An Overview of the Hydrogen Transition Framework Web Application

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Introduction and Overview

To assess the potential of clean hydrogen in the United States, the EFI Foundation developed a tool to profile the diverse array of potential energy resources, demand sources, political and economic interests, and human capabilities across the country. These distinct elements—ingredients with the potential to act as building blocks for regional hydrogen market formation—can be used by policymakers, private investors, and energy incumbents to evaluate regional opportunities to unlock clean hydrogen activities. Table 1 provides a complete list of those elements.

This document is an introduction and description of that tool. The Hydrogen Transition Framework (HyTF) web application is a public-facing interface for individuals seeking to understand the hydrogen hubs landscape in the United States. The tool combines data on several dozen crucial elements, grouped into five main categories: existing resources, enabling resources, interests, capabilities, and demand. The strength of an area's clean hydrogen market formation, relative to the rest of the country, is captured across these five categories. An area may not be strong in any of the categories or may be strong in all five, depending on its mixture of resources, interests, capabilities, and demand. If an area meets a certain threshold (defined in subsequent sections) for one or more of the categories, HyTF reflects that category's viability with a positive valuation of "Good," "Very Good," or "Excellent." An area with positive valuations across multiple categories indicates a high favorability for hydrogen market formation, especially if those categories crosscut physical capital (e.g., existing resources) and human capital (e.g., capabilities).

HyTF, built with more than two dozen data sets compiled from October 2021 to November 2022, comprises 11.1 thousand hexagonal areas of 400 square miles (m^2) each. Because of the unspecified dimensions or geographic scope of hydrogen hubs in the Bipartisan Infrastructure Law (BIL), hexagons reflect the approximate size of a large metropolitan city. A single hexagon on the map could constitute its own hub. However, hubs may develop on the scale of cities, states, or regions. As of April 2023, 26 hubs across the country have announced their intention to submit a hub application to the Department of Energy (DOE), varying from city-sized to multi-state endeavors. To remain flexible in the definition of "close proximity," as conveyed in DOE's Funding Opportunity Announcement (FOA) for hydrogen hubs, hexagons can be viewed in isolation or linked by adjacency or compatible elements, depending on a particular user's approach to hub development.[a,1] Notably, most publicly known hub applicants are developing their hubs at a regional level.[2]

HyTF aims to be as comprehensive as possible in identifying potential ingredients to be leveraged in hydrogen hubs without being prescriptive as to where hydrogen hubs *should* be located.

[a] Historically, industrial hubs are defined by close geographic proximity. They are usually neighbors operating in the same business zone, possibly sharing similar distribution lines, and ultimately are a centralized area of emitters. When DOE requested information for the H2Hubs FOA, they asked what is meant by "close-proximity," thinking that hubs are usually built within an area of a few dozen square miles. They resolved to remain flexible in their definition so that hubs could span many states.

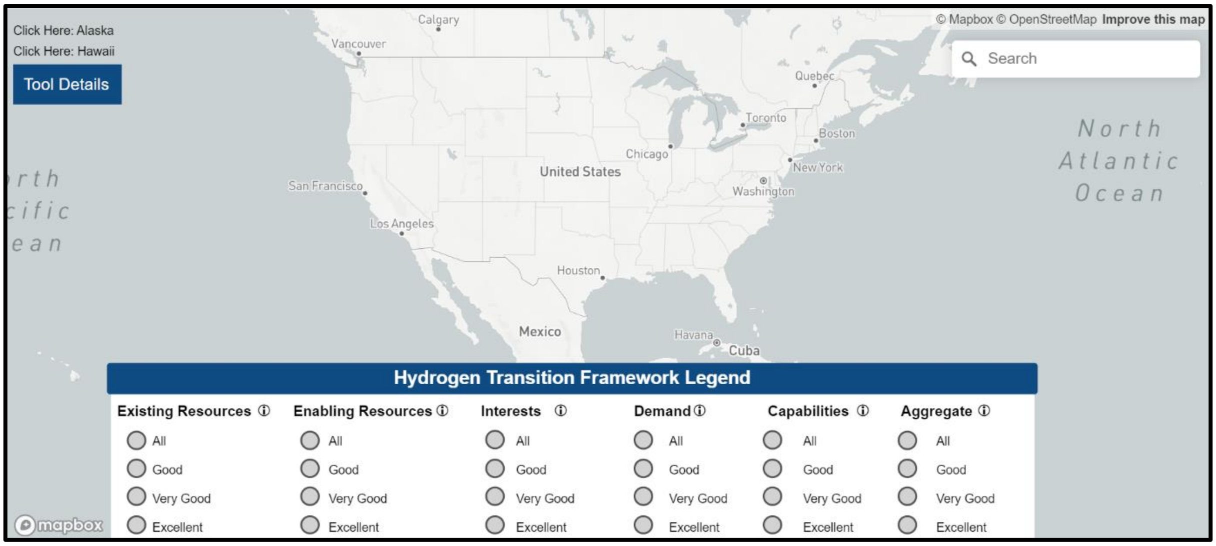
The tool is linked here: https://energyfuturesinitiative.org/map/hytf/

Interface

All relevant data are constrained to the 50 states and the District of Columbia. Links to Alaska and Hawaii are provided in the top left window of the tool for easy access. If nothing is clicked, HyTF should open to a blank map of the United States as shown in Figure 1. A few important features are discussed in more detail below.

Figure 1

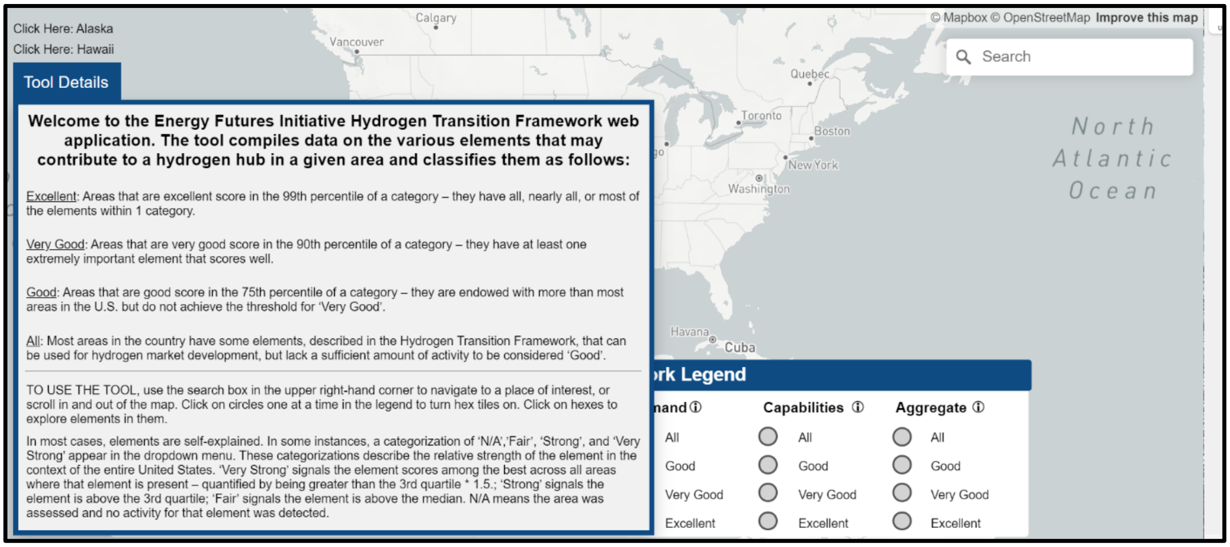
HyTF interface



Users should turn their attention to the Tool Details button in the upper left corner and click for more information about the functionality and purpose of the tool (Figure 2).

Figure 2

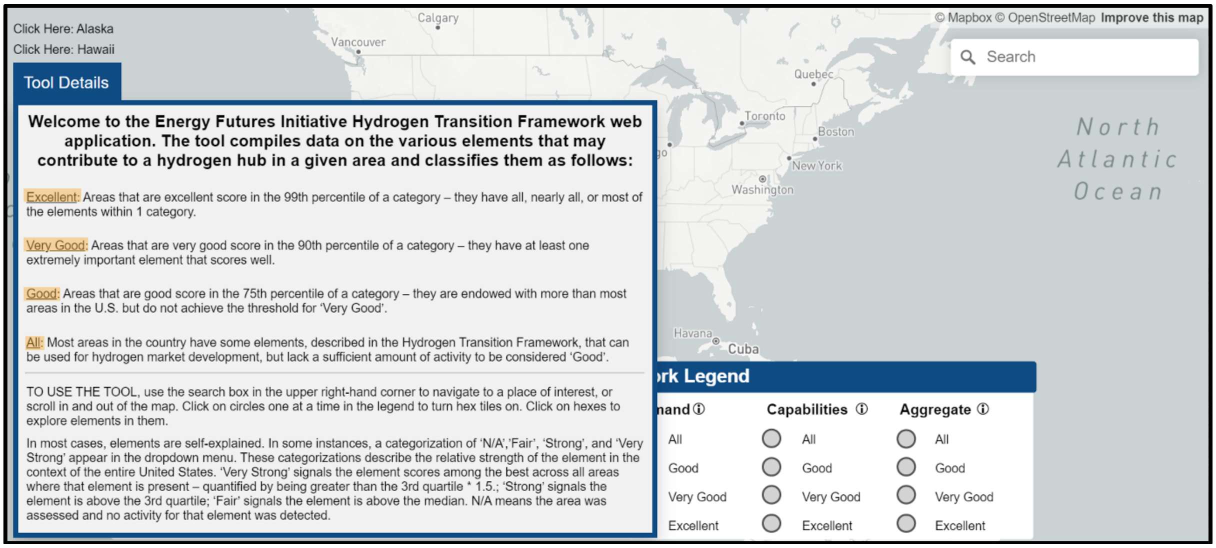
Tool Details drop-down menu



Of special note are the explanations of words such as "All," "Good," "Very Good," and "Excellent." Those mean that, in a specific category, an area has relatively more to offer for hydrogen hubs formation than much of the country. The Tool Details section (Figure 3) also offers explanations for both the legend and the informational drop-down boxes, which are discussed in more detail below.

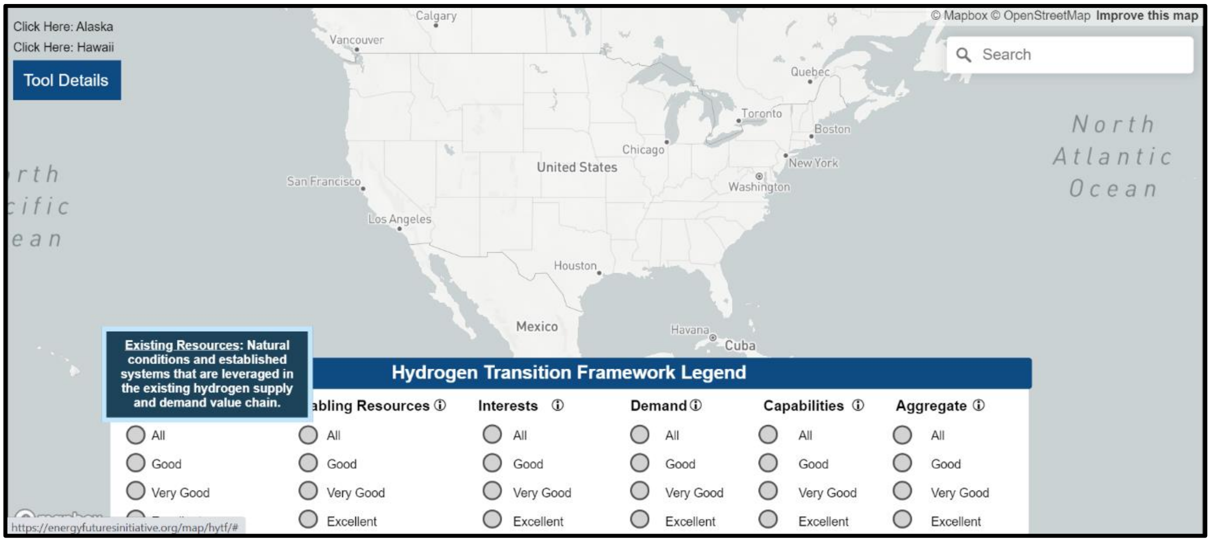
Figure 3

Tool Details drop-down menu information



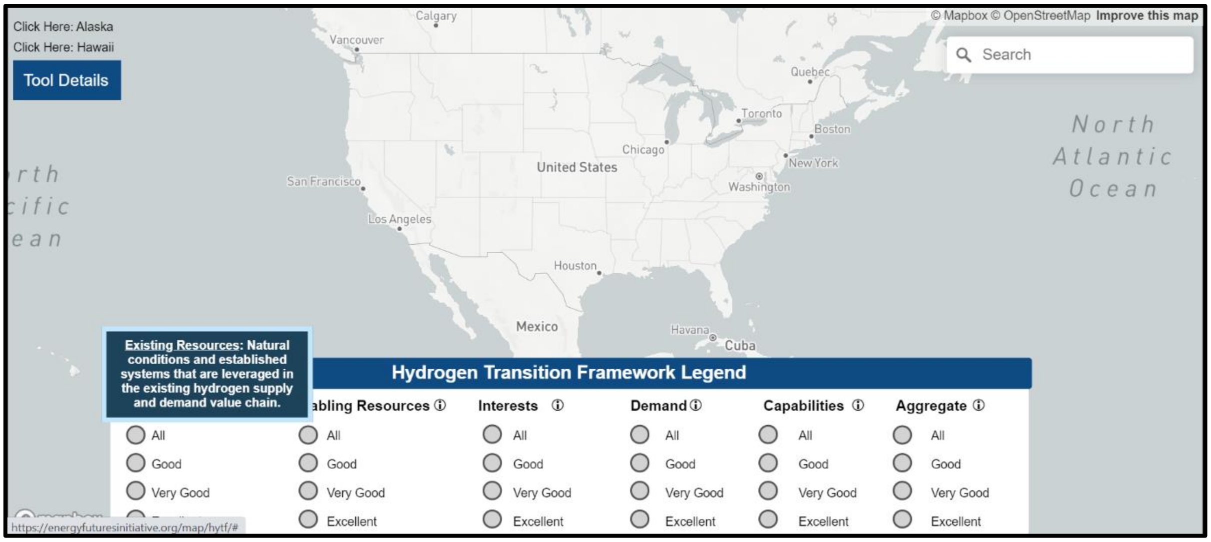
Next to each category is a circled "i" button, short for "information." If a user hovers a cursor over the "i," a description of the category appears next to the cursor (Figure 4).

Figure 4
Legend descriptions



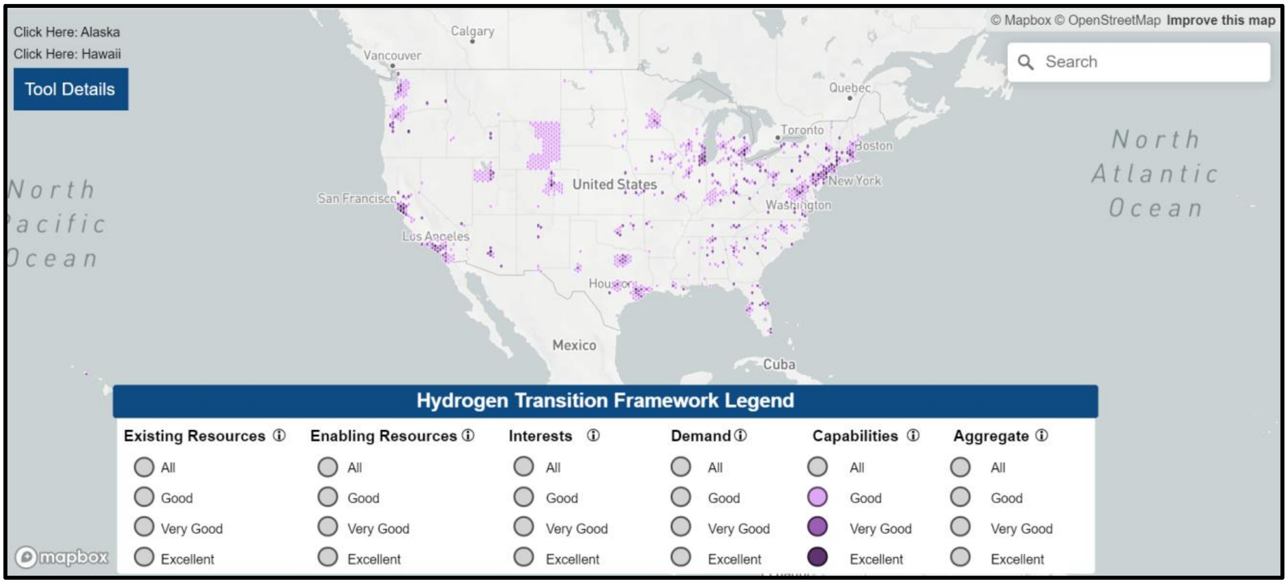
In the top right corner is a search bar where users can type addresses, coordinates, or locations of interest (Figure 5).

Figure 5
Search bar



Clicking on any of the circles in the legend will subsequently unveil hexagon (hex) areas in the United States (Figure 6).

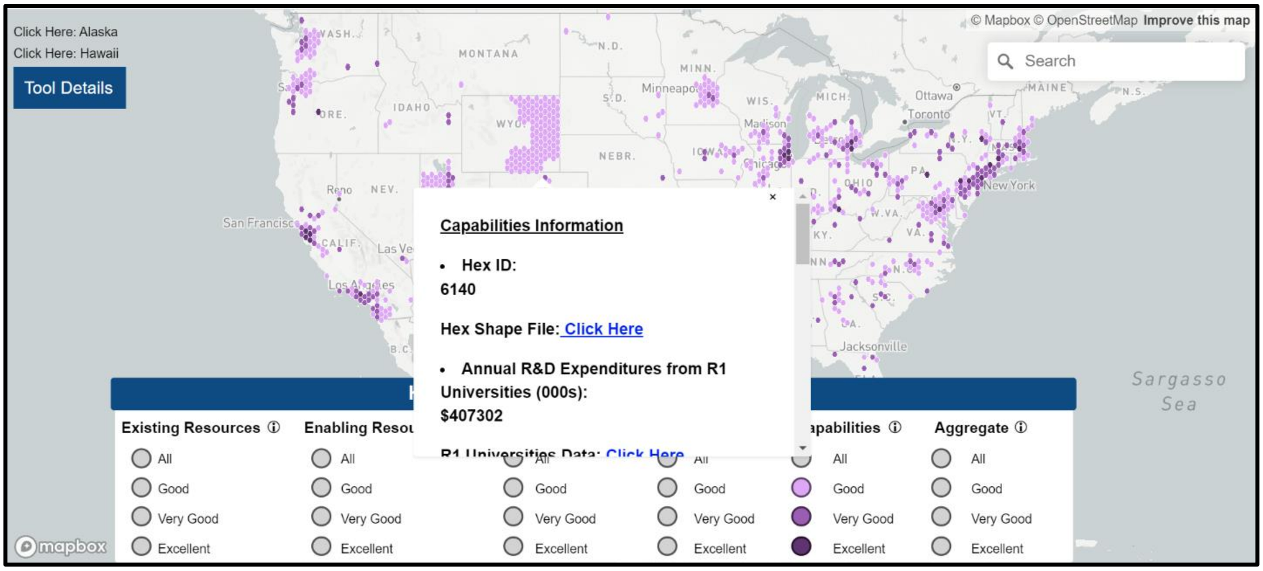
Figure 6
Hex areas unveiled



Clicking on hex areas reveals a pop-up box of information about the elements in that area. At the top of every pop-up is the hex identification code for that area. Users should scroll through the entire information box to get all relevant information for a given category. If multiple categories are turned on, some hex areas could be hidden beneath other hex areas. In other words, HyTF cannot show information for multiple categories simultaneously if there is overlap. However, pop-up boxes will appear for all categories turned on if an area is clicked. Clicking the “x” in the upper right corner of a box will reveal information boxes hidden underneath (see Figure 7).

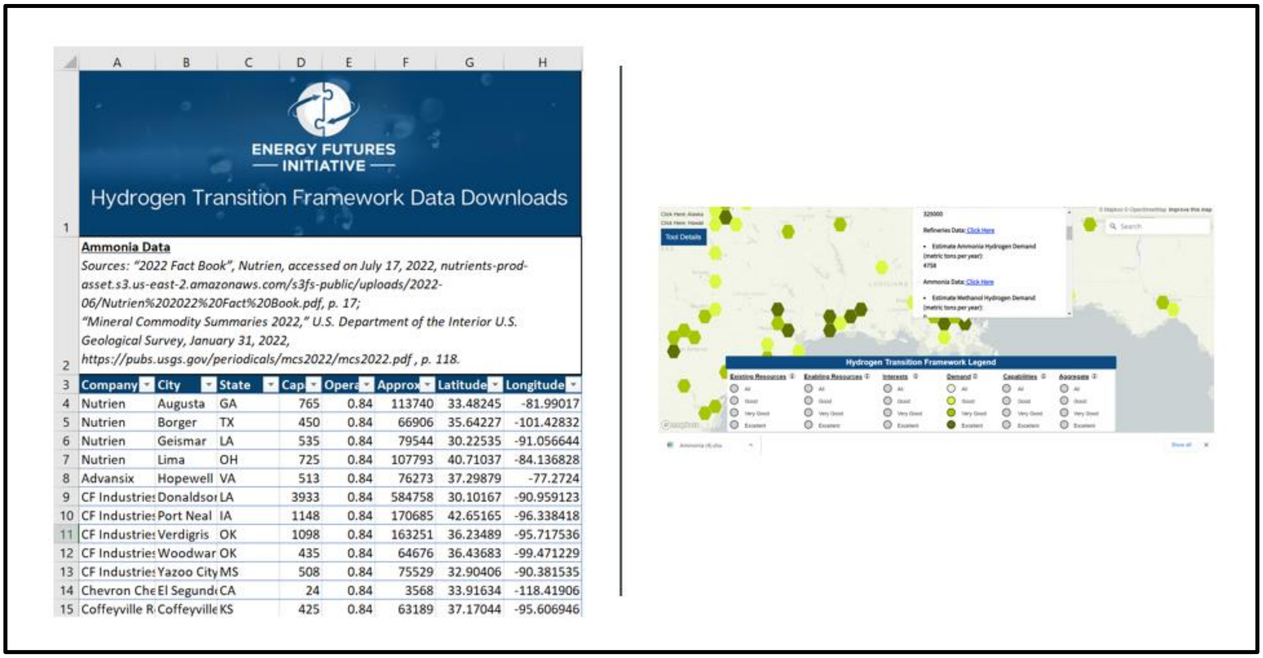
Figure 7

Hex area pop-ups



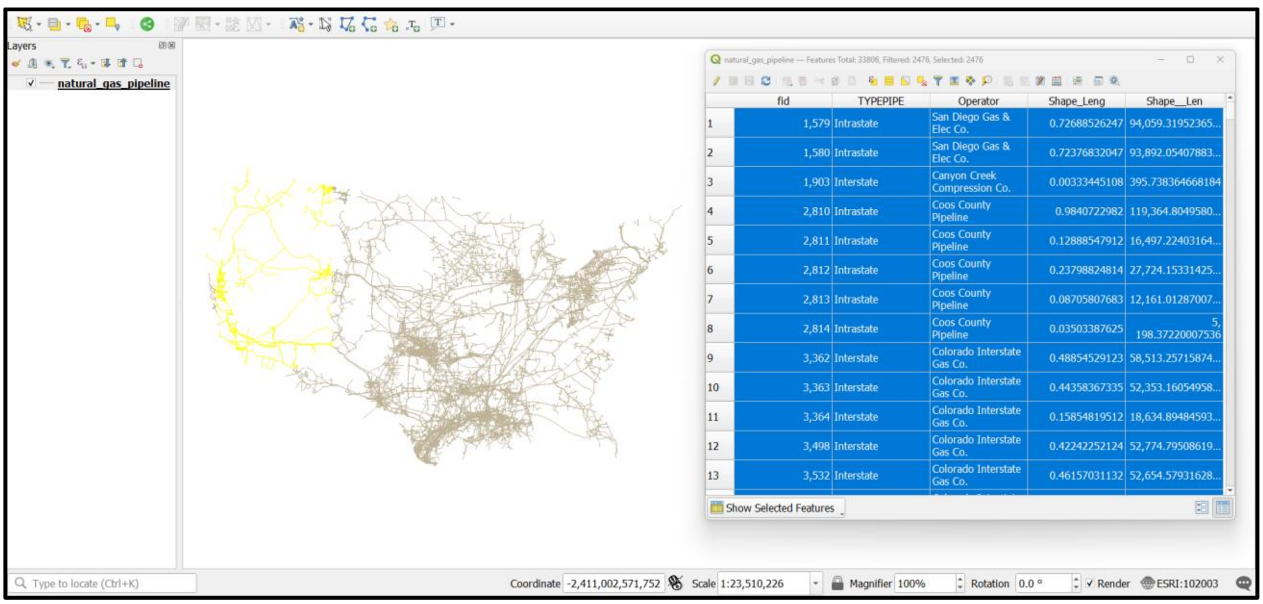
To make data easily accessible for any HyTF user, data that is not confidential is offered via downloadable links within pop-ups, beneath the bullets in the drop-down list. Clicking on the link will automatically download an Excel sheet that appears in the bottom left corner of the interface. The data file will provide a comprehensive overview of the element of interest. Figure 8 shows an example of the ammonia plants data downloads link and table. Certain data, including for pipelines, roads, waterways, railways, and salt caverns, are provided as GeoJSON files, which work like a shapefile to contain geographic data structures and their associative non-spatial attributes. Geographic information system (GIS) software is needed to see the files in this format, as with a shapefile. For example, figure 9 shows how a GeoJSON file would appear in GIS software for natural gas pipelines.

Figure 8
HyTF data downloads: ammonia plants example



Company	City	State	Cap	Opera	Approx	Latitude	Longitude
Nutrien	Augusta	GA	765	0.84	113740	33.48245	-81.99017
Nutrien	Borger	TX	450	0.84	66906	35.64227	-101.42832
Nutrien	Geismar	LA	535	0.84	79544	30.22535	-91.056644
Nutrien	Lima	OH	725	0.84	107793	40.71037	-84.136828
Advansix	Hopewell	VA	513	0.84	76273	37.29879	-77.2724
CF Industrie:	Donaldsor	LA	3933	0.84	584758	30.10167	-90.959123
CF Industrie:	Port Neal	IA	1148	0.84	170685	42.65165	-96.338418
CF Industrie:	Verdigris	OK	1098	0.84	163251	36.23489	-95.717536
CF Industrie:	Woodwar	OK	435	0.84	64676	36.43683	-99.471229
CF Industrie:	Yazoo City	MS	508	0.84	75529	32.90406	-90.381535
Chevron Che	El Segund	CA	24	0.84	3568	33.91634	-118.41906
Coffeyville R	Coffeyville	KS	425	0.84	63189	37.17044	-95.606946

Figure 9
GeoJSON file: natural gas pipelines example



	fid	TYPEPIPE	Operator	Shape_Leng	Shape__Len
1	1,579	Intrastate	San Diego Gas & Elec Co.	0.72688526247	94,059.31952365...
2	1,580	Intrastate	San Diego Gas & Elec Co.	0.72376832047	93,892.05407883...
3	1,903	Interstate	Canyon Creek Compression Co.	0.00333445108	395.738364668184
4	2,810	Intrastate	Coos County Pipeline	0.9840722982	119,364.8049580...
5	2,811	Intrastate	Coos County Pipeline	0.12888547912	16,497.22403164...
6	2,812	Intrastate	Coos County Pipeline	0.23798824814	27,724.15331425...
7	2,813	Intrastate	Coos County Pipeline	0.08705807683	12,161.01287007...
8	2,814	Intrastate	Coos County Pipeline	0.03503387625	5,198.37220007536
9	3,362	Interstate	Colorado Interstate Gas Co.	0.48854529123	58,513.25715874...
10	3,363	Interstate	Colorado Interstate Gas Co.	0.44358367335	52,353.16054958...
11	3,364	Interstate	Colorado Interstate Gas Co.	0.15854819512	18,634.89484593...
12	3,498	Interstate	Colorado Interstate Gas Co.	0.42242252124	52,774.79508619...
13	3,532	Interstate	Colorado Interstate Gas Co.	0.46157031132	52,654.57931628...

HyTF Development

This section provides an unabridged description of how each element in HyTF was developed, including data sourcing, cleaning, and scoring for hex areas. Users curious about particular elements can read this section for details that go beyond the information found in the map interface. Explanations of the tool's development also may clarify any issues users stumble upon in exploring the tool. For example, some data points (e.g., state-level policies) do not perfectly fit into hex areas, as hex areas may cross state lines. In that case, HyTF is coded to categorize a hex based on the state that takes up the most area. If a hex is 51% in one state, that hex will be associated with that state.

Table 1

Describing the Hydrogen Transition Framework (HyTF)

EFI's Hydrogen Transition Framework (HyTF)

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

CATEGORIES	**Resources** *Natural conditions and established systems that could support a hydrogen economy*	**Demand** *Current and potential end uses that will help drive the quantity of hydrogen supplied to the market*	**Capabilities** *Expertise and experience used to innovate, educate, or provide necessary skills to the hydrogen economy*	**Interests** *Demonstrated direct or indirect support for hydrogen from firms or policies*
ELEMENTS	*Existing* • Fresh water access • Natural gas reservoirs • Hydrogen pipelines • Salt domes	*Near-Term Demand (Currently Commercialized)* • Refineries • Ammonia plants • Methanol plants	*Education Centers* • Universities by RD&D budget	*Private Sector* • Largest investor-owned utilities • Other S&P 500 companies

	• Hydrogen production capacity	• Limited mobility applications		
	Enabling • Saline aquifers and oil & gas reservoirs • CO_2 pipelines • Natural gas pipelines • Roads, railways, waterways • Hydro, solar, wind, and biomass electricity generation installed capacity	*Medium-Term Demand (Commercialized 2025-2035)* • Data centers • Steel plants • Ports & maritime applications • Natural gas plants • Energy storage potential • Medium and heavy-duty mobility	*Skilled Labor* • Bureau of Labor Statistics regions with strongest adjacent hydrogen jobs/skills • Technical and community colleges	*Policy* • Favorable state climate policies/plans
		Long-Term Demand (Commercialized After 2035) • Airports • Biofuels Production Potential • Cement Plants	*Innovation Centers* • Patents for hydrogen technology • National laboratories	*Public-Private Partnerships* • Government grants, direct payments, and loans for hydrogen technologies Small Business Innovation Research (SBIRs) awards

Each of the categories in HyTF (see Table 1) has distinct elements that are scored by relative importance to other elements in their category from highest to lowest, which is the basis for the Excellent, Very Good, and Good descriptors shown in the HyTF legend. HyTF categories and their associated elements are informed by a thorough literature review, interviews with more than 80 stakeholders, and modeling exercises that have simultaneously informed the entire study.[b] If a hex area does not score above the 75th

[b] EFI's hierarchy of importance for a given element was established through a rigorous process of trial and error and verification from important industry stakeholders. HyTF awards certain elements many points because they are rare (e.g., national laboratories), and their

percentile in a category, but there is some level of clean hydrogen opportunity, that hex will still light up and describe the opportunity under the “All” button. If the hex area scores above the 75th percentile and at or below the 90th percentile, it is scored as Good. If the hex area scores above the 90th percentile, it is scored as Very Good. At the 99th percentile, a hex area is defined as Excellent. EFI intends to update HyTF annually to ensure numbers remain as up to date as possible and may add other elements to the tool over time as more is learned about the attributes of successful hub development. Overall, the elements consist of 500,000 separate data points that are publicly available and easily accessible. Below are the descriptions of each HyTF category and element.

Existing Resources

Elements for clean hydrogen development exist in nearly every region of the United States. The country can leverage its technical resource potential to produce substantial amounts of clean hydrogen—1 billion (B) metric tons, according to one DOE study.[3] The United States maintains considerable existing resources for clean hydrogen production—the resources, technologies, and systems in use by the hydrogen industry today. These resources include available water resources, natural gas potential, hydrogen pipelines, salt dome formations for long-duration storage, and current hydrogen production; as such they are the elements included in the existing resources category.[c] In HyTF, each of these elements is ranked in relation to one another, so current hydrogen capabilities translate to stronger hydrogen production potential. Each existing resource element can score between 2 and 5 points, depending on its relative size and importance for stimulating clean hydrogen market formation. A hex area’s default is zero points, and points are given only when it meets the thresholds established for each element. Table 2 shows the scores for each element in the existing resources category, though further explanation is provided in subsequent sections.

Table 2

Scoring the existing resources category

Category: Existing Resources		
Element	**Points**	**Explanation**
Freshwater access	2	Hex area receives points if freshwater access is above average

significance is such that not many other elements are needed to form a hydrogen hub. In other cases, elements are scored based on each individual opportunity within a hex area. For example, each hydrogen patent receives one point. Therefore, an area that has received many patents for hydrogen will show up as Good, Very Good, or Excellent in HyTF.

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

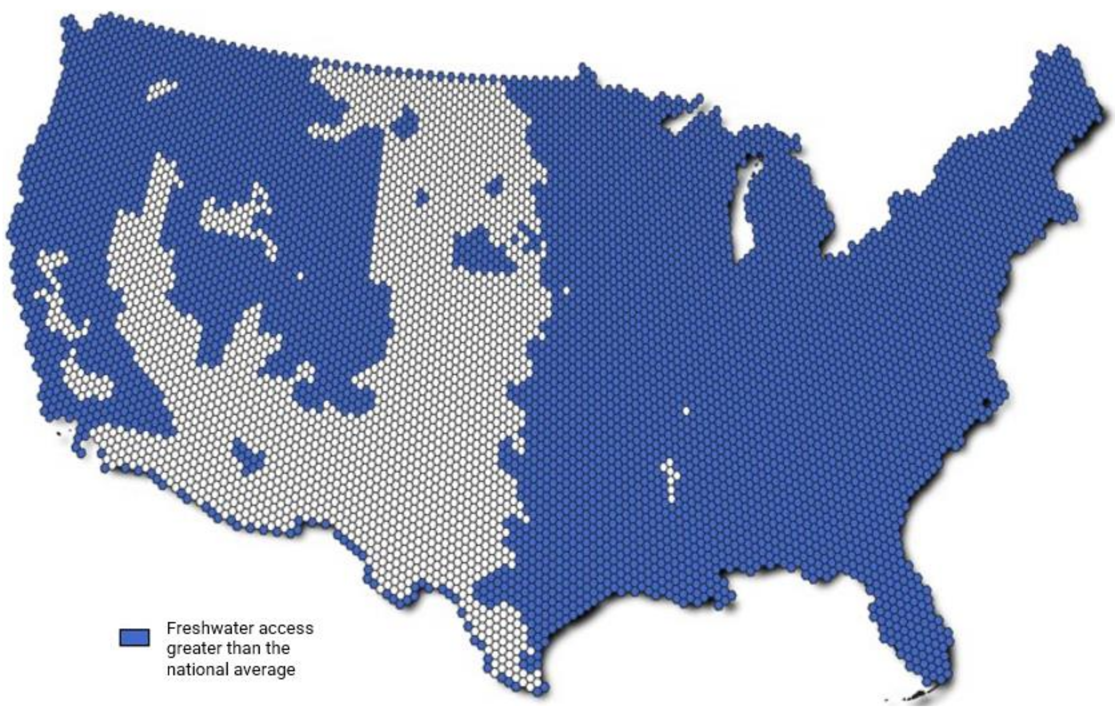
Hydrogen pipelines	2	Hex area receives points if there are hydrogen pipelines
Natural gas reserves	2 to 4	Hex area receives a normalized score based on the median and maximum supply
Salt caverns	3	Hex area receives points if there is a salt cavern
Hydrogen production	4 to 5	Hex area receives a normalized score based on the minimum and maximum annual production

1. Freshwater Access

Pure freshwater is an important input to nearly every energy system, regardless of production pathway or end use. Our data for freshwater availability comes from the Available Water Remaining for the United States (AWARE-US) model. Built on the AWARE global model, AWARE-US provides a granular analysis of water scarcity or stress at a county level. The AWARE model takes monthly data on the water scarcity footprint (WSF) of a county, which is a product of monthly water consumption and the monthly water stress capacity factor.

The national average annual WSF is 4.94 cubic meters.[4] In HyTF, the national average annual WSF is used as a cutoff for water availability. That is, counties are categorized as above or below average for freshwater access. Seasonal variations may affect certain areas more than others, but on an annual basis, the areas identified as "water scarce" are the most likely to confront challenges of meeting water demand for energy requirements. In HyTF, areas with freshwater scarcity score 0 points, and those with no scarcity score 2 points. Figure 10 shows the dichotomy of the hex areas. As with any polygonal data (e.g., county-level) that does not fit into hex areas neatly, a hex will light up entirely if a particular data point fills more than 50% of its area. Likewise, a polygonal shapefile that does not fill at least 50% of a hex will not light up.

Figure 10
Freshwater access[5]



Source: Lee et al., 2018.

2. Natural Gas Potential

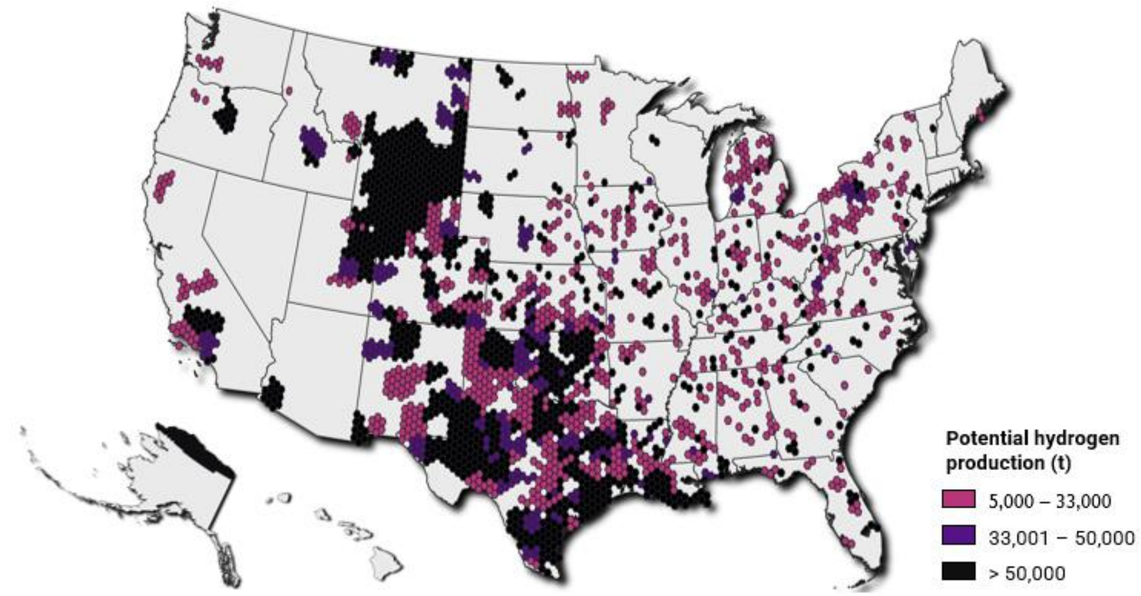
In HyTF, natural gas potential derives from the availability of natural gas reserves. As a result, areas with larger natural gas reserves receive a higher score than most other elements in the existing resources category. Natural gas potential is considered an existing resource because hydrogen is currently produced in the United States via steam methane reformation (SMR) using natural gas as a feedstock. The distribution of natural gas reserves throughout the contiguous United States and Alaska is highly variable. Some areas have particularly favorable access to natural gas. The Permian, Gulf Coast Mesozoic, and Appalachian Basins are the largest reserves in the country, each containing over 300 trillion cubic feet of natural gas. A county in those regions could produce anywhere from 0 to 3.4 million metric tons (Mt) of hydrogen a year if it used 100% of its natural gas supplies for that purpose.[6]

In the HyTF interface, natural gas potential is classified as Very Strong, Strong, Fair, Less than Fair, or N/A. If a hex area receives an N/A, no natural gas resources have been identified, according to DOE. If it receives a Less than Fair designation, there is natural gas in the area, but it is less than the median amount of gas. The distinction between Less than Fair and N/A is qualitative rather than quantitative, seeing as both are associated with scores of 0 in HyTF. Fair means the hex area is between the median and third quartile. Very Strong highlights hex areas with natural gas potential higher than the third quartile times 1.5. Typically, outliers are calculated by multiplying 1.5 times the interquartile range plus the third quartile. However, the unconventional HyTF method allows more areas to qualify as Very Strong, while maintaining a certain level of exclusivity. Initially, an outlier calculation was used, and almost no area qualified as (Very Strong. Naturally, Strong falls between Fair and Very Strong. Figure 11 shows the distribution of natural gas reserves across the country.

Natural gas potential's score is normalized between 2 and 4 points, with the median hex value receiving 2 points, and the hex area with the largest natural gas hydrogen production potential receiving 4 points. This normalized range reflects expert opinions from industry stakeholders and ensures HyTF awards a high valuation to areas with the best natural gas reserves in the country. As with any polygonal data that does not fit into hex areas neatly, a hex will light up entirely if a particular data point fills more than 50% of its area. Likewise, a polygonal shapefile that does not fill at least 50% of a hex will not light up.

Figure 11

Potential to produce hydrogen from natural gas reserve feedstock[7]

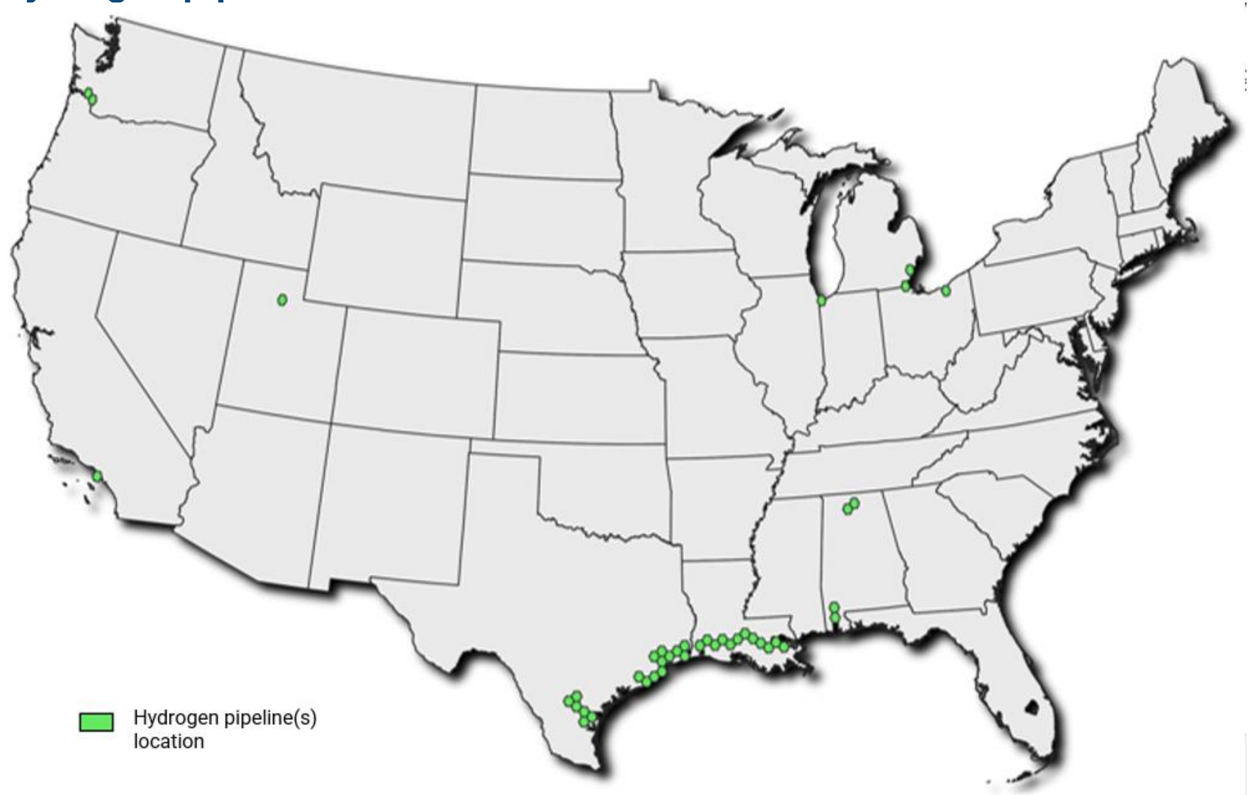


Source: National Renewable Energy Laboratory, 2020.

3. Hydrogen Pipelines

There are only 25 hydrogen pipelines in the United States, which together span approximately 1,600 miles. Most of these pipelines are in the Gulf Coast and are used to carry merchant or excess hydrogen to petrochemical users.[8] Often, the pipeline operator purchases excess on-site hydrogen production to sell to other users. Hydrogen pipelines were identified using the Pipeline and Hazardous Materials Safety Administration (PHMSA) database and manually recreated in GIS.[9] In HyTF, hex areas with current hydrogen pipelines receive 2 points. Those areas are shown in Figure 12.

Figure 12
Hydrogen pipelines[10]

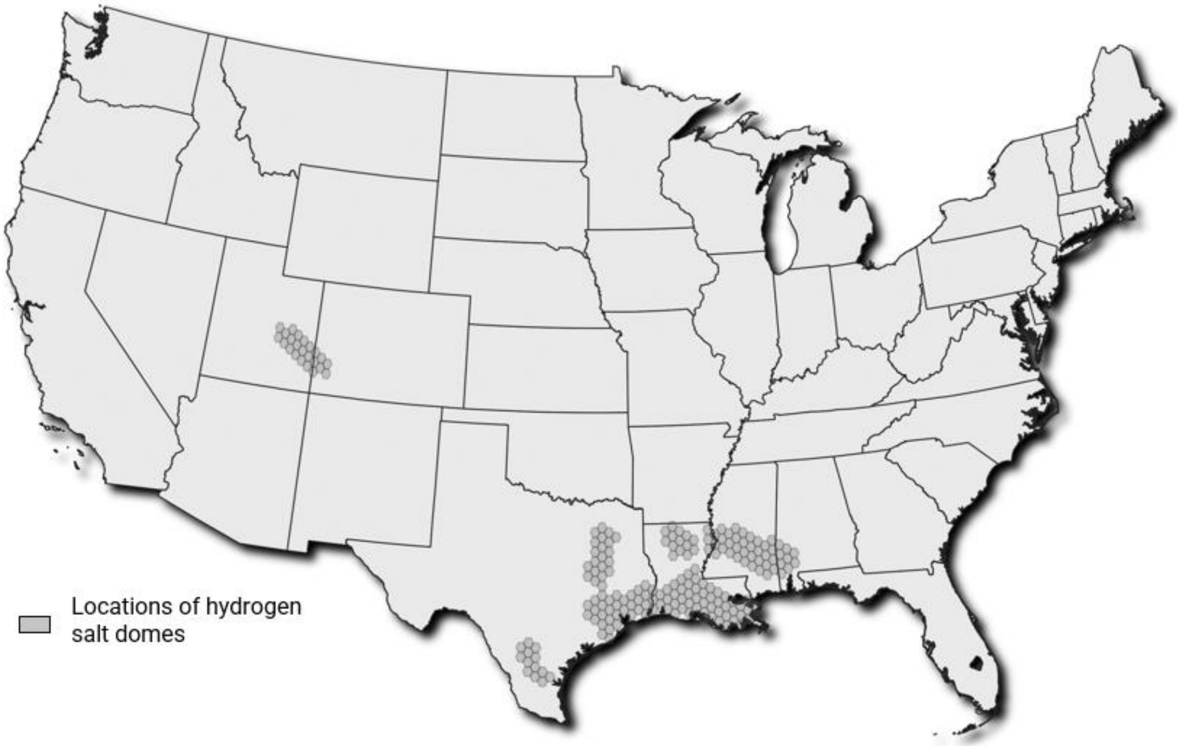


Source: U.S. Department of Transportation, 2022.

4. Discovered Salt Domes

Salt domes are important enablers of large-scale and long-term hydrogen storage. Yet few salt domes for natural gas and hydrogen storage are currently in use in the United States. They could become important resources for large long-term storage of hydrogen and may support several projects by allowing for multiple inputs and outputs simultaneously, working together in a “book and claims” system.[11] Salt domes are important but rare, and as a result, most hex areas in HyTF that contain salt domes appear as Very Good or Excellent in existing resources because they receive 3 points. Figure 13 highlights the location of these formations in the United States.

Figure 13
Salt domes[12]



Source: Hevin, 2019.

5. Hydrogen Production

As of 2021, almost all 216 hydrogen production facilities in the United States were merchant, by-product, or captive plants that supplied the petroleum refining industry. Some smaller facilities also may supply hydrogen for a variety of uses including chemicals, metals refining, food or electronics processing, glassmaking, and rocket fuel. Additional facilities (32 ammonia and nine methanol plants), some of which are the largest hydrogen producers in the country, are not accounted for in this category because they produce hydrogen at equilibrium: supply is equal to demand. In HyTF, these facilities feature in the demand category. Hydrogen producers receive the highest rank within the existing resources category of HyTF, scoring between 4 and 5 on a normalized scale, because one of the first steps in the transition to clean hydrogen will be to decarbonize the current hydrogen industry.

Enabling Resources

When building regional hydrogen hubs and making clean hydrogen investments, developers must rely on resources yet to be leveraged for hydrogen. Such enabling resource elements include clean energy, gas pipelines for blending, and the roads, railways, and waterways that will safely transport hydrogen across the country. They also include carbon dioxide (CO2) storage resources such as pipelines and reservoirs for permanent carbon storage, which are necessary if project developers are interested in producing hydrogen with SMR/autothermal reformation (ATR) capture technology. Elements in the enabling resources category are scored between 0 and 4 points within a hex area, and the cumulative score is the sum of all five elements' scores in this category. Table 3 shows the scores for each element in the enabling resources category, and further explanation is provided in subsequent sections.

Table 3

Scoring the enabling resources category

Category: Enabling Resources		
Element	**Points**	**Explanation**
Natural gas pipelines	1	Hex area receives a point if there are natural gas pipeline(s)
Roads, intermodal hubs, and waterways	1	Hex area receives a point if there are roads, intermodal hubs, or waterways
Wind and solar capacity	1 to 2	Hex area receives a normalized score if the area has at least 20 megawatts of solar or wind capacity, between 20 megawatts and the maximum capacity
CO_2 pipelines	2	Hex area receives 2 points if it contains CO_2 pipeline(s)
Nuclear Plants	2	Hex area receives 2 points if there is one or more nuclear plants

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

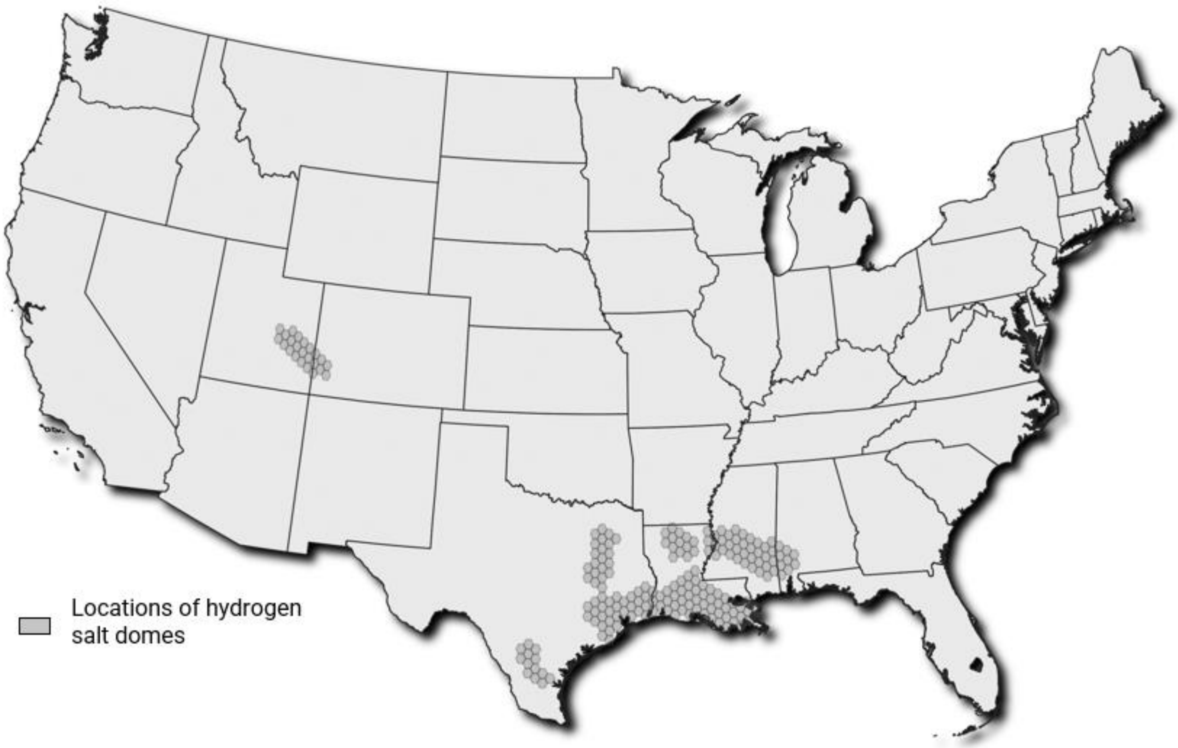
Saline aquifers and depleted oil and gas reservoirs play a crucial role in permanently storing CO_2 when producing hydrogen with carbon capture and storage (CCS). As such, hex areas with carbon storage potential are normalized between 3 and 4 points if they score at or above the median carbon storage index (CSI). The CSI allows users to understand the relative strength of carbon storage in an area. The index is calculated by dividing the capacity (metric tons) of an area by storage cost ($/ton), therefore capturing both technical and economic potential for CO_2 storage. The median CSI is 35.3. Less than Fair means that an area's CSI is 0.1 to 35.3, while a CSI greater than 35.3 and less than or equal to 43.5 is scored as Fair. Greater than 43.5 and less than or equal to 65.4 is graded as Strong, and a CSI of greater than 65.4 receives a Very Strong.

Data to build the CSI comes from two sources. The National Energy Technology Laboratory (NETL) open-source database provides oil and gas reservoir capacity data.[13] Saline aquifers' storage and cost data were acquired from Carbon Solutions LLC, which developed a model called SCO2T (Sequestration of CO2 Tool), SCO2T uses machine learning to link sequestration engineering (e.g., injection rates, reservoir capacities, and plume dimensions) with techno-economic information to estimate capacity and cost of CO_2 sequestration.[14] Notably, without cost data for oil and gas reservoirs, EFI used the saline aquifer cost data to create the CSI for oil and gas reservoir storage. The CSI of a hex bin combines storage capacities from oil and gas reservoirs as well as saline aquifers. Carbon storage costs range from 1 to 357 USD (in $2021), and capacities vary from 0.1 to 964 Mt.

To help ensure the best sequestration site mapping, modeling excludes areas such as military zones, densely populated communities, Native American territories, or areas at high risk of earthquakes. The data does not include Alaska, Hawaii, or offshore storage, one of the gaps in analysis that EFI hopes to ameliorate in future versions of HyTF. The CSI for carbon storage in the contiguous United States is shown in Figure 14.

Figure 14

Carbon storage index[15]



Source: Middleton et al., 2020.

2. Carbon Dioxide Pipelines

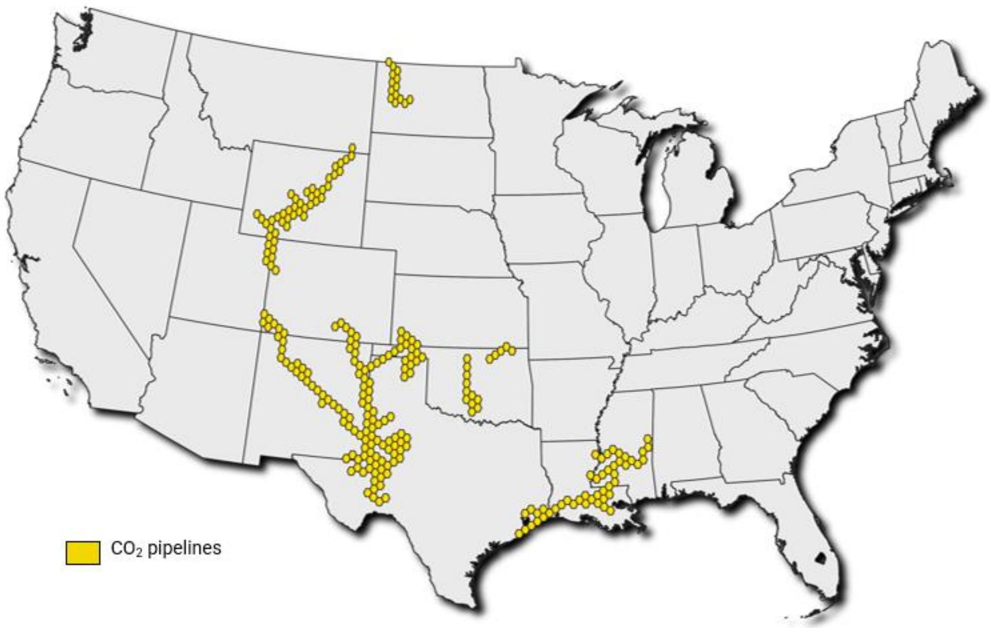
There are approximately 3,000 miles of CO_2 pipelines in the United States, mostly concentrated in the regions of the country with heavy oil and gas production. CO_2 pipelines are almost entirely used for enhanced oil recovery (EOR), though they could support permanent CO_2 sequestration from hydrogen production plants in the future. If a hex area contains a CO_2 pipeline, it scores 2 points.[d]

Hydrogen pipelines were identified using the Pipeline and Hazardous Materials Safety Administration (PHMSA) database and manually recreated in GIS.[16] Figure 15 shows the location of all CO_2 pipelines in the country as of 2022.

[d] CO_2 pipelines are given 2 points to reflect their significance in the clean hydrogen production value chain from natural gas feedstocks (i.e., SMRs/ATRs with carbon capture). They are weighted higher than natural gas pipelines and other midstream entities in the enabling resources category because of their relative rarity and importance to decarbonization, as described in industry interviews. However, there may be some amount of competition to use the existing CO_2 pipelines for their current EOR use cases.

Figure 15

CO_2 pipelines[17]

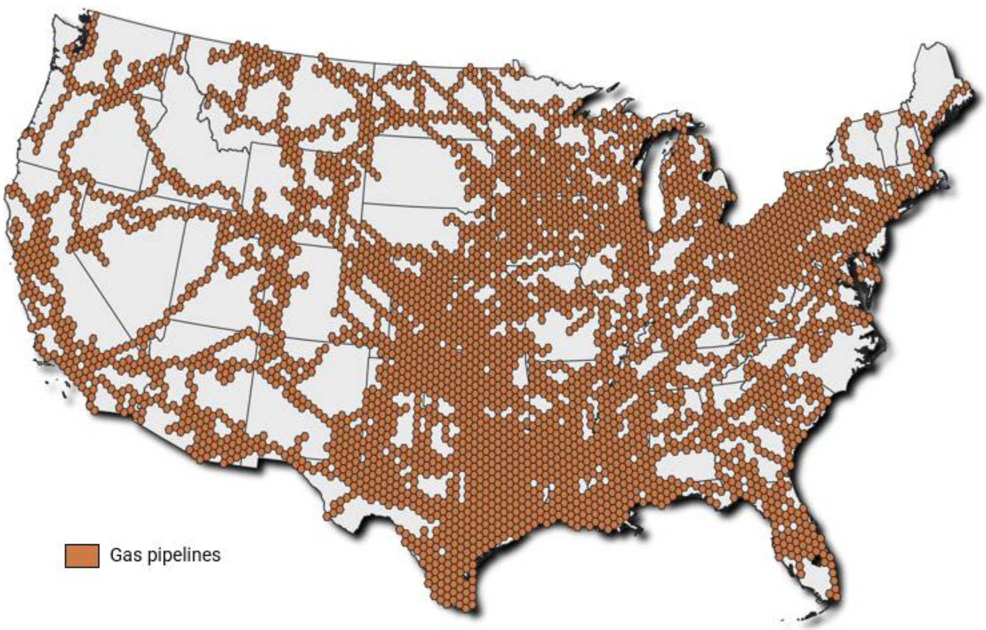


Source: U.S. Department of Transportation, 2022.

3. Natural Gas Pipelines

There are approximately 3 million miles of natural gas pipelines in the United States, many of which can support small blends of hydrogen. However, there are technical challenges with moving blends above 20% hydrogen in most natural gas pipelines. Therefore, decarbonization opportunities may be minimal without major pipeline retrofits. Gas pipelines are ubiquitous throughout the United States. As a result, hex bins with natural gas pipelines score just 1 point in HyTF, one of the lowest valued elements in the enabling resources category. Natural gas pipeline data pulled from a public Homeland Infrastructure Foundation-Level Data (HIFLD) geospatial database.[18] Figure 16 shows how the HIFLD data is translated to hex areas in HyTF. Data is not provided for Hawaii or Alaska, a gap that will be addressed in a future version of HyTF.

Figure 16
Natural gas pipelines[19]



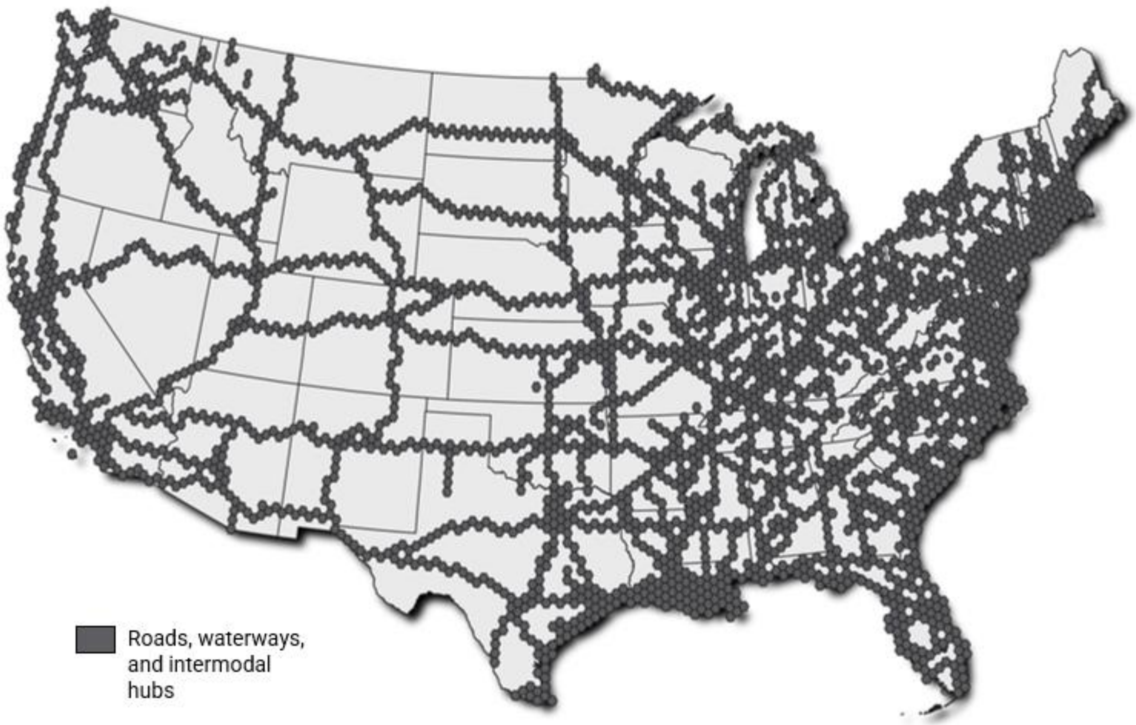
Source: Homeland Infrastructure Foundation-Level Data, 2022.

4. Roadways, Waterways, and Rail

Transportation networks (major roads, waterways, and rail) to move hydrogen from point to point will be important for the interconnectivity of hubs and the ultimate formation of a clean hydrogen market. Major highways and waterways were located using an HIFLD database. For rail, major intermodal freight facilities identified by the Department of Transportation (DOT) include ports, industrial centers, and other logistics hubs that facilitate the transport of freight in an intermodal container for use in rail, marine shipping, trucking, or even air shipping. If a hex area contains a major road, waterway, or intermodal freight facility, it receives only one point. This reflects the ubiquity of these corridors and intermodal hubs and the fact that nearly all facilities involved in the hydrogen value chain will be connected to these major corridors by other roadways. Hence, the roads, waterways, and rail element is another of the lowest scored in HyTF's enabling resources category.[20,21] Figure 17 captures all these transportation corridors as displayed in HyTF. Data are not provided for Hawaii or Alaska, a gap that will be addressed in a future version of HyTF.

Figure 17

Roads, waterways, and intermodal rail hubs[22,23]



Source: Homeland Infrastructure Foundation-Level Data, 2022.

5. Electricity Generation Installed Capacity

Nuclear Power Plants

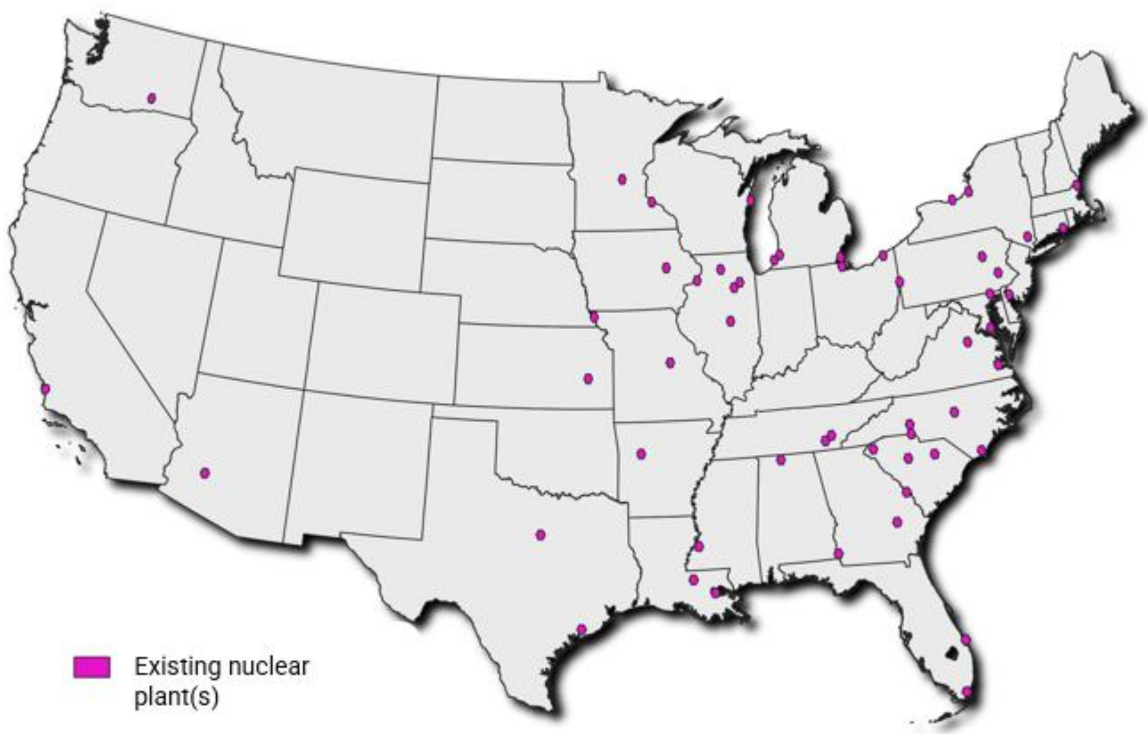
The Infrastructure Investment and Jobs Act (IIJA) mandates that at least one hydrogen hub should have a nuclear production pathway—most likely high-temperature electrolysis. Several projects are under development or being planned in the United States, as identified in EFI's hydrogen project database.[24] High-temperature heat or curtailed electricity are both feasible pathways for producing hydrogen. Hex areas with nuclear plants are ranked higher in HyTF than most areas with existing variable renewables capacity because of their rarity and opportunity to deliver clean, firm power.[e] Plant capacity was not factored into the score, nor did it make a difference if a hex area contained more than one plant. Most of the energy produced from a nuclear plant will not be dedicated to hydrogen production, and thus the relative capacity of a plant in the area will matter little. In other words, all nuclear plants offer similar potential for hydrogen production. Figure 18 shows where all operational nuclear

[e] Firm power, in this case, simply means it is reliable and can be produced on demand.

plants in the United States were located as of the end of 2022. Data were obtained from the World Resources Institute (WRI) global powerplant database.[25]

Figure 18

Nuclear power plants[26]



Source: World Resources Institute, 2021.

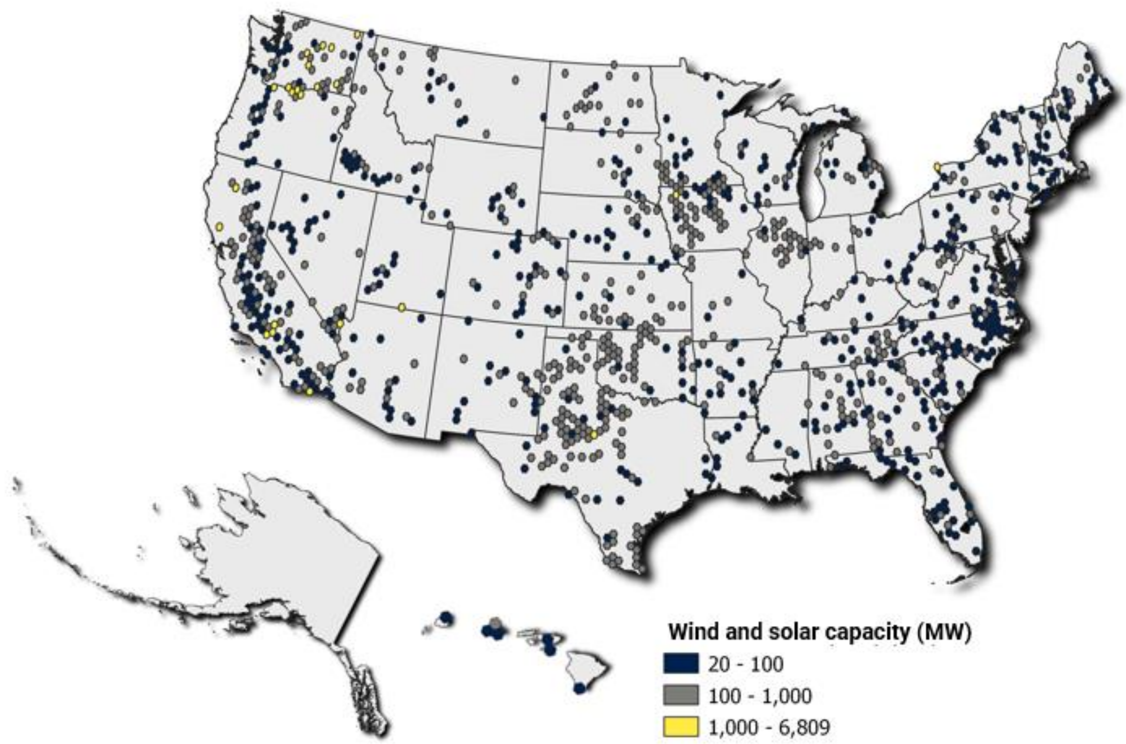
Existing Variable Renewable Energy Capacity

Wind and solar account for most of the electricity curtailment in the United States.[f] Therefore, because avoiding renewables curtailment is a potential benefit of hydrogen as a storage medium, EFI sought to understand where in the country sizable levels of variable renewables reside. In HyTF, a hex bin with more than 20 megawatts (MW) of solar and/or wind combined is ranked up to the highest level of capacity and normalized between 1 and 2 points. This score is relatively low compared with other elements in the enabling resources category to reflect the important yet small potential additions for future clean hydrogen production. For context, the highest-scoring hex area contains 6,809 MW of wind and solar capacity. HyTF does not consider geothermal, hydro, or biomass, which are firm power resources. Data were obtained from the WRI global powerplant database.[27] Figure 19

[f] Curtailment refers to periods of time when electricity supply from renewables must be stopped because there is insufficient demand or storage capacity.

provides a graduated look at the areas in the United States with the most wind and solar capacity.

Figure 19
Wind and solar capacity[28]



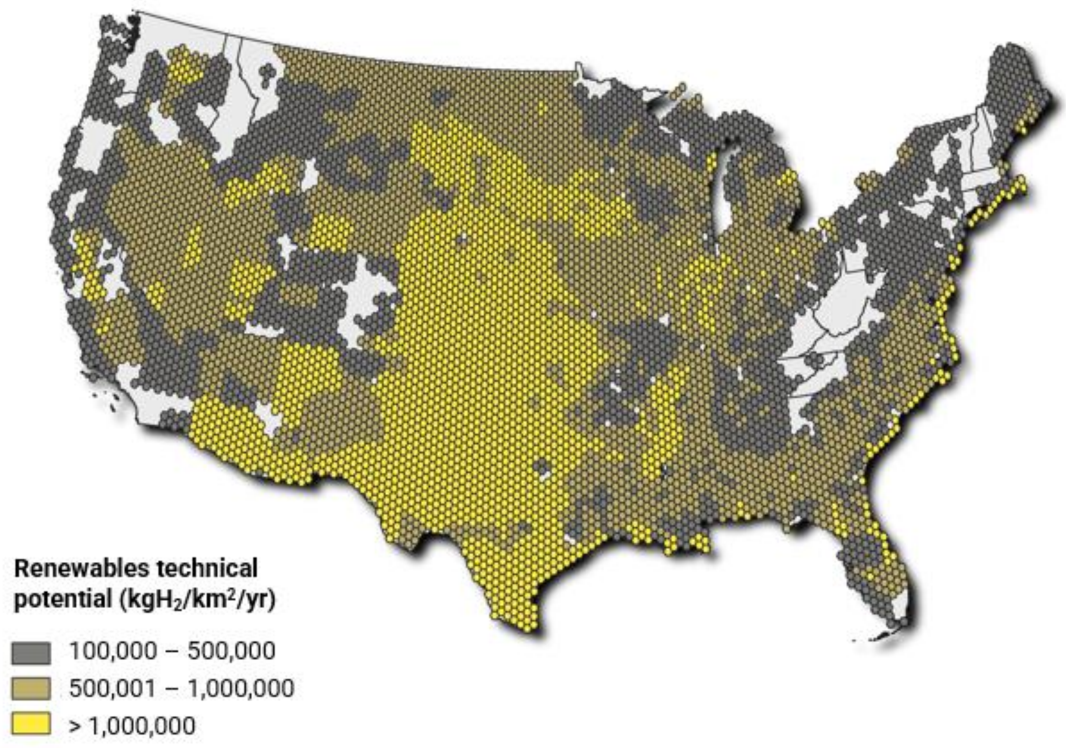
Source: World Resources Institute, 2021.

6. Renewable Energy Technical Potential (Wind, Solar, Hydro, and Biomass)

To produce green hydrogen on a large scale, a huge supply of electricity is required from clean energy sources. As such, compared to other elements in the HyTF enabling resources category, an area that presents great renewable energy technical potential is ranked among the highest, with 4 points. Such areas have the potential to produce more than 1,000,000 kilograms of hydrogen per kilometer squared per year (kgH_2/km^2/year), followed by areas that can produce between 1,000,000 and 500,000 kgH_2/km^2/year (scoring 3 points) and between 500,000 and 100,000 kgH_2/km^2/year (scoring 2 points). HyTF does not specify a technology but considers wind, solar photovoltaics (PV), concentrating solar-thermal power (CSP), biomass, and hydroelectricity as clean energy sources. DOE's H2@Scale report provides data on renewable energy technical potential throughout the country, allowing for an assessment of an area's relative strength for electrolytic hydrogen potential.[29] Geothermal potential is not included in HyTF because DOE data is constrained to areas where county-level data is available. The geospatial distribution of renewables technical potential is shown in Figure 20. Data is not provided for Hawaii or Alaska, a gap that will be addressed in a future version of HyTF.

Figure 20

Technical hydrogen production potential from renewables[30]



Source: National Renewable Energy Laboratory, 2020.

Demand

Assessing the current and potential demand for hydrogen is crucial for developing a hydrogen market. Demand will be a function of technology readiness, market structures, business models, and regulation. HyTF data includes near-, medium-, and long-term demand opportunities, some of which are driven by DOE's assessment of hydrogen-ready demand.[31] Near-term demand focuses on existing hydrogen use, while long-term demand expands to a variety of industries that could leverage hydrogen to decarbonize. Decarbonizing existing hydrogen production for refineries, ammonia, and methanol plants is a focal point of EFI's hydrogen strategy and can lower U.S. emissions by over 50 Mt of CO_2 equivalent (CO_2e) per year.[g,32] Decarbonizing these sectors also can positively affect

[g] CO_2 equivalent refers to greenhouse gas emissions (e.g., methane) expressed as equivalent amounts of carbon dioxide that would have the same global warming potential over a period of 100 years.

communities, as areas with strong current hydrogen demand are correlated with environmental justice concerns like heavy pollution. In HyTF, near-term demand elements score the highest, ranging from 3 to 4 points, medium-term demand receives greater than or equal to 2 and less than 3 points, and long-term demand scores between 1 and less than 2 points.

Beyond existing users, new applications for hydrogen can reach new consumers. Highly industrialized regions, particularly those with large steel plants, can use hydrogen to replace natural gas in emissions-intensive industrial processes such as iron reduction. The U.S. has dozens of facilities across the country that could explore this production pathway. Other areas of market potential are stationary power production, off-road operations at ports and airports (i.e., drayage trucks, yard trucks, top loaders, and ferry boats), on-road mobility, backup power generation at data centers, grid stability, biofuels production, and cement manufacturing. Table 4 summarizes scoring in HyTF's demand category.

Table 4

Scoring the demand category

Category: Demand			
Timetable	**Element**	**Points**	**Explanation**
Long-term opportunities (commercialization after 2035)	Airports and aviation	1	Hex area receives 1 point if there is at least one airport
	Cement plants	1 to 2	Hex area receives a normalized score between 1 and 2 points based on annual clinker production
	Biofuels production	1 to 2	Hex area receives a normalized score between the median and maximum level of technical potential for clean hydrogen in biofuels production
Medium-term opportunities (commercialization after 2025)	Medium and heavy duty on-road mobility	2 to 3	Hex area receives a normalized score between the median and maximum level of technical potential for clean hydrogen in medium and heavy duty on-road mobility options
	Grid storage	2 to 3	Hex area receives a normalized score between the median and maximum level of technical potential for clean hydrogen as a grid storage option
	Natural gas power plants	2 to 3	Hex area receives a normalized score between the median and maximum level of plant(s) capacity

	Ports and maritime applications	2	Hex area receives 2 points for containing at least one port
	Data centers	2	Hex area receives 2 points for containing at least one data center
	Iron and steel plants	2 to 3	Hex area receives a normalized score between the country's smallest and largest iron and steel plants, by annual production capacity
Near-term opportunities (existing hydrogen end uses at scale)[h]	Methanol plants	3 to 4	Hex area receives a normalized score between the plant with the smallest and largest estimated annual hydrogen demand
	Ammonia plants	3 to 4	Hex area receives a normalized score between the plant with the smallest and largest estimated annual hydrogen demand
	Refineries	3 to 4	Hex area receives a normalized score between the plant with the smallest and largest estimated annual hydrogen demand

Near-Term Demand (Currently Commercialized)

1. Refineries

Petroleum refining accounts for approximately 77% of hydrogen demand in the country, all of which is produced via SMR. To calculate hydrogen use by each refinery, EFI leveraged the methodology in DOE's H2@Scale report *Assessment of Potential Future Demands for Hydrogen in the United States*.[33] The variance in crude oils' sourness (i.e., impurities) affects the amount of hydrogen required to process a barrel of oil, depending on the refinery. Therefore, regional variance must be accounted for in an analysis of refinery hydrogen use.

The Energy Information Administration's (EIA) 2021 *Refinery Capacity Report* was consulted to locate refineries and calculate how many barrels of oil are produced per calendar day.[34] Data of crude oil capacity and the ratio of hydrogen per barrel of crude came from DOE's facility-level analysis of refineries, which is shown in Table 5.[35] The ratio of hydrogen is dependent on the Petroleum Administration for Defense Districts (PADD) regions and is expected to grow steadily year-over-year as crudes become sourer over time. Finally, cubic feet of hydrogen were converted into metric tons (t) of hydrogen. The resulting hydrogen demand from this exercise was 6.5 Mt for refineries in 2021, consistent with other studies to date. To ensure accuracy, these numbers were validated against proprietary IHS

[h] The applications listed here make up most of the hydrogen demand as of 2022 in the United States (~94%). Furthermore, industry stakeholders relayed to EFI the importance of decarbonizing hydrogen for refineries, ammonia, and methanol plants.

Markit data on captive and merchant hydrogen plants serving refineries. As an existing hydrogen market, hex areas with refinery hydrogen demand were normalized between 3 and 4 points by estimated hydrogen consumption level. Figure 21 shows the distribution of refinery hydrogen demand.

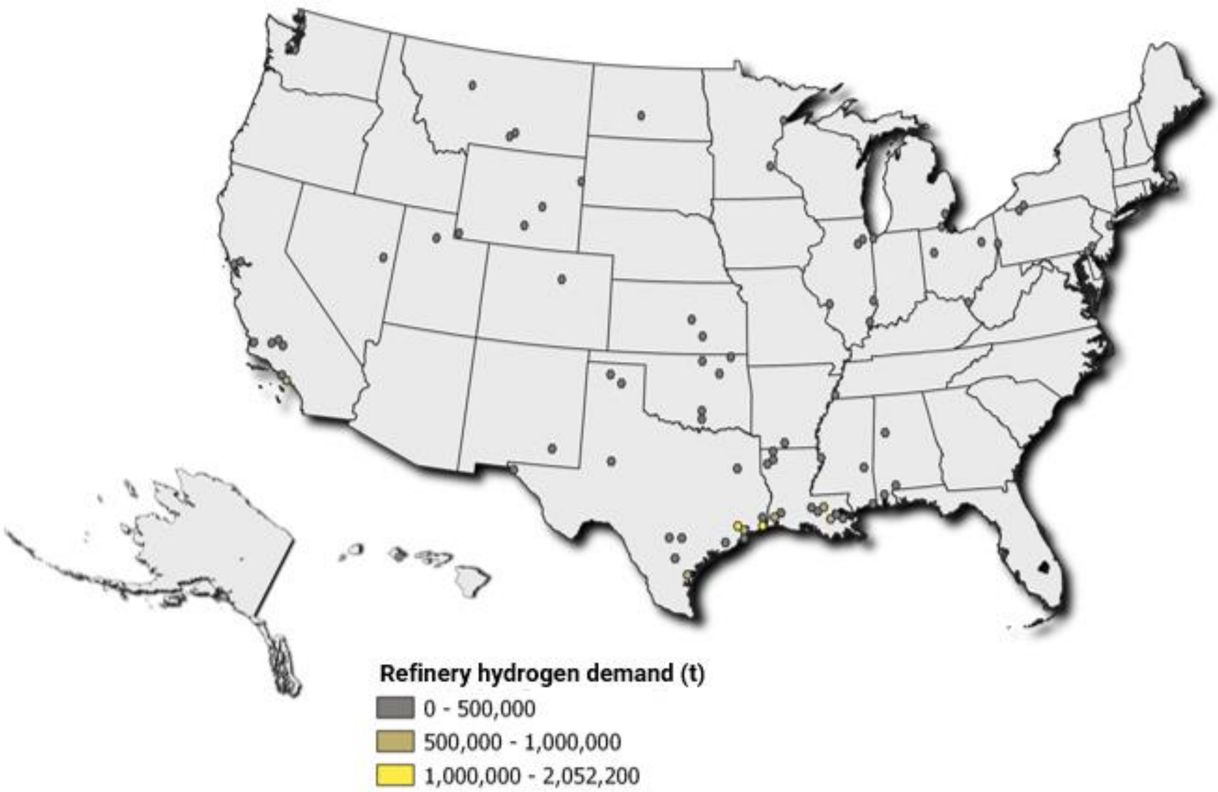
Table 5

Ratio of hydrogen per barrel of oil

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

Figure 21

Refinery hydrogen demand[36]



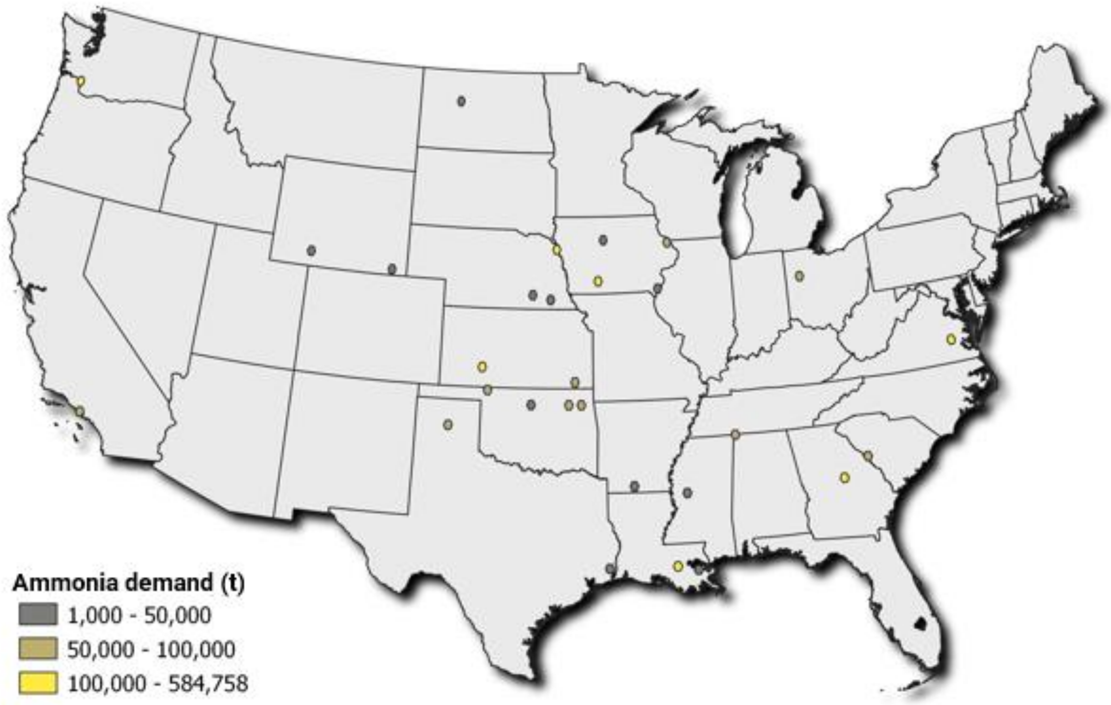
Source: U.S. Energy Information Administration, 2022.

2. Ammonia Plants

Ammonia plants are the second largest source of hydrogen demand in the U.S. All ammonia in the country is produced captively, resulting in no real existing market.[i] Hydrogen production capacity per plant data comes from Nutrien's *2022 Fact Book*, which identifies the 32 existing ammonia plants in the co2untry and their respective production capacities. In total, ammonia plants produced 17.9 Mt in 2021.[37] U.S. Geological Survey's *Mineral Commodity Summaries 2022* specifies that each of those plants has approximately an 84% operating capacity.[38] Using a hydrogen ratio of approximately 18% for every unit of ammonia produced at this operating capacity, existing ammonia plants were responsible for producing 2.6 Mts of hydrogen. As an existing hydrogen market, hex areas with ammonia plant(s)' hydrogen demand were normalized between 3 and 4 points by estimated hydrogen consumption level. Similar to refineries, the score reflects the immediate opportunity to transition a large emitter to a cleaner fuel. Figure 22 shows the distribution of ammonia hydrogen demand.

Figure 22

Ammonia hydrogen demand[39]



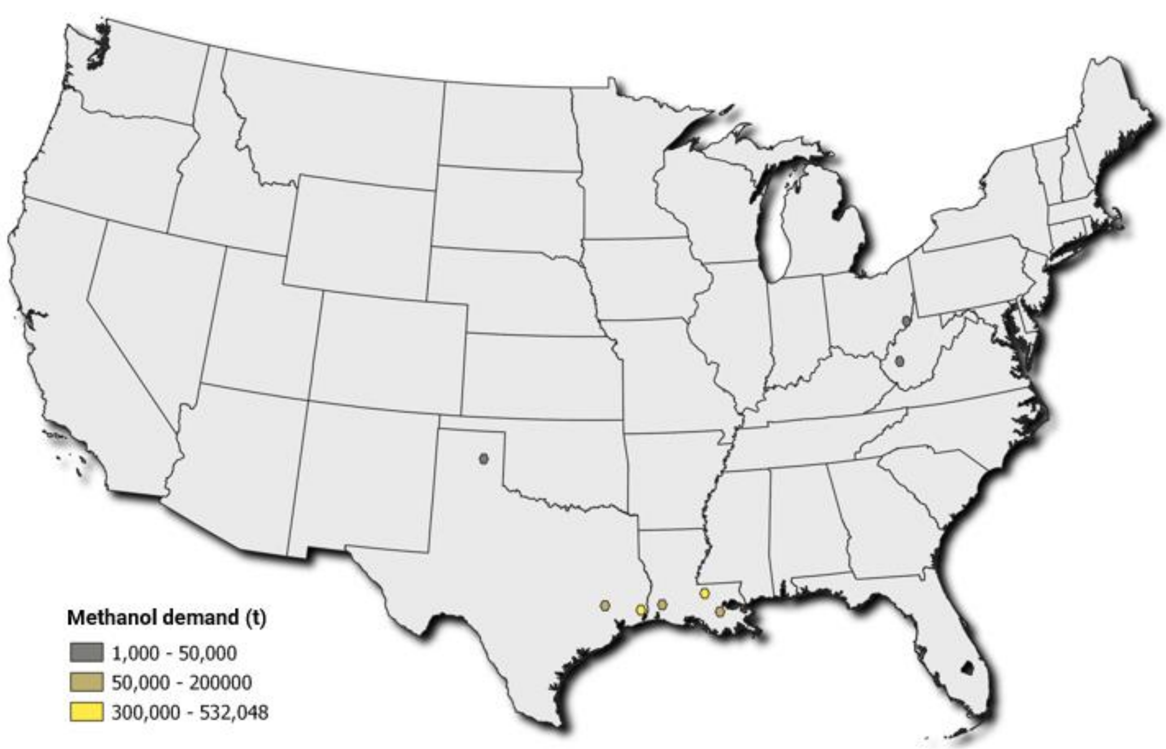
Source: Nutrien, 2022.

[i] Captive production means the facility produces something for internal consumption rather than something for sale to external customers.

3. Methanol Plants

There are nine operational methanol plants in the U.S. and they consume a large share of the total hydrogen demand—1.6 Mt annually. EIA compiled data on the methanol production capacity of each plant, and using a hydrogen/methanol ratio of 16%, this study found an estimated hydrogen production capacity for each plant.[40] As an existing hydrogen market, hex areas with methanol plant(s)' hydrogen demand were normalized between 3 and 4 points by estimated hydrogen consumption level. Figure 23 shows the distribution of methanol hydrogen demand.

Figure 23
Methanol hydrogen demand[41]



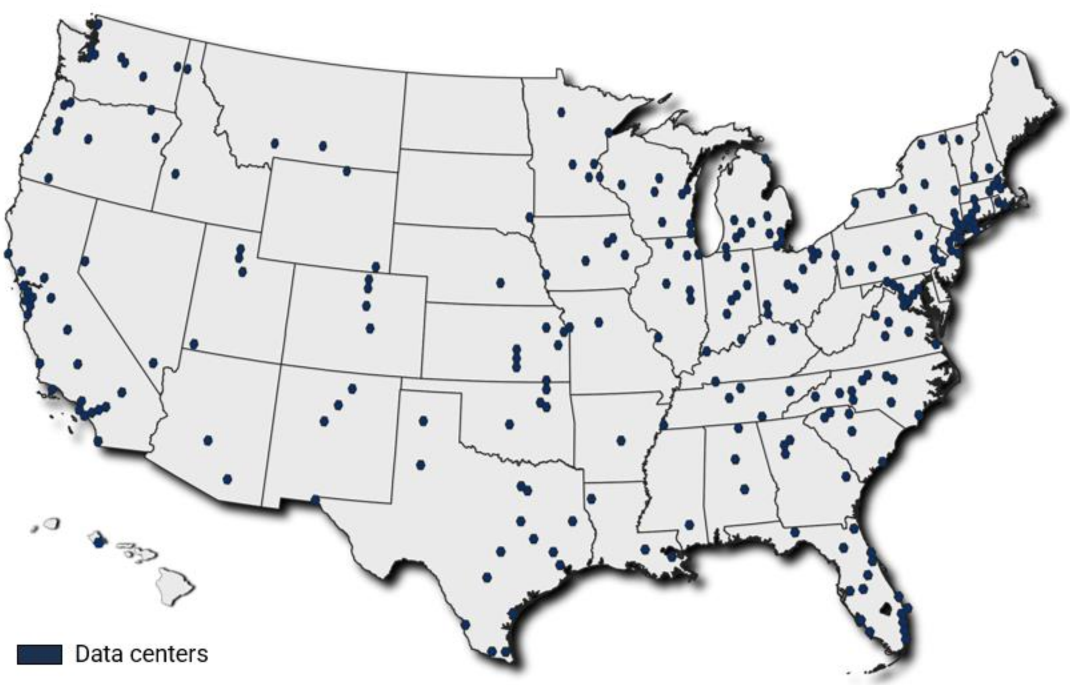
Source: Ameen and Tsai, 2019.

Medium-Term Demand (Commercialized 2025 to 2035)

1. Data centers

Stationary fuel cells can be used as a storage medium for backup power to replace high-emitting diesel generators that are unable to meet stringent Environmental Protection Agency (EPA) regulations. An area of interest for these stationary fuel cells is at data centers, which can provide reliable backup power options to facilities that are expected to operate at nearly all times. Microsoft, Amazon, and Meta are some of the companies that could profit from such applications. With some data centers requiring up to 100 MW of electricity capacity and a proof-of-concept complete at Microsoft, data centers can potentially leverage clean hydrogen without switching the primary power source. Even if clean hydrogen use is not possible at first, backup fuel cells still can operate using cheaper fossil-derived hydrogen or even natural gas.[42] All large-scale data centers in the United States were located using a database of U.S. data centers.[43] As a technology with medium-term potential (commercialization in the next 10 to 15 years), HyTF gives a hex area 2 points if it contains at least one data center. Insufficient data was available to determine the size of data centers. Thus, version one of HyTF does not give more points to areas with more data centers. Because no determination could be made about the overall capacity (i.e., electricity demand) of data centers, Figure 24 simply shows the distribution of data centers.

Figure 24
Data centers[44]



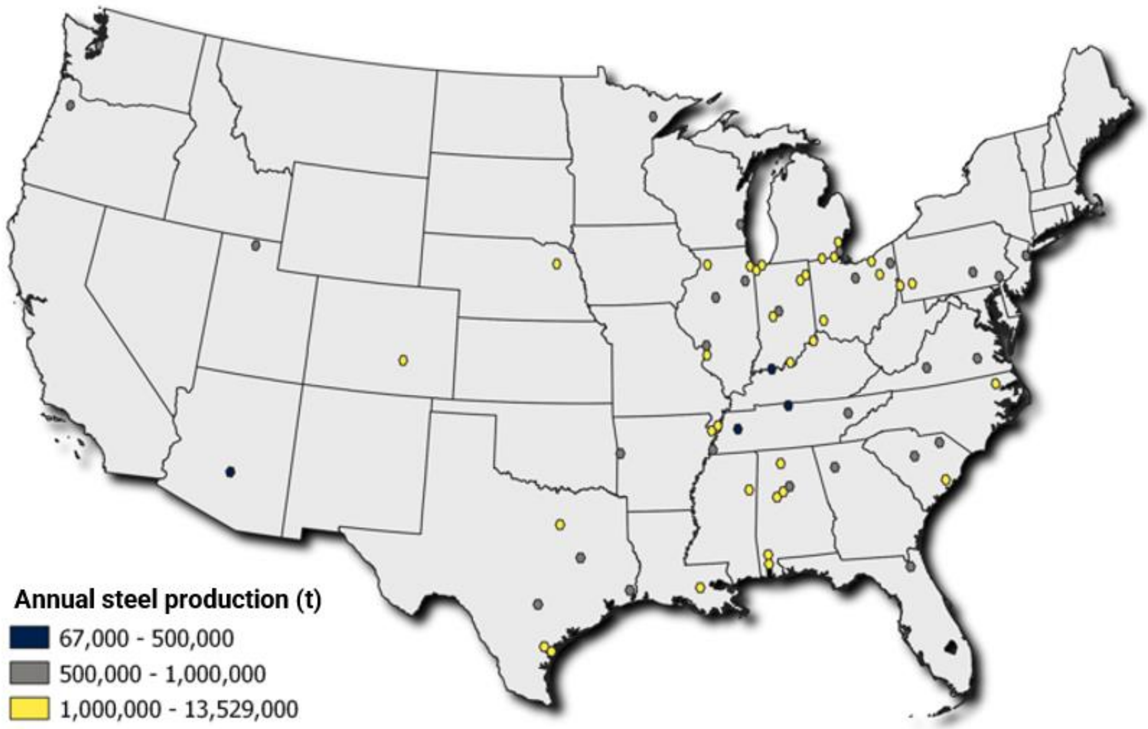
Source: Data Center Map, 2022.

2. Steel Facilities

The 77 steelmaking facilities across the United States were identified by location, capacity, and technology using the Global Energy Monitor.[45] The total capacity of annual steel production (metric tons) is estimated by hex area. As a technology with medium-term potential, HyTF normalizes hex areas with steel production from 2 to 3, with 3 representing the highest capacity. Hex areas have anywhere from 67,000 to 13.5 million tons of estimated annual steel production. Figure 25 shows where those facilities are concentrated.

Figure 25

Steel production[46]



Source: Global Energy Monitor, 2022.

3. Ports and Maritime Applications

The Pacific Northwest Laboratory used emissions data to estimate potential hydrogen demand for several ports around the country—more than 500,000 tons annually. A smaller port may use about 50 tons of hydrogen per day while a larger port could need up to 465 tons per day.[47] Most of the near-term hydrogen demand in ports would come from drayage trucking, though yard tractors, container handlers, frames, and straddle carriers could follow in the coming decades. Maritime hydrogen demand projections are not known because of uncertainties about decarbonizing the industry. Hydrogen has many applications on board a boat or ship, yet it is unclear whether pure hydrogen, liquid organic hydrogen carriers (LOHCs), ammonia, or other options present the best economics or properties to accommodate demand.

Currently, no commercial market for port or maritime hydrogen applications exists in the United States. However, many pilot projects and proof-of-concept designs are underway across the country. As of 2019, EPA's H2 Fuel Cells at Ports Initiative found 22 fuel cell demonstrations and deployment projects, which included seven drayage trucks, five power generators at the port, four yard tractors or top loaders, four hydrogen refueling stations, one portable light tower, and one ferry boat project.[48] HyTF used HIFLD data to locate the major ports in the country and awarded every hex area that contains a port with 2 points for its medium-term potential. Figure 26 shows where the major ports in the country are located.

Figure 26
Major ports[49]

Source: Homeland Infrastructure Foundation-Level Data, 2022.

4. Natural Gas Power Plants

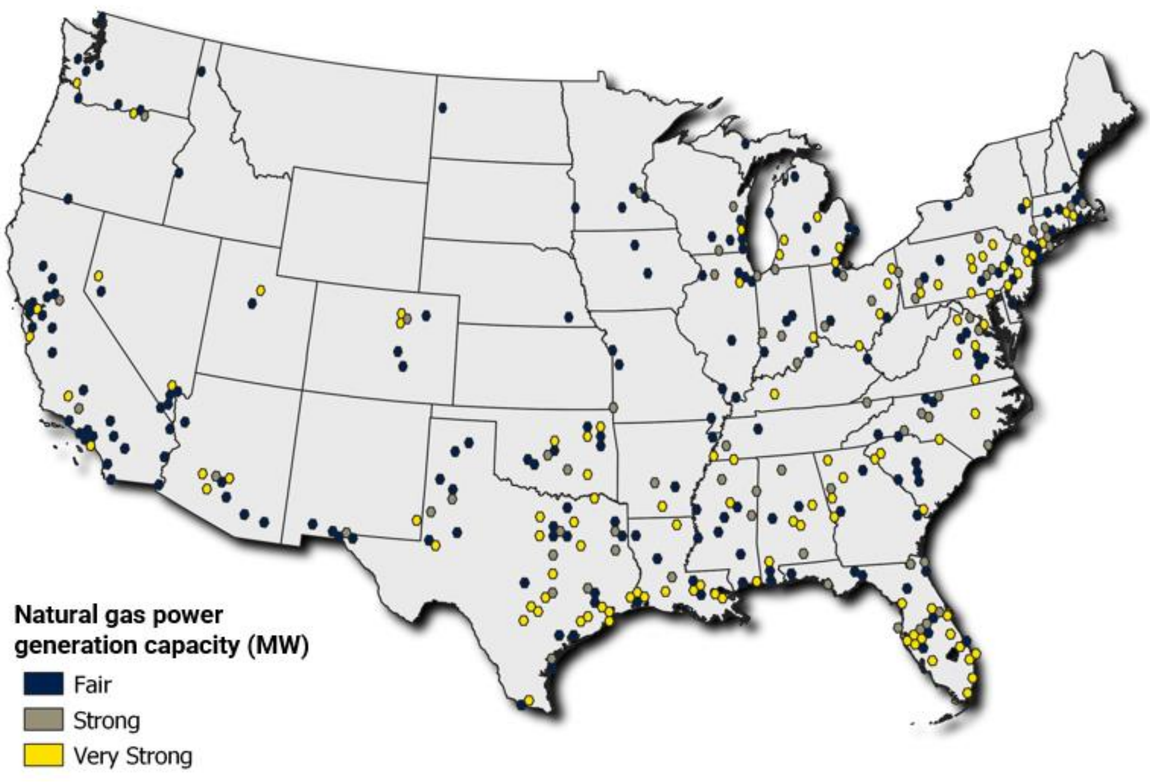
Thousands of natural gas power plants scattered across the United States could switch to hydrogen depending on the cost and duration of retrofits. In some cases, natural gas power plants already can use small blends of hydrogen with natural gas, and there are opportunities, albeit costly, to shift to 100% hydrogen. Even when costs are not considered, the amount of clean hydrogen needed to transition an average-sized plant to 100% hydrogen is not yet viable, considering it would require approximately 1% of the total hydrogen production in the United States to date.

Using WRI's global power plant database, HyTF identified the capacity in megawatts of each natural gas power plant.[50] Then, using GIS, the total capacity of natural gas power plants was found in each hex bin. In the HyTF interface, natural gas electricity generation capacity is classified as Very Strong, Strong, Fair, Less than Fair, or N/A. If a hex area receives an N/A, it means there are no identified natural gas power plants in the area. If it receives a Less than Fair designation, there is natural gas electricity generation capacity in the area, but it is less than the median amount relative to other hex areas with gas-powered generation. The distinction between Less than Fair and N/A is qualitative rather than quantitative, seeing as both are associated with scores of 0 in HyTF.

Fair means the hex area is between the median and third quartile relative to other hex areas with gas-powered generation. Very Strong highlights hex areas with gas-powered generation higher than the third quartile times 1.5. Naturally, Strong falls between Fair and Very Strong. Typically, outliers are calculated by multiplying 1.5 times the interquartile range plus the third quartile. However, the unconventional HyTF method allows more areas to qualify as Very Strong, while maintaining a certain level of exclusivity. Initially, an outlier calculation was used, and almost no area qualified as Very Strong. Hex areas that are at or above the median natural gas electricity generation capacity are normalized from 2 to 3 points in HyTF. Figure 27 shows the hex areas with natural gas electricity generation capacity at or above the median.

Figure 27

Natural gas plants' electricity capacity[51]



Source: World Resources Institute, 2021.

5. Grid Storage

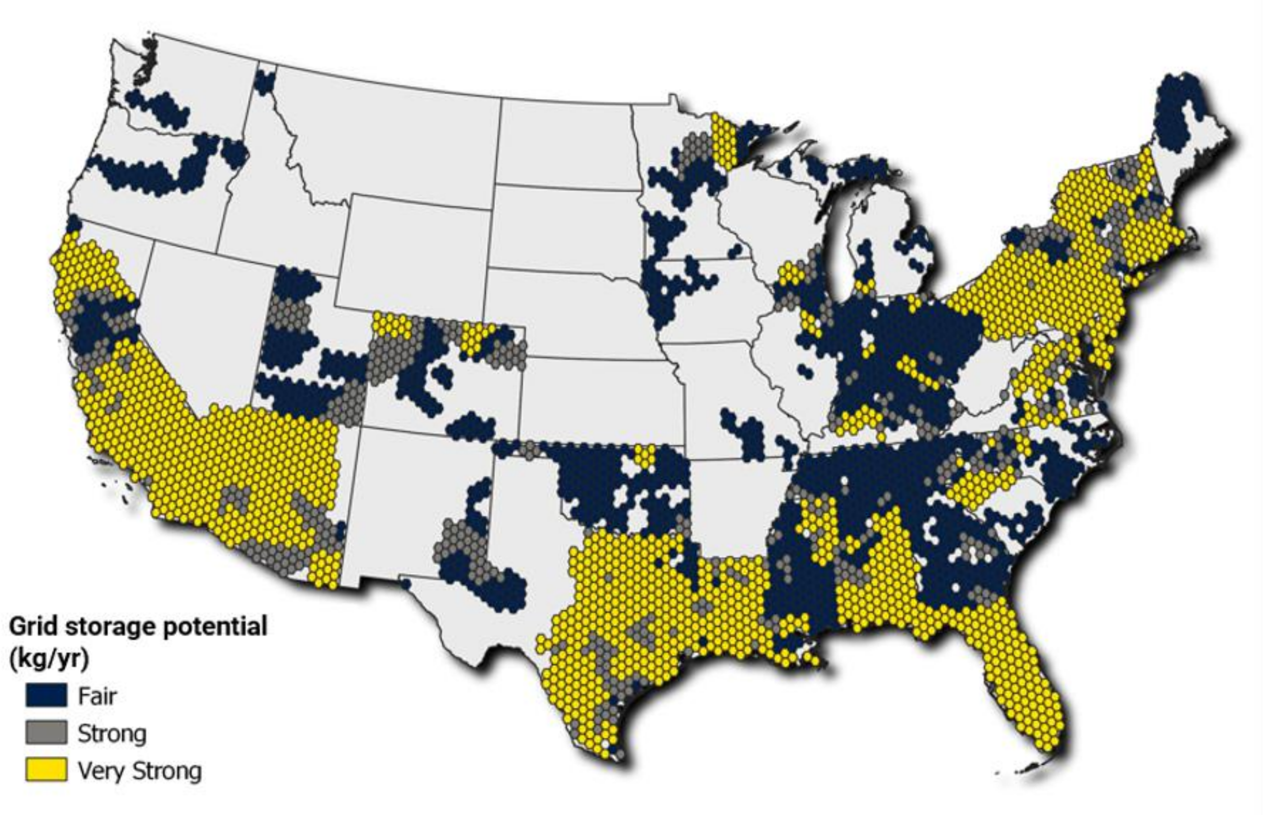
From a technical standpoint, hydrogen can act as a storage medium in ways batteries cannot—storing energy for weeks or months at a time to overcome seasonal weather and temperature changes. The National Renewable Energy Laboratory (NREL) calculated that the United States has the technical potential to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

Using NREL modeling outputs from the Regional Energy Deployment System (ReEDs) model, DOE found an estimated storage potential for hydrogen based on electricity generated with natural gas in a scenario with high penetration of variable renewables (i.e., solar and wind).[52] In such a scenario, natural gas is used sparingly at expensive rates and is highly emission intensive. By instead producing clean hydrogen to be stored for use during peak load hours at costs equivalent to running a peaker fossil plant, an electric grid can limit renewable energy curtailment. HyTF scores grid storage along a normalized score from 2 to 3 because of its medium-term potential.

In the HyTF interface, grid storage potential is classified as Very Strong, Strong, Fair, Less than Fair, or N/A. If a hex area receives an N/A, it means there is no identified grid storage potential in the area. If it receives a Less than Fair designation, there is grid storage potential in the area, but it is less than the median amount relative to other hex areas with grid storage potential. The distinction between Less than Fair and N/A is qualitative rather than quantitative, seeing as both are associated with scores of 0 in HyTF. Fair means the hex area is between the median and third quartile relative to other hex areas with grid storage potential. Very Strong highlights hex areas with grid storage potential higher than the third quartile times 1.5. Strong falls between Fair and Very Strong. Typically, outliers are calculated by multiplying 1.5 times the interquartile range plus the third quartile. However, the unconventional HyTF method allows more areas to qualify as Very Strong, while maintaining a certain level of exclusivity. Initially, an outlier calculation was used, and almost no area qualified as Very Strong. Figure 28 shows the hex areas with hydrogen grid storage potential at or above the median, according to DOE. As with any polygonal data (e.g., county-level) that does not fit into hex areas neatly, a hex will light up entirely if a particular data point fills more than 50% of its area. Likewise, a polygonal shapefile that does not fill at least 50% of a hex will not light up.

Figure 28

Grid storage technical potential[53]



Source: National Renewable Energy Laboratory, 2020.

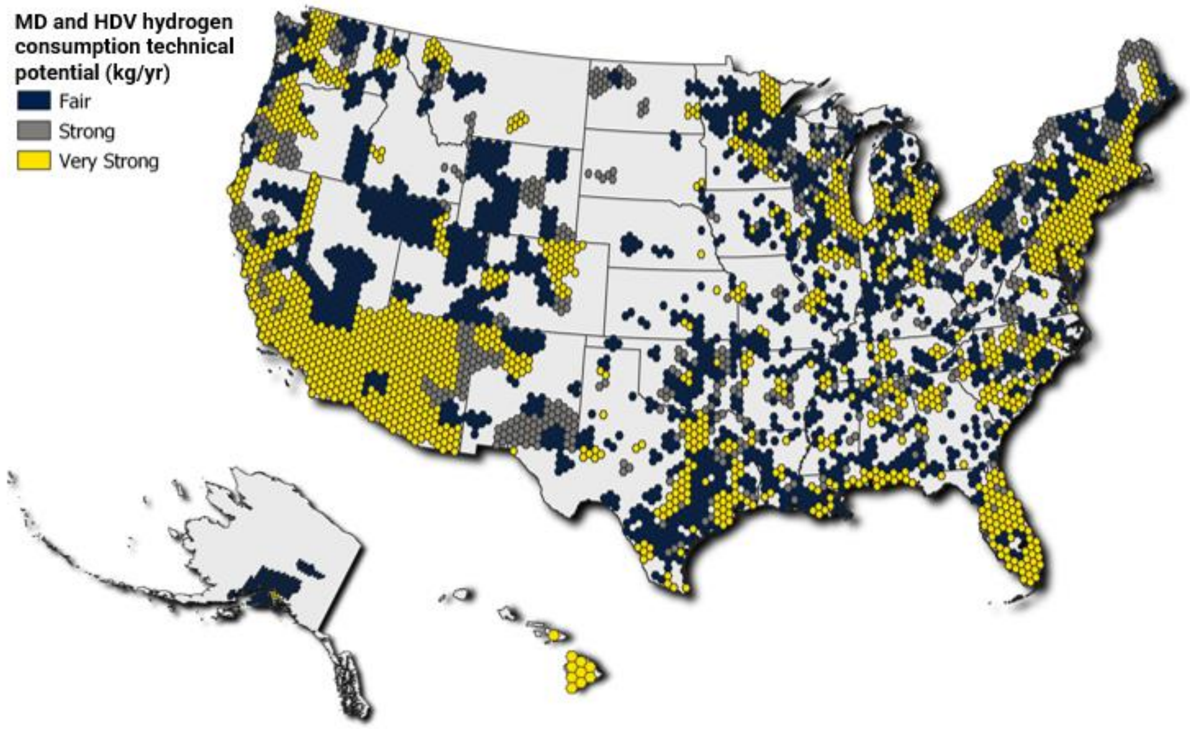
6. Medium- and Heavy-Duty On-Road Mobility

EFI research has found no evidence that a large-scale light-duty fuel-cell electric vehicles (FCEV) market will materialize in the United States. There may be opportunities, however, for limited medium- and heavy-duty vehicle (MDV and HDV) applications, depending on the region. Based on the market penetration rate of 35% for fuel cell vehicles in 2050, DOE estimates about 4.2 million MDVs and 2 million HDVs will be adopted. Fulfilling such demand would require 5.2 Mt of hydrogen annually. Using a market acceptance of advanced automotive technologies (ma3t) vehicle choice model, DOE subsequently projects adoption at a county level based on the percentage of zero-emission vehicles (ZEV) penetration that are FCEVs.[54] HyTF scores grid storage along a normalized score of 2 to 3 because of its medium-term potential.

In the HyTF interface, hydrogen fuel for on-road mobility potential is classified as Very Strong, Strong, Fair, Less than Fair, or N/A. If a hex area receives an N/A, it means there is no opportunity for FCEVs in the area. If it receives a Less than Fair designation, there is on-road mobility potential in the area, but it is less than the median amount relative to other hex areas with FCEV hydrogen consumption potential. The distinction between Less than Fair and N/A is qualitative rather than quantitative, seeing as both are associated with scores of 0 in HyTF. Fair means the hex area is between the median and third quartile relative to other hex areas with FCEV hydrogen consumption potential. Very Strong highlights hex areas with FCEV hydrogen consumption potential higher than the third quartile times 1.5. Naturally, Strong falls between Fair and Very Strong. Typically, outliers are calculated by multiplying 1.5 times the interquartile range plus the third quartile. However, the unconventional HyTF method allows more areas to qualify as Very Strong, while maintaining a certain level of exclusivity. Initially, an outlier calculation was used, and almost no area qualified as Very Strong. Figure 29 shows the hex areas with FCEV potential at or above the median, according to DOE. Because of its limited role in hydrogen market formation, on-road mobility potential should only be used to compare across different regions of the country. As with any polygonal data (e.g., county-level) that does not fit into hex areas neatly, a hex will light up entirely if a particular data point fills more than 50% of its area. Likewise, a polygonal shapefile that does not fill at least 50% of a hex will not light up.

Figure 29

Medium- and heavy-duty on-road mobility[55]



Source: Ruth et al., 2020.

Long-Term Demand (Commercialized After 2035)

1. Airports and Aviation

No proven business cases currently exist for hydrogen applications in aviation in the United States, and no fueling stations are available at any airports. Airports have run studies to prove the concept of hydrogen integration, though issues with hydrogen supply, terminal space, and infrastructure needs all prevented further analysis. Additionally, many opportunities for hydrogen integration in ground operations already have turned to battery electric technologies.[56] For airplanes in particular, the focus is mainly on sustainable aviation fuels (SAFs). If in the future hydrogen can fuel aviation technologies, the demand potential for airports and aviation is large. However, commercialization of such vessels is unlikely by 2050. Therefore, in this sector, demand is restrained to ground transportation, fueling, and hauling applications. HyTF gives a hex area with at least one major airport a score of 1 point to reflect the limited potential for hydrogen technologies in the long term. Figure 30 shows the location of these major airports using data from the Federal Aviation Association (FAA).

Figure 30
Airports[57]

Source: Federal Aviation Administration, 2021.

2. Biofuels Production

Biofuels are currently viewed as one of the primary options for replacing energy-dense fuels in heavy transportation applications, such as maritime and aviation. Since the production of biofuels, such as cellulosic ethanol, requires a carbon-intensive fermentation process, alternative technologies involving hydrogen, such as hydroprocess or hydrotreating biofuels, are under development.[58] One process, known as catalytic pyrolysis, develops bio-oil more efficiently because hydrogen chemically reacts with biomass, thus requiring no additional energy use while creating higher energy yields compared to traditional biofuel production processes.[59]

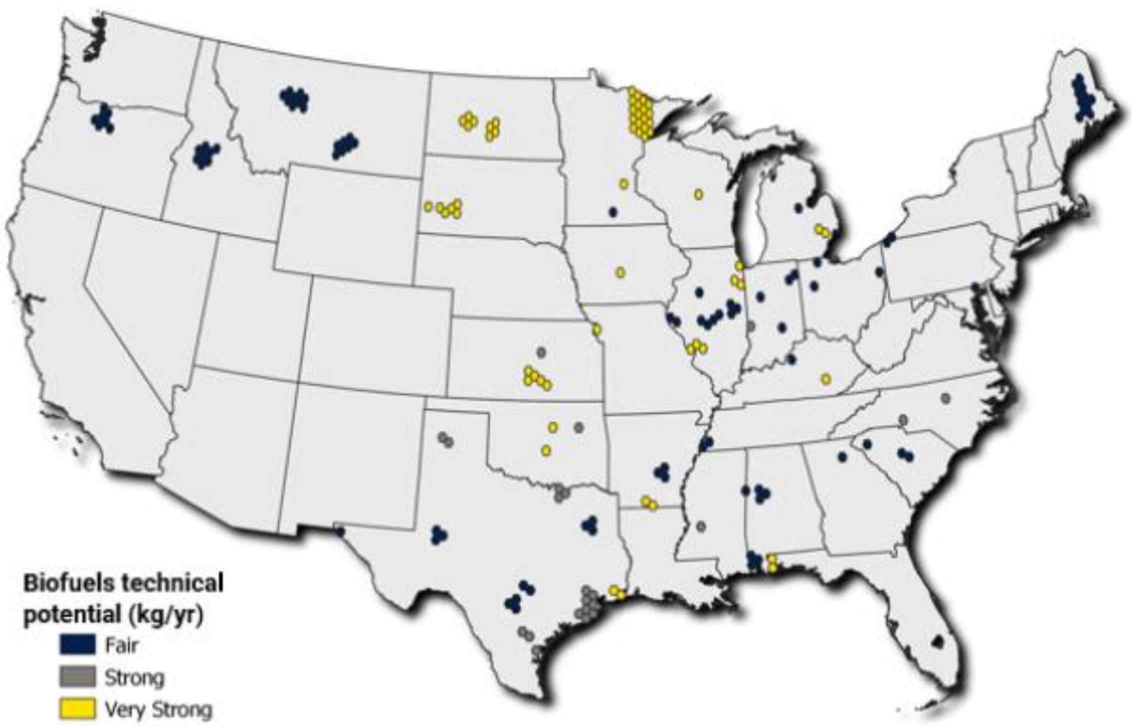
SAFs have the greatest use for hydrogen in biofuel production. NREL estimates a small portion of SAFs will be produced from hydrotreating fats, oil, and greases into diesel drop-in fuels, while the majority will be produced using catalytic pyrolysis of lignocellulosic biomass. NREL projected an annual serviceable consumption potential of 8.7 Mt of hydrogen will derive from the two processes. To distribute that potential geospatially, NREL found the distribution of available biomass based on the *Billion-Ton Report* DOE published in 2016, which makes assumptions about the location of biofuels production within a given state. In this case, biofuels are distributed to areas with refineries, ammonia plants, metals refining, and hydrogen production because of the available infrastructure to support a biofuel plant.[60] Because the SAF industry is still nascent (commercialization after 2040), and there is a high degree of uncertainty in the geographic distribution of biofuel plants, HyTF normalizes hex areas between 1 and 2 points if they are above the median hex area amount.

In the HyTF interface, hydrogen for biofuel production potential is classified as Very Strong, Strong, Fair, Less than Fair, or N/A. If a hex area receives an N/A, it means there is no opportunity for biofuels produced with hydrogen in the area. If it receives a Less than Fair designation, there is potential in the area, but it is less than the median amount relative to other hex areas with hydrogen-derived biofuel production potential. The distinction between Less than Fair and N/A is qualitative rather than quantitative, seeing as both are associated with scores of 0 in HyTF. Fair means the hex area is between the median and third quartile relative to other hex areas with hydrogen-derived biofuel production potential. Very Strong highlights hex areas with hydrogen-derived biofuel production higher than the third quartile times 1.5. Naturally, Strong falls between Fair and Very Strong. Typically, outliers are calculated by multiplying 1.5 times the interquartile range plus the third quartile. However, the unconventional HyTF method allows more areas to qualify as Very Strong, while maintaining a certain level of exclusivity. Initially, an outlier calculation was used, and almost no area qualified as Very Strong.

Figure 31 shows the hex areas with hydrogen-derived biofuel production potential at or above the median, according to DOE. As with any polygonal data (e.g., county-level) that does not fit into hex areas neatly, a hex will light up entirely if a particular data point fills more than 50% of its area. Likewise, a polygonal shapefile that does not fill at least 50% of a hex will not light up.

Figure 31

Biofuels production hydrogen consumption potential[61]



Source: National Renewable Energy Laboratory, 2020.

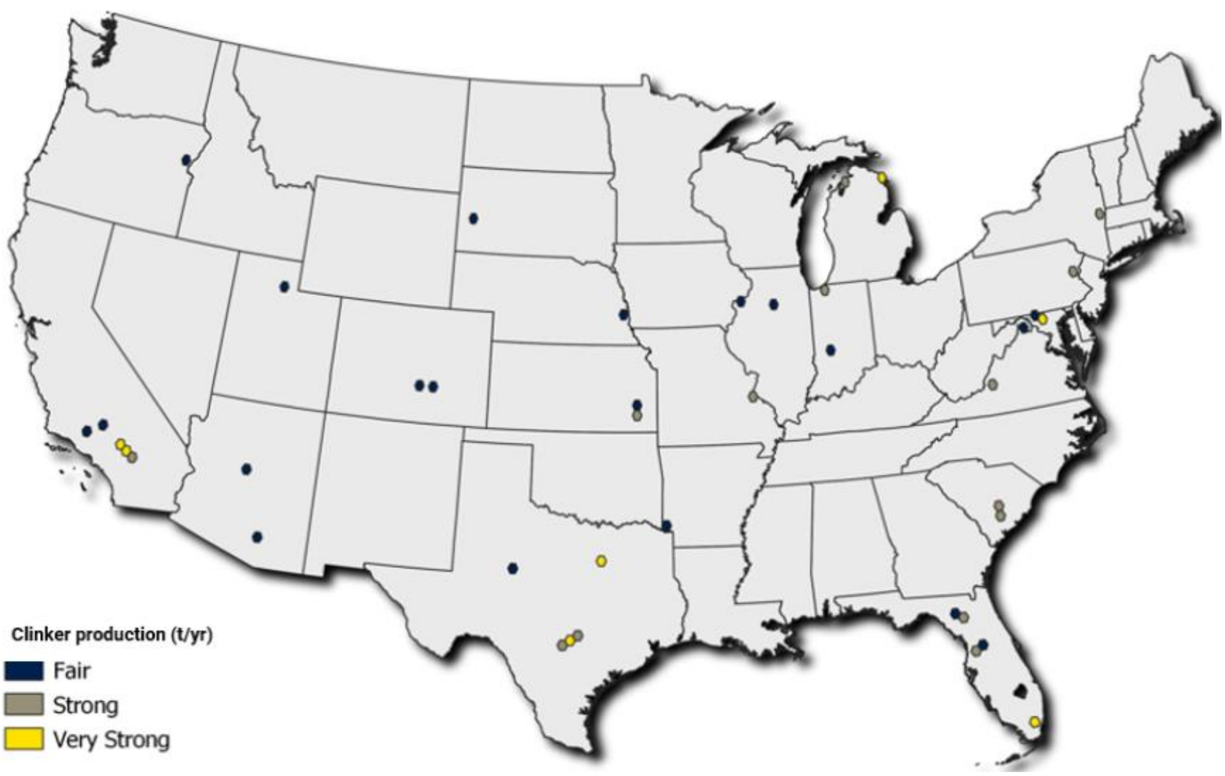
3. Cement Plants

The cement industry is the third largest energy consumer across the global industrial sector and responsible for approximately 7% of overall global emissions.[62] Cement production results in direct and indirect greenhouse gas (GHG) emissions. The former occurs from the chemical decomposition of limestone, known as calcination. The latter takes place when fossil fuels are used to generate high heat to produce clinker, the precursor to cement. Clinker is produced by mixing decomposed limestone with raw materials at a high temperature. Currently, coal is the most common fuel used to generate heat for clinker production. Coal decarbonized with CCS has the lowest cost increase per ton of clinker manufactured, followed by hydrogen produced from SMRs with CCS. Still, emissions reduction is limited because these pathways are restricted to process heat in clinker production, resulting in only a 30% reduction in total cement facility emissions.[63]

HyTF identified 91 cement plants and their estimated clinker production based on state-level data and the proportional emissions of each plant in that state.[64,65] Because fuel-switching to hydrogen cannot completely decarbonize clinker production, and using hydrogen to decarbonize process heat in clinker production is seen as a long-term solution (commercialization after 2040), HyTF gives hex areas with clinker production a normalized score between 1 and 2 depending on the overall production of that hex area.

In the HyTF interface, clinker production is classified as Very Strong, Strong, Fair, Less than Fair, or N/A. If a hex area receives an N/A, it means there is no clinker production in the area. If it receives a Less than Fair designation, there is clinker production, but it is less than the median amount relative to other hex areas with production. The distinction between Less than Fair and N/A is qualitative rather than quantitative, seeing as both are associated with scores of 0 in HyTF. Fair means the hex area is between the median and third quartile relative to other hex areas with clinker production. Very Strong highlights hex areas with clinker production higher than the third quartile times 1.5. Naturally, Strong falls between Fair and Very Strong. Typically, outliers are calculated by multiplying 1.5 times the interquartile range plus the third quartile. However, the unconventional HyTF method allows more areas to qualify as Very Strong, while maintaining a certain level of exclusivity. Initially, an outlier calculation was used, and almost no area qualified as Very Strong. Figure 32 shows the hex areas with clinker production in the United States.

Figure 32
Clinker production[66]



Source: Hatfield, 2022.

Interests

A successful regional hydrogen hub cannot rely only on resources and demand to develop a market. Human capital plays an integral role in whether a region can develop the proper governance and business models to fulfill the requirements established in the funding opportunity announcement (FOA) for H2Hubs. Interests, defined as the private companies and governments with business activities and/or interests related to clean hydrogen development, are important to stimulate supply and demand. In HyTF, interests are classified as private sector, public sector, or at the intersection of the two (public-private partnerships). HyTF considers large investor-owned utilities and S&P 500 companies with clean hydrogen activity as private sector. The public sector refers to state governments with favorable climate policies. The intersection of the two includes public-private partnerships: government grants, loans, and direct payments, as well as Small Business Innovation Research (SBIR) awards pertaining to hydrogen. Elements within interests are scored between 1 and 5 points, as shown in Table 6.

Table 6

Scoring the interests category

Category: Enabling Resources		
Element	**Points**	**Explanation**
Small Business Innovation Research (SBIR) award	1	Hex area receives point for each SBIR received
Federal government grants, direct payments, and loans	1 to 2	Hex area receives a normalized score between the smallest funding and largest funding amounts
Invest-owned utilities with hydrogen interest and activity	3	Hex area receives 3 points if it contains the service area of one of the identified utilities
S&P companies with hydrogen interest and activity	3 to 4	Hex area receives a normalized score between the smallest and largest market capitalization of a company considered, based on the location of the company’s headquarters

State climate policy	4 to 5	Hex area receives 4, 4.5, or 5 points based on an external resource's state climate policy impact scoring system

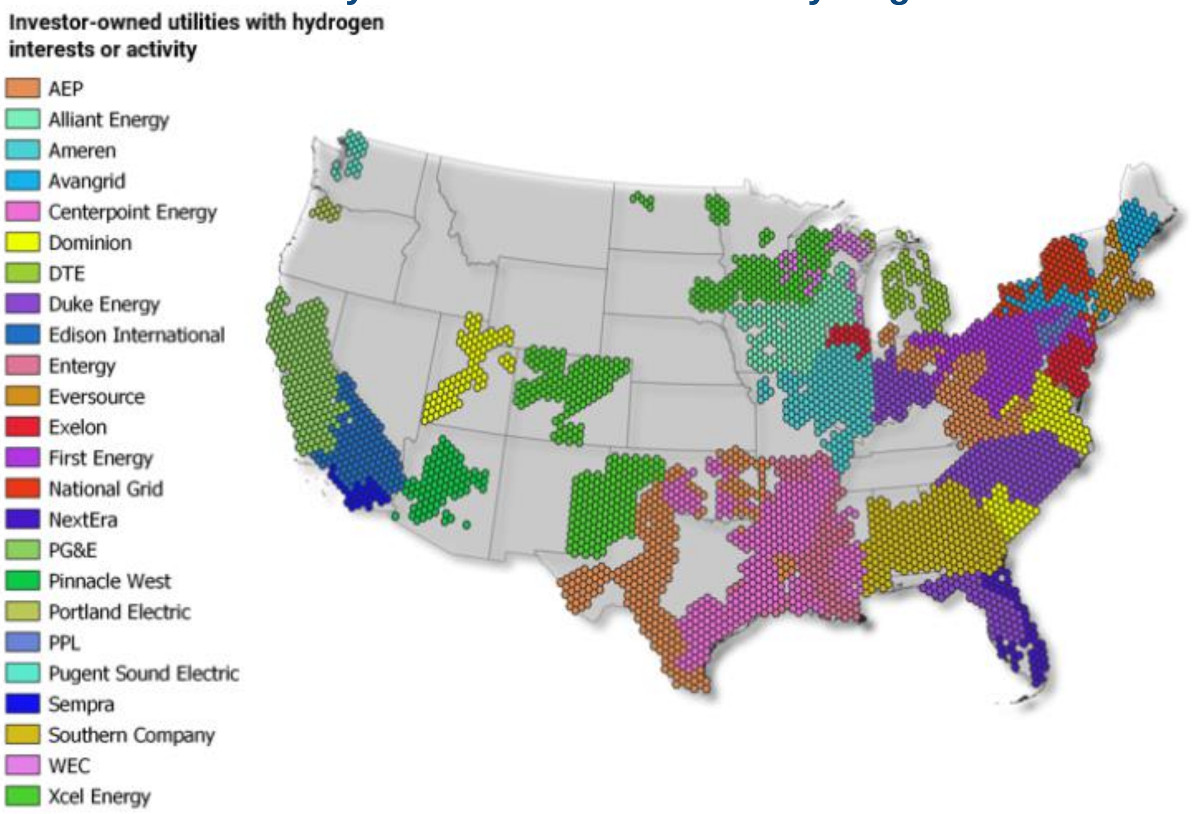
1. Investor-Owned Utilities

Utilities have a large interest in hydrogen along their value chain, including for energy storage, pipeline blending and residential heating, nuclear applications, and curtailment of renewables. An analysis of investor-owned utilities found at least 24 major utilities with ongoing or planned hydrogen activity. Those utilities' service territories are integrated into HyTF's hex areas to represent their interest in hydrogen development. Municipal utilities and utilities with small market capitalization were not considered in the analysis. In discussions with relevant industry stakeholders, EFI found utilities are among the most important businesses propelling clean hydrogen activity in the United States. Thus, service areas of a large investor-owned utility with hydrogen interest or activity score 3 points. The score indicates that while important, HyTF should not overly bias the service areas of utilities with hydrogen interest or activity because they are geographically extensive, and utilities may have assets outside their service territories as well. In other words, a service area is a fine but not all-encompassing proxy for mapping utility hydrogen activity or interests.

Figure 33 shows the landscape of relevant utility service territories integrated into HyTF hex area format. For specific details on a utility's interest or activity, the user can refer to the data downloads within the "Interest" pop-up window in the tool. Utility polygonal data is treated slightly differently than other polygonal data in HyTF. If there are several utilities within one hex area, the hex will be associated with whichever utility's service territory takes up the largest percentage of the hex.

Figure 33

Investor-owned utility service territories with hydrogen interest or activity[67]



Source: EFI Foundation, 2023.

2. S&P 500 Companies with Hydrogen Interest

The S&P 500 is an index that tracks the stock performance of 500 of the largest publicly traded U.S. companies. It is used to define the dominant industries in the U.S. economy.[68] As such, the S&P 500 contains many of the largest companies in the United States that would have a major impact on a clean hydrogen economy if they pursued hydrogen projects and partnerships. An analysis of all S&P 500 companies found that approximately 78 of these organizations have publicly announced activities or interest in clean hydrogen. All these companies fall under the S&P Global Industry Classification Standard (GICS) for industrial, energy, or utilities sectors.[j] In HyTF, S&P 500 companies are normalized by market capitalization and given a score between 3 and 4 points. Figure 34 shows the location of the relevant company headquarters. For specific details on a company's interest or activity, the user can refer to the data downloads within the "Interest" pop-up window in HyTF.

[j] Because of their significance, utilities were evaluated separately and are not part of this element despite their inclusion in the S&P 500 index.

Figure 34

Location of S&P 500 company headquarters with hydrogen interest or activity[69]

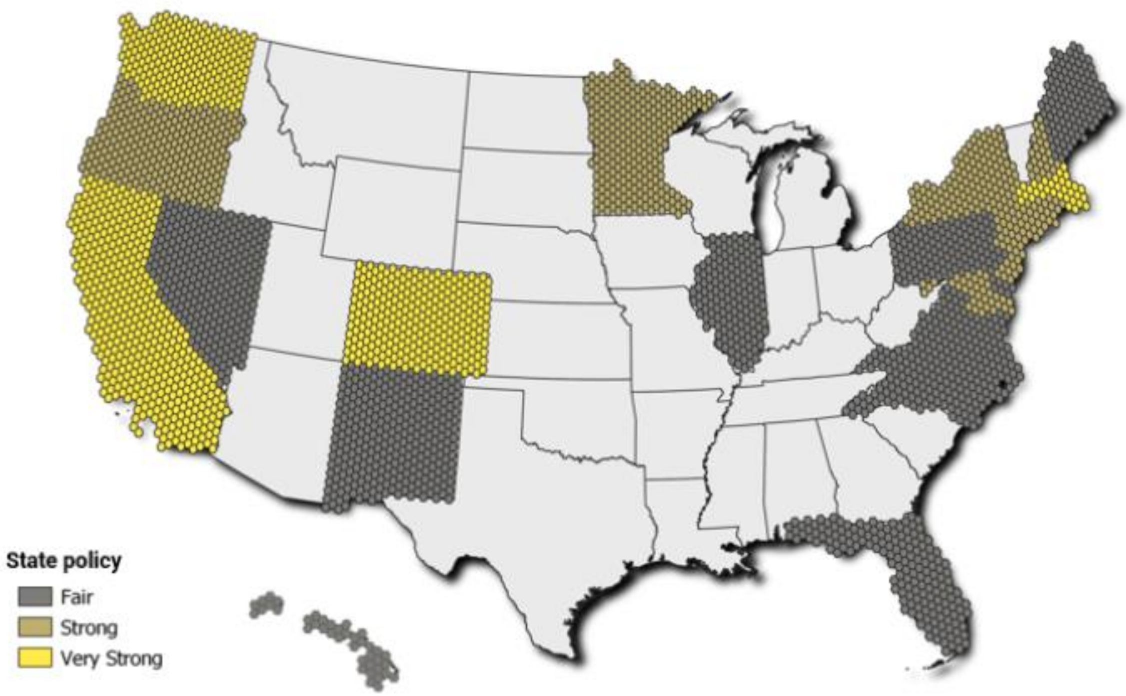
Source: EFI Foundation, 2023.

3. State Climate Policy

EFI's workshop report *The Potential for Clean Hydrogen in the Carolinas* noted long-term policy support is a requisite of hydrogen market growth.[70] The juxtaposition of states with strong and weak climate policy highlights the importance of state governments in meeting emissions reduction objectives. HyTF uses Climate Xchange's geospatial data to assess the strength of a state's climate policy (Figure 35).[71] Strong state policy is scored the highest relative to other elements in the Interests category because of the role it plays in setting targets, reducing uncertainties, holding stakeholders accountable, and stimulating growth of clean energy technologies such as hydrogen. Climate Xchange measures the "amount" of climate policy passed to date in a state relative to other states, as well as those policies' impact. For a state to have a Fair amount of climate policy means that state has passed more climate policies than at least 28 other states. States with Very Strong climate policy score 5 points, those with Strong climate policy score 4.5, and states with Fair climate policy score 4 points in the HyTF interface. Because HyTF leverages another resource's weighting system, state policy is the only element where Very Strong, Strong, Fair, and Less than Fair are used in this way. When hex areas in HyTF cross state lines, the state that takes up the greatest percentage of that hex's area determines which state it is associated with.

Figure 35

Relative strength of state climate policy[72]



Source: Climate Xchange, 2022.

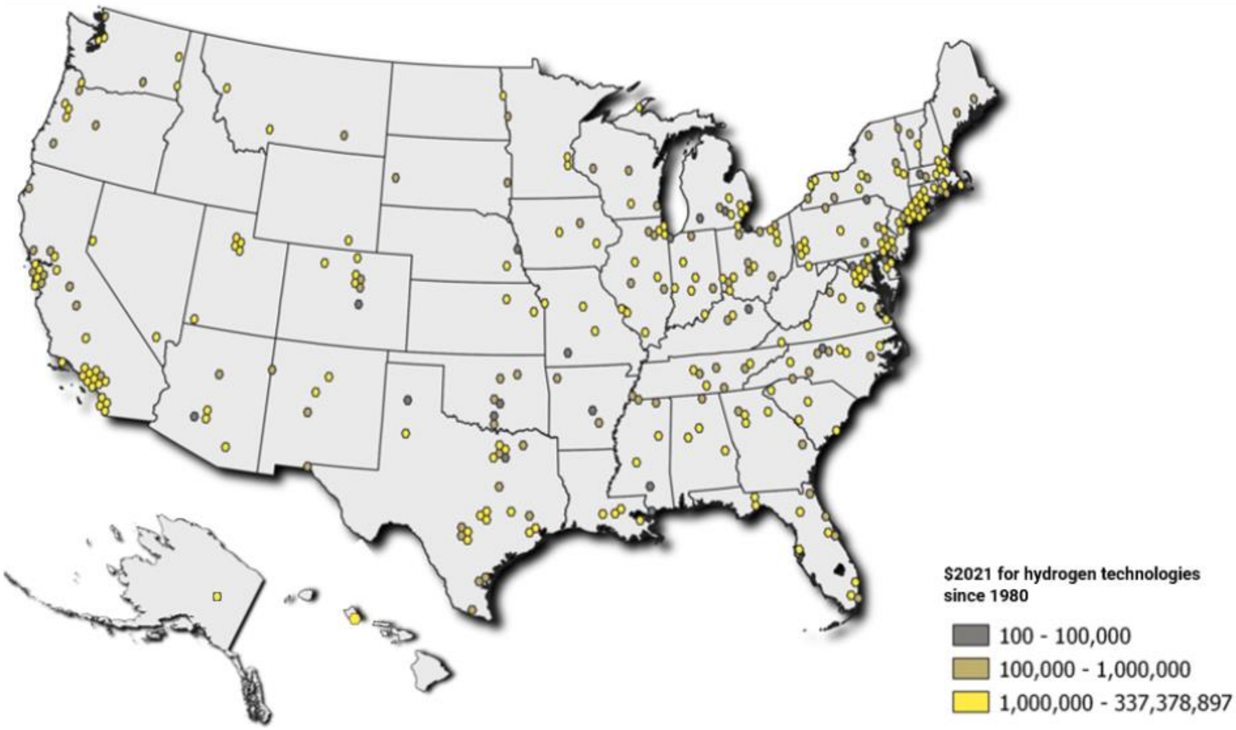
4. Federal Government Grants, Direct Payments, and Loans

Financial assistance from the federal government can stimulate research and development (R&D), help bridge the investor's "valley of death,"[k] and support the growth of a nascent but important industry. Hydrogen projects have received federal funding since 1980 across the value chain, according to USASpending.gov. Using keywords "hydrogen," "electrolysis," and "fuel cell," HyTF identified more than 1,800 projects relevant to hydrogen technology. More than 300 projects were screened out from the database for various factors (e.g., projects with $0 in funding). HyTF turns point data into cumulative dollar amounts (in 2021 dollars) for a given hex area and shows that total amount in the "Interest" pop-up window.[73] Hex areas with federal funding for hydrogen receive a normalized score between 1 and 2 points, depending on how much funding is recorded on USASpending.gov relevant to hydrogen

[k] In finance, the valley of death refers to the stage of a company's life cycle where it faces a lack of funding after early stage investment, heightening the risk of failure.

technologies since 1980. Figure 36 shows the distribution of federal direct payments, grants, and loans.

Figure 36
Federal government grants, direct payments, and loans[74]



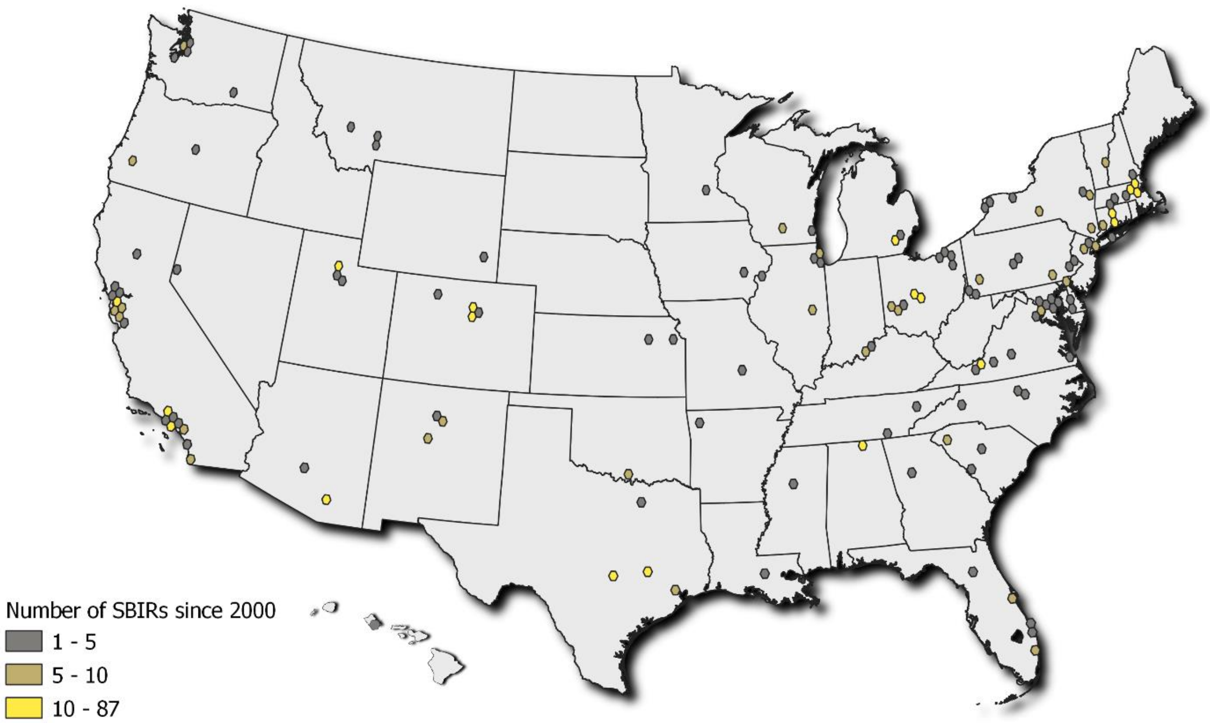
Source: U.S. Government, 2022.

5. Small Business Innovation Research (SBIRs) Awards

The SBIR and Small Business Technology Transfer (STTR) programs encourage small businesses to engage in federal R&D and help different technologies reach commercialization. Importantly, this competitive program builds up the technological potential of small businesses and provides an incentive for companies to benefit from R&D. For STTRs, small businesses also partner with non-profit research institutions that primarily bridge the basic science stage to commercialization.[75] In HyTF, the location of these programs represents areas of hydrogen entrepreneurship and innovation. HyTF identified 2,045 SBIRs and STTRs from 2000 to 2021 with the title keywords of “hydrogen,” “fuel cell,” and “electrolysis.”[76] Each award within a hex area receives 1 point because the projects are typically small in scale and relatively little federal R&D has focused on the commercialization of clean hydrogen technologies to date. Figure 37 identifies the areas that received SBIRs and provides a glimpse into those areas that have received more awards than others.

Figure 37

Hydrogen small business innovation research awards[77]



Source: Small Business Administration, 2022.

Capabilities

This HyTF category fleshes out important human capital elements that can be leveraged to catalyze resources or demand potential in an area. HyTF defines capabilities as the enabling systems that could support hydrogen investments. As such, the capabilities category encompasses the expertise and experience that can be used to innovate, educate, or provide necessary skills to the clean hydrogen economy. It includes universities, technical and community colleges, a labor pool capable of transitioning to a hydrogen economy, a track record of hydrogen technology patents, and the 17 national laboratories around the country. EFI's workshop report *The Potential for Clean Hydrogen in the Carolinas* found centers of innovation and a skilled labor force are important enablers of a clean hydrogen hub.[78] In other words, if an area has strong resources, demand, and capabilities, there is great potential for a hydrogen hub to materialize. The capabilities elements of HyTF are described below. Elements within capabilities are scored between 1 and 8 points. The variance in points between elements is higher than in any other category, which is due to the importance and rarity of a couple of primary elements in this section. Table 7 describes the scoring system for capabilities.

Table 7

Scoring the capabilities category

Category: Enabling Resources		
Element	**Points**	**Explanation**
Patents	1	Hex area receives a point for each patent received
Technical and community colleges	1	Hex area receives a point for each community or technical college
Non-R1 research universities	1 to 2	Hex area receives a normalized score between the smallest and largest university by research budget
Skilled labor	2 to 4	Hex area receives a normalized score between the median and maximum number of hydrogen-adjacent jobs per 1,000 people
Tier 1 research universities	4 to 8	Hex area receives a normalized score between the smallest and largest university by research budget
National laboratories	8	Hex area receives 8 points per laboratory

1. Education Centers

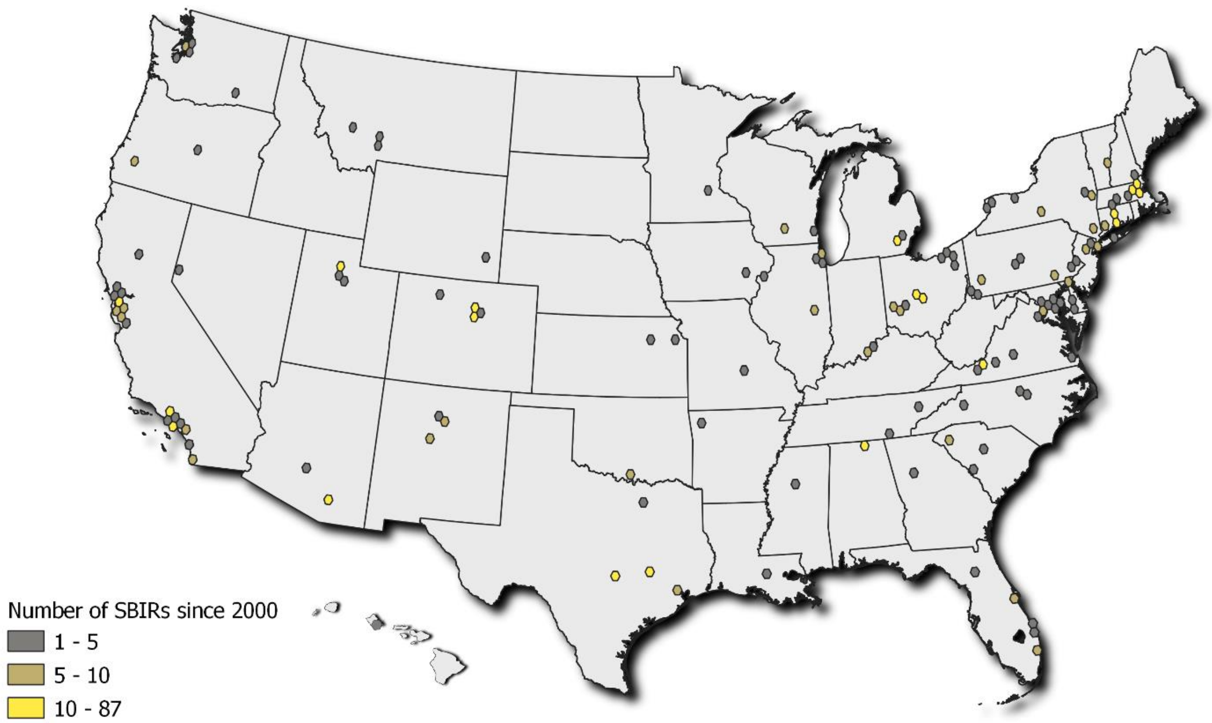
Tier 1 Research Universities

The Carnegie Classification of Institutions of Higher Education regards 146 schools as having “very high research activity in 2021.”[79] These universities, sometimes known as R1 universities, are designated as such if they: award at least 20 research/scholarship doctoral degrees in a given year; spend at least $5 million in total research (as reported through the

National Science Foundation Higher Education Research and Development Survey—HERD); and score high in a research activity index calculation. HyTF uses the HERD survey to identify R&D expenditure data for each school and geolocate them accordingly.[80] Schools were considered if at least one of the following scientific areas with potential hydrogen applications received some funding: geosciences, atmospheric sciences, ocean sciences, physical sciences, social sciences, and engineering. HyTF does not consider higher education schools with a focus on health sciences or medical, pharmaceuticals, cosmetics, hair, military, optometry, or dental training.

Tier 1 University R&D receives a normalized score between 4 and 8 points, depending on the total relevant R&D dollars in a hex area. Schools with energy research programs do not receive additional weight within capabilities, but they are identified in HyTF as potential institutions for clean hydrogen funding to flow through. Figure 38 shows R&D funding for Tier 1 universities across the country.

Figure 38
Tier 1 university R&D dollars[81]



Source: National Science Foundation, 2022.

Other Research Universities

Other universities include the list of remaining universities on the HERD survey—those research schools not designated as R1. These schools are included in the capabilities category because of their importance on two fronts: additional research capabilities and their contributions to an educated and skilled workforce. The other universities list contains 426 schools.[82] Hex areas with these other schools receive a normalized score between 1 and 2 points depending on their R&D budgets for science and technology, recognizing they do not have the capital or funds of R1 universities. Figure 39 shows the distribution of these other research universities across the country.

Figure 39

'Other' university R&D dollars[83]

Source: National Science Foundation, 2022.

2. Skilled Labor

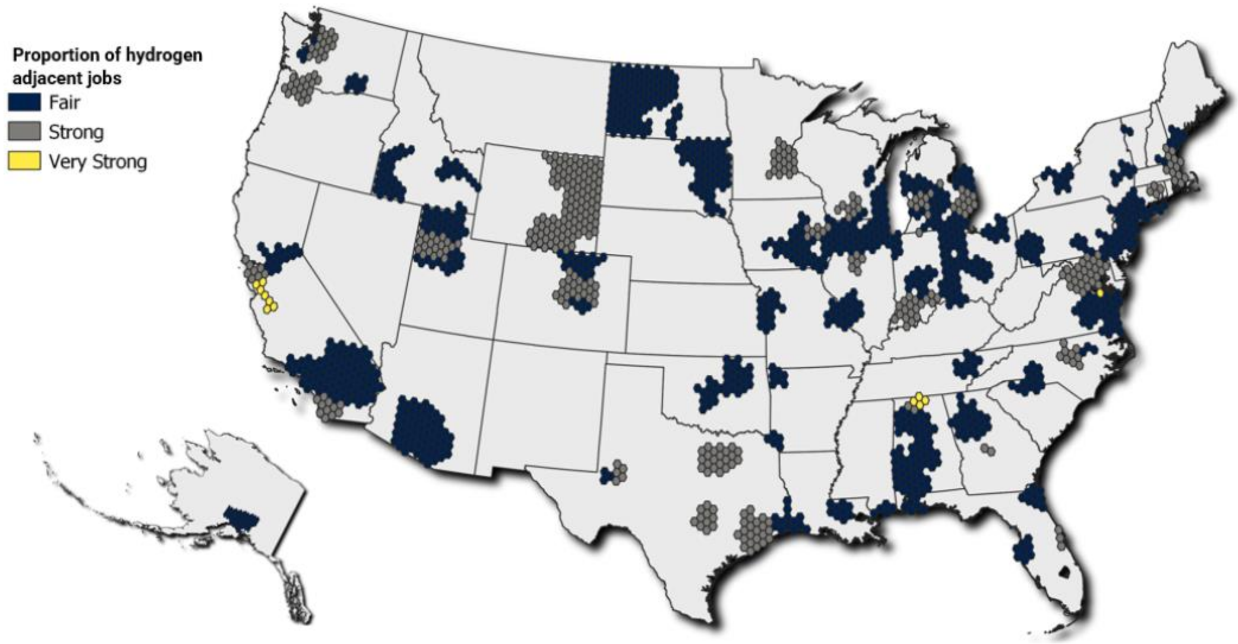
Bureau of Labor Statistics Regions with High Proportion of Adjacent Hydrogen Jobs/Skills

The classification of a relatively skilled or non-skilled area in the United States is an innovative feature of HyTF, which combines DOE's "Hydrogen and Fuel Cells" career map with the North American Industry Classification System (NAICS) data from the Bureau of Labor Statistics (BLS) at the metropolitan and nonmetropolitan area levels. DOE's career map profiles many hydrogen and fuel cell careers, or potential careers. Advanced careers include roles such as engineering manager, finance manager, attorney, regulatory expert, economist, site/plant manager, asset manager, budget analyst, communication manager, and professor. Mid-level roles include chemical engineers, material scientists, environmental scientists, software engineers, civil engineers, research engineers, environmental engineers, electrical engineers, mechanical engineers, project managers, safety and occupational health specialists, computational scientists, buyers, industrial engineers, power systems/transmission engineers, sales engineers, power marketers, logisticians, public affairs specialists, editors, and writers. Entry-level roles include electricians, instrumentation and electronics technicians, advanced manufacturing technicians, assemblers and fabricators, computer numerical control operators, plant operators, industrial equipment mechanics, legal assistants, salespersons, trade workers, construction workers, transportation workers, and educational aids).[84]

In HyTF, areas are classified as Very Strong, Strong, Fair, Less than Fair, or N/A. If a hex area receives an N/A, there is no identified hydrogen-adjacent work in the area. If it receives a Less than Fair designation, there are fewer than the median number of hydrogen-adjacent jobs in the area. The distinction between Less than Fair and N/A is qualitative rather than quantitative, seeing as both are associated with scores of 0 in HyTF. Fair means the hex area is between the median and third quartile. Very Strong highlights hex areas with a proportion of hydrogen-adjacent jobs, higher than the third quartile times 1.5. Strong falls between Fair and Very Strong. Typically, outliers are calculated by multiplying 1.5 times the interquartile range plus the third quartile. However, the unconventional HyTF method allows more areas to qualify as Very Strong, while maintaining a certain level of exclusivity. Initially, an outlier calculation was used, and almost no area qualified as Very Strong. The data on proportion of hydrogen-adjacent jobs at the metropolitan and nonmetropolitan level can be found under the “Capabilities” dropdown menu in HyTF. HyTF awards hex areas a normalized score between 2 and 4 points, depending on the number of hydrogen-adjacent workers per 1,000 residents in the area. Figure 40 shows the areas with the highest proportion of hydrogen-adjacent jobs.

Figure 40

Proportion of hydrogen-adjacent jobs[85]



Source: Bureau of Labor Statistics, 2022.

Each career listed has an NAICS-adjacent job code from the BLS. While not a perfect one-for-one, for every metropolitan and nonmetropolitan census area, EFI evaluated the proportion of people in hydrogen-adjacent sectors per 1,000 people.[86] This way, rural areas do not get devalued in the HyTF scoring system because they have fewer people. The jobs considered hydrogen-adjacent are shown in Table 8.

Table 8

Hydrogen-adjacent jobs[87]

Jobs	NAICS Code
Operations research analyst	152031
Budget analyst	132031
Public relations specialist	273031
Chemical engineer	172041
Environmental engineer	172081

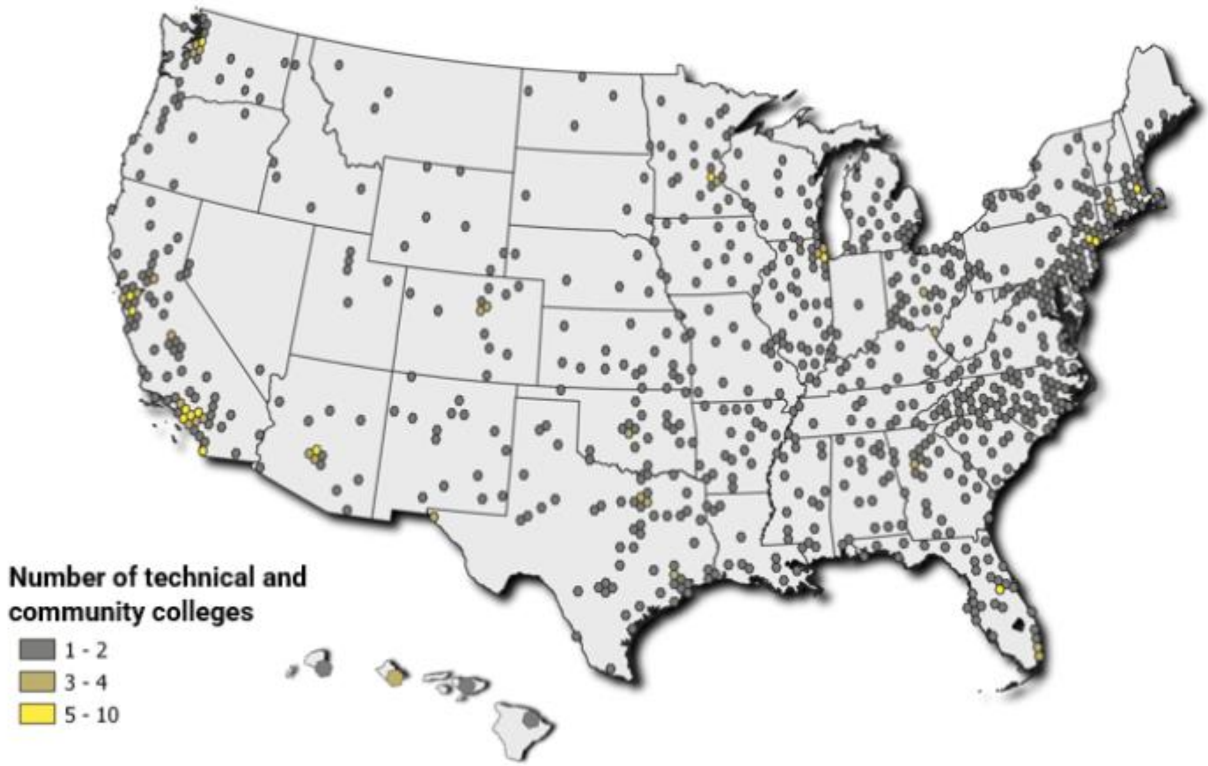
Computer programmer	151251
Software developer	151252
Software assurance	151253
Electrical engineer	172071
Electronics engineer	172072
Civil engineer	172051
Industrial engineer	172112
Health safety engineer	172111
Mechanical engineer	172141
Lawyer	231011
Legal assistant	232011
Engineering manager	119041
Financial manager	113031
Project manager	131082
Logistician	131081
Buyer	131020
Sales manager	112022
Sales rep tech and science	414011
Sales engineer	419031
Material scientist	192032
Power plant operator	518013
Geologic engineer	172171
Nuclear engineer	172161
Chemist	192031
Construction manager	119021

Construction equipment operator	472073
Electrician	472111
Occupational health and safety	195012
Crane and tower operator	532071
Dredge operator	537031
Hoist and winch operator	537021
Industrial truck driver	537051
Extruding metals	514021
Furnace, kiln, and oven operator	519051
Surveyor	171022
Sheet metal worker	472211
Structural iron and steel worker	472221
Solar photovoltaic installer	472231
Wind service technician	499081
Industrial machine mechanic	499041
Power line installer	499051
Welder	514121
Assembler and fabricator	512090

HyTF identified 1,040 technical, trade, and community colleges with student populations greater than 1,000 and at least one sciences program.[88] Community and technical colleges offer a wide range of opportunities, especially for financially disadvantaged students. Each community college receives 1 point within a hex area, but hex areas with multiple community colleges can score very high. For example, one hex area has 10 community colleges, which contributes to the hex lighting up as “Excellent.” The affordable education provided to a diverse pool of students is an important aspect of developing a labor force ready to contribute to this new energy commodity market. Figure 41 shows community and technical colleges throughout the country.

Figure 41

Community and technical colleges[89]



Source: U.S. Department of Education, 2022.

3. Hydrogen Patents

Locating areas where hydrogen technology innovation occurs enables us to understand if a region has the capabilities to develop a hub. Using the U.S. Patents and Trademarks Office (USPTO) Patents View, HyTF draws geospatial data for each patent based on the location of the patent assignee and the keywords “hydrogen,” “fuel cell,” and “electrolysis.” Additionally, the Cooperative Patent Class was specified as “Y02E,” which designates all patents related to the “reduction of GHGs, energy generation, or transmission and distribution.”[90] The nearly 2,000 patents in HyTF extend back to 1976, and each hex area receives 1 point for each patent. Multiple patents may result in the hex area lighting up as “Excellent.” For instance, one area in HyTF includes more than 190 patents fitting that description. Figure 42 highlights the distribution of these patents across the country.

Figure 42
Hydrogen patents[91]

Source: U.S. Patent and Trademark Office, 2021.

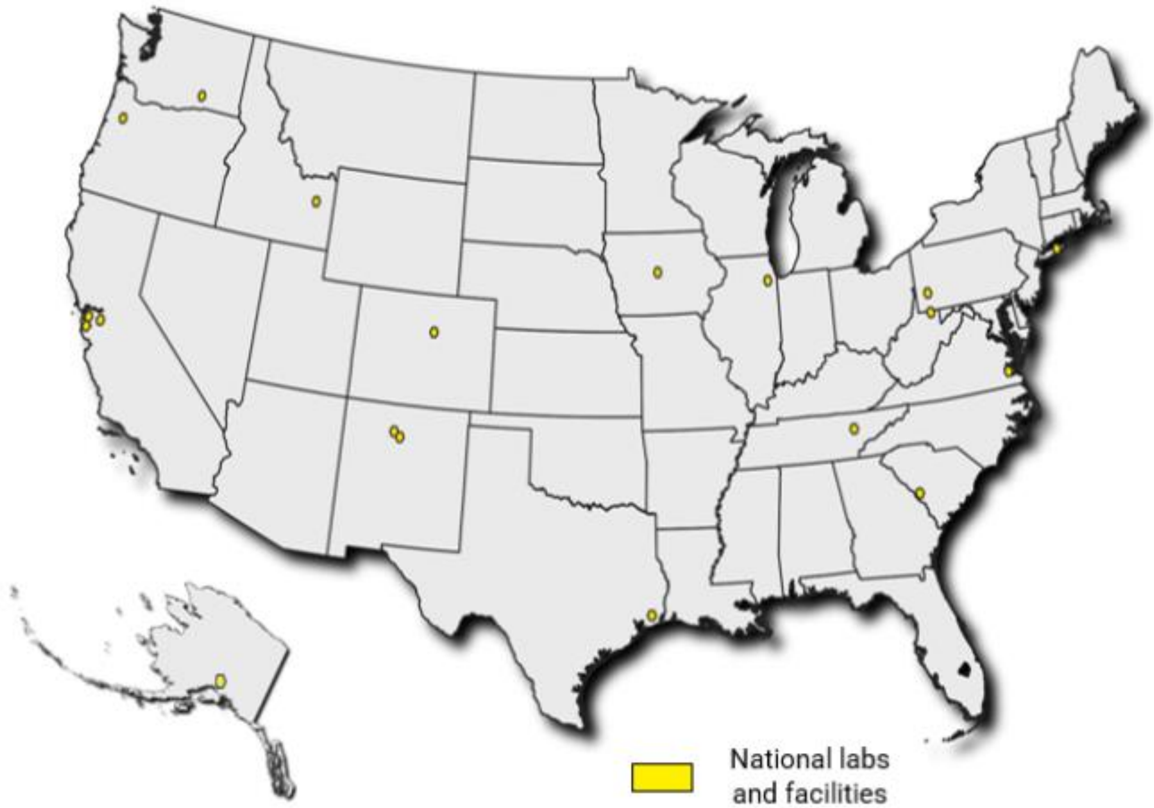
4. National Laboratories

HyTF provides the location of all DOE national laboratories.[l] The laboratories are important for this framework because researchers are developing new energy technologies, advancing the frontier of scientific discovery, protecting national security, incubating new industries, and fostering the next generation of scientists and engineers. Many have activities directly influencing hydrogen research and development worldwide. To ensure they appear in HyTF, they score the highest among elements in the capabilities category, with 8 points for each lab. Because of the nature of the locations for the national laboratories, there might not be a lot of other activity to draw upon. Still, with only a few labs scattered across the country, a region with a national laboratory has an advantage for the innovation plan of a hub design. Figure 43 shows the hex areas in which each lab is located.

[l] Includes National Energy Technology Laboratory (NETL) facilities in Texas and Alaska.

Figure 43

National labs with activity relevant to hydrogen[92]



Source: The National Laboratories, 2023.

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