and two ammonia plants. Displacing existing hydrogen use in refining is a prime near-term opportunity for clean hydrogen in this region. Proximity to Midcontinent agriculture also provides a nearby market for clean ammonia produced in the region.

The Rockies may leverage existing regional fossil fuel infrastructure, including natural gas and CO_2 pipelines and geologic CO_2 storage capacity to support SMR-based clean hydrogen production. However, the region also has significant solar and wind capacity, particularly in its high deserts, making it a prime candidate for hydrogen produced through clean energy electrolysis. Medium- and heavy-duty transport in the region could also utilize clean hydrogen for low-carbon fueling.

Pacific Northwest

Washington, Oregon

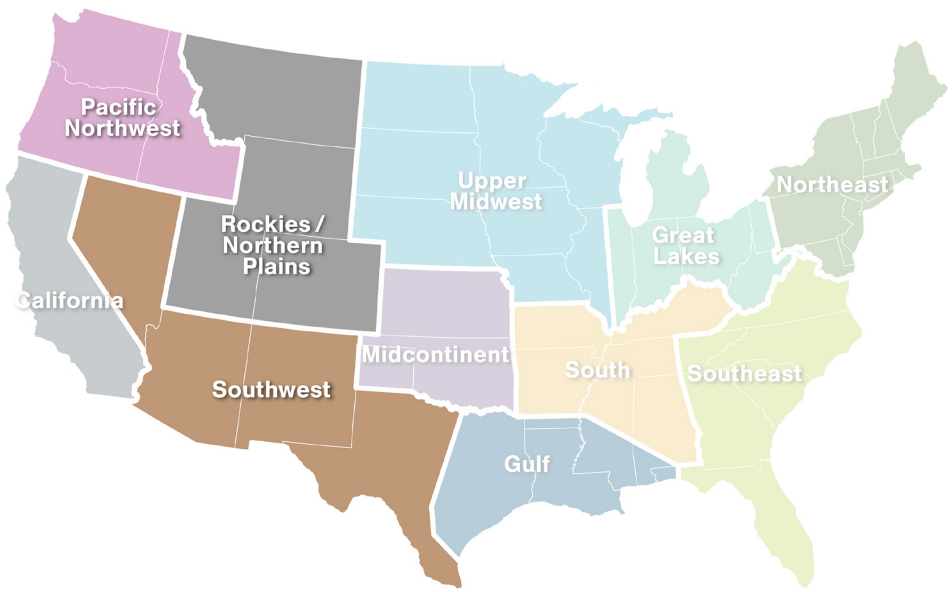
The Pacific Northwest hosts 10 hydrogen-producing facilities, with most hydrogen production occurring at two refineries and three ammonia plants. Displacing current uses in refining and ammonia represent near-term opportunities for clean hydrogen application in the region. With limited existing ammonia production in the region relative to rates of fertilizer use, there is opportunity to expand clean hydrogen-based ammonia production for the local agricultural market.

Clean hydrogen production could make use of the region's high geothermal or hydroelectric potential for electrolysis pathways. CO_2 sequestration and mineralization opportunities make SMR production paired with carbon capture a viable option for clean hydrogen production in this region as well. With somewhat limited existing hydrogen production and hydrogen-related industries, the Pacific Northwest may also focus on opportunities to explore more long-term uses of clean hydrogen such as synthetic fuels and sustainable aviation fuels.

Southwest

Arizona, New Mexico

The Southwest produces most of its hydrogen at a single refinery in New Mexico. With limited existing hydrogen production and use, the Southwest may have increased flexibility in exploring novel clean hydrogen applications. Hydrogen-based fuels could power regional freight transportation and supply low-carbon industrial heat. Abundant wind and solar resources make hydrogen energy storage for grid balancing another key opportunity. With favorable geology for CO_2 storage in the Permian Basin area, the Southwest could support hydrogen production paired with carbon capture. The Southwest may also engage with the hydrogen economy in neighboring regions as those markets evolve.



The Landscape of Clean Hydrogen | Section 7

Acronym Guide and Endnotes

Acronym Guide

ATR — Autothermal methane reforming
BECCS — Bioenergy with carbon capture and storage
BIL — Bipartisan Infrastructure Law
CCS — Carbon capture and storage
CO — Carbon oxide
CO_2 — Carbon dioxide
CO_2e — Carbon dioxide equivalent
DOE — US Department of Energy
DRI — Direct reduced iron
EIA — US Energy Information Agency
EPA — US Environmental Protection Agency
FCEV — Fuel cell electric vehicle
FHWA — Federal Highway Administration
FOA — Funding opportunity announcement
GHG — Greenhouse gas
H_2 — Hydrogen
IRA — Inflation Reduction Act
ITC — Investment tax credit
kW — Kilowatt
kWh — Kilowatt-hour
Mt — 1 million metric tons
MW — Megawatt
MWh — Megawatt-hour
NREL — National Renewable Energy Laboratory
OCED — Office of Clean Energy Demonstrations
PTC — Production tax credit
PtL — Power-to-liquid
ReEDS — NREL Regional Energy Deployment System model
SAF — Sustainable aviation fuel
SMR — Steam methane reforming
t — Metric ton
US — United States

Note: all mentions of tons in this document refer to metric tons.

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