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Hydrogen Brief 2: Producing Clean Hydrogen at Scale in the United States

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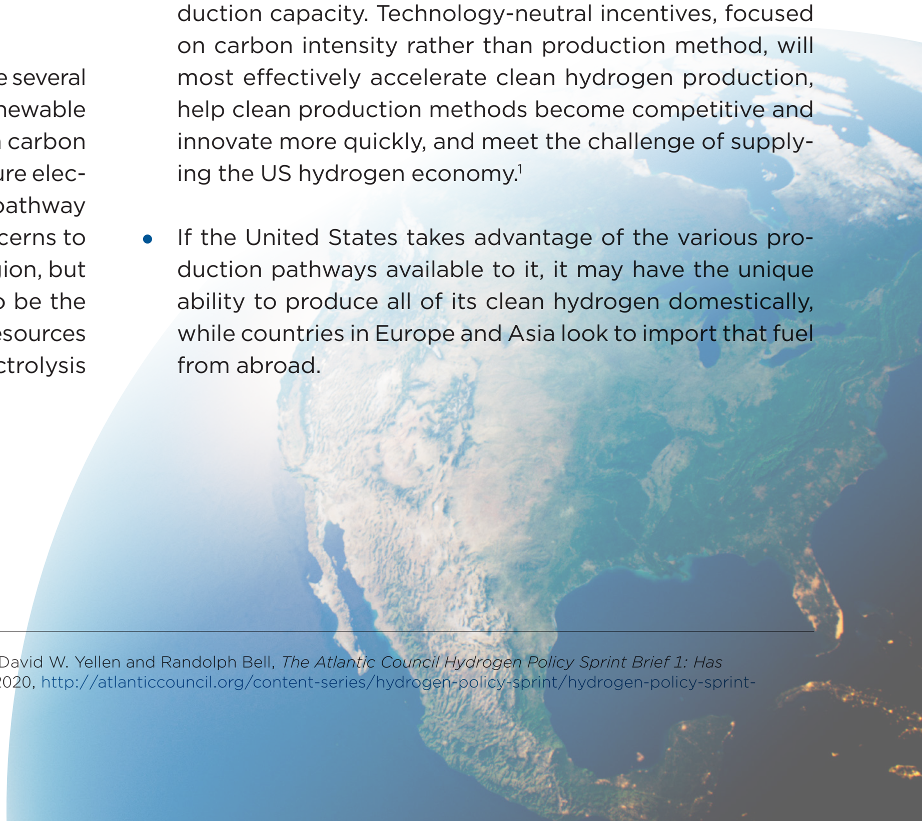
KEY TAKEAWAYS

- As ambitions for a clean hydrogen economy in the United States continue to grow, the largest obstacle to realizing those ambitions will likely be scaling clean hydrogen production quickly and economically to meet potential demand. Hydrogen demand could at least double over the next two decades if it is deployed into industrial applications, buildings, and blended into natural gas infrastructure, and it will grow by far more with broader use in long-distance transportation and energy storage applications. Meeting that demand with a single production pathway will be incredibly difficult; attempting to produce that volume using renewable electrolysis alone would require a massive build-out of renewable capacity far beyond the most optimistic renewables deployment scenarios. Multiple production pathways will thus be necessary to deploy hydrogen technologies quickly and efficiently in the short term and to reach scale in the longer term.

- The United States has a unique opportunity to pursue several clean hydrogen production pathways, including renewable electrolysis, steam methane reforming (SMR) with carbon capture, biomass to hydrogen, and high-temperature electrolysis using nuclear power, among others. Each pathway introduces tradeoffs—from cost and land use concerns to continued fossil fuel reliance—that will vary by region, but the most important differentiator will continue to be the carbon intensity of production. Where renewable resources are relatively cheap and abundant, renewable electrolysis will likely be the most popular production pathway. But where natural gas resources are cheap and there is legacy infrastructure, SMR with carbon capture or methane pyrolysis—or an alternative feedstock like biomethane—may be the most viable. Other methods—in particular, biomass to hydrogen and nuclear-powered electrolysis—may also play a critical role.

- Reaching cost competitiveness with incumbent hydrogen production methods will require innovation and scale for any of the clean hydrogen production pathways. Policy support, both in the form of innovation funding—which the Biden-Harris administration has signaled a continued commitment to—and demonstration and deployment funding or incentives, such as a clean hydrogen production tax credit, will be critical to short-term growth in clean production capacity. Technology-neutral incentives, focused on carbon intensity rather than production method, will most effectively accelerate clean hydrogen production, help clean production methods become competitive and innovate more quickly, and meet the challenge of supplying the US hydrogen economy.[1]

- If the United States takes advantage of the various production pathways available to it, it may have the unique ability to produce all of its clean hydrogen domestically, while countries in Europe and Asia look to import that fuel from abroad.



1 See first hydrogen policy sprint brief for a full discussion of this topic. David W. Yellen and Randolph Bell, *The Atlantic Council Hydrogen Policy Sprint Brief 1: Has Hydrogen's Time Come in the United States?*, Atlantic Council, March 2020, http://atlanticcouncil.org/content-series/hydrogen-policy-sprint/hydrogen-policy-sprint-brief-1/.

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Supplying a clean hydrogen economy

Scaling clean hydrogen production quickly and economically might be the biggest hurdle to developing a hydrogen economy in the United States. While the US already produces approximately 10 million metric tons (MMT) of hydrogen each year, deploying hydrogen into transportation, industry, buildings, or as a seasonal storage solution will require far more hydrogen in addition to current production. On top of that, almost all hydrogen in the United States is currently produced using steam methane reforming (SMR), which has a significant emissions footprint that will ultimately need to be mitigated.[2] Producing enough clean hydrogen to decarbonize these sectors will require a massive build-out of production capacity from current near-negligible levels.

Building that clean hydrogen production capacity, however, is critical to decarbonizing some hard-to-abate sectors.[3] Hydrogen produced using renewable electricity can also help to avoid curtailment and balance electricity prices during peak renewable production hours, thereby improving the business case for renewables. Any clean hydrogen production pathway can also substitute for dirty hydrogen production, and hydrogen can replace hydrocarbons in many sectors, which will immediately ameliorate local environmental impacts while also creating a new growth industry that can drive development and employment. To that end, clean hydrogen producers could look to opportunity zones—economically distressed regions as classified by the Internal Revenue Service, investment into which yields tax benefits—to deepen the economic impact of investment.

Production pathways

There are various clean hydrogen production pathways available to help reach scale, and each pathway relies on different resources and faces different challenges. In weighing these options, policy and investments should focus on carbon intensity and environmental impacts, rather than on the production method (often indicated through a color-coding system), in order to maximize the decarbonization benefit and accelerate scaling.[4]

Another key consideration, of course, is cost. The cost target to compete with SMR-produced hydrogen is $2/kilogram (kg), although the cost of hydrogen produced through SMR ranges from $0.90-3.20/kg, depending upon the cost of the natural gas feedstock.[5]

Another way of thinking about cost parity is to compare the lifecycle cost of switching to hydrogen technology (including the cost of clean hydrogen) with the lifecycle cost of current technology. Long-distance trucking is a good example. Accounting for the relative efficiencies of a class 8 hydrogen fuel cell electric vehicle (FCEV) and the average class 8 diesel vehicle in the United States—FCEV's have significantly higher efficiency engines compared to diesel trucks—hydrogen would reach cost parity at around $5.64/kgH_2$. If compared to a new, higher-efficiency diesel truck, hydrogen costs would need to fall below $2.98/kgH_2$.[6] In some locations and with some production methods, that target is already achievable. However, this does not account for the relative vehicle production and maintenance costs, which also need to be considered. While FCEV production costs will probably be higher than diesel vehicle production costs, FCEV maintenance costs are likely to be lower.

A price on carbon or other incentives would change these calculations by raising the price of carbon-intense incumbents such as diesel and SMR-produced hydrogen. Across the spectrum of clean hydrogen production methods, innovation—whether of the technologies to raise efficiencies, and/or of the processes involved in manufacturing and operation to lower costs—will be critical to competing with incumbent production methods and technologies.

2 See previous brief for a discussion of why hydrogen produced through SMR can provide immediate climate and environmental gains now, even as the emphasis must be on cleaner forms of production. David W. Yellen and Randolph Bell, The Atlantic Council Hydrogen Policy Sprint Brief 1: Has Hydrogen's Time Come in the United States?; Roadmap for the Deployment and Buildout of Renewable Hydrogen Production Plants in California, UC Irvine Advanced Power and Energy Program, final report for California Energy Commission, June 2020, http://cafcp.org/sites/default/files/Roadmap-for-Deployment-and-Buildout-of-RH2-UCI-CEC-June-2020.pdf.

3 Thomas Koch Blank and Patrick Molloy, "Hydrogen's Decarbonization Impact for Industry," Insight Brief, Rocky Mountain Institute, January 2020, http://rmi.org/wpcontent/uploads/2020/01/hydrogen_insight_brief.pdf.

4 David W. Yellen and Randolph Bell, *The Atlantic Council Hydrogen Policy Sprint Brief 1: Has Hydrogen's Time Come in the United States?*

5 "Hydrogen production costs by production source, 2018," International Energy Agency, March 6, 2020, http://iea.org/data-and-statistics/charts/hydrogen-production-costs-by-production-source-2018.

6 Calculations use ten-year average diesel price of $3.18 per gallon, current average diesel truck efficiency of 5.3 miles per gallon (mpg), new diesel truck efficiency of 10.0 mpg, and hydrogen truck efficiency of 9.4 miles per kilogram (mpkg). "US No 2 Diesel Retail Prices," US Energy Information Administration, accessed April 7, 2021, http://eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=emd_epd2d_pte_nus_dpg&f=a; "Average Fuel Economy by Major Vehicle Category," US Department of Energy Alternative Fuels Data Center, accessed April 7, 2021, http://afdc.energy.gov/data/10310; Jason Marcinkoski et al., "Hydrogen Class 8 Long Haul Truck Targets," US Department of Energy Fuel Cell Technologies and Vehicle Technologies Offices, October 31, 2019, http://hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf.

Renewable energy through electrolysis

Renewable electrolysis is the production pathway that has received the most attention as a long-term solution for clean hydrogen because it is zero carbon and minimizes environmental impacts, though it could have significant land use implications. Renewable electrolysis produces hydrogen when renewable electricity powers an electrolyzer, which splits water into hydrogen and oxygen. There are various electrolyzer technologies available:

- **Alkaline electrolysis** is the oldest commercial technology, but it requires a liquid electrolyte that raises maintenance costs and is less responsive to variations in energy supply.
- **Proton exchange membrane (PEM) electrolysis** is the current dominant technology for new production capacity, which usually uses platinum as a catalyst and is more responsive to supply variation.
- **Anion exchange membrane (AEM) electrolysis**, the newest technology, is smaller scale and does not require precious metal catalysts.[7]

At the end of 2019, global renewable electrolysis hydrogen production capacity reached 40,000 metric tons per year, with some forecasts predicting an increase to 5.7 million metric tons annually by 2030, an enormous jump in capacity that would demand a massive amount of clean electricity (see "Challenge of Scale" below).[8]

Current US PEM electrolyzer hydrogen production capacity stands at just over 14 megawatts (MW), most of which is concentrated in California; however, not all of this electrolyzer capacity has dedicated renewable power, and some may use power from fossil sources as well.[9] For context, the planned Florida Light and Power–NextEra renewable hydrogen production pilot plant would add 20 MW of capacity—which would produce about 2.5 metric tons per day without dedicated battery storage to increase the utilization rate—more than doubling the country's electrolyzer capacity.[10] In contrast, ACWA Power and Air Products are planning an electrolyzer facility in Saudi Arabia powered by 4 gigawatts (GW) of renewable power, projected to produce 650 metric tons of clean hydrogen each day.[11] The United States has major opportunities to expand renewable electrolysis, with abundant renewable resources in several regions. However, low capacity factors and, therefore, utilization rates may make cost competitiveness difficult until energy storage or electrolyzer costs and efficiencies can be improved. Several major demonstration projects are planned both in the United States and abroad, in addition to NextEra's pilot plant in Florida, including: a Plug Power-Brookfield Renewables plant in Pennsylvania projected to produce 15 metric tons per day,[12] a Plug Power plant in New York expected to produce 45 metric tons per day,[13] and a planned Enel hydrogen plant using power from one of its US solar projects.[14] A coalition of seven companies—ACWA Power, CWP Renewables, Envision, Iberdrola, Ørsted, Snam, and Yara—have also launched the "Green Hydrogen Catapult," an effort to scale the global production of hydrogen from renewable electrolysis fifty-fold over the next six years.[15]

However, without incentives or a price on carbon, renewable electrolysis remains far from cost competitive in most markets, as compared to non-abated SMR hydrogen. Current costs range between $3.00-7.50/kg, depending largely upon electricity costs, which may be competitive with diesel in fueling class 8 trucks, but is not currently competitive with SMR hydrogen.[16] Theoretically, the $2/kg cost target is achievable using current electrolyzer technologies with cheap electricity and a high utilization rate.[17] But the utilization rate when relying upon variable resources like wind and solar is often too low. BloombergNEF

7 Cornelia Lichner, "Electrolyzer overview: Lowering the cost of hydrogen and distributing its production," *pv magazine*, March 26, 2020, http://pv-magazine-usa.com/2020/03/26/electrolyzer-overview-lowering-the-cost-of-hydrogen-and-distributing-its-productionhydrogen-industry-overview-lowering-the-cost-and-distributing-production/.

8 Srihari Daivanayagam, "Global Green Hydrogen Production Set to Reach 5.7 Million Tons by 2030, Powered by Decarbonization," Frost & Sullivan, January 19, 2021, http://ww2.frost.com/news/global-green-hydrogen-production-set-to-reach-5-7-million-tons-by-2030-powered-by-decarbonization.

9 The US Department of Energy tracks PEM electrolyzer capacity specifically; there is less definitive data on total national capacity for other electrolyzer technologies. This also includes electrolyzers that use electricity from the grid, which may not produce clean hydrogen depending upon the carbon intensity of the grid. "US Hydrogen Electrolyzer Locations and Capacity," US Department of Energy Hydrogen Fuel Cell Technologies Office, February 12, 2021, http://energy.gov/eere/fuelcells/downloads/us-hydrogen-electrolyzer-locations-and-capacity.

10 Utilization rate refers to the fraction of the time that an electrolyzer is running. Output calculation assumes electrolyzer efficiency of 64 percent and capacity factor for dedicated renewable production of 30 percent [providing a generous estimate of output]. Karl-Erik Stromsta, "NextEra Energy to Build Its First Green Hydrogen Plant in Florida," *Greentech Media*, July 24, 2020, http://greentechmedia.com/articles/read/nextera-energy-to-build-its-first-green-hydrogen-plant-in-florida.

11 Jean-François Seznec and Samer Mosis, "The ACWA Power–Air Products joint venture for green hydrogen: A new Saudi energy policy?" *EnergySource*, Atlantic Council Global Energy Center, July 24, 2020, http://atlanticcouncil.org/blogs/energysource/the-acwa-power-air-products-joint-venture-for-green-hydrogen-a-new-saudi-energy-policy/.

12 "Plug Power, Brookfield Renewable to build green hydrogen plant," Reuters, March 30, 2021, http://reuters.com/article/us-plug-power-hydrogen/plug-power-brookfield-renewable-to-build-green-hydrogen-plant-idUSKBN2BM1NZ.

13 "Plug Power to Build North America's Largest Green Hydrogen Production Facility in Western New York," GlobeNewswire, February 25, 2021, http://globenewswire.com/news-release/2021/02/25/2183008/0/en/Plug-Power-to-Build-North-America-s-Largest-Green-Hydrogen-Production-Facility-in-Western-New-York.html.

14 Jules Scully, "Enel pens deal for US solar-powered green hydrogen project," PV-Tech, December 10, 2020, http://pv-tech.org/enel-pens-deal-for-us-solar-powered-green-hydrogen-project/.

15 "Green Hydrogen Catapult," Race to Zero, December 8, 2020, http://racetozero.unfccc.int/green-hydrogen-catapult/.

16 "Hydrogen production costs by production source, 2018," International Energy Agency.

17 Sunita Satyapal, "U.S. Department of Energy's Hydrogen and Fuel Cell Perspectives," US Department of Energy Office of Energy Efficiency & Renewable Energy, September 10, 2020, http://energy.gov/sites/prod/files/2020/10/f79/hfto-satyapal-fcell-sept10_0.pdf.

estimates that costs could fall to $0.80-1.60/kg, but only with innovation in electrolyzer technology and policy support to scale and reduce cost.[18] New electrolysis chemistries and technologies, such as AEM electrolyzers, may raise efficiency, allow for smaller-scale and modular electrolyzers that can lower costs and ease scaling, or rely on cheaper inputs.[19]

SMR with CCUS

SMR—the dominant current hydrogen production method—can be equipped with carbon capture, utilization, and storage (CCUS) to lower carbon intensity and produce clean hydrogen, although the carbon intensity of produced hydrogen varies depending on the capture rate. This method has already been deployed at industrial scale, particularly in the Netherlands and Norway, but also in the United States, including at Air Products' Port Arthur hydrogen plant. Hydrogen produced with SMR and CCUS is not zero carbon, but it has a lower carbon intensity than that produced from electrolysis using electricity from the grid in many locations.[20] In general, costs range from $1.40-2.90/kg and vary based upon the price of natural gas feedstock and the capture rate of the carbon capture system (higher capture rates tend to cost more).[21] Even without incentives, SMR with CCUS might be the most viable clean hydrogen pathway in areas with cheap gas and available geologic carbon dioxide storage. A CCUS incentive or price on carbon could bring it to cost parity with unabated SMR hydrogen. For companies that have invested in natural gas or legacy hydrogen production infrastructure, this pathway can avoid stranded assets and reduce barriers to entry into clean hydrogen production. The need for carbon dioxide infrastructure and storage at scale limits the geographic viability of this pathway and may raise associated costs, particularly if that infrastructure does not already exist. Additionally, the emissions intensity of produced hydrogen will depend upon stewardship of the natural gas supply chain; upstream methane leaks will reduce or even eliminate the carbon benefits of deploying CCUS. Similarly, medium- and long-term viability of the process depends upon reaching near-100 percent carbon capture rates.

Biomass to hydrogen

The gasification of biomass is an alternative clean hydrogen production method, sometimes described as "green" along with renewable electrolysis. If biomass waste is used as the fuel source, this pathway can actually generate carbon-negative hydrogen by avoiding methane emissions from that waste.[22] Biomass gasification operates similarly to coal gasification production of hydrogen, which has been deployed at large scale, but without the associated carbon emissions. Theoretically, this production pathway can also operate at lower costs than renewable electrolysis because of the low costs of the biomass feedstock. Instead of purchasing renewable power, a biomass-to-hydrogen plant could contract with a municipality to offtake rejected recyclable materials. The largest-scale biomass-to-hydrogen plant is currently under construction in Lancaster, California; if the project meets its cost and production targets, this pathway could become a critical piece of the US hydrogen economy.[23] The US Environmental Protection Agency is currently assessing several biomass-to-hydrogen pathways for inclusion under the federal Renewable Fuel Standard, which incentivizes biomass-based transportation fuels.[24]

Electrolysis utilizing nuclear power

Electrolysis powered by nuclear energy also shows promise as a hydrogen production method, particularly because nuclear can support high temperature electrolysis that is significantly more efficient and is a firm power resource with a high capacity factor, so the utilization rate of the electrolyzer can near 100 percent. Nuclear electrolysis is theoretically also already cost competitive and can be produced for less than $2/kg; new advanced reactor technologies could produce hydrogen for $0.90/kg by 2030.[25] The US Department of Energy has supported several projects in the United States to demonstrate nuclear-to-hydrogen's viability, including through new grants awarded in December 2020.[26] Because the technology is still in the demonstration phase, it remains to be seen whether nuclear-to-hydrogen can hit those theoretical cost targets and become commercially viable at scale. A particular advantage of using nuclear energy would be the significantly

18 Veronika Henze, "'Hydrogen Economy' Offers Promising Path to Decarbonization," BloombergNEF, March 30, 2020, http://about.bnef.com/blog/hydrogen-economy-offers-promising-path-to-decarbonization/.

19 "EnergySource Innovation Stream: Highly efficient hydrogen electrolyzers," *EnergySource Innovation Stream* event, Atlantic Council, May 27, 2020, http://atlanticcouncil.org/event/energysource-innovation-stream-highly-efficient-hydrogen-electrolyzers/.

20 Lucas van Cappellen, Harry Croezen, and Frans Rooijers, *Feasibility study into blue hydrogen*, CE Delft Report, July 2018, http://cedelft.eu/en/publications/download/2585; "Air Products & Chemicals, Inc.," US Department of Energy Office of Fossil Energy, accessed April 7, 2021, http://energy.gov/fe/air-products-chemicals-inc.

21 J Robinson, "Cost, logistics offer 'blue hydrogen' market advantages over 'green' alternative," *S&P Global Platts*, March 19, 2020, http://spglobal.com/platts/en/market-insights/latest-news/electric-power/031920-cost-logistics-offer-blue-hydrogen-market-advantages-over-green-alternative; "Hydrogen production costs by production source, 2018," International Energy Agency.

22 Darrell Proctor, "Group Says It Will Launch World's Largest Green Hydrogen Project," *POWER Magazine*, May 20, 2020, http://powermag.com/group-says-it-will-launch-worlds-largest-green-hydrogen-project/.

23 "World's Largest Green Hydrogen Project to Launch in California," *Business Wire*, May 20, 2020, https://www.businesswire.com/news/home/20200520005256/en/World%E2%80%99s-Largest-Green-Hydrogen-Project-to-Launch-in-California.

24 "Pending Petitions for Renewable Fuel Pathways," Renewable Fuel Standard Program, US Environmental Protection Agency, accessed April 7, 2021, http://epa.gov/renewable-fuel-standard-program/pending-petitions-renewable-fuel-pathways.

25 Eric Ingersoll and Kirsty Gogan, "Driving deeper decarbonization with nuclear energy," *International Atomic Energy Agency Bulletin*, Vol. 61-3 (September 2020), accessed April 7, 2021, http://iaea.org/nuclear-power-and-the-clean-energy-transition/driving-deeper-decarbonization-with-nuclear-energy.

26 "U.S. Department of Energy Announces $26.9 Million for Advanced Nuclear Technology," US Department of Energy Office of Nuclear Energy, October 8, 2020, http://energy.gov/ne/articles/us-department-energy-announces-269-million-advanced-nuclear-technology.

reduced land use associated with hydrogen production compared to electrolysis powered by solar or wind, though there is political opposition in some jurisdictions. This pathway also faces the tradeoff of using firm nuclear power to help decarbonize and stabilize the grid instead of diverting power to produce hydrogen.

Other pathways

Several other hydrogen production pathways are under development and hold promise. Methane pyrolysis would use natural gas to produce clean hydrogen and a solid carbon byproduct that could then be sold to improve the economic viability of the project. With early momentum behind demonstration projects, this pathway could become increasingly viable. An additional alternative is electrolysis using electricity from the grid; this would not currently be carbon-free but would lower the complexity of projects. This pathway may become more viable in the medium and long terms as the grid becomes cleaner.

The challenge of scale

A critical question in considering clean hydrogen production pathways in the United States is that of scale: simply, how much hydrogen will we need? The answer of course depends upon where hydrogen is deployed in the economy. Heavy transportation, industry, energy storage, and buildings all represent large potential markets for the fuel, any of which would significantly increase hydrogen demand from today's 10 MMT, even if the current demand in oil refining faded. For instance, replacing all diesel demand in the United States with hydrogen—an unlikely scenario, as some use cases for diesel are likely better suited to electrification, but illustrative of the challenges of scale—would require three times the country's current annual supply of hydrogen.[27] As hydrogen applications in each of these hard-to-abate sectors develop over the next two decades, hydrogen demand will at least double if policy supports decarbonization. A more ambitious deployment pathway—with hydrogen playing a key role across industries, and even in some passenger vehicle markets—could cause hydrogen demand to increase six-fold by 2050.[28]

Any of these deployment scenarios—even a mere doubling of current US hydrogen demand—would require a huge amount of energy input, particularly because current production will need to be replaced with clean production capacity or retrofitted with carbon capture.

If the industry attempts to meet all of that demand with renewable electricity, it will require a massive build-out of renewable resources beyond the most optimistic renewables deployment scenarios. Even if electrolyzer technology becomes much more efficient, producing 20 MMT of hydrogen each year—double what the United States produces annually now—from renewable power would require 93 percent of projected 2040 national solar capacity or 134 percent of projected wind capacity.[29] In other words, producing 20 MMT a year would require doubling projected annual capacity additions of wind or solar out to 2040. For more ambitious deployment scenarios, the scale becomes even more daunting. To replace all diesel demand in the United States with hydrogen vehicles, fuel production would require 600-800 GW of variable renewable energy capacity, or three to four times the United States' current total variable renewable capacity.[30]

Renewable resources will be critical to decarbonizing US electricity production and meeting rising electricity demand (as electrification across the economy advances) with clean energy; the opportunity cost of using that capacity for hydrogen production instead may be too steep. The European Union faces the same challenge, as their hydrogen strategy estimates that 80-120 GW of additional renewable capacity—dedicated to hydrogen production—will be necessary just to meet 2030 targets.[31] This is not to say that renewable electrolysis will not be a critical production pathway for clean hydrogen—it will likely be the most common clean production method—but merely that it will be incapable of meeting clean hydrogen demand alone, at least in the short and medium terms.

Regional opportunities

Opportunities for each of these production pathways will largely be determined by regional resources, including existing infrastructure.

In regions like California, the Pacific Northwest, and the Midwest—areas with abundant and inexpensive renewable energy

27 Based on annual US diesel demand of 47.2 billion gallons. Assumes hydrogen FCEV efficiency of 60 percent compared to diesel vehicle 40 percent, equivalence between 1 kg hydrogen and 1 gallon diesel. "Diesel fuel explained: Use of diesel," US Energy Information Administration, http://eia.gov/energyexplained/diesel-fuel/use-of-diesel.php; Nic Lutsey, "The ever-improving efficiency of the diesel engine," The International Council on Clean Transportation, August 14, 2015, http://theicct.org/blogs/staff/ever-improving-efficiency-diesel-engine.

28 "Road Map to a US Hydrogen Economy," Fuel Cell & Hydrogen Energy Association, ushydrogenstudy.org.

29 Elizabeth Connelly et al., *Resource Assessment for Hydrogen Production*, National Renewable Energy Laboratory, Technical Report, NREL/TP-5400-77198, July 2020, http://nrel.gov/docs/fy20osti/77198.pdf.

30 Assumes a capacity factor of renewable resources of 30 percent and potential electrolyzer efficiency range of 64-80 percent.

31 "A hydrogen strategy for a climate-neutral Europe," Communication from the European Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, European Commission, July 8, 2020, http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301.

Powering hydrogen at scale

To understand the challenges of producing hydrogen from renewable electrolysis at scale, we looked at two hypothetical examples of hydrogen demand: one where 20 MMT of hydrogen is demanded (double current US hydrogen production) and one in which all US diesel demand is replaced by hydrogen, an unlikely scenario but illustrative of the challenge.

The key variables for these calculations are electrolyzer efficiency and renewable power capacity factor. For the former, we looked at the scenarios using the current efficiency—66.7 MWh producing one metric ton of hydrogen (51 percent efficiency)—and a very ambitious target efficiency of 50 MWh producing one metric ton of hydrogen (80 percent efficiency). For renewable capacity factor, we used 30 percent, which is roughly the current capacity factor of installed variable renewable power in the US, and 50 percent, which is roughly the projected average capacity factor of offshore wind in the US.

Variable power required to produce 2x current US hydrogen demand (20 MMT)

Rated Renewable Power Required	=	**20,000,000** metric tons of hydrogen/year	X	MWh electricity/ metric ton of hydrogen	÷	CAPACITY FACTOR	÷	**8760** hours/year

Assuming 51 percent electrolyzer efficiency and 30 percent CF: 507.61 GW rated variable power
Assuming 80 percent electrolyzer efficiency and 30 percent CF: 380.52 GW rated variable power
Assuming 80 percent electrolyzer efficiency and 50 percent CF: 228.21 GW rated variable power

Even if all of the renewable power came from offshore wind, with a capacity factor around 50 percent, and electrolyzers hit the 80 percent efficiency target, supplying double current US hydrogen demand would still require 228.21 GW of rated offshore wind capacity solely dedicated to hydrogen production. For context, the United States' current total offshore wind target is 30 GW by 2030.

Variable power required to replace US diesel demand

While an extremely unlikely scenario, we thought it would be a useful thought exercise to see how much variable renewable power would be needed to replace US diesel demand with 'green' hydrogen. The US currently consumes 129.3 million gallons of diesel per day. One gallon of diesel has approximately the same energy density as one kilogram of hydrogen, but FCEVs are about 60 perrcent efficient while diesel engines are only 40 percent efficient, meaning 86,200 metric tons of hydrogen per day would replace 129.3 million gallons of diesel per day.

US daily diesel demand: 129.3 million gallons Energy Density: 1 gallon diesel approximately equal to 1 kg hydrogen

Metric tons of Hydrogen per Day	=	**129.3** million gallons diesel	X	Diesel engine efficiency	÷	Hydrogen engine efficiency	X	**1** kg H_2/ 1 gallon diesel

Assuming engine efficiencies of 40 percent for Diesel and 60 percent for FCEV: 86,200 metric tons H2/day

Rated Renewable Power Required	=	**86,200** metric tons/day	X	Electrolyzer Efficiency	X	**1** GW/ 1000 MW	X	**1** day/ 24 hours	÷	CAPACITY FACTOR

Assuming 51 percent electrolyzer efficiency and 30 percent CF: 798.55 GW rated variable power
Assuming 80 percent electrolyzer efficiency and 30 percent CF: 598.61 GW rated variable power
Assuming 80 percent electrolyzer efficiency and 50 percent CF: 359.17 GW rated variable power

Context: total US variable renewable power capacity (2019) = 200.7 GW

* "Energy Secretary Granholm Announces Ambitious New 30GW Offshore Wind Deployment Target by 2030," US Department of Energy, March 29, 2021, http://energy.gov/articles/energy-secretary-granholm-announces-ambitious-new-30gw-offshore-wind-deployment-target.

** "Diesel fuel explained: Use of diesel," US Energy Information Administration.

*** "Wind power facts," American Clean Power, accessed April 7, 2021, https://cleanpower.org/facts/wind-power/;
"U.S. Solar Market Insight," Solar Energy Industry Association, accessed April 7, 2021, https://www.seia.org/us-solar-market-insight.

resources—hydrogen produced from renewable electricity will likely continue to be the most attractive production method. California, in particular, offers excellent opportunities for scaled renewable electrolysis, particularly as the state begins to invest in major offshore wind energy capacity, for which hydrogen may be an excellent complement. The state's aggressive renewable energy goals, including a 60 percent renewable energy portfolio standard by 2030, promise to enhance these opportunities over time. Still, even in these regions, the scale of power necessary to produce hydrogen—as well as the need to decarbonize the grid itself—may make a diversity of production methods essential. California curtails a large amount of power each year that could be used to produce hydrogen without affecting the grid's decarbonization, but as mentioned above, the economics of using curtailed power for electrolysis are not currently viable because of low utilization rates. California already has one biomass-to-hydrogen project underway, and biomass and nuclear hydrogen pathways may prove invaluable complements even if the region primarily pursues renewable electrolysis.

Elsewhere, hydrogen produced from methane using CCUS could be the economic choice in areas with cheap and ready access to natural gas, existing steam methane reforming capacity, and geologic storage for captured carbon dioxide. Texas and the eastern industrial corridor—including West Virginia, Ohio, Pennsylvania, New Jersey, and southern New York—both have excellent opportunities for this pathway given their abundant natural gas resources and geologic storage potential for carbon dioxide. These regions also have significant existing hydrogen production that could potentially be retrofitted with carbon capture to produce clean hydrogen. This pathway is closest to profitability on the Texas Gulf Coast, which has access to very cheap methane feedstock, existing carbon capture and storage projects, and infrastructure. Similar to California, however, these regions will also likely need a diversity of production pathways in order to meet hydrogen demand, particularly with the opportunity presented by the abundant wind and solar resources also available in Texas.

Reaching scale through policy

Scaling clean hydrogen production will certainly be one of the most difficult challenges to achieving the lofty ambitions for hydrogen as a decarbonization solution in the United States. As described above, that challenge is unlikely to be overcome by any single production method. A diversity of methods and resources will thus be critical to enabling a more rapid and scalable transition toward a hydrogen economy. Technology-neutral policy—policy that can support innovation and deployment of several or all of these various methods—will best prepare states and the country to unlock the fuel's potential.

Incentives to support clean hydrogen production—whether an investment tax credit, a production tax credit, or coverage under a renewable fuels standard to enhance cost competitiveness—and investment in innovation are the most immediate and direct policy opportunities. (A price on carbon would also incentivize broader clean hydrogen production and deployment, though is politically unpopular.) There are no existing US federal policy incentives for hydrogen production or deployment, and hydrogen was a conspicuous omission from the Energy Act of 2020 (the US Environmental Protection Agency is also currently considering making biogas hydrogen pathways eligible under the renewable fuel standard). But the Biden-Harris administration's recently announced American Jobs Plan includes hydrogen demonstration projects in "distressed communities" along with a potential production tax credit for hydrogen, which would be a major boost to the competitiveness of clean production methods and to market creation.[32] The Plan also points to hydrogen as a priority for clean energy innovation and demonstration investment, which mirrored hydrogen's inclusion in the administration's innovation agenda and continued Department of Energy investment.[33] A production tax credit for clean hydrogen would incentivize deployment and help clean hydrogen production methods compete with incumbent production pathways.

Despite the rich opportunities for low-cost clean hydrogen production in the United States, policy support will likely be necessary—and can make a significant impact in the short term—to accelerate hydrogen's deployment and unlock its decarbonization potential. Still, given the challenges of scaling clean hydrogen production and the resources that will be necessary to do so, policy should prioritize the fuel's deployment to cases in which it is the most viable (or possible) decarbonization solution. These likely include long-distance transportation, certain industrial applications, and long-term energy storage for the power system. Whenever possible, directly using clean electricity will likely be more energy efficient and cost effective than using hydrogen where electricity is a viable decarbonization solution. The fourth and fifth briefs in this series will address potential use-cases for hydrogen.

32 "FACT SHEET: The American Jobs Plan," Statements and Releases, the White House Briefing Room, March 31, 2021, http://whitehouse.gov/briefing-room/statements-releases/2021/03/31/fact-sheet-the-american-jobs-plan/.

33 "Biden-Harris Administration Launches American Innovation Effort to Create Jobs and Tackle the Climate Crisis," Statements and Releases, the White House Briefing Room, February 11, 2021, http://whitehouse.gov/briefing-room/statements-releases/2021/02/11/biden-harris-administration-launches-american-innovation-effort-to-create-jobs-and-tackle-the-climate-crisis/.