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RECOMMENDATIONS FOR A US NORTHEAST HYDROGEN HUB

By Joseph Webster

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Table of Contents

RECOMMENDATIONS FOR A US NORTHEAST HYDROGEN HUB

Executive Summary

The hydrogen future appears to be in sight. Russia's invasion of Ukraine and the Inflation Reduction Act (IRA) have turbocharged investments in renewables and green hydrogen, and, potentially, served as tipping points in the energy transition. While hydrogen supply chains remain in their infancy and are subject to geopolitical risks, the energy sector appears poised to begin developing green hydrogen at scale, both domestically and internationally. To spur domestic hydrogen production, the US Department of Energy is awarding $8 billion to at least four hydrogen hubs across the United States. This paper will address the opportunities and challenges associated with a potential hydrogen hub in the northeastern United States, defined as Connecticut, Maine, Massachusetts, New Jersey, New York, and Rhode Island.

The northeast hydrogen hub enjoys several critical advantages and hydrogen-enabling conditions. Due to excellent offshore wind resources and substantial political support for clean energy, the northeastern hub states have set goals of collectively installing more than thirty-five gigawatts (GW) of offshore wind (OSW) generation capacity by 2035.[1] Having become the nation's leader in offshore wind development, the northeast is poised to leverage these resources to produce hydrogen. In addition, the region is in dire need of solutions that could limit electricity prices, as the northeast has some of the nation's highest electricity prices, particularly during winter peak-demand periods. Hydrogen's interseasonal storage capabilities could dampen regional electricity prices by shifting electrons generated from off-peak seasons to peak winter demand. A regional hydrogen-supportive supply chain is emerging, as the northeast possesses an electrolyzer industry and is developing several offshore wind ports. Moreover, the region enjoys a variety of use cases for hydrogen deployment, including blending in existing natural gas pipelines; desulfurization in refineries; industrial uses, such as steel and cement; and, potentially, over the long term, maritime transport. Finally, the region's world-class education system offers a unique—if potentially underappreciated—advantage in the hydrogen race. The northeast is one of the world's leaders in producing science, technology, engineering, and mathematics (STEM) graduates, enabling it to research, develop, and quickly absorb new technologies—including hydrogen.

While the northeast's prospective hydrogen has key advantages, it must also overcome several challenges. Green hydrogen may be most suitable for the northeast, but the region's onshore wind and solar resources that could power hydrogen production are constrained by unfavorable geography; offshore wind projects in the Atlantic Ocean could face scheduling setbacks; and New York's Great Lakes OSW potential might never reach fruition. Hydrogen demand also faces uncertainties over what percentage of hydrogen can be blended into existing natural gas infrastructure. Finally, there are unresolved questions in the hydrogen regional midstream economy surrounding regional storage, hydrogen pipeline blending vs dedicated pipelines, and cast-iron pipelines.

The report recommends that northeastern policymakers consider the following steps.

- Support and accelerate clean energy production. Additional offshore wind—and nuclear energy—capacity is crucial to maximizing local green hydrogen production. The region cannot produce blue hydrogen indigenously, while importing green hydrogen at scale from maritime sources will prove infeasible for years, probably more than a decade. The region is supporting Atlantic Ocean OSW through procurement contracts and infrastructure build-out, but it should also consider expanding Great Lakes OSW and nuclear energy capacity, to the greatest extent feasible.

- Nimbly adapt policy to meet changes in hydrogen technology. Policymakers must navigate uncertainty surrounding cutting-edge hydrogen technology, but also respond rapidly and decisively to changing technologies and market conditions, in order to enable new supply chains. For instance, if blending studies find that existing natural gas infrastructure can safely and reliably accommodate a high percentage of hydrogen throughput, policymakers will need to act accordingly. Striking a balance amid uncertainty will admittedly be difficult. Regional policymakers and decision-makers should follow H_2 blending in natural gas pipeline studies very closely, and adjust their governmental or corporate strategies as conditions dictate. With even cautious studies suggesting that blending percentages of 5 percent are safe, and with clean hydrogen likely reaching cost parity with grey hydrogen due to provisions in the Inflation Reduction Act, policymakers should consider blending mandates. While any mandates should start at low initial levels, it may be appropriate to escalate the acceptable level of hydrogen throughput, depending on the results of H_2-blending studies.

- Prepare the region's infrastructure for the hydrogen economy. Regardless of the results of hydrogen-blending studies, regional policymakers must replace existing iron-cast pipelines with all possible haste. These pipes are not recommended for transporting hydrogen, and are highly apt to emit methane even in existing pipeline systems. The region may also need to develop ammonia-related infrastructure for maritime shipping, but that is a more distant concern.

1 "New York's Commitment to Clean Energy," About Offshore Wind, last visited August 20, 2022, https://www.nyserda.ny.gov/All-Programs/Offshore-Wind/About-Offshore-Wind; An Act Driving Clean Energy and Offshore Wind. The 192nd General Court of the Commonwealth of Massachusetts, Bill H.5060 192nd (Current), last visited August 20, 2022, https://malegislature.gov/Bills/192/H5060; An Act Concerning the Procurement of Energy Derived from Offshore Wind, State of Connecticut, Public Act No. 19–71 Connecticut General Assembly, last visited August 20, 2022, https://www.cga.ct.gov/2019/ACT/pa/pdf/2019PA-00071-R00HB-07156-PA.pdf; Executive Order No. 92, State of New Jersey, November 19, 2019, https://nj.gov/infobank/eo/056murphy/.

I. Hydrogen Basics: Energy Properties and H2Hubs

Hydrogen could economically decarbonize industrial applications at scale, and set the world on a pathway to net-zero emissions. While most hydrogen fuel is currently produced via natural gas and coal, new technologies could enable hydrogen produced from solar, onshore and offshore wind, nuclear power, and natural gas with carbon storage.

Hydrogen has several advantages over other fuels due to its chemical properties. Hydrogen is abundant, can be sourced from water, and emits only water vapor and heat. It can be repurposed for synthetic gas or electricity. Finally, hydrogen can be produced locally, close to demand centers—or even co-sited with end users—whereas oil, natural gas, and coal typically require extensive transmission and distribution networks to reach final demand.

The two most common methods for producing hydrogen are steam methane reforming, or SMR, and electrolysis, which splits water via electricity.[2] The SMR production technique is utilized by coal and natural-gas producers, uses high-temperature steam to react with methane, and produces hydrogen, carbon monoxide, and carbon dioxide (CO_2).[3] Electrolysis, on the other hand, uses electricity to split hydrogen from water; it does not produce any byproducts other than hydrogen and oxygen.[4] Electricity can be supplied from any renewable or fossil-fuel source. In addition to SMR and electrolysis, there are other methods of hydrogen production, including biomass and microbial techniques, and efforts that use solar to split hydrogen from water. These techniques, however, are in their infancy.

The Department of Energy's Hydrogen Hub Program

US President Joe Biden signed H.R. 3684—Infrastructure Investment and Jobs Act, or IIJA, into law on November 15, 2021. The IIJA established several key features of the Department of Energy's Regional Clean Hydrogen Hub program (abbreviated to Hydrogen Hub or H2Hub throughout this document) and provided funding of $8 billion for this purpose.[5] The IIJA defined a Hydrogen Hub expansively, saying that "the term 'regional clean hydrogen hub' means a network of clean hydrogen producers, potential clean hydrogen consumers, and connective infrastructure located in close proximity."[6]

In order to satisfy regional diversity requirements, the Department of Energy (DOE) letter of intent specified there will be at least four hydrogen hubs across the country.[7] The DOE appears to have identified nine potential regional clusters, including the Great Lakes, New England, Appalachia, the Gulf Coast, Alaska and Hawaii, the Southwest, California, the Pacific Northwest, and the Central United States.[8] This report will discuss the path forward for the potential Northeast Hydrogen Hub, which comprises the states of Connecticut, Massachusetts, Maine, New Jersey, New York, and Rhode Island.

2 "Hydrogen Explained," US Energy Information Administration, January 21, 2022, https://www.eia.gov/energyexplained/hydrogen/production-of-hydrogen.php.
3 Ibid.
4 Ibid.
5 "DOE Launches Bipartisan Infrastructure Law's $8 Billion Program for Clean Hydrogen Hubs across U.S.," US Department of Energy, June 6, 2022, https://www.energy.gov/articles/doe-launches-bipartisan-infrastructure-laws-8-billion-program-clean-hydrogen-hubs-across.
6 Transportation and Infrastructure. Bill, H.R.3684—Infrastructure Investment and Jobs Act §. [[Page 135 STAT. 1008]] 117-58 (2021).
7 "Regional Clean Hydrogen Hubs," US Department of Energy, last visited August 11, 2022, https://www.energy.gov/bil/regional-clean-hydrogen-hubs.
8 "DOE Update on Hydrogen Shot, RFI Results, and Summary of Hydrogen Provisions," US Department of Energy, December 8, 2021, slide 14, https://www.energy.gov/sites/default/files/2021-12/h2iq-12082021.pdf.

RECOMMENDATIONS FOR A US NORTHEAST HYDROGEN HUB

Colors of Hydrogen and the Northeast

Hydrogen is often divided into different "colors," with each color describing the underlying energy source or raw material used in production. While hydrogen combustion emits only water, carbon intensities and the economics of different hydrogen production processes vary considerably, even dramatically.

Some policymakers and industry leaders seek to move away from using colors to describe hydrogen, with some advocating an emphasis on "carbon, not color." Indeed, the recent IIJA and IRA evaluate hydrogen by the production method's carbon intensity. In the IRA, clean hydrogen is eligible for a production tax credit (PTC) if the lifecycle greenhouse-gas (GHG) impact is less than four kilograms of carbon-dioxide emissions (CO_2e) per kilogram of hydrogen produced, with payouts rising inversely to emissions. Therefore, the largest PTC for hydrogen accrues to projects that enjoy a lifecycle GHG impact of less than 1.5 kilograms of CO_2e.[9] While brown and grey hydrogen will not be eligible for the PTC, blue, green, and, potentially, turquoise hydrogen will enjoy various levels of access to the PTC.

Hydrogen derived from coal, referred to as brown hydrogen, accounts for 19 percent of world hydrogen production.[10] If "byproduct hydrogen," or hydrogen produced in facilities (such as refineries) designed for other products, is excluded, brown hydrogen's share of pure hydrogen demand would rise to about 24 percent. According to the International Energy Agency (IEA), brown hydrogen demand used one hundred and fifteen megatons of coal equivalent in 2020, accounting for 2 percent of global coal demand.[11] Among hydrogen colors, brown produces the most pollution and comes predominantly from China.

Grey hydrogen derives from natural gas produced without any associated carbon capture, and accounted for the bulk (59 percent) of 2020 total hydrogen production.[12] If byproduct hydrogen is excluded, grey hydrogen accounts for about 74 percent of pure hydrogen production.[13] Grey hydrogen is not as polluting as brown hydrogen, but still produces approximately 9.2 kilograms of CO_2 per kilogram of hydrogen.[14]

Like grey hydrogen, blue hydrogen is produced from natural gas, but with an important exception: emissions are capped via carbon capture, utilization, and storage (CCUS). The blue-hydrogen decarbonization debate is highly contentious, with some estimates suggesting that total carbon-dioxide-equivalent emissions for blue hydrogen are only 9–12 percent lower than grey hydrogen; other studies have found that overall CO_2 capture rates vary between 50–90 percent.[15] Although blue hydrogen is being closely examined in several natural gas-producing regions—such as Texas, Pennsylvania, and West Virginia—the method of production supplied less than 1 percent of the world's total and pure hydrogen production in 2020.[16] Blue hydrogen faces severe challenges in the northeastern hydrogen hub region; there is virtually no indigenous natural gas production, while CCUS geologic storage locations are limited.

The northeast's lack of natural gas production will almost certainly prevent it from becoming a significant producer of blue hydrogen. In 2020, the last year for which full data are available, the entire region produced only 0.03 billion cubic feet per day (Bcf/d) of natural gas, all of it in New York.[17] Moreover, the Empire State appears to be in no position to increase production, as the state banned hydraulic fracturing as part of its fiscal year 2021 budget.[18] If the northeast region ever consumes blue hydrogen, it will almost certainly need to import the fuel. The Marcellus basin states, especially Pennsylvania and West Virginia, are prolific producers of natural gas and

9 H.R. 5376 Inflation Reduction Act of 2022, H.R. 5376, August 16, 2022, from https://www.congress.gov/bill/117th-congress/house-bill/5376/text.
10 "Hydrogen Supply" in "Global Hydrogen Review 2021," International Energy Agency, 2021, https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf.
11 Ibid.
12 Ibid.
13 Ibid.
14 Pingping Sun and Amgad Elgowainy, "Argonne Greet Publication: Updates of Hydrogen Production from SMR Process in GREET 2019," Argonne National Laboratory, September 30, 2019, https://greet.es.anl.gov/publication-smr_h2_2019.
15 Robert W. Howarth and Mark Z. Jacobson, "How Green Is Blue Hydrogen?" *Energy Science & Engineering* 9, 10 (2021), 1676–1687, https://doi.org/10.1002/ese3.956; Guido Collodi, Giuliana Azzaro, and Noemi Ferrari, "Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS," International Energy Agency Greenhouse Gas R&D Programme, February 2017, 5, https://ieaghg.org/exco_docs/2017-02.pdf.
16 "Hydrogen Supply."
17 "Natural Gas Gross Withdrawals and Production," US Energy Information Administration, last visited August 6, 2022, https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_VGM_mmcf_a.htm.
18 "Governor Cuomo Announces Highlights of the FY 2021 State Budget," New York State Division of the Budget, press release, April 2, 2020, https://www.budget.ny.gov/pubs/press/2020/fy-2021-state-budget-highlights.html.

may be able to ship blue hydrogen to the northeast, if hydrogen-dedicated pipelines can overcome permitting challenges. Similarly, the northeastern hub states could conceivably import blue hydrogen from international sources.

Nuclear power can produce hydrogen by powering the electrolysis of water, which splits water into oxygen and hydrogen. This process, which produces pink hydrogen, is theoretically possible and releases virtually no carbon emissions. Still, nuclear power's contribution to northeast hydrogen production may be limited by several factors. Nuclear power plants tend to run at nearly full capacity.[19] Accordingly, there is relatively little room for nuclear plants to increase throughput to power new production processes, such as hydrogen, without diverting generation from the grid. Moreover, because nuclear power plants provide baseload energy for the grid, it will be difficult for grid operators to divert electrons without potentially compromising grid resiliency. Still, there is an emerging discussion about "flexible" nuclear power plants.[20] If nuclear power can become more flexible, pink hydrogen production could become more prevalent over time during periods of renewable "overgeneration," or curtailment. Given the very low penetration of renewables on the northeastern grid, however, local pink hydrogen production is not expected to play a major role in regional H_2 production for the foreseeable future, barring a dramatic expansion of nuclear power generation capacity, renewables, or both.

Turquoise hydrogen, also referred to as "methane pyrolysis," uses electricity to split natural gas feedstocks into hydrogen and solid carbon; the process is considered to fall between blue and green hydrogen in terms of carbon intensity. Unlike blue hydrogen, however, it does not require underground carbon capture and storage (CCS) or carbon capture, utilization, and storage (CCUS), and produces a solid-carbon product that can be used for other markets and manufacturing. Furthermore, it can displace carbon-intensive processes that produce solid carbon, such as coal used to produce carbon black/graphene products. While turquoise hydrogen has yet to be proven at scale, Monolith Materials received a $1-billion loan from the US Department of Energy's Loan Program Office, suggesting that the technology could become more viable in future years.[21]

19 Mike Mueller, "Nuclear Power Is the Most Reliable Energy Source and It's Not Even Close," US Department of Energy, March 24, 2021, https://www.energy.gov/ne/articles/nuclear-power-most-reliable-energy-source-and-its-not-even-close.

20 Sonal Patel, "Flexible Operation of Nuclear Power Plants Ramps Up," *POWER*, July 9, 2019, https://www.powermag.com/flexible-operation-of-nuclear-power-plants-ramps-up/.

21 Jigar Shah, "Open for Business: LPO Issues New Conditional Commitment for Loan Guarantee," US Department of Energy, December 23, 2021, https://www.energy.gov/lpo/articles/open-business-lpo-issues-new-conditional-commitment-loan-guarantee.

RECOMMENDATIONS FOR A US NORTHEAST HYDROGEN HUB

Finally, green hydrogen refers to the production of hydrogen via water electrolysis powered by renewables sources, such as solar, wind, and hydropower. Although green hydrogen releases virtually no carbon emissions, it is also relatively expensive to produce.[22]

The economics of green hydrogen production, however, may be shifting rapidly. One estimate from the Independent Commodity Intelligence Services, a market-data provider, suggested that green hydrogen is cheaper than grey hydrogen in Europe amid record-setting natural gas prices sparked by Russia's invasion of Ukraine.[23] Rapid price changes are not confined to the continent, however, as US legislation has dramatically altered the economics of green hydrogen.

Green hydrogen is on the rise. As part of the IRA, a clean hydrogen credit, called 45V, will offer up to $3 per kilogram in tax credits for producers on the basis of lifecycle greenhouse gas emissions, as well as the producers' compliance with prevailing wage and apprenticeship requirements.[24] It is hard to overstate the potential significance of this legislation for hydrogen, particularly green hydrogen. A post-IRA analysis by the Rhodium Group found that US green hydrogen prices will fall to between $0.4–2 per kilogram by 2030, versus a "conventional hydrogen" price range of $0.99–$1.54 per kilogram.[25] With that level of support, green hydrogen can be expected to outcompete grey hydrogen in many key locations and contexts.

Some analysts believe that green hydrogen will dominate compared to blue hydrogen, particularly over the long term, as the underlying renewables generation becomes cheaper due to greater efficiency and policy support from the IRA. One consultancy claimed in a May 2021 report that green hydrogen will outcompete blue hydrogen "everywhere" by 2030—and this was before Russia's invasion of Ukraine drove up world gas prices, and before the passage of incentives in the IRA altered hydrogen economics.[26] While geopolitical tensions present substantial and potentially underappreciated risks to renewable supply chains, green hydrogen is riding a wave of favorable policy and economic trends. Green hydrogen will almost certainly be at the heart of a northeast hydrogen hub.

22 "Executive Summary" in "Global Hydrogen Review 2021 ." International Energy Agency, October 2021. https://www.iea.org/reports/global-hydrogen-review-2021/executive-summary.

23 Leigh Collins, "'Green Hydrogen Now Cheaper to Produce than Grey H2 across Europe Due to High Fossil Gas Prices,'" Recharge, November 12, 2021, https://www.rechargenews.com/energy-transition/green-hydrogen-now-cheaper-to-produce-than-grey-h2-across-europe-due-to-high-fossil-gas-prices/2-1-1098104.

24 David S. Miller, et al., "A Summary of Inflation Reduction Act's Main Energy Tax Proposals," Lexology, August 8, 2022, https://www.lexology.com/library/detail.aspx?g=4ad0902c-8128-442b-b22e-da62835ad89a.

25 John Larsen, et al., "A Turning Point for US Climate Progress: Assessing the Climate and Clean Energy Provisions in the Inflation Reduction Act," Rhodium Group, August 18, 2022, https://rhg.com/research/climate-clean-energy-inflation-reduction-act/.

26 "'Green' Hydrogen to Outcompete 'Blue' Everywhere by 2030," BloombergNEF, May 5, 2021, https://about.bnef.com/blog/green-hydrogen-to-outcompete-blue-everywhere-by-2030/.

RECOMMENDATIONS FOR A US NORTHEAST HYDROGEN HUB

II. Northeast Green Hydrogen Production Fundamentals

Given renewables' importance for green hydrogen, northeast electricity fundamentals will prove immensely important for a future regional hydrogen hub. Over the long term, the region's ability to expand clean energy generation could determine its hydrogen future.

According to the US Energy Information Administration, existing renewables generation capacity in the six northeastern states of Connecticut, Massachusetts, Maine, New Jersey, New York, and Rhode Island stood at approximately 13.2 gigawatts (GW) in July 2022, out of an existing 86 GW of existing generation capacity.[27] Hydropower accounted for 5.8 GW of total renewables capacity, utility-scale solar capacity stood at 4.0 GW, and onshore wind turbines added approximately another 3.4 GW.[28] The six states also have an additional 9.2 GW of clean energy capacity via nuclear energy. There are no planned nuclear plant closures, according to the EIA.[29] While the region is rapidly emerging as the nation's leader in offshore wind, it has only one operating offshore wind turbine, Rhode Island's Block Island Wind.

The region's existing clean energy capacity pales in comparison to its operating fossil fuel generation capacity. The northeast has approximately 35.5 GW of natural gas combined cycle generation capacity, while lower-utilization plants, such as steam turbines and combustion turbines, account for another 20.5 GW of capacity.[30] More surprisingly, at least for individuals outside of the region, petroleum-liquids capacity stands at 9.1 GW, as consumers and businesses in the northeast rely on fuel oil for heating in the winter.[31] There are still two coal plants operating in New Jersey, with approximately 0.5 GW of capacity, although the Chambers and Logan coal-fired power plants are expected to close within the next five years.[32] While New Hampshire is not currently in the northeastern hydrogen hub, it also has about 0.5 GW of existing coal capacity at the Merrimack plant.[33]

Unsurprisingly, the region's electricity mix is dominated by natural gas, which accounted for half of all generation within the New York/New Jersey/Massachusetts/Connecticut/Rhode Island/Maine region.[34] Still, clean generation (nuclear, hydropower, wind, and solar) reached 45 percent of all regional electricity generation in the same year.[35] The region has nearly phased out coal, which accounted for less than 1 percent of electricity generation in 2021.[36] As seen in Figure 1, however, wind and solar comprise only a small portion of the region's electricity mix.

27 "Preliminary Monthly Electric Generator Inventory (Based on Form EIA-860m as a Supplement to Form EIA-860)," US Energy Information Administration, August 24, 2022, https://www.eia.gov/electricity/data/eia860m/.

28 Ibid.

29 Ibid.

30 Ibid.

31 Ibid.

32 Ibid.

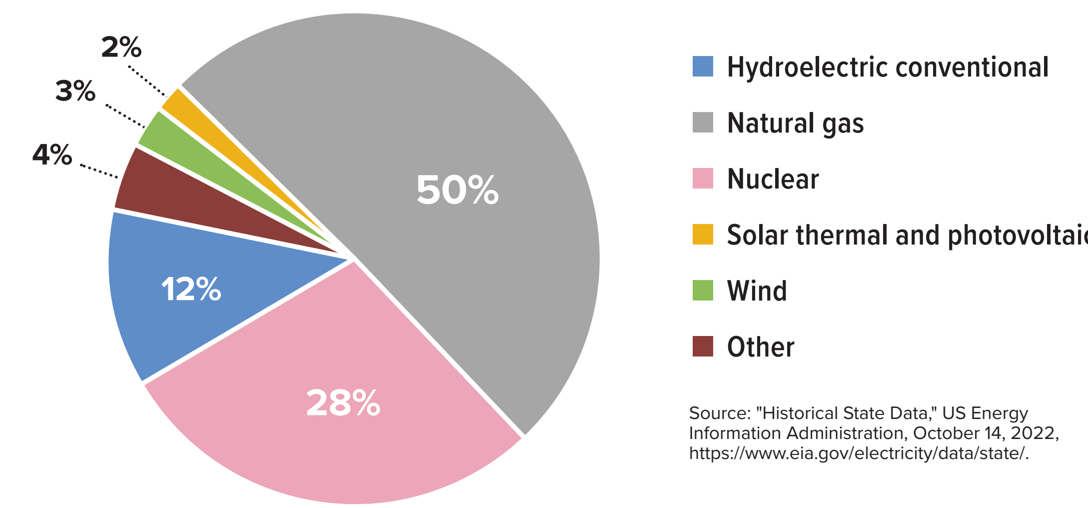
33 Ibid.

34 "Historical State Data," US Energy Information Administration," October 14, 2022, https://www.eia.gov/electricity/data/state/.

35 Ibid.

36 Ibid.

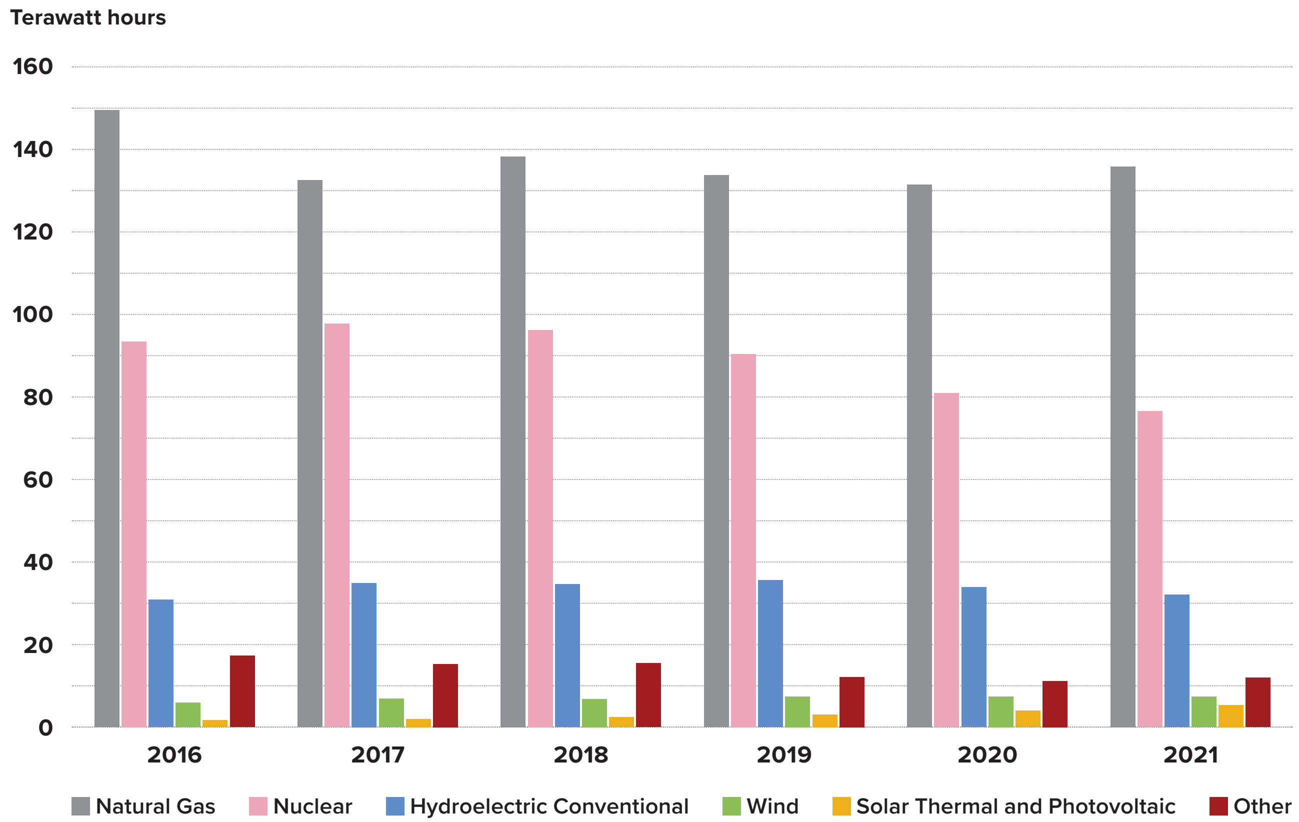
Figure 1: Northeastern Regional Electricity Generation by Fuel Source, 2021



Source: "Historical State Data," US Energy Information Administration, October 14, 2022, https://www.eia.gov/electricity/data/state/.

The northeast region's generation mix has shifted over time, as clean energy production has actually fallen due to the closure of regional nuclear plants, including New Jersey's Oyster Creek plant, the Pilgrim Nuclear Power Station in Massachusetts, and the Indian Point 2 and Indian Point 3 generating units in New York. Coal generation (included in the "other" category below) has also fallen steeply. While solar and wind generation continue to grow very rapidly, they are nevertheless starting from a very low base.

Figure 2: Northeastern Regional Electricity Generation by Fuel Source, 2016–2021



Source: "Historical State Data," US Energy Information Administration, October 14, 2022, https://www.eia.gov/electricity/data/state/.

Moreover, while the region enjoys outstanding offshore wind resources, its solar and onshore wind natural resources are less than ideal. The northeast's solar irradiation is relatively low compared to that in many parts of the country, especially the southwest, while the region's terrain is often wooded, hilly, or both.[37]

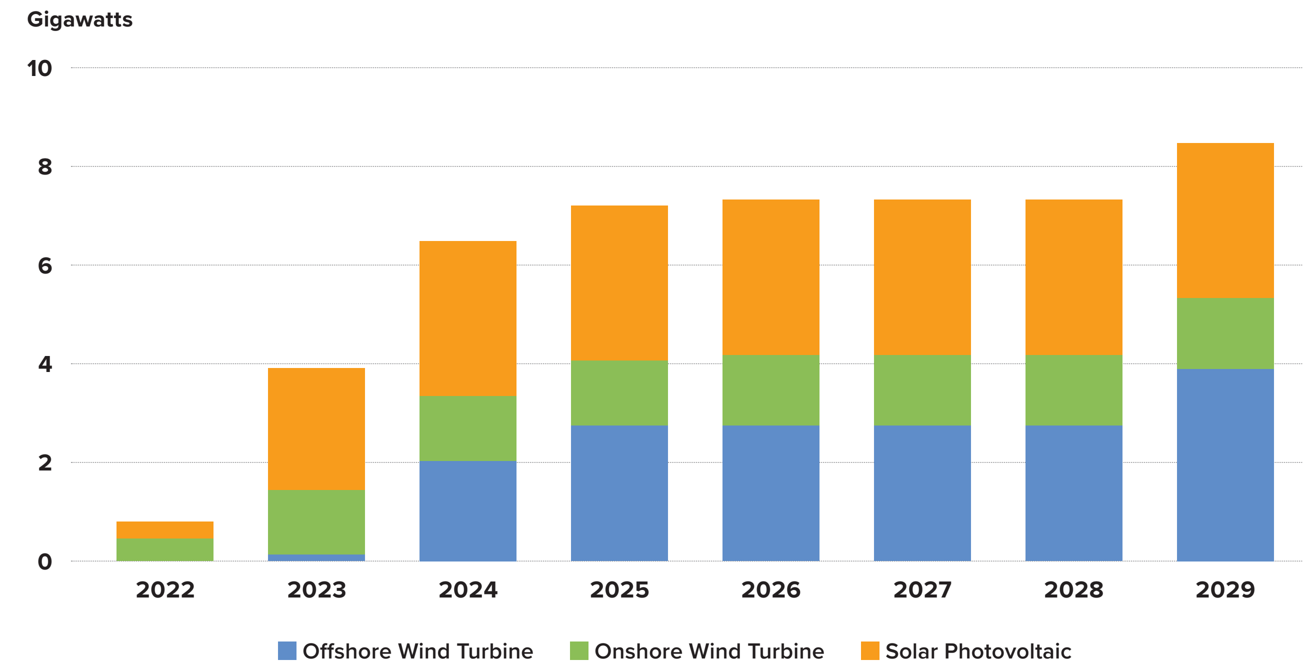
Onshore wind resource development is constrained by the region's topography. Broader, flatter land features are ideal for multiple rows of wind turbines.[38] Multiple rows can lead to economies of scale, lower per-unit costs, and limit land requirements. The region is generally hilly, however, so many regional wind farm locations must be placed on hilltops and ridge lines, raising land acquisition costs and harming onshore wind project economics.

37 "Global Solar Atlas Map," Global Solar Atlas, last visited August 6, 2022, https://globalsolaratlas.info/map.

38 "Wind Energy Site Selection: Identifying Optimal Sites for Wind Energy Development" in "New York State Wind Energy Guidebook," New York State Energy Research and Development Authority, last visited August 7, 2022, https://www.nyserda.ny.gov/All-Programs/Clean-Energy-Siting/Wind-Guidebook.

RECOMMENDATIONS FOR A US NORTHEAST HYDROGEN HUB

Figure 3: Planned Incremental Capacity Additions, Cumulative



Source: "Preliminary Monthly Electric Generator Inventory (Based on Form EIA-860m as a Supplement to Form EIA-860) U.S. Energy Information Administration (EIA)." U.S. Energy Information Administration, July 26, 2022. https://www.eia.gov/electricity/data/eia860m/.

The region's geography will make it difficult to add new onshore wind and solar to the grid. Indeed, the EIA interconnection queue suggests that fewer than 8 GW of new renewables generation capacity will be added to the northeastern grid by 2029, versus total existing generation capacity of about 86 GW.[39]

There are several caveats to the above estimate. First, there is considerable uncertainty around the EIA's planned incremental renewable capacity additions: not every plant will open, of course, but additional incremental projects could come online. Second, estimates of offshore wind's future generation capacity are subject to wide confidence intervals. Offshore wind (OSW) projects could face delays; alternatively, however, the region could conceivably enjoy double-digit gigawatt OSW generation capacity by 2030. Finally, the Inflation Reduction Act has dramatically altered the economics of new renewables sources and will likely lead, et ceteris paribus, to significant increases in renewables generation capacity.

The northeast will require significant new indigenous renewables generation capacity for green hydrogen production. Most incremental northeastern renewables generation will likely consist of offshore wind—primarily in the Atlantic Ocean, but potentially in the Great Lakes as well.

39 Ibid.

Offshore Wind Capacity: the Atlantic Ocean

The northeast region is arguably the nation's leader in offshore wind. Rhode Island's 30-megawatt (MW) Block Island Wind Farm became the United States' first operating commercial offshore wind farm in December 2016. Nearly six years later, the US Bureau of Ocean Energy Management closed a record-breaking sale of $4.37 billion for six leases along the coasts of New York and New Jersey.[40] This lease sale, by itself, could ultimately provide between 5.6–7 GW of offshore wind capacity.[41] New York is also launching its third offshore wind solicitation, which could provide an additional 2 GW of capacity.[42]

The region has set ambitious offshore wind targets. New York's Climate Leadership and Community Protection Act calls for the development of 9 GW of offshore wind energy by 2035, Massachusetts' Bill H.5060 authorizes OSW nameplate capacity procurements of 5.6 GW by June 2027, Connecticut's Public Act No. 19-71 mandated procurement of 2 GW of offshore wind by 2030, and New Jersey has set a goal of reaching 7.5 GW of OSW generation capacity by 2035.[43] While ends must be matched with means, the region's ambitions and, importantly, predictable procurement programs are sending positive signals to renewables and green hydrogen market actors, helping to solve the "chicken-and-egg" problem of creating new supply chains from scratch.

The northeast is also making significant strides in building out regional offshore wind supply chains, particularly port infrastructure. The New Jersey Wind Port is the first purpose-built offshore wind marshalling port in the United States; New York's South Brooklyn Marine Terminal is a private and public sector partnership between Equinor, BP, Sustainable South Brooklyn Marine Terminal (SSBMT), and the New York City Economic Development Corporation (NYCEDC); and Massachusetts is investing $100 million in the development of three offshore wind ports.[44]

The region's offshore wind complex is arguably more advanced than that of any other region. The region's offshore wind port system is progressing rapidly, there is an emerging OSW labor ecosystem, and policymakers have demonstrated their seriousness in establishing the region's offshore wind capabilities.

Offshore Wind Capacity: the Great Lakes

The Great Lakes could present significant, long-term opportunities for northeastern renewables and hydrogen production. Initial estimates suggest that the potential offshore wind generation capacity of the Great Lakes (Superior, Michigan, Huron, Erie, and Ontario) could theoretically total 700 GW, or about one-fifth of the United States' total offshore potential.[45] There has been some tangible progress on the Great Lakes. NYSERDA is conducting a Great Lakes Wind Feasibility Study, suggesting that northeastern policymakers are engaged on the issue.[46] There are also signs of increasing amounts of commercial interest in the Great Lakes region. Project Icebreaker, a proposed 21-megawatt, $127-million offshore wind plant in Lake Erie, has survived a court challenge in the Ohio Supreme Court.[47]

In addition to court challenges and standard "not-in-my-backyard" problems, Great Lakes OSW faces other development hurdles. According to preliminary findings from NYSERDA, locks on the St. Lawrence Seaway limit vessel sizes, and Federal Aviation Administration (FAA) regulations may restrict maximum heights to 610 feet.[48] Both of these obstacles could constrain or prevent the installation of larger, more efficient wind turbines.[49]

The future of Great Lakes OSW is uncertain, but a potential game changer. If New York can develop its Great Lakes OSW resources, the impact on regional hydrogen deployment could be significant.

Hydrogen Import Pathways

If indigenous production of green hydrogen cannot satisfy local demand, the region may be forced to turn to hydrogen produced outside the region. The northeast will likely receive domestically produced but out-of-region hydrogen, either through existing natural gas pipelines repurposed for hydrogen, or from newly constructed hydrogen-dedicated pipelines. Overland hydrogen imports to the region could derive from Canada, West Virginia, or even the Gulf Coast. Alternatively, the northeast could import internationally produced hydrogen via maritime vessels transporting liquid hydrogen or, perhaps more likely, ammonia, which is close to 18 percent hydrogen by weight and can be burned directly with no carbon emissions or split for its hydrogen. While these potential import pathways are the subject of further discussion in a section on hydrogen-related infrastructure, it is worth emphasizing the need for policy flexibility in the face of uncertainty.

The scope, nature, and even chemical properties of hydrogen imports are uncertain. Future supply-demand hydrogen balances are unknown; the northeast's ability to source hydrogen from existing overland natural gas infrastructure or new, hydrogen-dedicated pipelines is uncertain, and the debate over liquid H_2/ammonia maritime imports remains unsettled. Given these market-technological uncertainties, regional policymakers should aim to be flexible, nimble, and deeply engaged with dynamic hydrogen markets.

Regional Electricity Prices

The northeastern hydrogen states pay some of the highest retail electricity prices in the nation, creating opportunities for renewables development and hydrogen. All states in the hub program paid at least 13.54 cents per kilowatt hour in 2020, the most recent data available from the EIA, placing them in the eleven most expensive states.[50] Moreover, two other northeastern states—New Hampshire and Vermont—also suffer from elevated electricity prices. In 2020, eight of the eleven most expensive state retail electricity markets were in the United States' northeast.[51]

Figure 4: Average Electricity Retail Price, by State

State	Average Retail Price, 2020 (Cents/kWh)
Hawaii	27.55
Alaska	19.82
Connecticut	19.13
Rhode Island	18.54
Massachusetts	18.19
California	18
New Hampshire	16.63
Vermont	16.63
New York	14.87
New Jersey	13.63
Maine	13.54
U.S.	10.59

Source: "Historical State Data," US Energy Information Administration, October 14, 2022, https://www.eia.gov/electricity/data/state/.

Not only does the region's high levelized cost of electricity (LCOE) incentivize new renewables development, but its cold winters and seasonal electricity spreads may render hydrogen an economic source for inter-seasonal storage. As seen in the chart below, the northeast's frigid weather often produces winter price spikes.

40 Emma Newburger, "Auction for the Right to Build Wind Farms off New York and New Jersey Raises a Record $4.37 Billion," CNBC, February 26, 2022, https://www.cnbc.com/2022/02/25/us-offshore-wind-auction-in-ny-nj-raises-a-record-4point37-billion.html.

41 Jared Anderson, "First US Federal Offshore Wind Power Lease Auction since 2018 Receives High Interest," S&P Global Commodity Insights, February 23, 2022, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/022322-first-us-federal-offshore-wind-power-lease-auction-since-2018-receives-high-interest.

42 "Governor Hochul Announces New York's Third Offshore Wind Solicitation to Accelerate Clean Energy Development: Seeks to Procure at Least 2,000 Megawatts of Renewable Energy, Enough to Power 1.5 Million Homes," New York State Energy Research and Development Authority, July 27, 2022, https://www.nyserda.ny.gov/About/Newsroom/2022-Announcements/2022-07-27-Governor-Hochul-Announces-Third-Offshore-Wind-Solicitation.

43 "About Offshore Wind," New York State Energy Research and Development Authority, last visited August 20, 2022, https://www.nyserda.ny.gov/All-Programs/Offshore-Wind/About-Offshore-Wind.; An Act Driving Clean Energy and Offshore Wind.; An Act Concerning the Procurement of Energy Derived from Offshore Wind.; "Executive Order No. 92," State of New Jersey, November 19, 2019, https://nj.gov/infobank/eo/056murphy/.

44 "New Jersey Wind Port," State of New Jersey, last visited August 11, 2022, https://nj.gov/windport/; Mike Schuler, "Plan for New York Offshore Wind Port Hits Major Milestone," gCaptain, May 12, 2022, https://gcaptain.com/plan-for-new-york-offshore-wind-port-hits-major-milestone/; "Massachusetts Targets $100 Million Investment in Wind Ports," *Maritime Magazine*, May 21, 2022, https://maritimemag.com/en/massachusetts-targets-100-million-investment-in-wind-ports/.

45 "Fact Sheet—Great Lakes Offshore Wind Energy Consortium," Department of Energy Office of Energy Efficiency & Renewable Energy, last visited August 11, 2022, https://www1.eere.energy.gov/wind/pdfs/gl_mou_fact_sheet.pdf.

46 "Great Lakes Wind Feasibility Study," New York State Energy Research and Development Authority, last visited August 11, 2022, https://www.nyserda.ny.gov/great-lakes-wind-feasibility-study.

47 Angel Adegbesan, "Great Lakes Offshore Wind Gets Boost From Ohio Supreme Court Ruling," Bloomberg, August 11, 2022, https://www.bloomberg.com/news/articles/2022-08-11/great-lakes-offshore-wind-gets-boost-from-ohio-supreme-court?sref=IDgLmqjg.

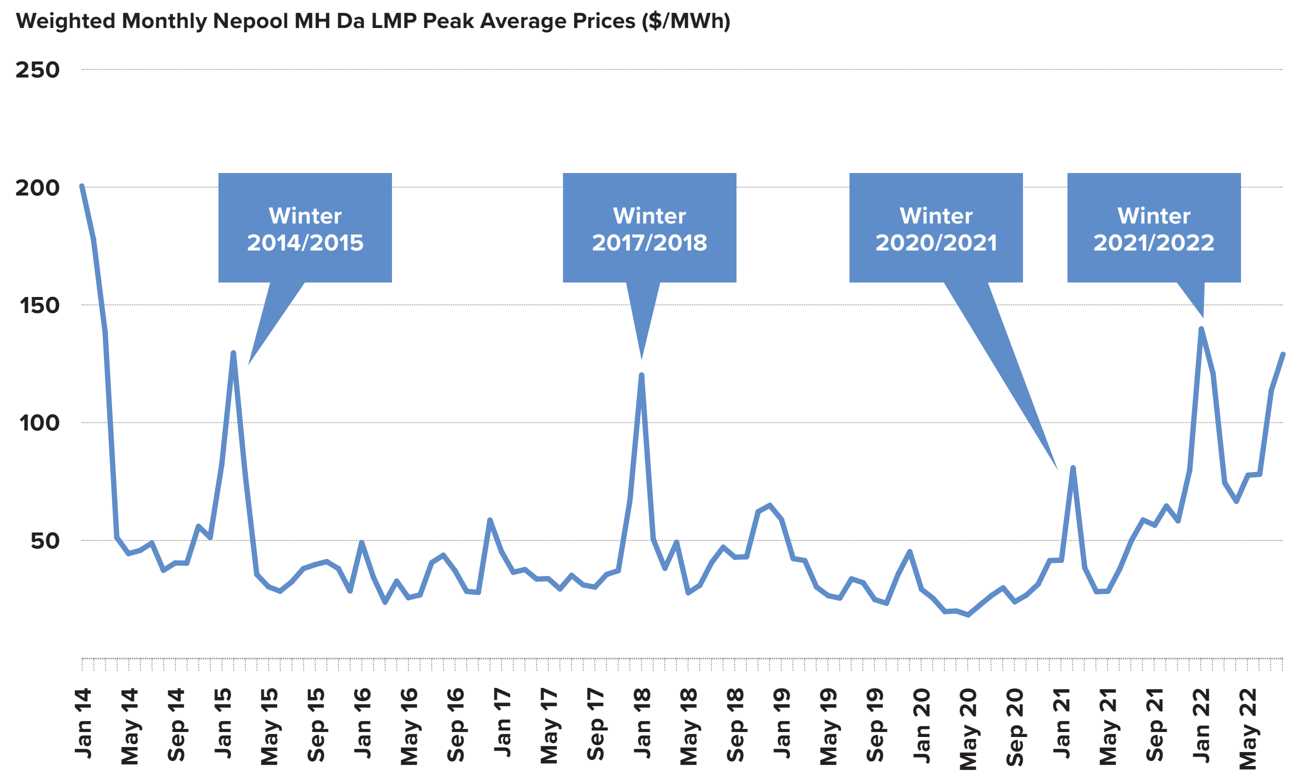
48 "Great Lakes Wind Feasibility Study," slides 12–14.

49 Ibid.

50 "State Electricity Profiles," US Energy Information Administration, November 4, 2021, https://www.eia.gov/electricity/state/.

51 Ibid.

Figure 5: Northeastern Electricity Peak Average Prices



Source: "Wholesale Electricity and Natural Gas Market Data ." EIA - independent statistics and analysis. U.S. Energy Information Administration, August 11, 2022. https://www.eia.gov/electricity/wholesale/#history.

Hydrogen's long-duration storage capabilities could dampen the region's winter price spikes by shifting electricity generated in the summer or the shoulder seasons to the winter, when demand is highest. It's also worth noting that the region may be able to ameliorate winter pricing peaks by improving transmission connectivity to Canadian hydropower.

In addition to potentially reducing winter pricing peaks, hydrogen deployment from long-duration storage could also significantly reduce carbon emissions. Some of the region's most polluting hydrocarbon-generation sources, such as coal, fuel oil, and natural gas from liquefied natural gas (LNG), ramp up production during peak-demand times. The northeast could see significant electricity sector decarbonization if it can replace its hydrocarbon winter generation with clean hydrogen generation.

Green Hydrogen, Equity, and Energy Insecurity

While the northeastern states are relatively wealthy, they also suffer from some of the highest residential electricity bills in the country, increasing energy insecurity among the region's poorest residents. Using data from the EIA's latest publicly available "Residential Energy Consumption Survey," Electric Choice found that Rhode Island, New York, Maine, Massachusetts, and Connecticut residents suffered, respectively, the second, third, fourth, fifth, and eighth highest electricity bills as a percentage of salary in the nation.[52] Given that individuals with lower incomes are disproportionately affected by rising electricity prices, particularly during the winter, inter-seasonal supply-demand balancing via long-duration hydrogen storage could benefit individuals with lower incomes and historically underserved communities.

52 "Percentage of Household Income Spent on Electricity by State," Electric Choice, last visited August 15, 2022, https://www.electricchoice.com/blog/percentage-income-electricity/.

III. Regional Hydrogen Demand

In order to establish an effective hydrogen hub, long-term demand sources and offtakers must be identified. There are several potential hydrogen demand end-use cases in the northeast. These potential end-use cases include hydrogen blending in existing natural gas pipelines; refineries; industrial applications, such as steel and cement; and, over the long term, the maritime shipping sector. This section will examine these potential use cases, while clarifying hydrogen's limitations in the transportation sector.

Blending Hydrogen in Natural Gas Pipelines

If hydrogen can be safely blended in existing natural gas pipelines, it could be a game changer for US climate goals—and the northeast hydrogen hub. There are about 1,600 miles of existing, hydrogen-dedicated pipelines across the United States.[53] To put that in perspective, the US natural gas pipeline system, including mainlines and other pipelines, comprises three million miles.[54] Repurposing even a fraction of the existing natural gas pipeline network for hydrogen safely, reliably, and economically would, therefore, accelerate US economic, security, and climate objectives.

Blending hydrogen in existing natural gas infrastructure could significantly reduce US GHG emissions. In 2020, US CO_2 emissions from natural gas totaled 1,647 million metric tons.[55] If, as seems likely, at least 2–5 percent of natural gas-related emissions can be eliminated by substituting hydrogen for natural gas in existing pipelines, and assuming negligible emissions from the additional hydrogen production, US emissions would fall by 33–82 million metric tons. That emissions reduction is the equivalent of removing approximately 7.2 million to 17.8 million passenger vehicles from US roads, based on a typical passenger vehicle emission of 4.6 metric tons of carbon dioxide per year.[56]

Despite the potentially seismic importance of hydrogen blending in pipelines, there is no consensus on what percentage of hydrogen can be blended with natural gas in existing pipelines without compromising safety or efficiency. A July 2022 study commissioned by the California Public Utilities Commission found that while blends of hydrogen of up to 5 percent in the natural gas stream are generally safe, adding additional hydrogen in gas pipelines overall could result in a greater chance of pipeline leaks and the embrittlement of steel pipelines.[57] Other studies are more optimistic, including a 2013 National Renewable Energy Laboratory (NREL) study that found concentrations of hydrogen between 5 and 15 percent could be blended in existing pipeline systems or end-use appliances, with very few modifications necessary despite some location-to-location variation.[58] The United Kingdom's HyDeploy study found, however, that all tested domestic appliances could operate safely with hydrogen concentrations of up to 28.4 percent.[59] It's worth noting that end-use applications tend to impose the most significant constraints on hydrogen-blending percentages, as many devices are optimized to throughput pure natural gas.[60]

The hydrogen-blending percentage debate will not be settled conclusively for some time. Several initiatives, including Pacific Gas and Electric's Hydrogen to Infinity project, are evaluating blending percentages under real-world con-

53 "Hydrogen Pipelines," US Department of Energy, last visited August 13, 2022, https://www.energy.gov/eere/fuelcells/hydrogen-pipelines.

54 "Natural Gas Explained: Natural Gas Pipelines," US Energy Information Administration, November 5, 2021, https://www.eia.gov/energyexplained/natural-gas/natural-gas-pipelines.php.

55 "U.S. Energy-Related Carbon Dioxide Emissions, 2020," US Energy Information Administration, December 22, 2021, https://www.eia.gov/environment/emissions/carbon/.

56 "Greenhouse Gas Emissions from a Typical Passenger Vehicle," US Environmental Protection Agency, June 30, 2022, https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle.

57 "CPUC Issues Independent Study on Injecting Hydrogen into Natural Gas Systems," California Public Utilities Commission, July 21, 2022, https://www.cpuc.ca.gov/news-and-updates/all-news/cpuc-issues-independent-study-on-injecting-hydrogen-into-natural-gas-systems.

58 M. W. Melaina, O. Antonia, and M. Penev, "Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues," US Department of Energy Office of Scientific and Technical Information, March 2013, https://www.osti.gov/biblio/1068610.

59 Tommy Isaac, "HyDeploy: The UK's First Hydrogen Blending Deployment Project," *Clean Energy* 3, 2, 114–125, https://doi.org/10.1093/ce/zkz006.

60 Erin M. Blanton, Dr. Melissa C. Lott, and Kirsten Smith, "Investing in the US Natural Gas Pipeline System to Support Net-Zero Targets," SIPA Center on Global Energy Policy, Columbia University, April 22, 2021, https://www.energypolicy.columbia.edu/research/report/investing-us-natural-gas-pipeline-system-support-net-zero-targets.

ditions, while many domestic and international initiatives are studying blending percentages.[61] Federal and state governments, along with university research centers, should seek to accelerate research and development on hydrogen blending in existing natural gas pipelines.

There has been relatively little federal support of research and development in hydrogen blending in existing natural gas pipelines, despite its potentially game-changing importance and role in accelerating clean hydrogen deployment at scale. The DOE reports $11 million of federal funding for its HyBlend Initiative, which seeks to address technical barriers to blending hydrogen in natural gas pipelines.[62] This level of funding is inadequate, as hydrogen could easily become a trillion-dollar industry by 2050 (or even 2030).[63] Blending in natural gas pipelines will likely prove to be a key accelerator, the technology's environmental benefits could prove momentous, and the outlays required to investigate blending issues are miniscule, implying potential outsized return on investment (ROI). The federal government must resource this priority adequately.

Additional areas for greater federal involvement include the collection and sharing of safety data. Several experts say there is not enough information sharing in the hydrogen space, particularly surrounding blending in pipelines, hydrogen in appliances, and safety data.[64] While companies understandably want to protect their intellectual property, both state and federal authorities should consider creating an authoritative safety clearing-house database. Indeed, European policymakers have already begun intensive efforts to collect safety data.[65] Given the importance of hydrogen blending, and safety and reliability's importance in accelerating adoption, northeastern policymakers should look to expand intra- and inter-regional safety-data cooperation.

Expanding research-and-development (R&D) funding for hydrogen-blending demonstration projects and enhancing safety-data cooperation could prove instrumental in accelerating hydrogen hubs. Indeed, according to the IEA, "by providing a temporary solution until dedicated hydrogen transport systems are developed, blending hydrogen in gas networks can support initial deployment of low-carbon hydrogen and trigger cost reductions for low-carbon hydrogen production technologies."[66]

Natural Gas Fundamentals in the Northeast Hub

While the northeast lacks natural gas to produce blue hydrogen, the fuel could nevertheless play a vital role for any northeast hydrogen hub. Natural gas in pipelines can be safely "blended" with hydrogen and used in many of the same applications, which means that existing natural gas consumption and infrastructure provide opportunities to spur hydrogen development. While decarbonization efforts will ultimately require the removal or remediation of carbon dioxide from natural gas production and consumption, the fuel may ultimately prove to be a bridge to hydrogen and a cleaner future. The northeast's natural gas consumption and natural gas pipeline system may provide significant opportunities for hydrogen.

Northeastern consumption of natural gas stood at approximately 7.5 Bcf/d in 2020, the last full year that data are available from the EIA.[67] Northeast natural gas consumption has edged upward over time on cheaper prices resulting from the shale boom, population growth, and coal- and nuclear-plant decommissionings, rising from about 7.3 Bcf/d in 2010 to nearly 7.5 Bcf/d in 2020, when demand was suppressed by the COVID pandemic.[68]

61 "PG&E Launches the Nation's Most Comprehensive Study on Hydrogen's Feasibility Within Gas Pipelines," Pacific Gas and Electric, press release, May 2, 2022, https://www.pge.com/en_US/about-pge/media-newsroom/news-details.page?pageID=66b8ed99-3175-48da-95d6-1a1fde0a4f18&ts=1651546270622; Devinder Mahajan, et al., "Hydrogen Blending in Gas Pipeline Networks—a Review," *Energies* 15, 10 (2022), 3582, https://doi.org/10.3390/en15103582.

62 "Hyblend: Opportunities for Hydrogen Blending in Natural Gas Pipelines," US Department of Energy Office of Energy Efficiency and Renewable Energy, June 2021, https://www.energy.gov/sites/default/files/2021-08/hyblend-tech-summary.pdf.

63 "To Reach Net Zero, Invest $5 Trillion in Hydrogen," Goldman Sachs, February 17, 2022, https://www.goldmansachs.com/insights/pages/from-briefings-17-february-2022.html.

64 "*Hydrogen Hub Roundtable*," *Atlantic Council*, July 27, 2022.

65 Ibid.

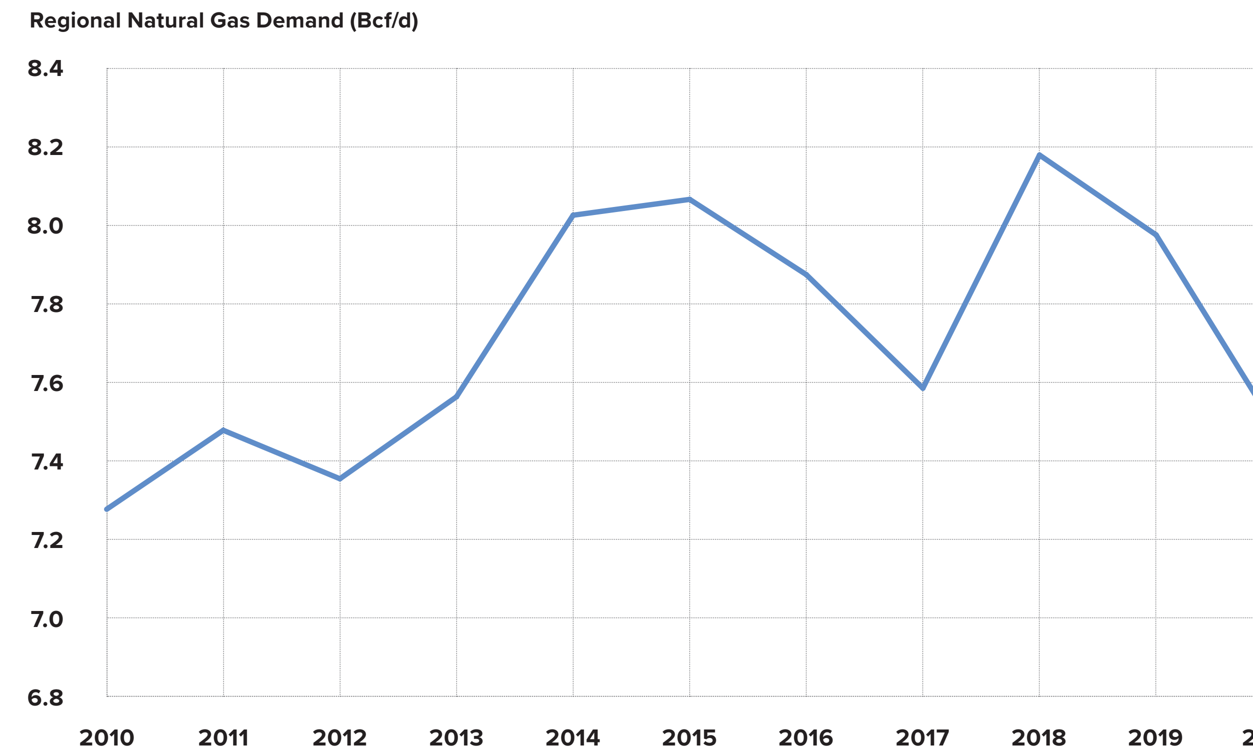
66 "Global Hydrogen Review 2021," 145.

67 "Natural Gas Consumption by End Use," US Energy Information Administration, July 29, 2022, https://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm.

68 Ibid.

RECOMMENDATIONS FOR A US NORTHEAST HYDROGEN HUB

Figure 6: Northeastern Regional Natural Gas Demand



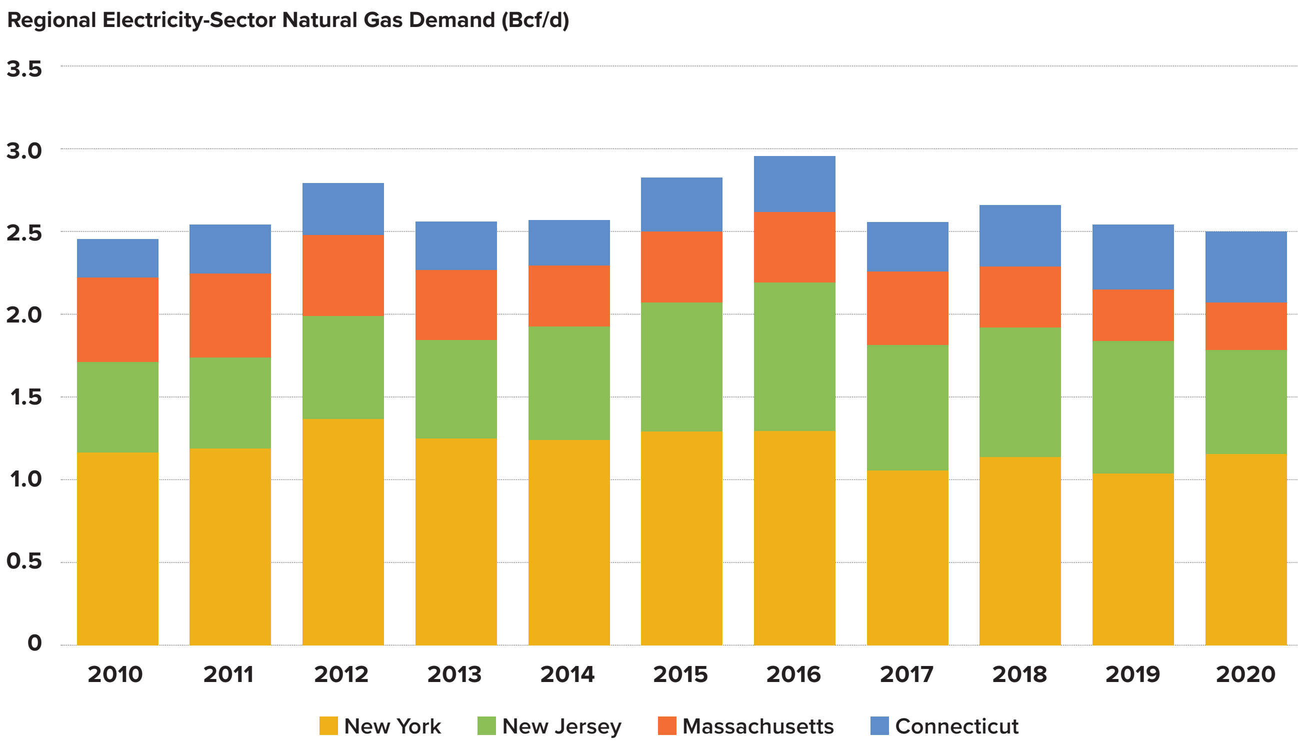
Source: "Natural Gas Consumption by End Use," US Energy Information Administration, last visited October 29, 2022, https://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm.

While northeastern natural gas consumption figures for 2021 are not yet finalized by the EIA, it is worth noting that demand does not appear to have experienced a resurgence in the post-vaccination period. Based upon initial data reported from the EIA, the author estimates that final 2021 regional consumption will likely range somewhere between 7.4–7.8 Bcf/d.

Northeastern electricity-sector natural gas demand stood at about 2.5 Bcf/d in 2020, accounting for about 36 percent of all regional natural gas demand in the same period.[69] Reducing natural gas demand in the northeast electricity sector via renewables generation could improve hydrogen fundamentals in two distinct but related ways: greater solar and wind uptake would likely lead to regional economies of scale and accelerate declines on the cost curves. Moreover, reducing electricity-sector natural gas demand would ease physical capacity constraints along existing natural gas pipelines, particularly in the winter, creating more opportunities for hydrogen fuel blending.

69 Ibid.

Figure 7: Electricity-Sector Natural Gas Demand



Source: "Preliminary Monthly Electric Generator Inventory (Based on Form EIA-860M as a Supplement to Form EIA-860)," US Energy Information Administration, October 25, 2022, https://www.eia.gov/electricity/data/eia860m/.

Regional Refineries

Refineries could play an important role in fostering the adoption of the hydrogen economy. While US refineries currently use natural gas feedstocks to produce hydrogen, refineries may increasingly turn to cleaner feedstocks for hydrogen.

The northeast region has two oil refineries. P66's Bayway refinery in Linden, New Jersey, has a crude throughput capacity of approximately 258,000 barrels per day and is, as of this writing, the region's only operating refinery.[70] PBF's Paulsboro refinery, meanwhile, has been shut down since 2020 amid declining demand from COVID. While there has been interest in restarting the Paulsboro refinery as late as January 2022, the facility remains shut down as of this writing.[71]

Regional refineries are expected to contribute a limited, but important, amount of hydrogen demand. The Paulsboro refinery will not use hydrogen as long as it remains idle. The Bayway refinery, meanwhile, uses only a limited amount of hydrogen due to its relatively low Nelson Complexity Factor of 7.7.[72] Refineries use hydrogen to lower the sulfuric content of diesel fuel.[73] Therefore, lower complexity scores imply that refineries process relatively lighter, sweeter (i.e., less sulfuric) barrels of crude oil, limiting their hydrogen-desulfurization needs. Indeed, in 2021, the East Coast PADD 1 region, which includes the entire eastern seaboard, not just the northeast, used only 4 percent of the country's natural gas feedstock for hydrogen production at refineries.[74]

While the region's refineries have only limited hydrogen needs, especially compared to other regions such as the Gulf Coast, they could nevertheless plan an important role in kickstarting a regional hydrogen hub. The Bayway refinery is already an important user of hydrogen and a target market for any green hydrogen supplier. Notably, Phillips 66 and Plug Power signed a memorandum of understanding (MOU) to advance green hydrogen in October 2021.[75]

Moreover, the Bayway refinery—and refineries more generally—could help solve green hydrogen's "chicken-and-egg problem." Unlike many other use cases, refineries' demand for hydrogen already exists and is quite sizable: refineries accounted for about 44 percent of total world hydrogen demand in 2020.[76] The Bayway refinery could prove to be an important early clean hydrogen offtaker for the northeast regional hydrogen hub.

Industrial Uses: Steel and Cement

While the northeast is often regarded as a post-industrial economy, there are still significant steel, cement, and paper facilities located across the region. These industries are studying ways to integrate hydrogen into their operations. While these industries may have limited scope for the initial "chicken-and-egg" problem of supply and demand, they may have significant impacts on medium- and long-term demand.

The northeast's steel industry is noteworthy, and may be growing. According to the Global Energy Monitor, the Commercial Metals Company, or CMC, operates a 653,000-ton/year steel plant, an electric arc furnace (EAF) in New Jersey.[77] CMC is also considering opening another plant that would "primarily serve the Northeast, Mid-Atlantic, and Mid-Western United States markets."[78] Auburn, New York, is also home to Nucor Steel Auburn, a scrap-based steel mill.

According to the United States Geological Survey (USGS), there were four operating cement plants in Maine and New York in 2020, when they produced 1,719 thousand metric tons of cement (to preserve company-level anonymity, the USGS does not provide more granular state-level data).[79] There are three cement plants in the Empire State; two are owned by Lehigh Northeast, while Holcim owns the Ravena cement plant.

Steel and cement, as well as paper and pulp, are industries that could become potential hydrogen offtakers. Still, participants in these industries express concerns that, because they operate in commodity industries and can be undercut on price alone, they will require policy support before introducing hydrogen at scale.[80]

Transportation Sector: Little Near-Term Demand; Long-Term Uptake Possible

While hydrogen will likely play an important role in transportation-sector decarbonization, many policymakers overestimate H_2's impact on mobility in the medium term. Electric vehicles (EVs) will almost certainly remain more economical than hydrogen-fueled vehicles across most consumer segments, including personal transport. While hydrogen is believed to have advantages over EVs in certain markets, especially long-haul trucking, it will take several years—perhaps more than a decade—for hydrogen-fueled trucks to become commercially viable. Moreover, most industry participants believe that the marine sector will be slow to adopt hydrogen. Therefore, while policymakers should play close attention to hydrogen in the transportation sector, H_2 is unlikely to receive significant demand from the automobile or maritime sector for years. Transportation-sector demand is important, but not urgent. Northeastern transportation-sector hydrogen demand will likely lag other, more important use cases, especially hydrogen for blending in existing natural gas pipelines, and hydrogen use for refinery applications.

Consumer-vehicle market data suggest that battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs) will continue to dominate the zero-emission personal-vehicle segment. In 2021, approximately 3,300 hydrogen fuel cell

70 "Bayway Refinery," Phillips 66, last visited August 15, 2022, https://www.phillips66.com/refining/bayway-refinery/.

71 Barbara J. Powell and Gerson Freitas Jr., "New Jersey Refinery Set to Restart Some Idled Fuel Production," Bloomberg, January 28, 2022, https://www.bloomberg.com/news/articles/2022-01-28/pbf-to-resume-some-idled-fuel-production-at-new-jersey-refinery-kyyqyrd2?sref=lDgLmqjg. Board.; "Time for a Farewell Tour for Mothballed Refineries?" *South Jersey Times*, June 19, 2022, https://www.nj.com/opinion/2022/06/time-for-a-farewell-tour-for-mothballed-refineries-letters.html.

72 "Bayway Refinery."

73 Susan Hicks and Peter Gross, "Hydrogen for Refineries Is Increasingly Provided by Industrial Suppliers," US Energy Information Administration, January 20, 2016, https://www.eia.gov/todayinenergy/detail.php?id=24612.

74 "Natural Gas Used as Feedstock for Hydrogen Production at Refineries," US Energy Information Administration, June 21, 2022, https://www.eia.gov/dnav/pet/PET_PNP_FEEDNG_K_A.htm.

75 "Phillips 66, Plug Power Sign Agreement to Advance Green Hydrogen," Phillips 66, press release, October 13, 2021, https://investor.phillips66.com/financial-information/news-releases/news-release-details/2021/Phillips-66-Plug-Power-Sign-Agreement-to-Advance-Green-Hydrogen/default.aspx.

76 "Hydrogen Supply."

77 "Steel Plant Tracker Map," Global Energy Monitor, February 24, 2021, https://globalenergymonitor.org/projects/global-steel-plant-tracker/tracker-map/.

78 "Commercial Metals Announces Plan to Build State-of-the-Art Micro Mill," PR Newswire, January 10, 2022, https://www.prnewswire.com/news-releases/commercial-metals-announces-plan-to-build-state-of-the-art-micro-mill-301456917.html.

79 "Cement Statistics and Information: 2020 Annual Tables; Table 3," US Geological Survey, July 29, 2022, https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information.

80 "Hydrogen Hub Roundtable."

RECOMMENDATIONS FOR A US NORTHEAST HYDROGEN HUB

electric vehicles, or FCEVs, were sold in the United States.[81] Conversely, US hybrid vehicles sales stood at about eight hundred thousand vehicles in 2021, while BEVs accounted for about another 435,000 vehicle sales.[82] Electrified vehicles accounted for 12.6 percent of all US vehicle sales in the second quarter of 2022, up from 8.9 percent in the same prior-year period.[83] It remains to be seen if BEVs and PHEVs can continue to increase market share, but some analysts have projected EV cost parity with traditional internal combustion vehicles (ICE) vehicles by 2027.[84] Moreover, the Inflation Reduction Act's pro-EV and pro-renewables provisions could dramatically accelerate the cost-parity timeline.

With EV adoption likely to receive a major boost from provisions in the Inflation Reduction Act, the technology will likely continue to charge ahead of hydrogen-fueled personal automobiles. Indeed, there are no US hydrogen-fueling stations outside of the state of California.[85] Hydrogen-fueled personal automobiles will almost certainly provide little to no northeastern hydrogen demand for the foreseeable future.

Buses are a potential hydrogen demand source for a northeast hydrogen hub. There is an ongoing debate about the relative advantages and disadvantages of hydrogen-fueled buses vis-à-vis electric buses. Hydrogen buses often have a larger tank range, enjoy shorter refueling times, and can operate more efficiently than battery-electric buses in very hot and very cold climates. BEVs appear positioned to beat out hydrogen in the bus market, however, due to costs and infrastructure. Unlike EVs, which "only" need a connection to the grid, there is little to no hydrogen-vehicle refueling infrastructure, and many cities are finding that electric buses are much less expensive than their hydrogen counterparts. A city in France, for instance, canceled an order for fifty hydrogen fuel cell buses after determining they would cost six times as much to operate as battery-electric buses.[86]

Battery-electric buses' storage capabilities can deliver important advantages over hydrogen-fueled buses in many contexts. For instance, electric school buses may enjoy enormous advantages over hydrogen due to specific use factors. School buses currently have an extraordinarily low utilization rate throughout the year: on school days, they are idled except while transporting students, or while transiting to and from bus depots. When schools are closed—including during the summer vacation—bus capacity is nearly completely idled. Predictable diurnal use patterns and long stretches of idle capacity suggest that electric buses could double as a grid-balancing service, storing electricity during peak renewables generation periods while discharging to the grid during peak-demand hours. While electric-battery charging times may preclude certain diurnal grid-balancing operations during school days, so-called vehicle-to-grid (V2G) technologies could help balance the grid on days when schools

81 Mark Kane, "US: Hydrogen Fuel Cell Car Sales Rebounded in 2021," InsideEVs, February 5, 2022, https://insideevs.com/news/565185/us-hydrogen-car-sales-2021/.

82 Hyunjoo Jin, "U.S. Hybrid Electric Car Sales Hit Record Highs," Reuters, January 6, 2022, https://www.reuters.com/business/autos-transportation/us-hybrid-electric-car-sales-hit-record-highs-2022-01-06/.

83 "EV Sales Hit New Record in Q2 2022," Cox Automotive, July 13, 2022, https://www.coxautoinc.com/market-insights/ev-sales-hit-new-record-in-q2-2022/.

84 Karin Rives, "Global Electric Vehicle Sales Doubled; US Made EV Comeback in 2021," S&P Global Market Intelligence, May 24, 2022, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/global-electric-vehicle-sales-doubled-us-made-ev-comeback-in-2021-70489884.

85 "Hydrogen Fueling Station Locations," US Department of Energy, last visited August 15, 2022, https://afdc.energy.gov/fuels/hydrogen_locations.html#/find/nearest?fuel=HY.

86 Steve Hanley, "French City Cancels Hydrogen Bus Contract, Opts for Electric Buses," CleanTechnica, January 11, 2022, https://cleantechnica.com/2022/01/11/french-city-cancels-hydrogen-bus-contract-opts-for-electric-buses/.

RECOMMENDATIONS FOR A US NORTHEAST HYDROGEN HUB

are closed. These V2G technologies could provide limited but sizable electricity storage: the Environmental Protection Agency (EPA) estimates that if half of all US school buses went electric, they could store enough power to electrify more than half of Vermont's homes for up to three days.[87]

Northeastern states may already be coalescing around electric school buses—and, potentially, electric buses in general. An electric school bus in Beverly, Massachusetts, used V2G technology to power the grid in the summer of 2021.[88] Other states are building out their electric school-bus fleets: New Jersey has created a $45-million electric school-bus program, Boston public schools are launching an electric school-bus pilot program during the 2022–2023 school year, and New York City's Metropolitan Transportation Authority announced in April 2022 that it will deploy sixty electric buses with zero tailpipe carbon emissions.[89] Hydrogen-powered buses could eventually dominate the segment, but initial signs suggest that BEVs have a head start.

The maritime industry is a potential H_2 offtaker, but not in the near term. There are concerns about retrofitting ships for liquid hydrogen, as the fuel's low energy density requires greater space than conventional fuels, limiting room for cargoes. According to some experts, any liquid-hydrogen-fueled vessels built within the next half decade will likely be small and produced for niche markets, such as the passenger market or for small-scale, short-sea shipping.[90]

Ammonia, which is produced by reacting hydrogen from electrolysis and with atmospheric nitrogen, is potentially a much more economical alternative to liquid hydrogen for the maritime industry.[91] Still, there is little prospect of major maritime ammonia shipping in the near term: Yara International, a major ammonia producer, is constructing the world's first carbon-free ammonia fuel-bunker network servicing the local Scandinavian market, with a planned delivery date of 2024.[92] Given that the planned start date may be ambitious, even given the reach of Yara and expected policy support from Scandinavian governments, there is little prospect of the northeast requiring ammonia for the maritime sector in the near term. Still, over the long term, Northeastern policymakers may need to reevaluate ammonia's role in maritime shipping and consider adjusting the region's infrastructure.

In sum, there is little evidence that hydrogen will serve as a major transportation fuel in the northeast for years. Battery-electric vehicles and plug-in hybrid electric vehicles will likely continue to dominate zero-emissions vehicle sales, while electric buses may have a first-mover advantage over hydrogen buses, partly due to electric school buses' use-case benefits. Meanwhile, the maritime sector is unlikely to emerge as a significant H_2 demand source for years, perhaps more than a decade. Hydrogen could play a role in northeastern transportation, but not for many years.

87 "What If Electric School Buses Could Be Used to Supply Power When Off Duty?" US Environmental Protection Agency, November 1, 2021, https://www.epa.gov/greenvehicles/what-if-electric-school-buses-could-be-used-supply-power-when-duty.

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IV. Midstream, Supply Chains, Infrastructure, and Storage

Energy systems, including hydrogen hubs, need more than just supply and demand. A northeast H2Hub will require midstream connections between supply and demand; stable supply chains; relevant infrastructure, such as electrolyzers; a capable workforce; and storage for diurnal and, potentially, inter-seasonal balancing. While the region faces transmission challenges, the northeast has already developed significant electrolyzer capacity and possesses a highly skilled technology workforce.

Inter-regional and Intra-regional Transmission

Hydrogen's success in the northeast could ultimately depend on the region's ability to build out more inter-regional and intra-regional electricity transmission and pipeline networks. Additional renewables capacity may need to be constructed in places where there is little to no existing transmission capacity. Moreover, some industrial facilities may co-site renewables generation with green hydrogen production. Therefore, the northeast must be able to quickly site new transmission and distribution capacity, retrofit existing natural gas pipeline networks for hydrogen, or even build new, hydrogen-dedicated pipelines.

The region's ability to incorporate electricity grid transmission at scale is uncertain. On November 3, 2021, Maine voters rejected a $1-billion transmission project that would have delivered clean, renewable hydropower from Quebec to New England.[93] Conversely, in July 2022, New York completed a new, twenty-mile, 345-kilovolt line called Empire State Line, enabling the transmission of 3.7 GW of renewable energy throughout New York.[94] In addition to standard "not in my backyard" opposition to new transmission, some research indicates the northeast could suffer from "regionalist" biases, with some slice of voters more likely to oppose wind power projects if the generated electrons flow to another, rival state.[95]

As discussed extensively in the demand section, hydrogen blending in pipelines is of major concern to the northeastern hydrogen hub, but an issue fraught with uncertainty. One area in which policymakers can and should act immediately, however, is replacing the region's cast-iron pipeline infrastructure. Cast-iron pipelines are not recommended for hydrogen gas service, according to the American Society of Mechanical Engineers.[96] Moreover, cast-iron or wrought-iron pipelines comprise a substantial fraction of the northeast's distribution mains: 16.7 percent in Massachusetts, 14.4 percent in New York, 14.3 percent in Connecticut, and 9.4 percent in New Jersey.[97] Because cast-iron pipelines account for a disproportionate level of methane emissions, regulators and policymakers should prioritize their replacement, even in the absence of any hydrogen requirements.[98] Moreover, because safety incidents could disrupt the regional, or even national, transition to a hydrogen economy, policymakers must prioritize the removal of unsafe, unreliable, and leak-prone cast-iron pipelines.

Regional policymakers should also begin to consider how to streamline permitting and construction for hydrogen-dedicated pipelines in case they are needed. While utilizing the northeast's existing natural gas pipeline system for hydrogen is surely preferable to constructing new pipelines, the region may ultimately need to construct new hydrogen-dedicated pipelines, depending on the results of hydrogen-blending safety studies. The region's states should support efforts to create—or at least identify—a federal entity, such as the Federal Energy Regulatory Commission (FERC), responsible for the siting and approval of hydrogen-dedicated pipelines.

The future of northeastern hydrogen-transmission requirements is uncertain. Much will depend on a complex interplay of technology, regulation, politics, and economics. Regional policymakers, therefore, must be able to respond rapidly and decisively to changing technologies and market conditions, adapting the region's transmission and pipeline networks to meet shifting requirements.

Storage Considerations

As discussed previously, hydrogen could be used for the power sector to balance inter-seasonal demand, matching generation during low-demand months with peak winter electricity needs. However, the long-term storage of hydrogen is an important but unsettled question. While the DOE is investigating alternatives to salt caverns, it also notes that "large-volume underground hydrogen storage has been demonstrated to be safe and effective only in salt dome structures or caverns."[99] Other studies suggest that "underground hydrogen storage in geological formations could be a cheap and environmentally friendly medium- and long-term storage route."[100]

The region may enjoy an ability to store hydrogen locally, near demand centers. In May 2021, Mitsubishi Power and Texas Brine Company signed an agreement to develop large-scale, long-duration hydrogen-storage solutions across the eastern United States, including in New York state.[101]

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The Northeast's Hydrogen Supply Chain: Electrolyzers and Human Capital

The Northeast's hydrogen-related supply-chain infrastructure is expanding rapidly. The region enjoys some of the nation's most advanced hydrogen infrastructure. The northeast is developing offshore wind resources that could ultimately produce hydrogen; is investing in ports that will service offshore wind; and enjoys local electrolyzer production, which could enable green hydrogen production using the electrolysis method. Moreover, the region's immense reserves of human capital allow it to flexibly adjust to any new H_2 developments, drive innovation, and absorb new technologies and best practices.

A green hydrogen ecosystem is emerging in the northeast. Construction has begun at a Plug Power's green-hydrogen fuel-production facility in Genesee County; when completed, the facility will be the largest green hydrogen plant in North America.[102] Air Products, one of the world's largest hydrogen producers, is investing $500 million to construct a green hydrogen production and distribution facility in Massena, New York.[103] Plug Power is one of the world's largest manufactures of proton-exchange membrane (PEM) electrolyzers, and is headquartered in Latham, New York. The industrial gas company Linde, meanwhile, announced it will build its first North American PEM electrolyzer plant in Niagara Falls, New York, after strategic investment facilitation from the New York state government's Empire State Development.[104] The region's existing and planned PEM infrastructure could prove to be an enormous advantage if, as seems likely, PEM electrolyzers enjoy cost advantages over their alkaline competitors, particularly as system size increases.[105]

The Northeast's highly educated workforce and outstanding educational system could provide enormous advantageous for establishing a hydrogen hub. One survey by Wallet Hub found that Massachusetts, Connecticut, and New Jersey earned the highest three rankings for US public high schools.[106] The region is also home to a variety of leading research institutions, and routinely absorbs some of the world's brightest minds in science, technology, engineering, and mathematics fields. The northeast's highly educated workforce is extremely productive, dynamic, and able to integrate new technologies, including hydrogen.

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RECOMMENDATIONS FOR A US NORTHEAST HYDROGEN HUB

Conclusion and Recommendations

Hydrogen is a dynamic, exciting field, but one filled with uncertainty. While some technical issues, including the feasibility and safety of blending hydrogen into natural gas pipelines, will likely be resolved in the near term, other key questions, such as the economic competitiveness of clean hydrogen, will not be answered for some time—potentially a decade or longer. Building hydrogen-supporting supply chains will take years, so policymakers will have to act decisively under conditions of uncertainty. In order to maximize the region's hydrogen potential, northeastern policymakers will need to strike a difficult balance between humility, flexibility, and decisiveness; they may need to execute industrial policy in the face of uncertainty.

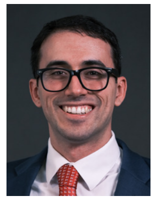
Despite macro uncertainty in hydrogen markets, policymakers and market participants in the region can act now, in the near term, without waiting for resolution of important debates.

- **Support expanded clean energy production.** Additional offshore wind and nuclear energy capacity is crucial to maximizing local green hydrogen production. The region cannot produce blue hydrogen indigenously, while importing green hydrogen at scale from maritime sources will prove infeasible for years, potentially more than a decade. While offshore wind should be at the center of the region's clean energy generation strategy, nuclear energy could play a key role in improving the capacity factors of electrolyzers by increasing the amount of aggregate clean energy on the grid. Alternatively, nuclear energy could power the production of pink hydrogen. Regional policymakers should continue to prioritize rapid adoption of all forms of clean energy, including via policy support, but also by reducing permitting timelines. Importantly, while expanding clean energy production could deliver major benefits for a hydrogen economy, it could also, by itself, lower electricity prices and decarbonize the electricity sector.
  - Great Lakes offshore wind presents intriguing possibilities for providing the energy required to produce hydrogen in the northeast, particularly over the medium and long terms. Developing Great Lakes offshore wind could require the involvement of federal institutions, however, due to FAA limitations on wind turbine heights.
- **Prepare the region's infrastructure for the hydrogen economy.** Regardless of the results of hydrogen-blending studies, regional policymakers must replace existing cast-iron pipelines with all possible haste. These pipes are not recommended for hydrogen service, and are high emitting even in existing pipeline systems.
  - Current federal efforts to study hydrogen blending in pipelines are insufficient. The federal government should seek to identify what levels of hydrogen can be blended into existing natural gas pipelines and infrastructure, and under what conditions. The current approach, which relies on individual states and stakeholders to conduct their own safety studies, appears duplicative, wasteful, and inefficient.
  - The region's states should support efforts to create—or at least identify—a federal entity responsible for the siting and approval of hydrogen-dedicated pipelines.
  - The northeast should continue to prepare the region's human infrastructure by building on its dominant advantage in education, which will bolster its hydrogen high-tech ecosystem. The northeast's outstanding public education system, expertise in STEM fields, and commitment to workforce training will prove enormously useful for establishing and sustaining a local hydrogen economy.
- **Nimbly adapt policy to meet changes in hydrogen technology.** Policymakers must navigate uncertainty surrounding cutting-edge hydrogen technology by responding rapidly and decisively to changing technologies and market conditions. Regional policymakers and decision-makers should follow H_2 market conditions very carefully—especially studies on blending hydrogen in natural gas pipelines—and adjust their governmental or corporate strategy as needed.
  - The northeast must address obstacles to intra-regional clean deployment and inter-regional clean energy transmission.
  - Northeastern policymakers should, over the medium and long terms, consider supporting regional ammonia-re-

lated infrastructure, given the fuel's potential use in the northeast's maritime sector.

As the field of hydrogen continues to evolve, regional decision-makers will need to attune policy to the latest developments. H_2 market conditions and technology will not remain static; pipeline blending percentages, offshore wind economics, and maritime transport dynamics could all change significantly over the next decade. The northeast hydrogen market will have to adapt to changing realities. There are plenty of reasons to think the region can rise to the challenge: a regional hydrogen-supportive supply chain is emerging, policymakers and the public are largely supportive of climate goals, there is a real need to lower regional electricity prices, and the northeast enjoys a world-class education system, including in STEM. Still, the northeast must overcome significant challenges, including limited onshore solar and wind resources, while the region's cast-iron pipelines need to be replaced with all possible haste. Offshore wind is arguably the most important element in the success of a future northeast hydrogen hub: if the region can successfully develop its OSW potential in the Atlantic Ocean (and, preferably, the Great Lakes as well), climate goals will be in easier reach. The northeast needs to keep working if it is to develop its full hydrogen potential. If it does, the future will be bright—and green.

About the Author



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