American Clean Hydrogen:
A Tremendous Export Opportunity

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Executive Summary

As the world moves toward a clean energy future, every clean technology tool in the toolbox will be needed. One new area of innovation that has gained popularity in recent years is hydrogen. As many countries begin to include hydrogen in their decarbonization efforts, a global race to supply clean hydrogen has begun. This report considers the role the United States could play in meeting global clean hydrogen demand through exports, as well as the rapidly developing American infrastructure and policy environment for hydrogen. The analysis includes several key findings:

1. **EU and Japan Will Face Clean Hydrogen Supply Gaps**
   Global demand for hydrogen could increase rapidly; however, the largest markets are likely to face supply gaps. The European Union and Japan have the most ambitious plans to utilize clean hydrogen for decarbonization, but their domestic production plans fall short of potential demand.

2. **Global Competitors Are Poised to Fill these Gaps**
   Russia, the Middle East, and Australia are positioning themselves to meet this potential demand by creating strong, export-oriented strategies and are already signing export contracts.

3. **The USA Can be a Highly Competitive Clean Hydrogen Exporter**
   In addition to meeting its own projected demand growth, the United States can be a highly competitive exporter of clean hydrogen to meet supply gaps in both the European Union and Japan. In particular, the U.S. has a cost advantage when exporting hydrogen produced from natural gas with a high rate of carbon capture. This is due to both the low cost of natural gas and the existing carbon capture tax credit, 45Q, which can lower the cost of production by up to 30 percent.

4. **Emerging U.S. Hydrogen Hubs Could Meet International Demand**
   A number of U.S. regions are well-suited to capitalize on this opportunity and become “hydrogen hubs,” as they already have significant hydrogen production capacity, which could be converted to clean production. The federal government can help lay the groundwork for these hubs to succeed in a competitive future hydrogen market.

Main Takeaways

1. The European Union and Japan Will Face Clean Hydrogen Supply Gaps

The International Energy Agency (IEA) predicts that global demand for hydrogen could increase another two to six times by 2050 if hydrogen is adopted as a decarbonization tool that cuts across many sectors.[1] Europe and Japan have the most ambitious plans to utilize clean hydrogen for decarbonization, especially in their industrial and transportation sectors. The European Union's annual demand for hydrogen is predicted to increase anywhere from 11 million to 48 million metric tons (MMt) by 2050 compared to 2015 levels.[2] Japan is considering a similar level of growth, where annual consumption is predicted to increase to 10-20 MMt per year by 2050.[3]

While the EU's and Japan's demand for hydrogen could increase rapidly, their production plans are lagging behind. In the EU, where annual demand is expected to grow to between 12.2-16.9 MMt by 2030, only around 10 MMt of new clean hydrogen capacity is planned; this is only enough to decarbonize today's level of hydrogen consumption.[4] In Japan, companies like Kawasaki are already preparing to build ships for import capacity of up to 99 MMt per year.[5] The scale of clean hydrogen procurement is compounded by the need to reduce emissions from existing facilities. These gaps in clean hydrogen production present an opportunity for imports from other regions.

2. Russia, the Middle East, and Australia Plan to Fill Clean Hydrogen Gaps

The growing European and Japanese hydrogen import opportunity has led several countries to develop comprehensive clean hydrogen export strategies. These include Russia, Saudi Arabia, the United Arab Emirates, and Australia.

The Russian government views hydrogen as a significant export opportunity and has begun to increase hydrogen production capacity with an eventual export goal of 2 MMt of hydrogen by 2030.[6] Russia is positioned to supply hydrogen to Europe and Japan through both its existing pipeline network and a blue hydrogen hub in development on the Yamal Peninsula in Siberia.[7]

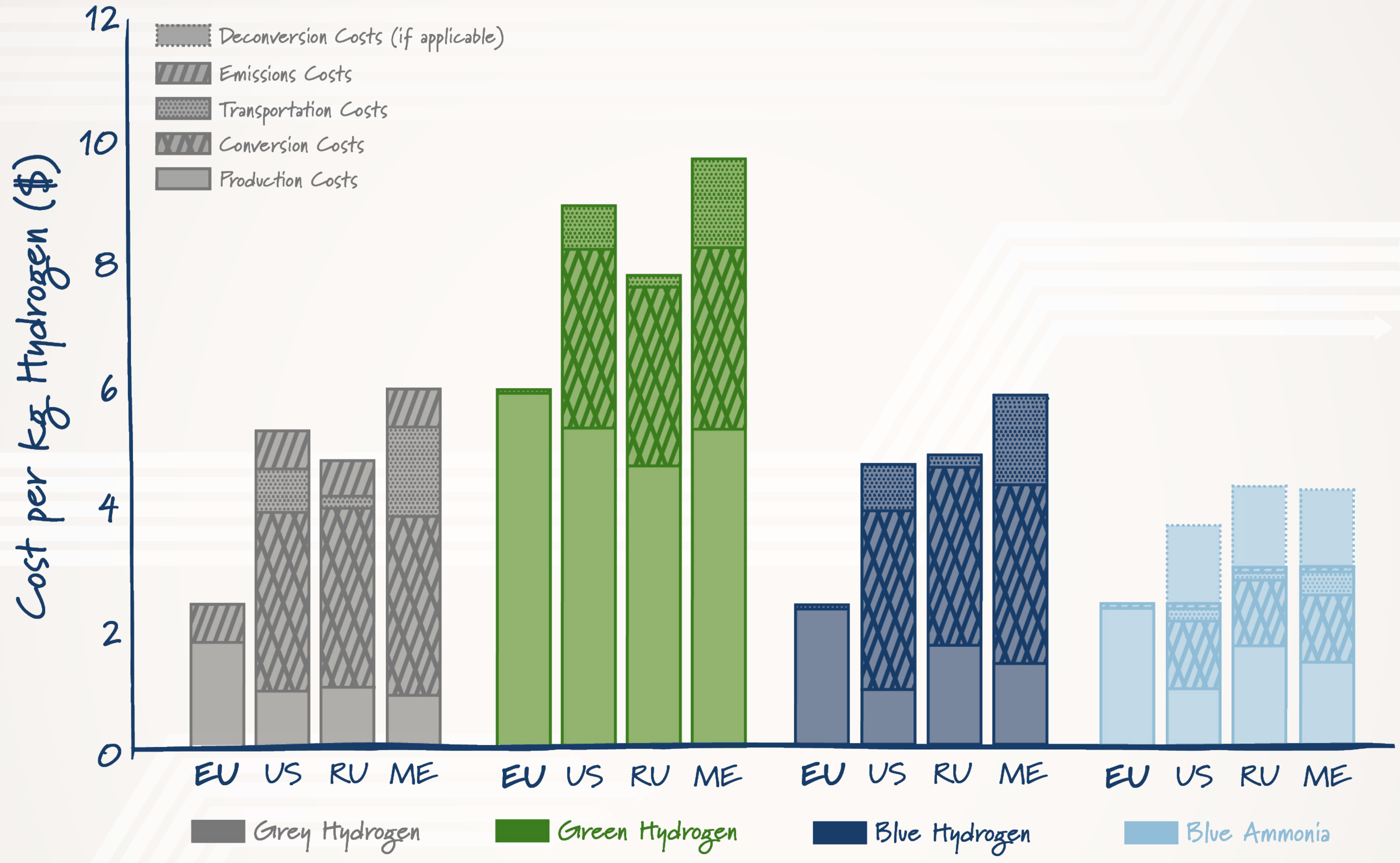
Some Middle Eastern countries have already worked to secure footholds in emerging hydrogen markets. The United Arab Emirates and the Abu Dhabi National Oil Company, for example, recently signed agreements with Malaysia and South Korea to develop international hydrogen supply chains.[8] In 2020, Saudi Arabia sent the world's first shipment of blue ammonia (a variation of hydrogen that is cheaper to transport) to Japan, signaling both their ability and intent to become a global leader in clean ammonia production and export.[9]

A number of hydrogen initiatives are underway in Australia, with a focus on developing multiple hydrogen export hubs.[10] The government has begun fostering hydrogen exports to Japan, beginning with a coal gasification pilot plant that will supply liquefied hydrogen.[11] Production plans include both large-scale blue hydrogen projects and green hydrogen projects, including a green hydrogen hub, which is anticipated to send 3 MMt of hydrogen to Japan by 2030.

3. The United States Can Be a Highly Competitive Clean Hydrogen Exporter

The United States has a big role to play in filling the potential clean hydrogen supply gaps in the EU and Japan. Clean hydrogen produced in the United States can be highly competitive with other export options. Figure 1 demonstrates the EU's average total costs in 2020 for hydrogen from various countries and sources.[A] Ammonia is included in this analysis, as it is a well understood and widely traded hydrogen carrier that can be manufactured and reverse-manufactured to either store or extract hydrogen.

Figure 1: Cost per Kilogram (kg) of Hydrogen Shipped to EU



It's clear that compared to other import options, American clean hydrogen can be highly competitive, particularly hydrogen or ammonia produced from natural gas with a carbon capture rate of at least 90 percent (hydrogen and ammonia produced with carbon capture is called "blue"). This is due to the low cost of natural gas and the carbon capture tax credit that lowers the cost of production by up to 30 percent.[B]

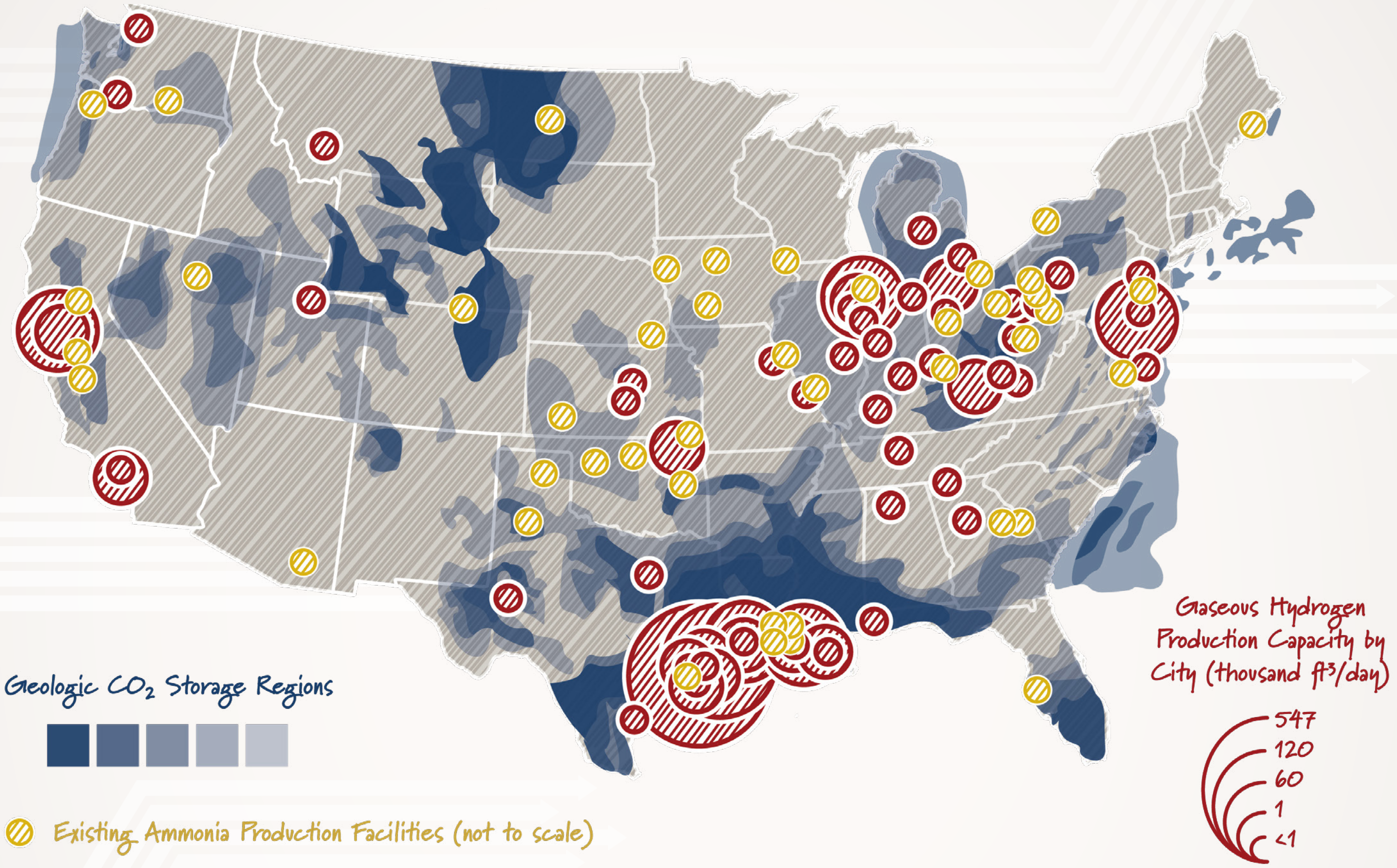
[A] Assumptions regarding numbers can be found on page 16.

[B] Costs here are based on 90 percent carbon capture. For the U.S. to be highly competitive against the EU and Russia, 90 percent capture is essential to take full advantage of the 45Q tax credit. U.S. production costs for blue hydrogen and ammonia are reduced by the expected value of 45Q.

4. Emerging American Hydrogen Hubs Could Meet International Demand

In addition to providing a general cost advantage over some other nations, several U.S. regions are poised to benefit from hydrogen exports. These “hydrogen hubs” typically have some hydrogen or ammonia production capacity, access to geologic storage for carbon dioxide, and transportation infrastructure. These regions, highlighted in the map below, are most likely to benefit from hydrogen exports in the near term.[12]

Figure 2: Potential U.S. Hydrogen Hubs and Geologic CO2 Storage Regions



The Ohio River Valley, the Gulf Coast, and California are well positioned to export hydrogen and ammonia. Funding to develop American hydrogen hubs is in the bipartisan infrastructure bill, with a total of $8 billion dollars allocated across four regions. If the legislation moves forward it could soon provide funding for these ideal regions.

Recommendations

While the U.S. is a strong competitor in the global hydrogen market, future energy leadership is not guaranteed. Australia, Russia, and the Middle East are quickly positioning themselves as major clean hydrogen exporters and developing their own regional hubs and trade relationships; the first hydrogen export shipments to Japan are happening this year. If the United States does not capitalize on its current advantage, these other countries will likely have lower costs than the United States over time. Unlike Russia, Australia, Japan, Saudi Arabia, and the European Union, the United States has no formally articulated strategy or policy initiative to develop large-scale hydrogen infrastructure. Without establishing a strategy and appropriate policy such as extending tax credit support, this competitive advantage could shrink by 2030. To cement the United States' pole position in clean hydrogen exports, the federal government should consider the following steps.

1. **The Department of Energy and Department of Commerce should initiate a joint strategy on federal policies to enable the scale-up of American clean hydrogen exports.** This strategy should, at minimum, consider near-term needs for scaling domestic hydrogen production and consumption, export financing opportunities, and any legal challenges facing large-scale hydrogen and ammonia exports.

2. **The Department of Commerce, Department of Energy, and the Department of State should look to establish hydrogen-related trade relationships.** Countries looking to increase their hydrogen consumption should be targeted for joint development of consistent methodologies and protocols to track embedded greenhouse gas emissions throughout the hydrogen life cycle.

3. **Enact the Senate-passed bipartisan Infrastructure Jobs and Investment Act.** The bill includes funding to develop four regional hydrogen hubs, modernizes the hydrogen research and development program at the Department of Energy, and includes significant funding for electrolyzer research and development. All told, the bill includes $10 billion in direct hydrogen funding. The bill also includes funding to enable carbon capture infrastructure, including more funding to the Environmental Protection Agency to permit carbon storage wells and a new Carbon Infrastructure Financing Agency to support carbon pipeline buildout.

4. **Extend the 45Q carbon capture tax credit through 2030, and enact a hydrogen production tax credit.** These credits would reduce the cost of clean hydrogen over the long term, ensuring that American hydrogen remains competitive in the face of cost declines in other countries.

Introduction

As countries around the world reduce their greenhouse gas emissions, hydrogen is emerging as a low-carbon energy carrier that could be used nearly as universally as electricity. Due to its high energy density; zero carbon emissions from utilization; high temperature potential; and multi-sector use cases, interest in hydrogen has steadily increased. In recent years Hydrogen can be used in a variety of end-use sectors, including transportation, industry, and electricity generation.[13] For some of these sectors, particularly industry, clean hydrogen could be one of the most cost-effective ways to reduce carbon emissions because it can be used as a clean feedstock for chemical processes and as a source of high-temperature heat.[14] There are a number of countries and regions taking the lead on hydrogen research, supply chain, and production opportunities, such as the U.S., Japan, the EU, and the Middle East. Countries like Malaysia and South Korea are looking into hydrogen's potential in their own energy systems. This report analyzes the role of U.S.-produced hydrogen in meeting other countries' rapidly growing hydrogen demands.

Hydrogen and Hydrogen Carrier Options

In the U.S., there are two main methods of hydrogen production.[C] These include natural gas pathways, in which natural gas is combined with steam to produce hydrogen and CO_2, and electrolysis, which utilizes electricity to split water into hydrogen and oxygen. Both production pathways can either be clean or produce significant emissions. Clean natural gas pathways yield what is commonly referred to as "blue hydrogen," while clean electrolysis pathways yield "green hydrogen."

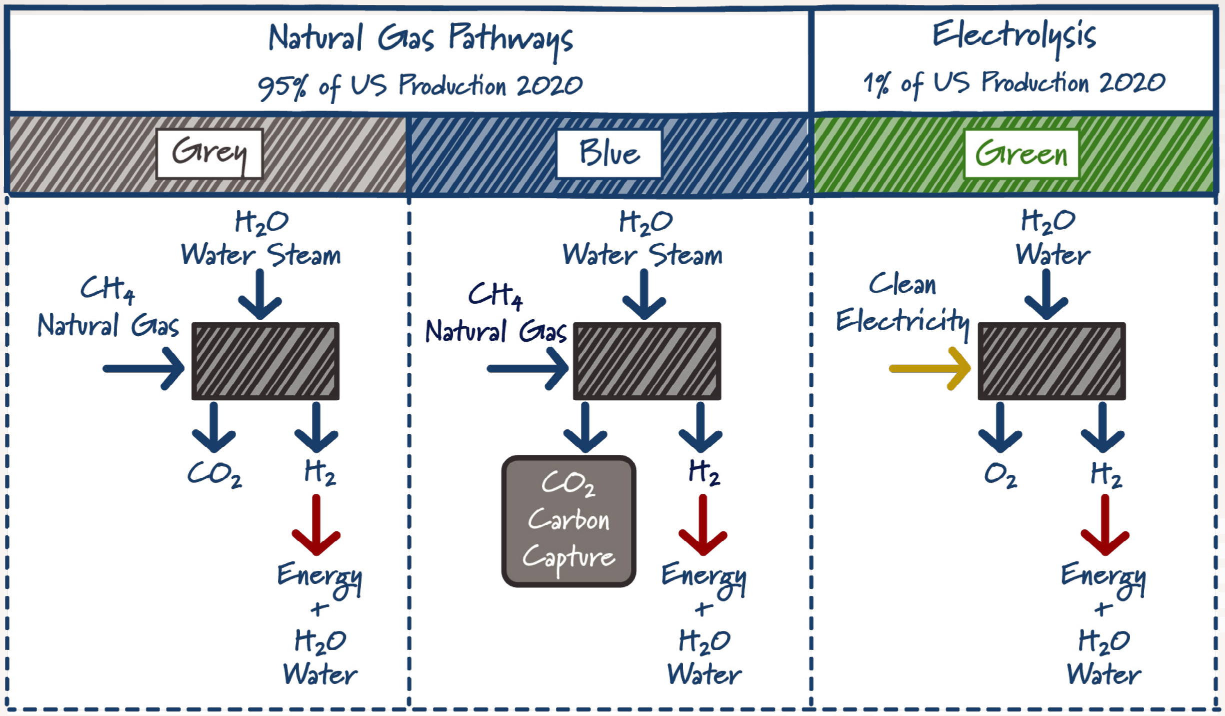
Around 95 percent of hydrogen in the U.S. is produced through a natural gas pathway known as steam methane reformation (SMR), in which natural gas is combined with steam at a high temperature to produce hydrogen and CO_2. When the resulting CO_2 is vented rather than captured, this process produces "grey hydrogen."[15] Autothermal reforming (ATR) is a natural gas pathway similar to SMR, but it's much more efficient and uses pure oxygen rather than air. Any natural gas production pathway in which the resulting CO_2 is captured instead of released into the atmosphere is referred to as "blue hydrogen." Carbon capture equipment can be installed on existing SMR facilities, or on new SMR and ATR facilities.

Another hydrogen production method is electrolysis, a process that uses electricity to split water into hydrogen and oxygen. Any source of electricity can be used for electrolysis, but if that electricity is supplied by unabated fossil sources, it is not considered clean. "Green hydrogen" is produced through electrolysis powered by low-carbon energy sources like renewables or nuclear. Both green and blue hydrogen are considered clean under the right circumstances because they release far fewer carbon emissions than grey hydrogen, but these sources must be analyzed on a life cycle basis.[D] Only 1 percent of hydrogen is produced through clean methods in the United States today.[16]

[C] This paper focuses on steam methane reforming and electrolysis for hydrogen production, as they are the most common methods of clean hydrogen production. Other methods, such as coal gasification, autothermal reforming, and methane pyrolysis, are not considered.

[D] This paper defines clean hydrogen as less than 2 kg CO2e per kg H2 on a life cycle basis, which is examined in the next section.

Figure 3: Main Hydrogen Production Methods



A variety of hydrogen carrier molecules can either be used as an energy source directly or as a hydrogen conveyor, depending on the need. These carriers allow hydrogen to be moved more affordably and efficiently compared to liquid hydrogen, which must be kept at a temperature below -253°C to prevent boiling.[17] While these carriers would need to undergo additional processing to be converted back into hydrogen, the benefits outweigh the costs in many long-distance transportation scenarios. All of the hydrogen carriers aim to address the cost and logistics of hydrogen transportation.

Ammonia, a well understood molecule used to make fertilizer,[E] could find a new market as a hydrogen carrier molecule. Compared to hydrogen, ammonia is far easier to liquefy and transport, which decreases long-distance transportation costs. With a liquefaction temperature of -33°C, ammonia requires significantly less energy to liquefy than hydrogen, which has a liquefaction temperature of -253°C.[18] As a liquid, ammonia is around 50 percent more energy dense than hydrogen by volume.[19] Increasing the energy content per shipment could significantly lower the cost of transportation.

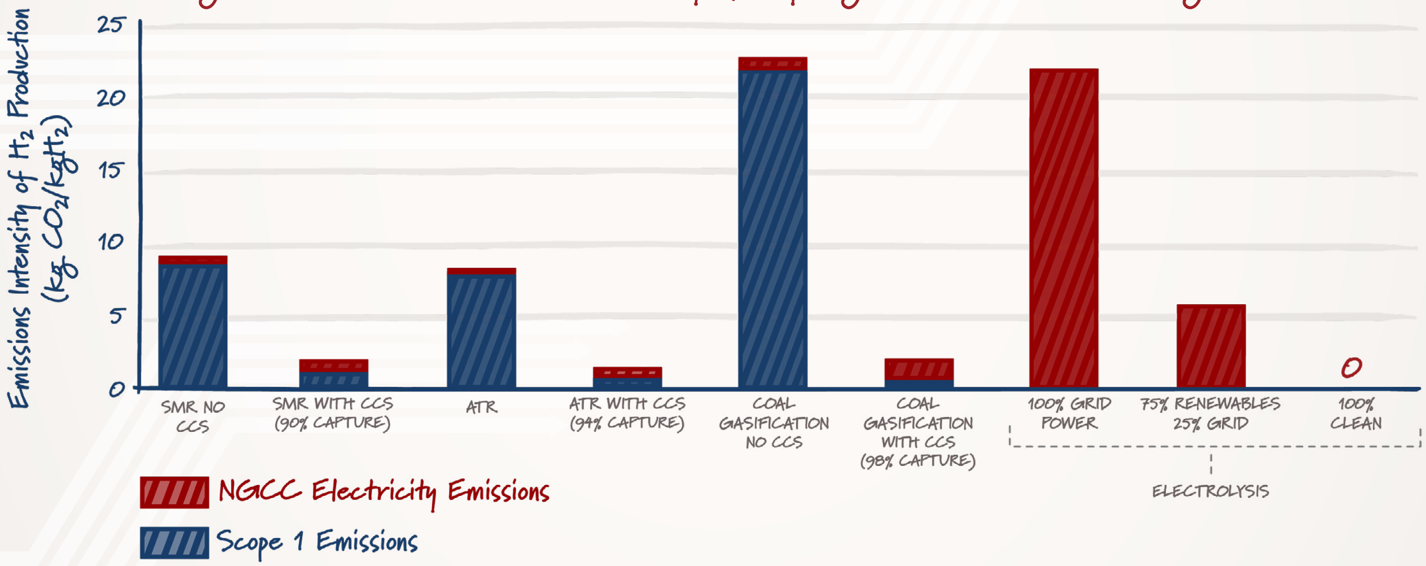
[E] Methanol is another potential hydrogen carrier, but methanol emits carbon unless it is produced from renewable natural gas. As the scale-up of renewable methanol is limited, it is not included in this analysis. See: Corbett, James J., and James J. Winebrake. 2018. “Life Cycle Analysis of the Use of Methanol for Marine Transportation.” U.S. Department of Transportation. https://www.maritime.dot.gov/sites/marad.dot.gov/files/docs/innovation/meta/11056/marine-methanol-report-20180810final-002.pdf.

Carriers may need to undergo additional processing to reconvert to hydrogen. If countries plan to ship hydrogen using hydrogen carriers such as ammonia, these conversion and deconversion costs and associated energy efficiency losses will need to be accounted for in the final cost and emissions estimates.[F] In some cases, these costs can contribute greatly to the final cost of shipped hydrogen, which could be a deciding factor in determining U.S. competitiveness in future hydrogen markets. It is also possible to directly utilize ammonia as a fuel in turbines or fuel cells, potentially eliminating the need for reconversion.

Defining Clean Hydrogen

Recently, there has been significant debate about what level of emissions qualifies hydrogen as a clean energy source. These questions matter, as clean hydrogen must represent a significant reduction compared to the energy source it is replacing in order to be considered an effective climate technology. Direct emissions from various hydrogen production methods are shown in figure 4 below. The figure shows the full range of potential direct emissions from hydrogen production, from net-negative emissions, such as biomass gasification with carbon capture, to high emissions, such as coal gasification or grid-based electrolysis in regions with significant coal or gas electricity production. Some technologies, such as green hydrogen, emit no direct carbon at all.

Figure 4: Direct Emissions Intensity of Hydrogen Production Technologies[H]

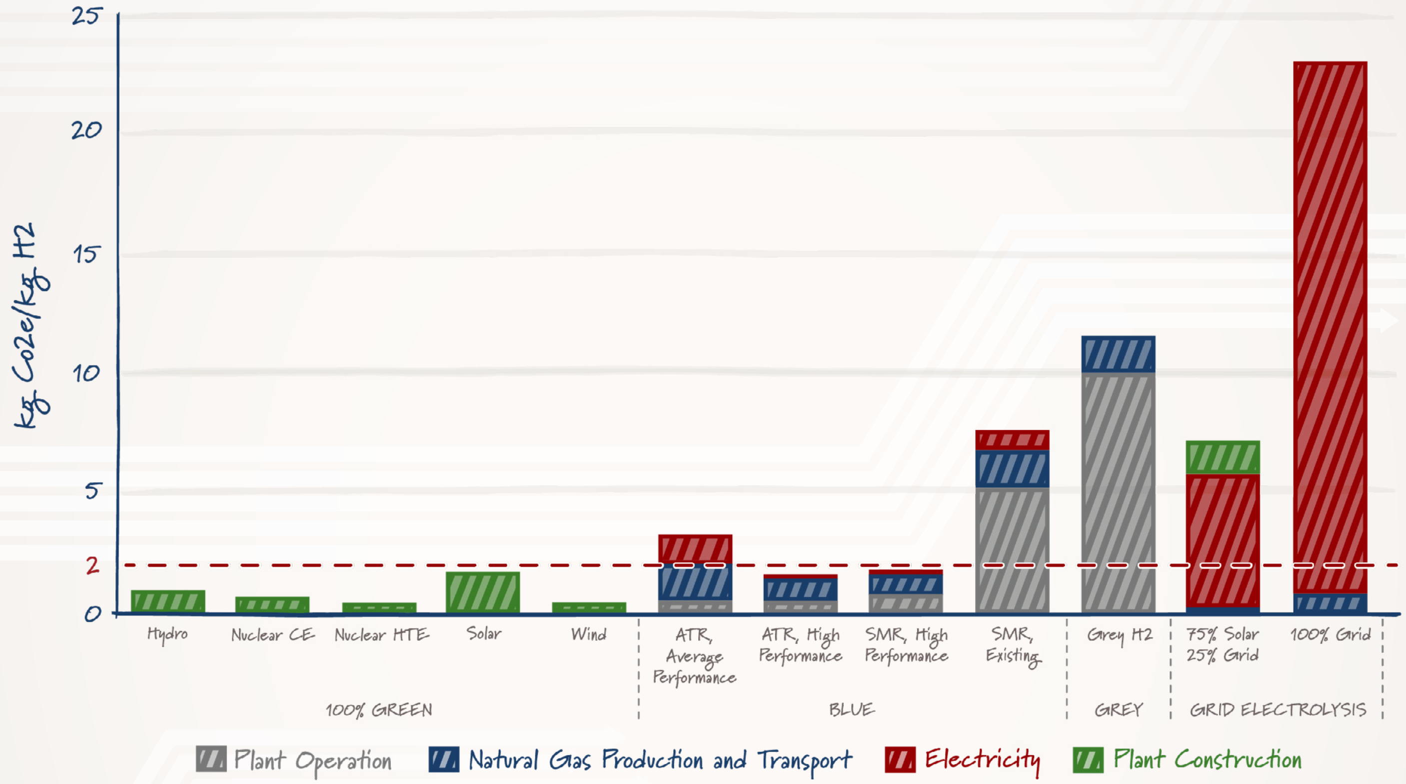


Ultimately, blue hydrogen can be produced cleanly, even including upstream emissions. But the direct emissions associated with hydrogen production do not tell the full story. To truly compare the emissions of various hydrogen production options, a life cycle approach, from construction through production, must be taken. For natural gas-based technologies, upstream methane emissions make up a sizable portion of life cycle emissions, while for green hydrogen technologies, sizable emissions result from the construction of electricity generation capacity and the electrolyzer.

[H] Figure adapted from Global Carbon Capture and Storage Institute report on Blue Hydrogen, April 2021.

Figure 5 demonstrates the range of life cycle emissions associated with common methods of hydrogen production. Blue hydrogen production has a potential life cycle emissions range of approximately 1.5 to 7.6 kg CO_2e per kg hydrogen, depending on the cleanliness of electricity, carbon capture rate, and the rate of leakage.[I] Reaching blue hydrogen's lower range requires a capture rate at 90 percent or above, a low natural gas leakage rate, and a clean electric grid. At those rates, blue hydrogen can be produced with life cycle emissions equivalent to or lower than solar-powered electrolysis, and significantly below the emissions of renewable electrolysis firmed by grid electricity.

Figure 5: Life Cycle Carbon Intensity of Hydrogen Production[20]



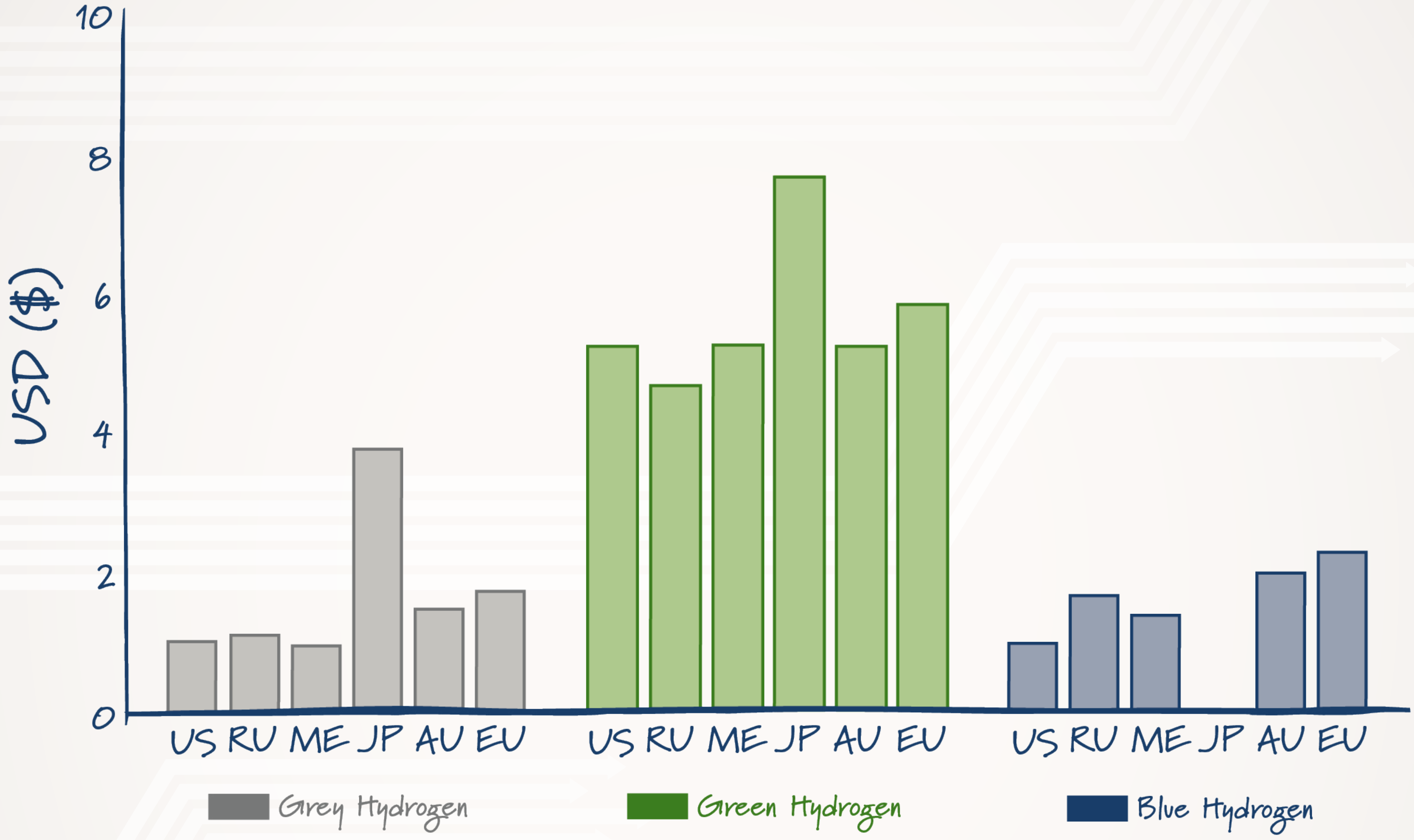
At existing levels of carbon capture and utilizing existing grid electricity, SMR with carbon capture has a higher rate of emissions than pure green hydrogen; however, there are very few green electrolysis projects not firmed by grid electricity. Governments and companies must strive to make hydrogen as clean and affordable as possible. For the purposes of this report, clean hydrogen is defined as less than 2 kg of CO_2 per kg of hydrogen, inclusive of best-in-class blue hydrogen options. Government policy is likely to push new blue hydrogen production facilities toward best-in-class options. As discussed later in the report, the 45Q carbon capture tax credit provides a strong incentive for reaching higher rates of carbon capture, and new tax incentives for hydrogen production all include a life cycle assessment process that provides higher credits for cleaner resources.

[I] "High Performance" assumes 90 percent carbon capture, upstream production GHG intensity of 4.83kg CO2e/mmBTU of natural gas (5.1 kg CO2e/GJ NG), and zero carbon electricity. Grey H2, ATR average performance, and SMR existing are assumed to have upstream production GHG intensity of 7.9 kg CO2e/mmBTU of natural gas (8.4 kg CO2e/GJ NG). SMR existing is assumed to have a capture rate of 48%, based on the Quest facility.

Global Export Competitors

A number of countries are emerging as potential exporters of clean hydrogen, due to low production costs or strategic locations. Some of the most likely exporters in the emerging hydrogen economy include the U.S., Russia (RU), Middle Eastern energy-producing nations like the United Arab Emirates and Saudi Arabia (ME), Australia (AU), and the European Union (EU).

Figure 6: Production Cost per kg Hydrogen in Various Countries[J]



* Note: Japan (JP) cannot currently produce blue hydrogen in significant quantities due to insufficient carbon storage capabilities, and has limited capability to produce hydrogen through renewable electrolysis.

United States Production and Export Trends

The United States produces 10 MMt MMt of hydrogen each year. Most is produced through SMR, a method that costs only around $1 per kg due to the low cost of natural gas in the U.S.[21] The U.S. is also emerging as a leader in carbon capture technology with more than 40 projects in development.[22] These factors, along with ample carbon storage potential, make the U.S. an ideal manufacturer of blue hydrogen. The cost of

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[J] US: United States; RU: Russia; ME: Middle East; JP: Japan; AU: Australia, EU: European Union. For grey and blue hydrogen, natural gas costs per mmBTU were as follows: US $3.3, AU: $5.4, JP: $10.9, EU $7.3, based on International Energy Agency's *Future of Hydrogen Technical Annex*.

production is about $1.50 per kg, an extremely competitive price in the global market.[23] This cost is lowered to around $1 per kg due to the 45Q tax credit, which provides an effective benefit of $0.35 to $0.50 per kg of blue hydrogen produced with high rates of carbon capture.

One disadvantage that American clean hydrogen faces is the long transportation distance to emerging hydrogen markets in Europe and Asia. This distance can quickly raise the international price of U.S. hydrogen as transportation, conversion, and deconversion costs become increasingly significant, unless a hydrogen carrier like ammonia is used.

Russian Production and Export Trends

Unlike many other countries, Russia has not proposed any significant plans to expand domestic clean hydrogen consumption.[24] However, the Russian government does view hydrogen as a significant export opportunity and has begun to increase hydrogen production capacity with an eventual export goal of 2 MMt of hydrogen by 2030.[25]

If produced with carbon capture, the cost of blue hydrogen production would be approximately $1.60 per kg due to the low cost of Russian natural gas. As no blue hydrogen facilities currently operate in Russia, this cost is only an estimate.[26] For now, estimates of Russian blue hydrogen production costs are comparable to U.S. costs, likely due to the size and maturity of Russia's natural gas industry.[27] Russia's natural gas pipeline network is second only to the U.S., further lowering the overall cost of their natural gas.[28] One concern is the potential for illegal subsidization of exports. Historically the Russian government has heavily subsidized the export of ammonium nitrate, which led the U.S. and EU to impose countervailing duties. While those duties were recently overturned, Russia could try to undercut fair value using export-oriented subsidies.

Middle Eastern Production and Export Trends

A number of countries are producing hydrogen at scale in the Middle East, including Qatar, Saudi Arabia, and the UAE.[29] If blue hydrogen were developed in the Middle East, it would likely cost around $1.40 per kg, making it among the cheapest sources of clean hydrogen available today, on par with the U.S.[30] Some Middle Eastern countries have already worked to secure footholds in emerging hydrogen markets. The United Arab Emirates and the Abu Dhabi National Oil Company, for example, recently signed agreements with Malaysia and South Korea to develop international hydrogen supply chains.[31]

Due to an immense potential for high quality complementary solar and wind energy, the Middle East is uniquely positioned to take advantage of future advances in green hydrogen production.[32] While the cost of electrolytic hydrogen production using renewable energy is still too high to be competitive with blue and grey hydrogen, technology developments that increase electrolyzer efficiency and decrease the cost of electricity could quickly change this.

Australian Production and Export Trends

Like many other countries, Australia considers clean hydrogen production and consumption a crucial tool for decarbonization, job creation, and energy security. There are a number of hydrogen initiatives underway nationwide, with a focus on developing hydrogen export hubs.[33] Once these hubs are ready to begin exports, Australia will already have established hydrogen-based trading partnerships with Korea, Japan, Singapore, and Germany.[34]

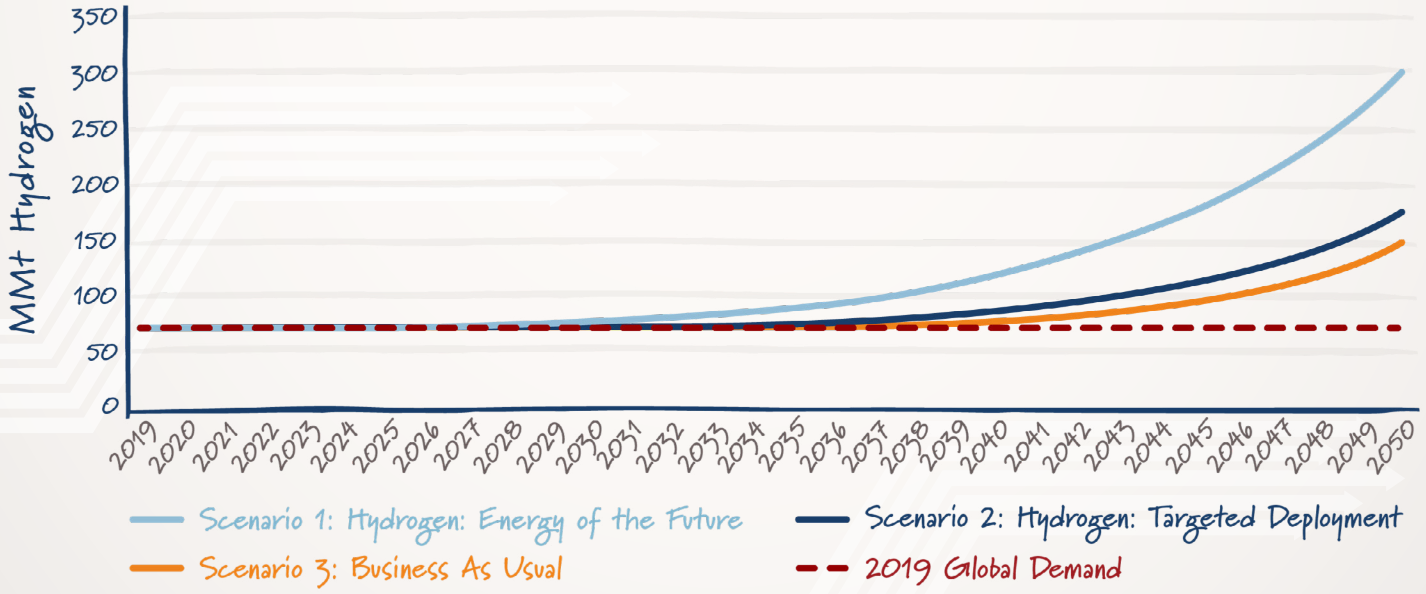
The Australian government has begun fostering hydrogen exports to Japan, beginning with a coal gasification pilot plant that will supply liquefied hydrogen.[35] Hydrogen production plans include both large-scale blue hydrogen projects and green hydrogen projects. A green hydrogen hub in development in Western Australia plans to send 3 MMt of hydrogen to Japan by 2030, at a production cost of $2/kg.

If Australia did begin producing blue hydrogen, it would likely cost around $2 per kg due to high natural gas costs.[36] While the blue hydrogen price point does not make Australia competitive on the global market, their proximity to and preexisting energy trade relationships with countries such as Japan, China, and South Korea position Australia as an attractive source of clean hydrogen for many regions.[37] With a wealth of carbon storage options available both inland and offshore, Australia has a number of viable locations for blue hydrogen production facilities.[38] While the current price is too high to be considered competitive, Australia is one of the most promising countries for green hydrogen production given its extremely high solar and wind energy potential.[39]

Hydrogen Demand Projections

Worldwide, the current demand for hydrogen is over 70 MMt per year, with the largest end uses being petroleum refining (38 MMt) and ammonia production (31 MMt).[40] Demand is largest in China, the Middle East, and the U.S., with these regions making up over 50 percent of global hydrogen consumption.[41] Global annual hydrogen demand per year is predicted to increase to anywhere between 90-304 MMt by 2050, with applications in industrial heat and natural gas blending growing the most in this time frame.[42] Two of the largest potential markets are Europe and Japan.

Figure 7: Global Forecasted Hydrogen Demand[43]



Today Europe produces a little less than 10 MMt of hydrogen annually, which is primarily used in ammonia production (~50 percent) and oil refining (~30 percent).[44] Both the European Commission and many European countries see clean hydrogen as a critical decarbonization and job creation strategy.[45] As a result, hydrogen demand in Europe is expected to range anywhere from 19.8 MMt to 57 MMt by 2050 (an increase of 140 percent to 590 percent compared to 2015).[45] European countries see hydrogen production not only as an important decarbonization pathway for the power, transportation, and industrial sectors, but also as a way to utilize existing infrastructure and excess renewable electricity. The EU plans to develop 10 MMt of green hydrogen production capacity from renewables by 2030, a development that will require significant new solar and wind capacity, as well as electrolyzers, but demand in 2030 could be as high as 17 MMt. Achieving these domestic renewable hydrogen plans will pose a significant challenge. Limited space prevents the development of renewable energy projects at scale, and high electricity costs ($0.06 per kWh, 50 percent more than the U.S.) raise the price of hydrogen produced by electrolysis.[47]

In Japan, another emerging hydrogen market, hydrogen is viewed as a path toward both decarbonization and energy security. The government has announced plans to dramatically increase its hydrogen consumption over the next 30 years.[48] These plans include increasing the domestic hydrogen vehicle fleet size by over 210 times, increasing the number of hydrogen refueling stations by more than 6.5 times, and acquiring 1,100 new fuel cell buses by 2030. Japan has a broader goal of consuming 5-10 MMt by 2030 and ultimately supplying up to 10 percent of its electricity from clean ammonia by 2050.[49] If Japan achieves its stated hydrogen and climate goals, clean hydrogen consumption could top 20 MMt by 2050.[50]

But Japan will likely struggle to produce enough clean hydrogen to meet its targets, unless it restarts mothballed nuclear power plants to produce green hydrogen. Japan’s ability to produce hydrogen from fossil fuels with carbon capture is limited by its carbon storage capacity. Most potential storage is offshore, with only one pilot facility currently in operation.[51]

Scaling up green hydrogen production presents a challenge, as 80 percent of Japan's land area is mountainous. One of the largest renewable electrolysis facilities in the world is located in the Fukushima prefecture and produces up to 107 kg of hydrogen per hour using solar electricity (considering solar capacity factor, this facility could produce approximately 122 metric tons per year.[52] Replicating this facility on the scale required to meet such ambitious hydrogen targets would ultimately require nearly 30,000 square kilometers of land.[K] A larger offshore wind facility that could produce 550 metric tons of hydrogen per year is under development, but the water depth around Japan requires floating wind at scale, which raises the price of domestically generated green hydrogen.[53] A more attractive option would be to produce hydrogen from electrolysis powered by nuclear energy, which can be produced at scale with minimal land use.[54] Japan has a number of nuclear reactors in standby mode, neither producing electricity nor decommissioned, that could be used to produce hydrogen. However, the restart of nuclear reactors in standby mode has been slow, and the Japanese government recently lowered the target for nuclear electricity generation in its strategic energy plan.[55] The combination of these factors means that Japan will face a significant supply gap that will need to be met through imports of either hydrogen or ammonia.

[K] Assumptions include a solar capacity factor of 13 percent, common in Japan, along with the land use assumption of .18 square kilometers per hydrogen production facility, which is the same as the Fukushima facility.

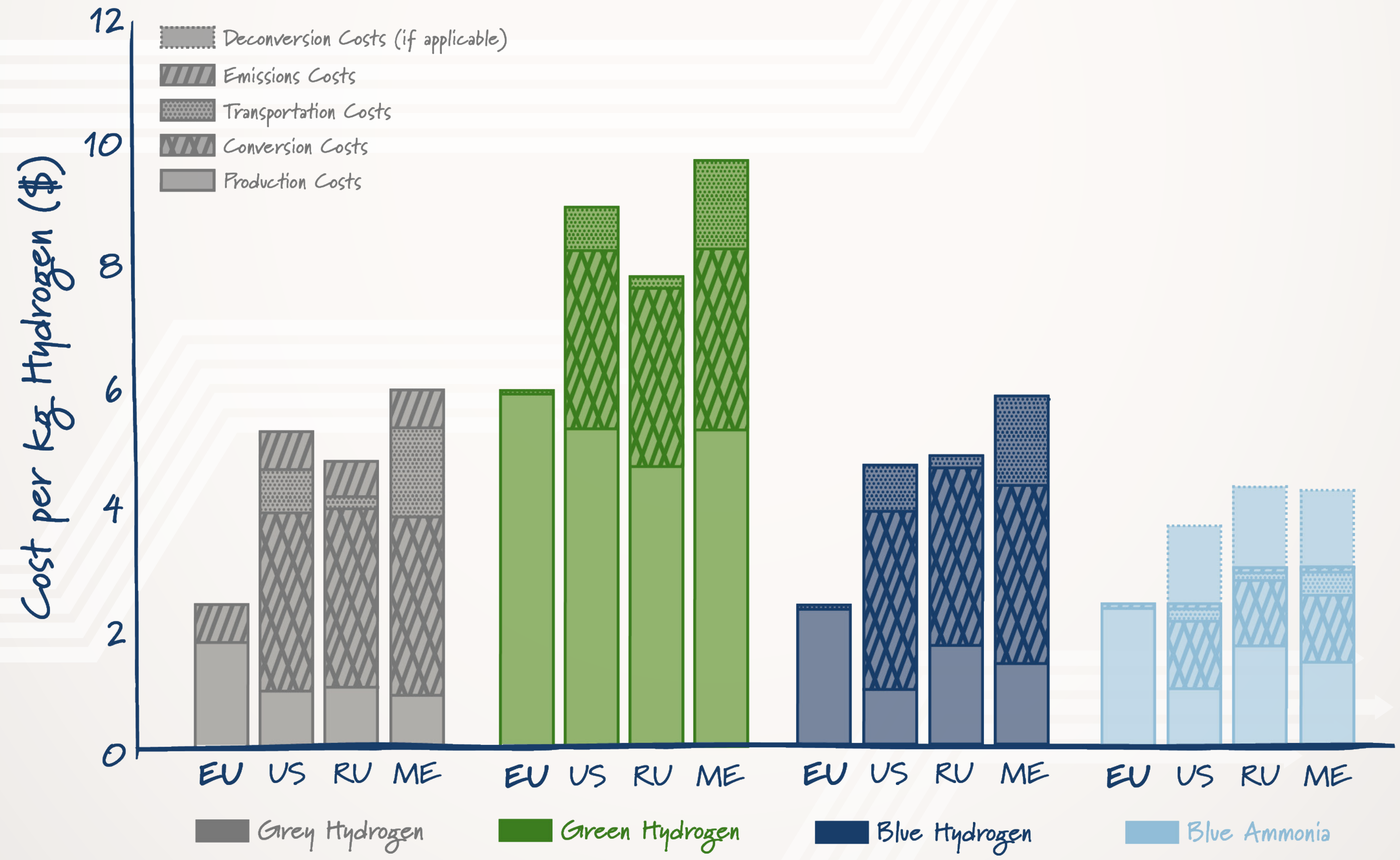
Supplying the European Hydrogen Market

Due to the difficulties of scaling domestic electrolyzer and renewable energy capacity, coupled with the need to decarbonize existing hydrogen capacity, the EU is likely to have a clean hydrogen supply gap over the next several decades. Leading countries like Germany have begun to include imported hydrogen as part of their clean hydrogen economy planning.[56] In total, the EU's import needs could be well over 10 MMt if they attempt net-zero decarbonization of the economy.[57]

Several countries could help close this supply gap. Historically, the EU has been a major importer of energy from nearby Russia and the Middle East, ultimately relying on these two regions for 54 percent of its crude oil imports, 47 percent of its solid fuel imports, and 46 percent of its natural gas imports.[58] More recently, LNG exports to Europe from the U.S. have grown exponentially, and the U.S. has been a longstanding trade partner for other energy sources like biomass.[59]

Not all of these import options are created equal; there are economic, emissions, and security constraints to consider. Figure 8 compares the costs for various regions to supply hydrogen to the EU using current estimates across the production life cycle.

Figure 8: Cost per kg of Hydrogen Shipped to EU

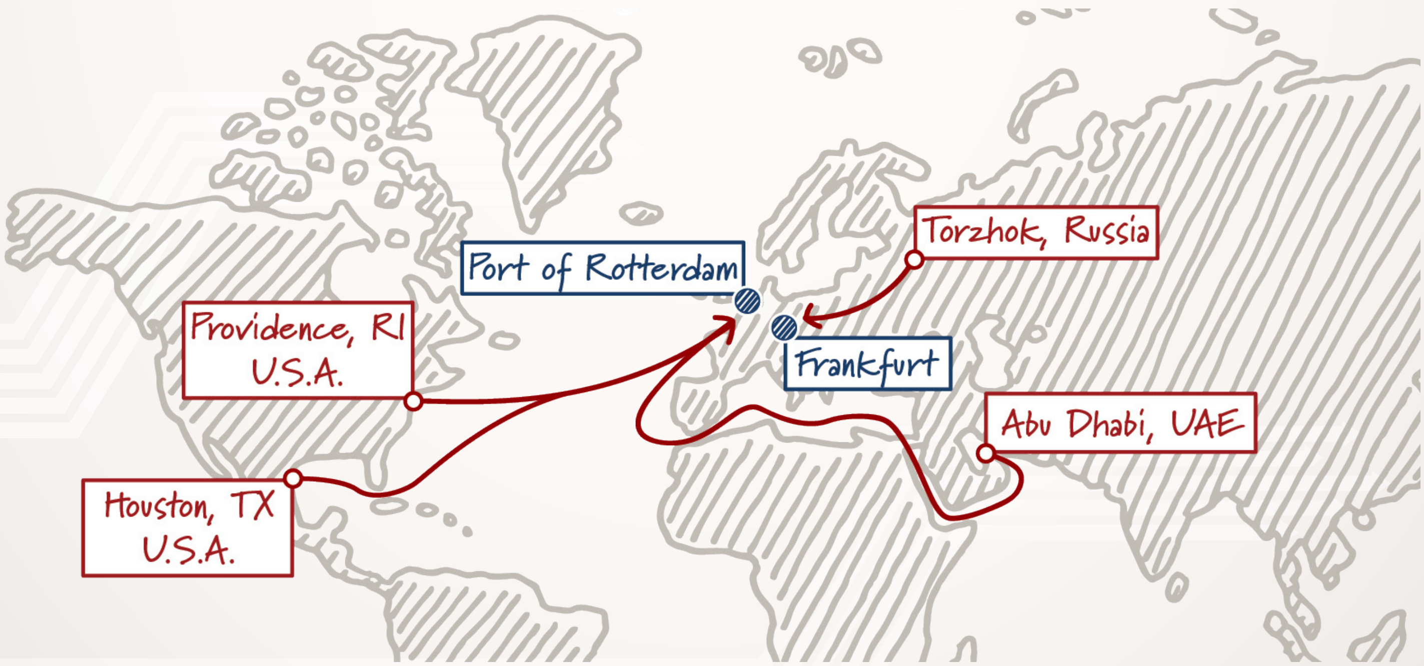


The direct costs, including for production, conversion, and deconversion, were found using sources from the International Energy Agency, PricewaterhouseCoopers, and the European Commission's Directorate-General for Energy.[60] The production cost of grey hydrogen is the cost of SMR based on the local cost of natural gas, while the production cost of green hydrogen is the cost of electrolysis utilizing the cheapest local renewable energy resource. The cost of production for blue hydrogen and ammonia includes SMR and carbon capture equipment. Production costs for blue hydrogen and blue ammonia are identical, as hydrogen production is required prior to conversion to ammonia. Conversion costs, where applicable, include all modifications prior to transportation. For hydrogen, this is liquefaction, and in the case of ammonia, conversion costs include both the conversion from hydrogen to ammonia and the cost of liquefaction for ammonia, which is far cheaper than liquefying hydrogen. Deconversion cost is the cost of turning ammonia back into hydrogen. The costs of various transportation methods between the below points were found using sources from Argonne National Lab and the EU transportation routes.[61]

Table 1: Transportation Routes to the EU for All Non-EU Sources

Origin	Description	Method
Providence, RI, U.S.A.	Port of Rotterdam	Maritime Ship
Abu Dhabi, UAE	Port of Rotterdam	Maritime Ship
Torzhok, Russia	Frankfurt	Pipeline

Figure 9: Basic Transportation Paths for EU Imports



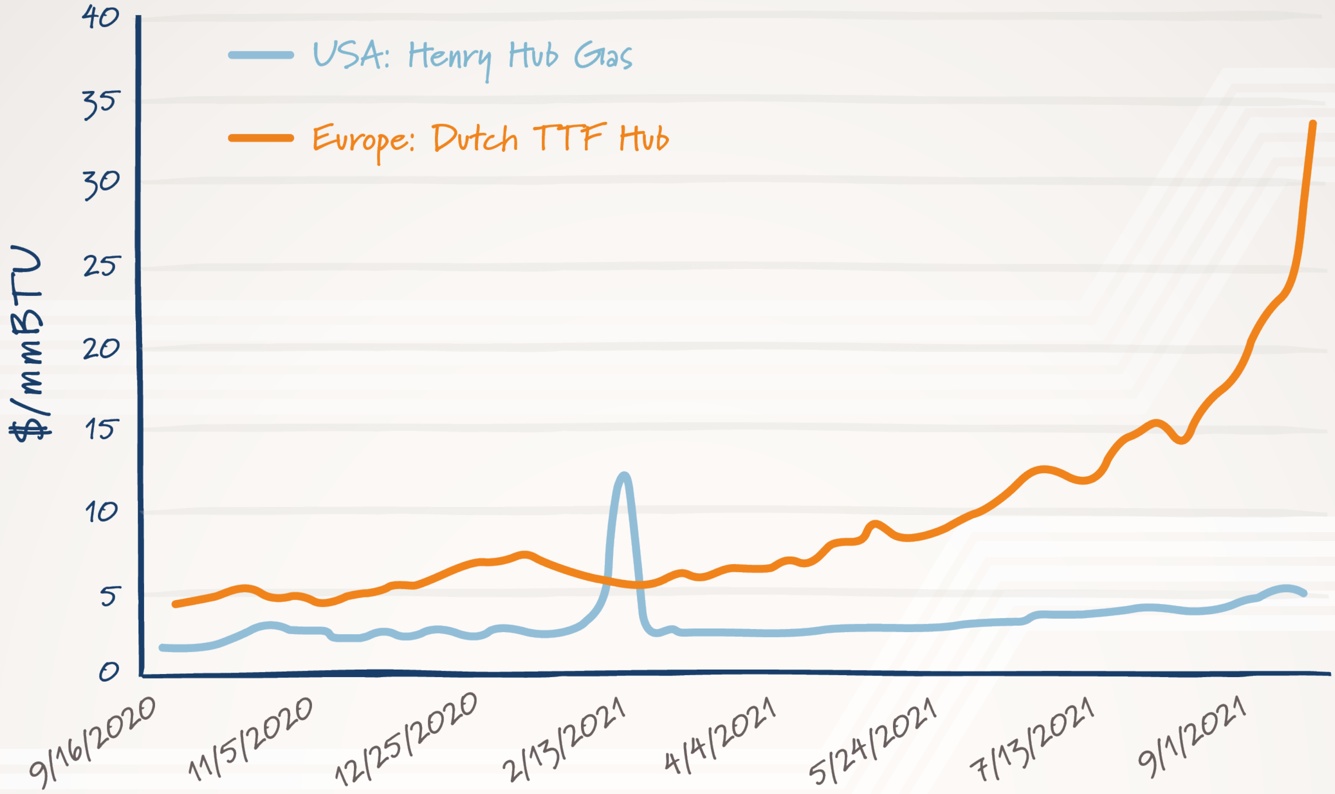
Finally, the carbon emissions associated with the production of hydrogen were priced at $65 per metric ton, equivalent to 55 euros per metric ton, the current EU emissions trading scheme price.[62] Emissions were assumed to be 9 kg of CO_2 emitted per kg of hydrogen produced via SMR, of which 90 percent is assumed to be captured for blue hydrogen and ammonia.[63] While there are other natural gas-based hydrogen production methods, SMR was used because it is by far the most common method today. No emissions are assumed for green hydrogen, although, as discussed above, on a life cycle basis, green hydrogen's emissions are similar to blue hydrogen produced with 90 percent capture and supplied by natural gas operations with minimal fugitive emissions.

The graph makes clear that the EU's cheapest source of clean hydrogen would be to directly produce blue or green hydrogen. However, as previously discussed, the EU may struggle to scale production and will likely need to import hydrogen, much as it currently imports LNG, oil, and biomass. Among options for imported clean hydrogen for the EU is U.S.-produced blue ammonia. This ammonia would depart in tankers from major ports along either the East or Gulf coasts of the U.S. and arrive at one of Europe's major ports, either in the Netherlands, Belgium, or Germany. This cost differential is mainly due to the reduced processing and transportation cost for ammonia, even after accounting for conversion and deconversion costs.

The U.S. emerged as one of the cheapest sources of blue ammonia imports primarily because of low domestic natural gas prices.[64] Whereas the U.S. produces most of its natural gas domestically, most of Europe imports its natural gas (primarily from Russia).[65] The cost of natural gas in Europe is therefore more than double than in the U.S., which drives up the cost of hydrogen production.[66]

At the time of publication, global natural gas prices, particularly in Europe, are spiking due to unexpected levels of demand and lack of natural gas storage. This may call into question the feasibility of natural gas pathways to hydrogen production. However, American natural gas production is more elastic than other regions and therefore has a more stable price. While the cost of natural gas in Europe has increased by six fold since last year, the United States has only increased by half that much, as shown in figure 10. This market reliability is also demonstrated in natural gas futures markets. American Henry Hub price futures eventually stabilize back at their previous level of $3/mmBTU by 2023, while the Dutch TTF hub ultimately stabilizes at nearly twice the level of the U.S. (nearly $7/mmBTU).[67]

Figure 10: Weekly Natural Gas Spot Price in Europe and United States



Another major, unique reason for this American cost advantage is the 45Q carbon capture tax credit. 45Q provides up to $50 per metric ton of CO_2 that is permanently sequestered in deep saline aquifers, or $0.35 per metric ton utilized in a manner to prevent reemission into the atmosphere. This effectively provides a $0.28 to $0.40 tax credit for each kg of blue hydrogen produced with 90 percent carbon capture, leading to a nearly 30 percent reduction in the cost of blue hydrogen compared to competitors. This credit makes American blue hydrogen nearly as cheap as grey hydrogen.

These cost differentials make a big difference. If 10 MMt of clean hydrogen were ultimately imported, opting for American blue ammonia would save $6 billion dollars over the next cheapest alternative.[68] To procure the same amount of blue ammonia from all considered regions, either through import or regional production, would cost as follows:

Table 2: Annual Cost for EU to Import 10 MMt of Clean Hydrogen from a Given Region

Region	Cost for 10 MMt of Hydrogen
U.S.	$36.5 billion
Middle East	$42.4 billion
Russia	$42.9 billion

Importing American hydrogen could also present additional advantages to the EU from a geopolitical and energy security perspective. The EU receives approximately 40 percent of its natural gas imports from Russia (a percentage likely to increase with the expected approval of the Nordstream 2 pipeline).[69] Depending on Russia for hydrogen, an additional energy resource, could present an energy security issue.[70] At the time of publication, many European leaders are accusing Russian gas suppliers of manipulating supply in order to open a new pipeline.[71] By diversifying their import sources, the EU could avoid an outsized dependence on a single country (the EU does not get a large portion of its natural gas and crude oil imports from the U.S.).

The U.S. already provides EU member countries with more than a third of their total biomass consumption.[72] The U.S. could leverage this existing relationship, as well as recent LNG trade with Europe, to establish a reliable source of clean hydrogen imports in the near future.

All of these factors make U.S.-produced blue ammonia one of Europe's cheapest options for clean hydrogen imports. This, along with the fact that Europe is already discussing the national security implications of increased reliance on Russian natural gas, means that the U.S. has a significant opportunity to export hydrogen to Europe in the near future.[73]

Supplying the Japanese Hydrogen Market

In recognition of Japan's impending supply gap, Kawasaki Heavy Industries in 2019 built the world's first ship designed to transport liquefied hydrogen (LH2).[74] Kawasaki has since announced its plan to build 80 more LH2 carriers by 2050, representing a total annual capacity of 9 MMt of hydrogen.[75]

A major source of clean hydrogen for Japan will likely be Australia, which already has a strong position in the Japanese energy system. Australia provides Japan with around two-thirds of their coal, one-third of their natural gas imports, and is currently the largest supplier of hydrogen imports.[76] Most hydrogen exported to Japan is produced by gasifying brown coal without carbon capture, but Australian producers could eventually export up to 1 MMt of green hydrogen per year to Japan by 2030.[77]

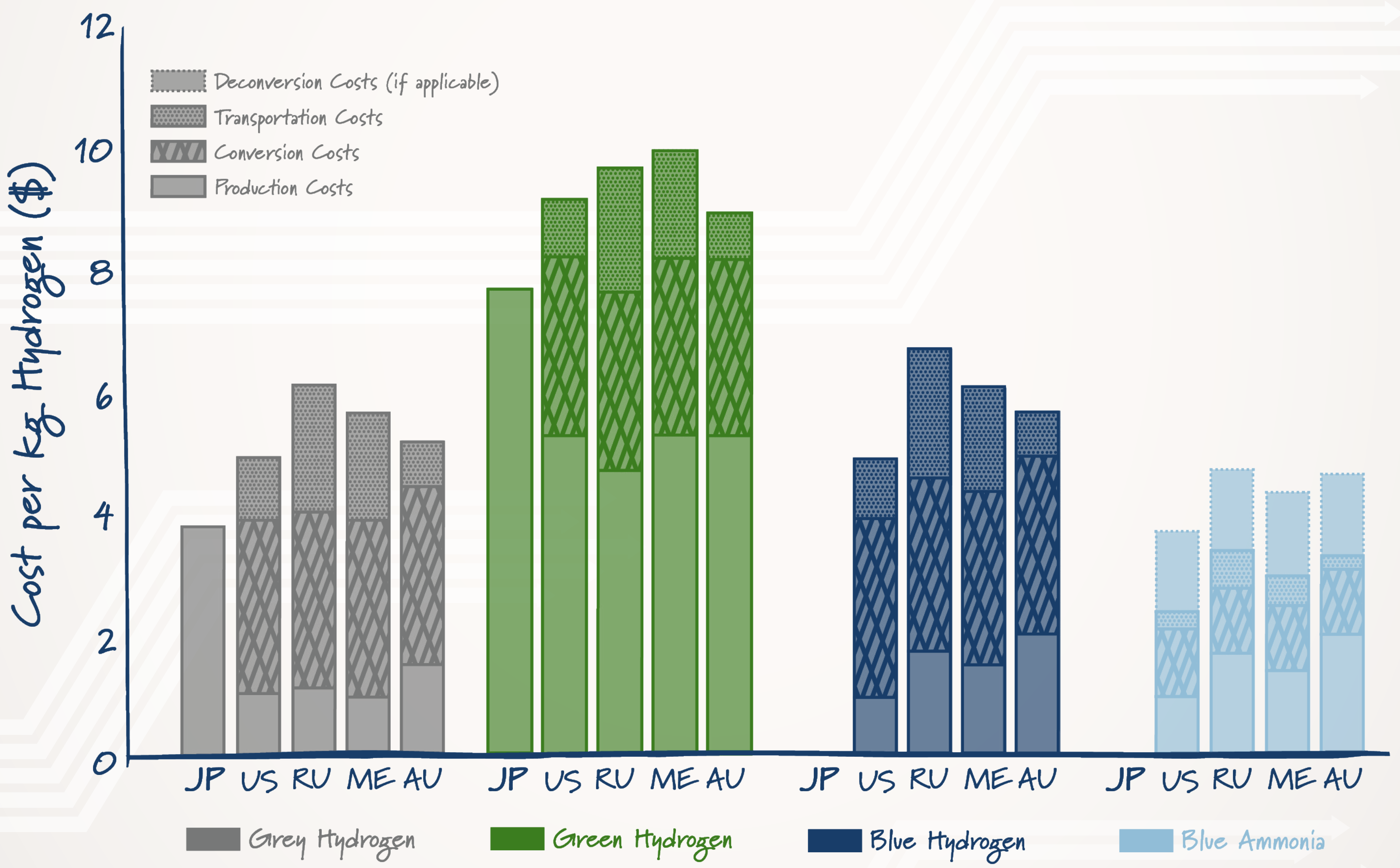
Other countries have taken note of the emerging Japanese hydrogen market. In 2020, for example, Saudi Arabia sent the world's first shipment of blue ammonia to Japan, signaling both their ability and intent to become a global leader in clean ammonia production and export.[78] In July 2021, the Abu Dhabi National Oil Company signed an agreement with three Japanese energy companies to explore commercial pathways for supplying Emirati clean hydrogen to Japan.[79] ADNOC plans to further this commitment by increasing its hydrogen production from 300,000 metric tons per year to more than 500,000 metric tons yearly and establish themselves as a major exporter of hydrogen to Japan in the coming years.[80]

Russia could also emerge as a supplier of blue ammonia and hydrogen for the Japanese market. Russia's largest independent gas producer, Novatek, recently received financing to develop a low-carbon blue ammonia and hydrogen hub near its gas fields on the Yamal Peninsula in western Siberia.[81] In September 2021, Japan's energy ministry signed a memorandum of cooperation with Novatek on blue hydrogen and ammonia, and Novatek also signed a cooperation agreement with Japan Bank to finance future low-carbon projects.[81]

The U.S. could also supply clean hydrogen to Japan. All states on the western coast of the U.S. have clean energy standards requiring 100 percent zero-carbon electricity by 2050, and California is positioning itself as a green hydrogen leader.[83] A new clean hydrogen production facility outside of Los Angeles will be the largest clean hydrogen facility in the world when completed, with an annual production capacity of over 3 MMt.[84] The technology employed by this facility gasifies waste streams, which results in clean hydrogen production that is far cheaper than renewable electrolysis and uses significantly less land.

In light of the relative cost of supplying clean hydrogen to Japan, there are a number of strong competitors. Using similar methods as above for the EU, the figure below outlines the cost of producing and transporting hydrogen to Japan from various likely exporters. Unlike the EU model, the emissions costs were left out because there is no carbon price in Japan.

Figure 11: Cost per kg of Clean Hydrogen Shipped to Japan



* Note: Japan cannot currently produce blue hydrogen or blue ammonia in significant quantities due to insufficient carbon storage capabilities.

Transportation distance assumptions are listed in table 3, and a stylized transportation path for each route is included in figure 12.

Table 2: Annual Cost for EU to Import 10 MMt of Clean Hydrogen from a Given Region

Region	Destination	Method
Seattle, WA, U.S.	Kantō Region	Maritime Ship
Abu Dhabi, UAE	Kantō Region	Maritime Ship
Port of Darwin, Australia	Kantō Region	Maritime Ship
Yamal Peninsula, Russia	Kantō Region	Maritime Ship

Figure 12: Basic Transportation Paths for Japanese Imports

As with the EU imports case, American clean hydrogen emerges as a cost-effective source of hydrogen imports for Japan. The lower cost of transportation associated with ammonia, coupled with the 45Q carbon capture tax credit, makes it the cheapest source of imported clean hydrogen at approximately $4 per kilogram. If the ammonia were used directly for power production, the cost is far lower, as the deconversion step is avoided.

The American Advantage

The U.S. has significant potential to export clean hydrogen to Japan and Europe, thanks to its status as a hydrogen and ammonia leader, policies around clean hydrogen production, and growing interest in developing large-scale clean hydrogen "hubs." The U.S. has a head start on hydrogen production. It produces about 10 MMt of hydrogen each year, primarily through steam methane reformation, and has 1,600 miles of hydrogen pipelines, mostly on the Gulf Coast.[85] In addition, the U.S. has steadily increased its domestic ammonia production over the last decade, which is currently at 17 MMt per year.[86] While this ammonia is mainly used domestically rather than exported, a modest increase in ammonia production capacity would significantly increase the amount of blue ammonia that could be exported as a clean fuel source. The U.S. is poised to establish itself as a global leader in clean hydrogen production through blue hydrogen and ammonia.[87]

Supportive Policy Environment

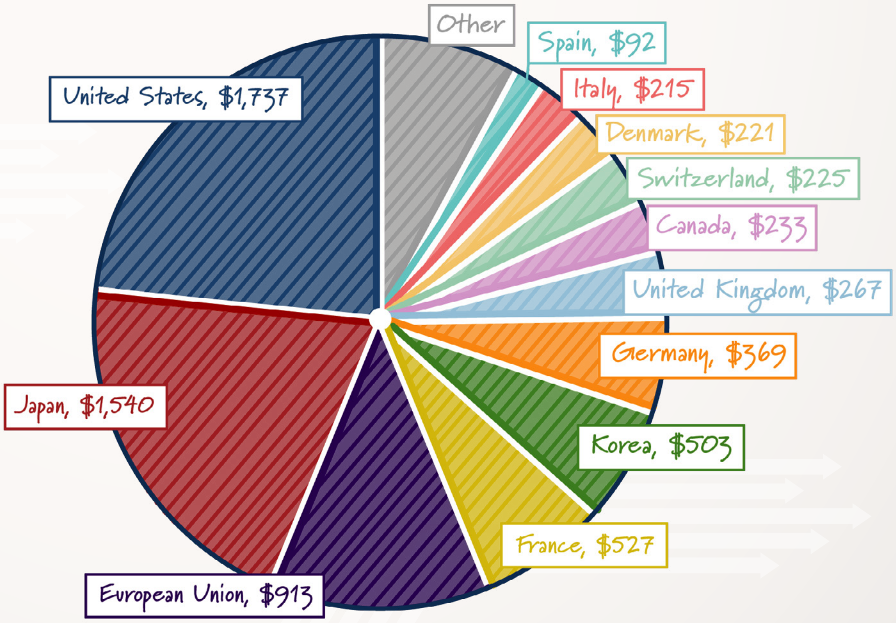
The United States has a highly supportive policy environment that can aid in the export of clean hydrogen and clean hydrogen carriers.

Research and Development

The United States has a strong hydrogen and fuel cell research culture. In recent years the United States has been tied with the European Union for second place behind Japan in total funding for hydrogen and fuel cell research; however, on a cumulative basis over the last decade, the United States has been the largest funder of public R&D in hydrogen and fuel cell technology among IEA member countries, as shown in figure 13.

The Hydrogen and Fuel Cell Technology Office (HFTO) is the primary funder of hydrogen R&D activities. It operates programs regarding hydrogen production, delivery, transportation, fuel cells, storage, and systems analysis. The HFTO program recently kicked off the "H2@Scale" initiative, designed to target funding toward the development of a broader hydrogen economy, including many industrial applications.[89]

Figure 13: Total Hydrogen and Fuel Cell Public R&D in IEA Countries 2010-2019 (Millions)[88]



HFTO recently partnered with the Office of Nuclear Energy to fund multiple demonstrations of hydrogen production from existing nuclear power plants in the United States. This energy generation pathway has the potential to provide an additional revenue stream for nuclear plants when electricity prices are very low.[90] In June 2021, the Department of Energy announced a "Hydrogen Earthshot" initiative to center hydrogen R&D around reducing the cost of clean hydrogen to $1 per kilogram by 2030.[91]

45Q Carbon Capture Tax Credit

The United States currently offers a tax credit for carbon oxides (the most common carbon oxide is CO_2), either utilized or sequestered, that would have otherwise been emitted into the atmosphere from an industrial source in the United States.[92] This credit is available to industrial facilities that emit CO_2 or commence construction on carbon capture equipment prior to January 1, 2026, and the credit is available for 12 years after the facility starts operations. The credit level is up to $35 per ton of carbon oxide for utilization,[M] and up to $50 per ton for geologic storage of carbon oxide. To receive this credit, the captured carbon oxide must be utilized or stored so that it is guaranteed not to be reemitted into the atmosphere.

The 45Q tax credit could significantly benefit hydrogen and ammonia producers. At an emissions rate of 9 kg CO_2 per kg of hydrogen produced at a SMR facility, 45Q would be worth between $0.29 and $0.40 per kilogram of hydrogen, depending on whether the captured CO_2 is utilized or sequestered. The 45Q credit is unique; there are no similar credits currently in place in other countries. At a $3/MMBtu gas price, this credit would reduce production costs between 21 and 30 percent.[93]

Potential Policies

A number of policies on the horizon could support clean hydrogen exports from the United States. Taken together, these bills show broad bipartisan support for clean hydrogen technologies.

The Infrastructure Investment and Jobs Act, a bipartisan infrastructure bill that passed the U.S. Senate in August 2021,[94] includes significant new programs and funding to support clean hydrogen research, development, and deployment. The bill includes the first rewrite and modernization of hydrogen research and development programs at the DOE since 2005. It has a total of $10 billion in funding for various clean hydrogen activities, including $8 billion to establish four clean hydrogen hubs, with at least one each dedicated to hydrogen produced from fossil fuels with carbon capture, renewable electrolysis, and nuclear electrolysis. Another $1 billion would fund a new clean electrolysis research and development program, while a further $1 billion would go toward a fuel cell recycling research and development program. Beyond the hydrogen-specific section, the bill includes billions in funding for broader carbon capture infrastructure, which is necessary to expand blue hydrogen.

Congress is also considering the extension and expansion of the 45Q tax credit. Various bills have been introduced, but common themes include a direct pay option for the credit, which allows cash payments in lieu of the tax credit; an increase in the value of the tax credit to $85 or $90 per metric ton of CO_2 permanently sequestered; and a five- to ten-year extension of the deadline to commence construction. Most proposals have multiple Republican and Democratic cosponsors, and have been introduced in both the Senate and the House.

[M] The most common method of carbon utilization currently in the United States is to aid in enhanced oil recovery.

Several clean hydrogen-specific production tax credit (PTC) proposals would incentivize hydrogen production, as long as it is produced from low-carbon resources that undergo a life cycle assessment. The first of these bills is the Energy Sector Innovation Credit (ESIC), a tax credit introduced in the Senate by Senators Mike Crapo (R-ID) and Sheldon Whitehouse (D-RI), and introduced in the House by U.S. Representatives Reed (R-NY), LaHood (R-IL), and Panetta (D-CA). ESIC would support any new low-carbon hydrogen production with a production tax credit (PTC), until that production method reaches production equivalent to three percent of total electricity generation.[N] The credit level is initially set at 1.5 times the average national wholesale hydrogen price and doubles if the production method has a carbon intensity of zero or less.[95] For example, if the current average hydrogen price is $1 per kilogram for grey hydrogen, the ESIC hydrogen credit would initially provide a credit of $1.50 per kilogram for blue hydrogen production and $3 per kilogram for green hydrogen production.

The other major hydrogen tax credit proposal is the Clean Hydrogen Production Act, a bill proposed by Senator Tom Carper (D-DE) that was marked up in the Senate Finance Committee in May 2021. This bill would create a new hydrogen PTC at varying levels of credit, depending on the production method's performance in a life cycle assessment. The credit would be worth up to $3 per kilogram of clean hydrogen produced, with lower levels of credit available for hydrogen that is at least 50 percent cleaner than grey hydrogen.[96]

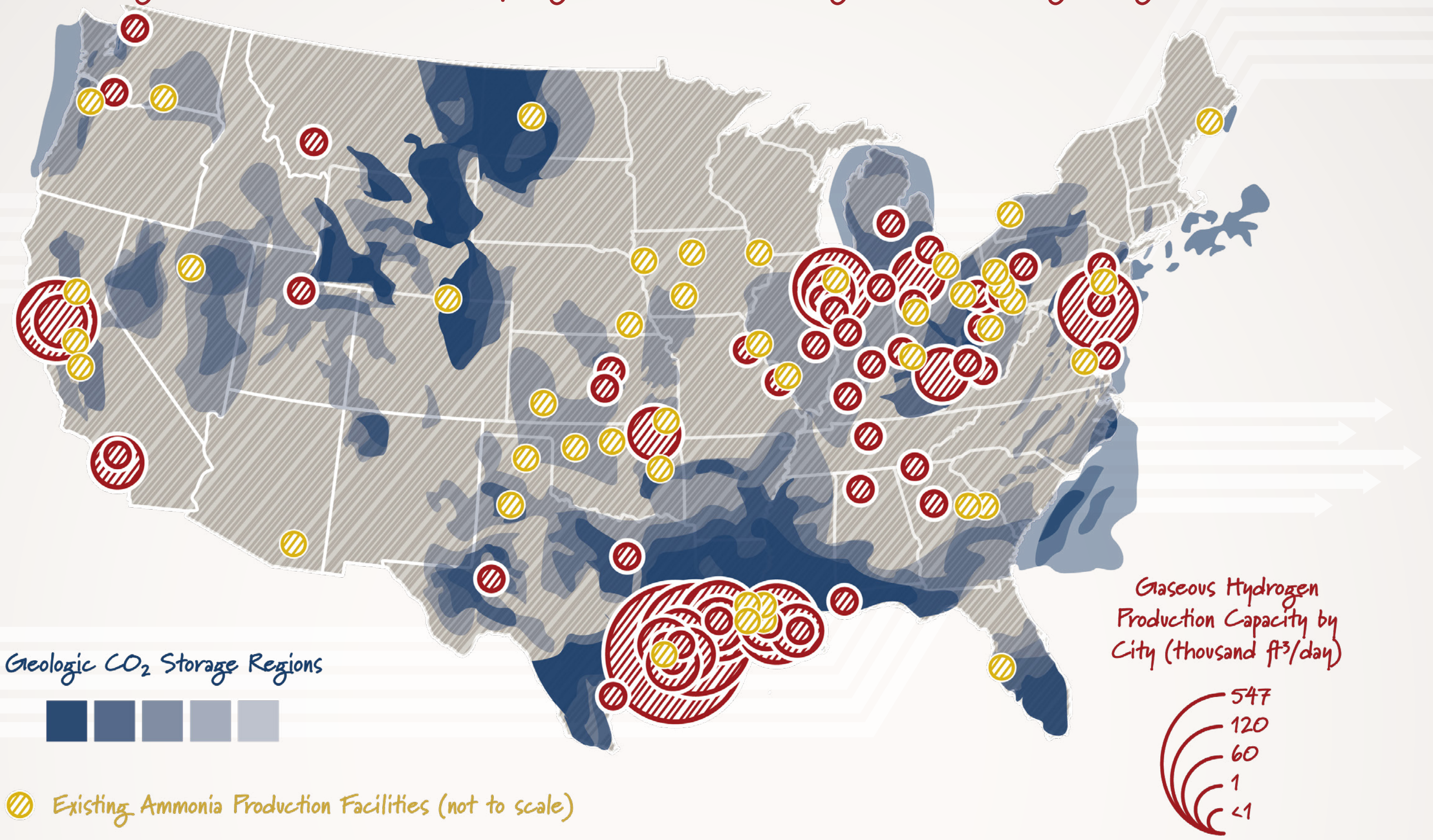
Hydrogen Hubs Are Under Development

Several U.S. regions produce significant quantities of hydrogen or ammonia and could lead future clean hydrogen production efforts. These early movers include the Ohio River Valley, the Gulf of Mexico, and California, although there are certainly other regions that could benefit.[97] Many companies have already recognized this potential and begun investing in various cities in the hopes of getting ahead of the quickly developing hydrogen market. Bakken Energy and Mitsubishi Power invested in North Dakotan hydrogen (where the only blue ammonia facility in the U.S. is located); Equinor plans a hydrogen and CCS hub in the Ohio River Valley; and Los Angeles is retrofitting its natural gas power plants to run on hydrogen.[98] Many of these areas already have supportive infrastructure, such as CO_2 pipelines and potential domestic hydrogen offtakers, like steel plants and chemical manufacturing facilities. These hubs, particularly California and the Gulf Coast, are coastal regions that already export energy.

[N] The tax credit phases out separately for electrolysis and for steam methane reformation based on each method's market penetration level.

Figure 14 outlines several potential hydrogen hubs and highlights current hydrogen and nitrogen-based fertilizer production, as well as geologic formations that could be suitable for long-term CO_2 storage.

Figure 14: Potential U.S. Hydrogen Hubs and Geologic CO2 Storage Regions[99]



Several U.S. regions stand ready to benefit from clean hydrogen development and are best suited to develop hydrogen and ammonia exports to meet international demand over the next decade.

Recommendations

While the U.S. is a strong competitor in the global hydrogen market, future energy dominance is by no means assured. Australia and the Middle East are quickly positioning themselves as major clean hydrogen exporters and developing their own regional hubs and trade relationships, with the first hydrogen exports to Japan happening this year. If the United States does not capitalize on its current advantage, these other countries will likely have lower costs than the United States and dominate the emerging market. Unlike Russia, Australia, Japan, Saudi Arabia, and the European Union, the United States has no formally articulated strategy or policy initiative to develop large-scale hydrogen infrastructure. Without establishing a strategy and extending tax credit support, this competitive advantage could shrink by 2030. To cement the United States' pole position in clean hydrogen exports, the federal government should consider the following steps.

1. **The Department of Energy and Department of Commerce should initiate a joint strategy on federal policies to enable the scale-up of American clean hydrogen exports.** This strategy should, at minimum, consider near-term needs for scaling domestic hydrogen production and consumption, export financing opportunities, and any legal challenges facing large-scale hydrogen and ammonia exports.

2. **The Department of Commerce, Department of Energy, and the Department of State should look to establish hydrogen-related trade relationships.** Countries looking to increase their hydrogen consumption should be targeted for joint development of consistent methodologies and protocols to track embedded greenhouse gas emissions throughout the hydrogen life cycle.

3. **Enact the Senate-passed bipartisan Infrastructure Jobs and Investment Act.** The bill includes funding to develop four regional hydrogen hubs, modernizes the hydrogen research and development program at the Department of Energy, and includes significant funding for electrolyzer research and development. All told, the bill includes $10 billion in direct hydrogen funding. The bill also includes funding to enable carbon capture infrastructure, including more funding to the Environmental Protection Agency to permit carbon storage wells and a new Carbon Infrastructure Financing Agency to support carbon pipeline buildout.

4. **Extend the 45Q carbon capture tax credit through 2030, and enact a hydrogen production tax credit.** These credits would reduce the cost of clean hydrogen over the long term, ensuring that American hydrogen remains competitive in the face of cost declines in other countries.

Conclusion

As countries around the world look to reduce their greenhouse gas emissions as quickly as possible, clean hydrogen has emerged as a supplement for existing natural gas streams.[100] Hydrogen is an energy-dense and zero-emission fuel that, most importantly, has the potential to be useful today. With global hydrogen demand projected to grow between two and six times by 2050 compared to current levels, now is the time to invest.[101]

The U.S. should consider investing further in cleaning its existing hydrogen production facilities while encouraging growth in the many emerging hydrogen hubs around the country. The U.S. should also seriously consider fostering hydrogen export relationships with the EU and Japan, some of the fastest-growing hydrogen markets. This analysis found that low natural gas prices and the 45Q carbon capture credit uniquely position the U.S. to take the lead on blue hydrogen and ammonia exports to both the EU and Japan. Policymakers and private industry should take advantage of this substantial opportunity, which reduces emissions while promoting economic growth.

Sources

1. Blank, Thomas K. and Patrick Molloy. 2020. “Hydrogen’s Decarbonization Impact for Industry.” https://rmi.org/wp-content/uploads/2020/01/hydrogen_insight_brief.pdf. IEA. 2019. “The Future of Hydrogen.” https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf; Deloitte. 2019. “Australian and Global Hydrogen Demand Growth Scenario Analysis.” https://www2.deloitte.com/content/dam/Deloitte/au/Documents/future-of-cities/deloitte-au-australian-global-hydrogen-demand-growth-scenario-analysis-091219.pdf.
IEA. 2021. “Net Zero by 2050.” https://www.iea.org/reports/net-zero-by-2050.
2. FCH 2 JU. 2019. “Hydrogen Roadmap Europe.” https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf.
3. Dvorak, Phred. 2021. “How Japan’s Big Bet on Hydrogen Could Revolutionize the Energy Market.” Wall Street Journal (Eastern Ed.), June 13, 2021. https://www.wsj.com/amp/articles/japans-big-bet-on-hydrogen-could-revolutionize-the-energy-market-11623607695.
4. Kurmayer, Nikolaus J. 2021. “Europe Could Save €2 Trillion by 2050 with Low-Carbon Hydrogen, Says Report.” EURACTIV. July 12, 2021. https://www.euractiv.com/section/energy-environment/news/europe-could-save-e2-trillion-through-2050-thanks-to-low-carbon-hydrogen-says-report/.
5. Kawasaki. 2019. “World’s First Liquefied Hydrogen Carrier SUISO FRONTIER Launches Building an International Hydrogen Energy Supply Chain Aimed at Carbon-Free Society.” https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20191211_3487.
6. BakerMcKenzie. 2021. “Russia Taking a Stand in Global Hydrogen Race.” https://www.bakermckenzie.com/en/insight/publications/2021/02/russia-taking-a-stand-in-global-hydrogen-race.
7. Afanasiev, V. 2021. “Novatek subsidiary seeks drillers for Blue Ammonia and hydrogen initiative.” Upstream Online. August 5, 2021. https://www.upstreamonline.com/energy-transition/novatek-subsidiary-seeks-drillers-for-blue-ammonia-and-hydrogen-initiative/2-1-1048849.
8. ADNOC. 2021. “ADNOC and PETRONAS Sign Comprehensive Strategic Framework Agreement.” https://www.adnoc.ae/en/news-and-media/press-releases/2021/adnoc-and-petronas-sign-comprehensive-strategic-framework-agreement; ADNOC. 2021. “ADNOC and Korea’s GS Energy Explore Opportunities to Grow Abu Dhabi’s Hydrogen Economy and Carrier Fuel Export Position.” https://www.adnoc.ae/en/news-and-media/press-releases/2021/adnoc-and-koreas-gs-energy-explore-opportunities.
9. Ratcliffe, Verity. 2020. “Saudi Arabia Sends Blue Ammonia to Japan in World-First Shipment.” Bloomberg News. September 27, 2020. https://www.bloomberg.com/news/articles/2020-09-27/saudi-arabia-sends-blue-ammonia-to-japan-in-world-first-shipment.
10. COAG Energy Council Hydrogen Working Group. 2019. “Australia’s National Hydrogen Strategy.” https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf; Pendlebury, Russell, Tom Meares, and James Tyrrell. 2021. “Hydrogen: The New Australian Manufacturing Export Industry and the Implications for the National Electricity Market (NEM).” AEMC. 2021. https://www.aemc.gov.au/hydrogen-new-australian-manufacturing-export-industry-and-implications-national-electricity-market.
11. Lee, Bernadette. 2021. “Australia, Japan Begin Operations of Complete, Integrated Supply Chain for Hydrogen Plant.” IHSMarkit. March 23, 2021. https://ihsmarkit.com/research-analysis/australia-japan-begin-operations-of-complete-integrated-supply.html.
12. Bakken Energy, LLC. 2021. “Bakken Energy and Mitsubishi Power Establish Clean Hydrogen Partnership.” June 2, 2021. https://www.globenewswire.com/news-release/2021/06/02/2240760/0/en/BAKKEN-ENERGY-AND-MITSUBISHI-POWER-ESTABLISH-CLEAN-HYDROGEN-PARTNERSHIP.html; St. John, Jeff. 2020. “How to Build a Green Hydrogen Economy for the US West.” Greentech Media. November 17, 2020. https://www.greentechmedia.com/articles/read/how-to-build-a-green-hydrogen-economy-for-the-u.s-west; Magill, Jim. 2021. “California and Texas Vie to Be America’s Hydrogen Capital.” Forbes Magazine, February 23, 2021. https://www.forbes.com/sites/jimmagill/2021/02/23/california-texas-vie-to-determine-which-will-be-us-hydrogen-capital/.
13. ReportLinker. 2021. “Hydrogen Powered Transport Global Market Report 2021: COVID-19 Growth and Change.” March 8, 2021. https://www.globenewswire.com/news-release/2021/03/08/2188701/0/en/Hydrogen-Powered-Transport-Global-Market-Report-2021-COVID-19-Growth-And-Change.html.
14. Griffiths, Steve, Benjamin K. Sovacool, Jinsoo Kim, Morgan Bazilian, and Joao M. Uratani. "Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options." Energy Research & Social Science 80 (2021): 102208.

15. US DOE. 2020. “Department of Energy Hydrogen Program Plan.” https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf.
16. DOE. 2020. “Hydrogen Strategy: Enabling a Low Carbon Economy.” https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf.
17. Air Liquide Energies. 2017. “How Is Hydrogen Stored ?” June 16, 2017. https://energies.airliquide.com/resources-planet-hydrogen/how-hydrogen-stored.
18. DHS. 2021. “Securing Transportation of Ammonia.” June 17, 2021. https://www.dhs.gov/science-and-technology/news/2021/06/17/feature-article-securing-transportation-ammonia; Department of Energy. “Liquid Hydrogen Delivery.” Accessed August 13, 2021. https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery.
19. El Kadi, Joseph, Collin Smith, and Laura Torrente-Murciano. 2020. “H2 and NH3 – the Perfect Marriage in a Carbon-Free Society.” The Chemical Engineer. May 28, 2020. https://www.thechemicalengineer.com/features/h2-and-nh3-the-perfect-marriage-in-a-carbon-free-society.
20. Figure adapted from Pembina Institute’s Carbon Intensity of Blue Hydrogen Production report, as revised in August 2021. Additional modifications were made to change emissions to units of kg of hydrogen rather than GJ (at a higher heating value of 7.05 kg H2 per GJ H2), and to add nuclear-produced hydrogen based on data from Karaca et al. Nuclear CE=conventional electrolysis, while HTE=high temperature electrolysis.
Karaca, Ali Erdogan, Ibrahim Dincer, and Junjie Gu. 2020. "Life cycle assessment study on nuclear based sustainable hydrogen production options." International Journal of Hydrogen Energy 45, no. 41: 22148-22159.
21. IEA. 2019. “The Future of Hydrogen.” https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf.
22. Nagabhushan, Deepika. 2020. “Interactive Map of CCUS Projects in Development in the U.S.” CATF. July 27, 2020. https://www.catf.us/2020/07/ccus-interactive-map/.
23. IEA. 2019. “The Future of Hydrogen.” https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf.
24. FKopteva, Alexandra, Leonid Kalimullin, Pavel Tcvetkov, and Amilcar Soares. 2021. “Prospects and Obstacles for Green Hydrogen Production in Russia.” Energies 14 (3): 718; Zabanova, Yana and Kirsten Westphal. 2021. “Russia in the Global Hydrogen Race.” German Institute for International and Security Affairs. https://doi.org/10.18449/2021C34.
25. BakerMcKenzie. 2021. “Russia Taking a Stand in Global Hydrogen Race.” https://www.bakermckenzie.com/en/insight/publications/2021/02/russia-taking-a-stand-in-global-hydrogen-race.
26. IEA. 2019. “The Future of Hydrogen.” https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf.
27. BP. 2020. “Statistical Review of World Energy.” https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf; Afanasiev, Vladimir. 2021. “Russia Eyes Large-Scale Export of Blue Hydrogen in Partnership with Local Oil & Gas Majors.” Recharge News. July 23, 2021. https://www.rechargenews.com/energy-transition/russia-eyes-large-scale-export-of-blue-hydrogen-in-partnership-with-local-oil-gas-majors/2-1-1043974.
28. CIA. n.d. “Pipelines.” Accessed August 9, 2021. https://www.cia.gov/the-world-factbook/field/pipelines/.
29. Cochrane, Paul. 2021. “Green Hydrogen: The Gulf’s next Big Fuel - or a Load of Hot Air?” Middle East Eye. https://www.middleeasteye.net/news/gulf-qatar-saudi-arabia-uae-hydrogen-green-next-fuel.
30. IEA. 2019. “The Future of Hydrogen.” https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf.
31. ADNOC. 2021. “ADNOC and PETRONAS Sign Comprehensive Strategic Framework Agreement.” https://www.adnoc.ae/en/news-and-media/press-releases/2021/adnoc-and-petronas-sign-comprehensive-strategic-framework-agreement; ADNOC. 2021. “ADNOC and Korea’s GS Energy Explore Opportunities to Grow Abu Dhabi’s Hydrogen Economy and Carrier Fuel Export Position.” https://www.adnoc.ae/en/news-and-media/press-releases/2021/adnoc-and-koreas-gs-energy-explore-opportunities.
32. Energy Sector Management Assistance Program. 2020. “Global Photovoltaic Power Potential By Country.” https://documents1.worldbank.org/curated/en/466331592817725242/pdf/Global-Photovoltaic-Power-Potential-by-Country.pdf; PricewaterhouseCoopers. n.d. “Green Hydrogen Economy - Predicted Development of Tomorrow.” Accessed August 9, 2021. https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html.

33. COAG Energy Council Hydrogen Working Group. 2019. "Australia's National Hydrogen Strategy." https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf; Pendlebury, Russell, Tom Meares, and James Tyrrell. 2021. "Hydrogen: The New Australian Manufacturing Export Industry and the Implications for the National Electricity Market (NEM)." AEMC. https://www.aemc.gov.au/hydrogen-new-australian-manufacturing-export-industry-and-implications-national-electricity-market.

34. Hee Young, Yoon. 2021. "President Moon Holds Talks with Australia, Germany at G7 Summit." Korea. https://www.korea.net/NewsFocus/policies/view?articleId=199452; Paul, Sonali. 2021a. "In Australia, Japanese Start Producing Hydrogen from Brown Coal." Reuters, March 11, 2021. https://www.reuters.com/article/australia-hydrogen-kawasaki-heavy-idUSL4N2L81IF; Ministers for the Department of Industry, Science, Energy and Resources. 2021. "Australia Partners with Singapore on Hydrogen in Maritime Sector." https://www.minister.industry.gov.au/ministers/taylor/media-releases/australia-partners-singapore-hydrogen-maritime-sector; Eckert, Vera and Elaine Hardcastle. 2021. "Germany, Australia Sign Hydrogen Accord to Boost Lower-Emissions Technology." Reuters, June 13, 2021. https://www.reuters.com/business/sustainable-business/germany-prepares-set-up-hydrogen-accord-with-australia-2021-06-13/.

35. Lee, Bernadette. 2021. "Australia, Japan Begin Operations of Complete, Integrated Supply Chain for Hydrogen Plant." IHSMarkit. March 23, 2021. https://ihsmarkit.com/research-analysis/australia-japan-begin-operations-of-complete-integrated-supply.html.

36. Deloitte. 2019. "Australian and Global Hydrogen Demand Growth Scenario Analysis." https://www2.deloitte.com/content/dam/Deloitte/au/Documents/future-of-cities/deloitte-au-australian-global-hydrogen-demand-growth-scenario-analysis-091219.pdf.

37. "Australia Is on Track to Become World's Largest LNG Exporter." 2019. EIA. 2019. https://www.eia.gov/todayinenergy/detail.php?id=40853.

38. Carbon Storage Taskforce. 2009. "NATIONAL CARBON MAPPING AND INFRASTRUCTURE PLAN – AUSTRALIA." https://www.parliament.wa.gov.au/parliament/commit.nsf/($lookupRelatedDocsByID)/518FAC2BBA6C246648257C29002DB8E6/$file/NCM_Full_Report.pdf.

39. Energy Sector Management Assistance Program. 2020. "GLOBAL PHOTOVOLTAIC POWER POTENTIAL BY COUNTRY." https://documents1.worldbank.org/curated/en/466331592817725242/pdf/Global-Photovoltaic-Power-Potential-by-Country.pdf.; PricewaterhouseCoopers. n.d. "Green Hydrogen Economy - Predicted Development of Tomorrow." PwC. Accessed August 9, 2021. https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html.

40. Connelly, Elizabeth, Amgad Elgowainy, and Mark Ruth. 2019. "DOE Hydrogen and Fuel Cells Program Record." https://www.hydrogen.energy.gov/pdfs/19002-hydrogen-market-domestic-global.pdf.

41. "Geographic Hydrogen Hotspots." 2021. KPMG. February 4, 2021. https://home.kpmg/xx/en/home/insights/2021/01/geographic-hydrogen-hotspots.html.

42. Deloitte. 2019. "Australian and Global Hydrogen Demand Growth Scenario Analysis." https://www2.deloitte.com/content/dam/Deloitte/au/Documents/future-of-cities/deloitte-au-australian-global-hydrogen-demand-growth-scenario-analysis-091219.pdf.

43. Ibid. Some industry estimates project hydrogen demand upwards of 500 MMt by 2050.

44. Kakoulaki, G., I. Kougias, N. Taylor, F. Dolci, J. Moya, and A. Jäger-Waldau. 2021. "Green Hydrogen in Europe – A Regional Assessment: Substituting Existing Production with Electrolysis Powered by Renewables." Energy Conversion and Management 228: 113649.

45. European Commission. 2020. "A Hydrogen Strategy for a Climate-Neutral Europe." https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf.

46. FCH 2 JU. 2019. "Hydrogen Roadmap Europe." https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf.

47. "What Are the Latest Electricity Prices by Country?" 2019. PaylessPower. July 3, 2019. https://paylesspower.com/blog/european-cost-of-electricity-per-kwh-by-country/.

48. Japan Hydrogen and Fuel Cell Council. 2019. "Strategic Roadmap for Hydrogen and Fuel Cells." METI. 2019. https://www.meti.go.jp/english/press/2019/pdf/0312_002b.pdf.

49. ""Basic Hydrogen Strategy Determined (METI)." 2017. METI. 2017. https://www.meti.go.jp/english/press/2017/1226_003.html.

50. "Phred Dvorak and Go Takayama, "How Japan's Big Bet on Hydrogen Could Revolutionize the Energy Market," The Wall Street Journal (Dow Jones & Company, June 13, 2021), https://www.wsj.com/articles/japans-big-bet-on-hydrogen-could-revolutionize-the-energy-market-11623607695.

Tasuku Kuwabara et al., "How Japan Could Reach Carbon Neutrality by 2050," McKinsey & Company (McKinsey & Company, August 25, 2021), https://www.mckinsey.com/business-functions/sustainability/our-insights/how-japan-could-reach-carbon-neutrality-by-2050.

51. Hendriks, Chris, Wina Crijns-Graus, and Frank Bergen. 2004. "Global Carbon Dioxide Storage Potential and Costs." https://www.researchgate.net/profile/Wina-Crijns-Graus/publication/260095614_Global_Carbon_Dioxide_Storage_Potential_and_Costs/links/02e7e52f8a006a9854000000/Global-Carbon-Dioxide-Storage-Potential-and-Costs.pdf.

52. Toshiba Energy Systems. n.d. "The World´s Largest-Class Hydrogen Production, Fukushima Hydrogen Energy Research Field." Accessed September 3, 2021. https://www.toshiba-energy.com/en/info/info2020_0307.htm.

53. Mukano, Ryo. 2021. "Offshore Wind to Power Japan's Biggest Green Hydrogen Plant." Nikkei Asia. July 26, 2021. https://asia.nikkei.com/Business/Energy/Offshore-wind-to-Power-Japan-s-biggest-green-hydrogen-plant2.

54. Ingersoll, E. and K. Gogan. 2020. "Missing Link to a Livable Climate: How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals." LucidCatalyst. https://www.lucidcatalyst.com/hydrogen-report.

55. Kumagai, T. 2021. "Japan set for 60% non-fossil fuel power supply in 2030 in GHG slash drive." S&P Global Platts. https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/072121-japan-set-for-60-non-fossil-fuel-power-supply-in-2030-in-ghg-slash-drive.

56. Umbach, Frank, and Joachim Pfeiffer. 2020. "Germany and the EU's Hydrogen Strategies in Perspective – The Need for Sober Analyses." https://www.kas.de/documents/274425/8492225/German+%2B+EU+Hydrogen+Strategies.pdf/b069d44b-5af0-9ec8-da1c-e0c10335e08e?version=1.0&t=1597804839540.

57. Deloitte. 2021. "Hydrogen4EU: Charting pathways to Enable Net Zero" July 7, 2021. https://2d214584-e7cb-4bc2-bea8-d8b7122be636.filesusr.com/ugd/2c85cf_69f4b1bd94c5439f9b1f87b55af46afd.pdf.

58. Kurmayer, Nikolaus J. 2021a. "EU Countries Clash over Scale of Future Hydrogen Imports." EURACTIV. June 15, 2021. https://www.euractiv.com/section/energy-environment/news/eu-countries-clash-over-scale-of-future-hydrogen-imports/; Europa. n.d. "Shedding Light on Energy on the EU: From Where Do We Import Energy?" Accessed August 9, 2021. https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2c.html; Europa. 2020. "Oil and Petroleum Products - a Statistical Overview." https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Oil_and_petroleum_products_-_a_statistical_overview.

59. EIA. "U.S. liquefied natural gas exports grew to record highs in the first half of 2021." https://www.eia.gov/todayinenergy/detail.php?id=48876.

60. IEA. 2019. "The Future of Hydrogen." https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf; PricewaterhouseCoopers. n.d. "Green Hydrogen Economy - Predicted Development of Tomorrow." Accessed August 9, 2021. https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html; Jan Cihlar et al. 2020. "Hydrogen Generation in Europe: Overview of Costs and Key Benefits." https://op.europa.eu/en/publication-detail/-/publication/7e4afa7d-d077-11ea-adf7-01aa75ed71a1/language-en.

61. Elgowainy, Amgad, Ed Frank, and Krishna Reddi. 2021. "Analysis of Hydrogen Export Potential"; Jan Cihlar et al. 2020. "Hydrogen Generation in Europe: Overview of Costs and Key Benefits." https://op.europa.eu/en/publication-detail/-/publication/7e4afa7d-d077-11ea-adf7-01aa75ed71a1/language-en.

62. Abnett, Kate and Susanna Twidale. 2021. "EU Proposes World's First Carbon Border Tax for Some Imports." Reuters. July 14, 2021. https://www.reuters.com/business/sustainable-business/eu-proposes-worlds-first-carbon-border-tax-some-imports-2021-07-14/.

63. Further discussion of capture rate can be found in the section titled "Defining Clean Hydrogen."
Sun, Pingping and Amgad Elgowainy. 2019. "Updates of Hydrogen Production from SMR Process in GREET® 2019." https://greet.es.anl.gov/publication-smr_h2_2019.

64. IEA. 2021. "Natural Gas Prices for the Industrial Sector in Selected Countries, 2019." https://www.iea.org/data-and-statistics/charts/natural-gas-prices-for-the-industrial-sector-in-selected-countries-2019.

65. EIA. 2021. "Natural Gas Imports and Exports - U.S. Energy Information Administration (EIA)." https://www.eia.gov/energyexplained/natural-gas/imports-and-exports.php; Europa. n.d. "Shedding Light on Energy on the EU: From Where Do We Import Energy?" Accessed August 9, 2021. https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2c.html.

66. "EU Natural Gas Import Price." https://ycharts.com/indicators/europe_natural_gas_price.

67. CME Group. 2021. "Henry Hub Natural Gas Futures and Options." https://www.cmegroup.com/markets/energy/natural-gas/natural-gas.quotes.html, CME Group. 2021. "Dutch TTF Natural Gas Calendar Month Futures." https://www.cmegroup.com/markets/energy/natural-gas/dutch-ttf-natural-gas-calendar-month.quotes.html

68. Kakoulaki, G., I. Kougias, N. Taylor, F. Dolci, J. Moya, and A. Jäger-Waldau. 2021. "Green Hydrogen in Europe – A Regional Assessment: Substituting Existing Production with Electrolysis Powered by Renewables." Energy Conversion and Management 228 (113649): 113649.; Hydrogen Europe. n.d. "Green Hydrogen Investment and Support Report." http://profadvanwijk.com/wp-content/uploads/2020/05/Hydrogen-Europe_Green-Hydrogen-Recovery-Report_final.pdf.

69. Popovic, Nemanja. 2020. "The Energy Relationship between Russia and the European Union." E-IR. February 24, 2020. https://www.e-ir.info/2020/02/24/the-energy-relationship-between-russia-and-the-european-union/.
70. Europa. n.d. "Shedding Light on Energy on the EU: From Where Do We Import Energy?" Accessed August 9, 2021. https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2c.html; Bartuška, Václav, Petr Lang, and Andrej Nosko. 2019. "The Geopolitics of Energy Security in Europe." Carnegie Europe - Carnegie Endowment for International Peace. https://carnegieeurope.eu/2019/11/28/geopolitics-of-energy-security-in-europe-pub-80423.
71. Sam Meredith, "Ukraine's Naftogaz CEO Accuses Russia of Using Gas as a Geopolitical Weapon as Energy Crisis Deepens," CNBC, September 24, 2021, https://www.cnbc.com/2021/09/24/europe-energy-crisis-naftogaz-accuses-russia-of-using-gas-as-a-geopolitical-weapon.html.
72. NREL. 2013. "International Trade of Wood Pellets." https://www.nrel.gov/docs/fy13osti/56791.pdf; Aguilar, Francisco X., Ashkan Mirzaee, Ronald G. McGarvey, Stephen R. Shifley, and Dallas Burtraw. 2020. "Expansion of US Wood Pellet Industry Points to Positive Trends but the Need for Continued Monitoring." Scientific Reports 10 (1): 18607.
73. Popovic, Nemanja. 2020. "The Energy Relationship between Russia and the European Union." E-IR. February 24, 2020. https://www.e-ir.info/2020/02/24/the-energy-relationship-between-russia-and-the-european-union/.
74. Kawasaki. 2019. "World's First Liquefied Hydrogen Carrier SUISO FRONTIER Launches Building an International Hydrogen Energy Supply Chain Aimed at Carbon-Free Society." https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20191211_3487.
75. Bocobza, Julien and Claire Tuch. 2021. "Hydrogen and Japan." ProjectFinance. https://www.projectfinance.law/publications/2021/april/hydrogen-and-japan/.
76. EIA. 2020. "Japan." https://www.eia.gov/international/analysis/country/JPN.
77. Paul, Sonali. 2021. "Australia Warms to Green Hydrogen amid Japanese Demand." Reuters. May 27, 2021. https://www.reuters.com/business/energy/australia-warms-green-hydrogen-amid-japanese-demand-2021-05-27/.
78. Ratcliffe, Verity. 2020. "Saudi Arabia Sends Blue Ammonia to Japan in World-First Shipment." Bloomberg News. https://www.bloomberg.com/news/articles/2020-09-27/saudi-arabia-sends-blue-ammonia-to-japan-in-world-first-shipment.
79. ADNOC. 2021. "ADNOC and Three Japanese Companies to Explore Hydrogen and Blue Ammonia Opportunities." https://www.adnoc.ae/en/news-and-media/press-releases/2021/adnoc-and-three-japanese-companies-to-explore-hydrogen-and-blue-ammonia-opportunities.
80. Saadi, Dania. 2021. "INTERVIEW: UAE to Focus on Blue Hydrogen to Capitalize on Oil and Gas Industry." S&P Global Platts. May 18, 2021. https://www.spglobal.com/platts/en/market-insights/latest-news/agriculture/051821-interview-uae-to-focus-on-blue-hydrogen-to-capitalize-on-oil-and-gas-industry.
81. Afanasiev, V. 2021. "Novatek subsidiary seeks drillers for Blue Ammonia and hydrogen initiative." Upstream Online. August 5, 2021. https://www.upstreamonline.com/energy-transition/novatek-subsidiary-seeks-drillers-for-blue-ammonia-and-hydrogen-initiative/2-1-1048849.
82. Kumagai, T. and R. Griffin. 2021. "Japan, Russia sign agreements for hydrogen, ammonia cooperation, Kamchatka LNG reloading." S&P Global Platts. September 2, 2021. https://www.spglobal.com/platts/en/market-insights/latest-news/energy-transition/090221-japan-russia-sign-agreements-for-hydrogen-ammonia-cooperation-kamchatka-lng-reloading.
83. DiChristopher, T. 2021. "Los Angeles aims to be nation's 1st Green Hydrogen Hub." S&P Global. May 19, 2021. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/los-angeles-aims-to-be-nation-s-1st-green-hydrogen-hub-64376930.
84. SGH2 Energy. n.d. "World's largest green hydrogen project to launch in California." https://www.sgh2energy.com/worlds-largest-green-hydrogen-project-to-launch-in-california.
85. Ruth, Mark, Paige Jadun, Nicholas Gilroy, Elizabeth Connelly, Richard Boardman, A. J. Simon, Amgad Elgowainy, and Jarett Zuboy. 2020. "The Technical and Economic Potential of the H2@scale Hydrogen Concept within the United States." Office of Scientific and Technical Information (OSTI); Office of Fossil Energy. 2020. "Hydrogen Strategy." https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf.
FCHEA. 2021. "Road Map to a U.S. Hydrogen Economy." https://cafcp.org/sites/default/files/Road+Map+to+a+US+Hydrogen+Economy+Full+Report.pdf; Deloitte. 2019. "Australian and Global Hydrogen Demand Growth Scenario Analysis." https://www2.deloitte.com/content/dam/Deloitte/au/Documents/future-of-cities/deloitte-au-australian-global-hydrogen-demand-growth-scenario-analysis-091219.pdf.
86. Apodaca, Lori E., ed. 2021. NITROGEN (FIXED)—AMMONIA. USGS. https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-nitrogen.pdf.

87. Deloitte. 2019. “Australian and Global Hydrogen Demand Growth Scenario Analysis.” https://www2.deloitte.com/content/dam/Deloitte/au/Documents/future-of-cities/deloitte-au-australian-global-hydrogen-demand-growth-scenario-analysis-091219.pdf.

88. https://www.iea.org/data-and-statistics/data-product/energy-technology-rd-and-d-budget-database-2#documentation

89. DOE HFTO. 2021. “H2@Scale Program.” https://www.energy.gov/eere/fuelcells/h2scale

90. Keith Ridler, “US Nuclear Lab Partnering with Utility to Produce Hydrogen” (Associated Press, November 11, 2020), https://apnews.com/article/technology-minnesota-minneapolis-nuclear-power-hydrogen-fuel-554bd1bfe749919053f74becb12bc80d.

91. Department of Energy. 2021 “HydrogenShot”. https://www.energy.gov/eere/fuelcells/hydrogen-shot

92. House of Representatives. 2021. “26 U.S.C. 45Q Tax Credit” https://uscode.house.gov/view.xhtml?req=(title:26%20section:45Q%20edition:prelim)%20OR%20(granuleid:USC-prelim-title26-section45Q)&f=treesort&edition=prelim&num=0&jumpTo=true.

93. Global CCS Institute. 2021. ‘Blue Hydrogen” https://www.globalccsinstitute.com/wp-content/uploads/2021/04/CCE-Blue-Hydrogen.pdf.

94. Us. Congress. 2021. H.R.3684 Infrastructure Investment and Jobs Act. *https://www.congress.gov/bill/117th-congress/house-bill/3684.*

95. Senator Mike Crapo. 2021. “Crapo, Risch, Whitehouse, Reed, Panetta Introduce Legislation To Encourage Innovation In The Clean Energy Sector.” https://www.crapo.senate.gov/media/newsreleases/crapo-risch-whitehouse-reed-panetta-introduce-legislation-to-encourage-innovation-in-the-clean-energy-sector.

96. Senate Environment and public Works Committee. 2021. “Carper Introduces Clean Hydrogen Tax Legislation.” *https://www.epw.senate.gov/public/index.cfm/2021/5/carper-introduces-clean-hydrogen-tax-legislation.*

97. Heller, Matt. 2021. “The Ohio Valley is an Emerging Hub for Carbon Capture and Hydrogen Generation.” https://www.americanmanufacturing.org/blog/the-ohio-valley-is-an-emerging-hub-for-carbon-capture-and-hydrogen-generation/

Magill, Jim. 2021. “California and Texas Vie to Be America’s Hydrogen Capital.” Forbes Magazine, February 23, 2021. https://www.forbes.com/sites/jimmagill/2021/02/23/california-texas-vie-to-determine-which-will-be-us-hydrogen-capital/.

98. DiChristopher, Tom. 2021. “Los Angeles Aims to Be Nation’s 1st Green Hydrogen Hub.” SPGlobal. May 19, 2021. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/los-angeles-aims-to-be-nation-s-1st-green-hydrogen-hub-64376930; Klinge, Naomi. 2021. “Equinor Plans Hydrogen, CCS Hub in US Appalachian Region with US Steel.” UpstreamOnline. June 29, 2021. https://www.upstreamonline.com/energy-transition/equinor-plans-hydrogen-ccs-hub-in-us-appalachian-region-with-us-steel/2-1-1032681; “Burgum Joins Bakken Energy, Mitsubishi Power in Announcing Partnership to Create Hydrogen Hub in ND.” 2021. https://www.governor.nd.gov/news/burgum-joins-bakken-energy-mitsubishi-power-announcing-partnership-create-hydrogen-hub-nd.

99. Warwick, Peter D., and M. D. Corum, eds. 2012. “Geologic Framework for the National Assessment of Carbon Dioxide Storage Resources.” *Open-File Report. US Geological Survey. https://doi.org/10.3133/ofr20121024.*

100. Burgess, James. 2021. “Interview: UK’s National Grid Looks to Prove Case for Hydrogen Blending.” S&P Global Platts. April 29, 2021. https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/042921-interview-uks-national-grid-looks-to-prove-case-for-hydrogen-blending.

101. Chestney, Nina. 2021. “$15 Trillion Global Hydrogen Investment Needed to 2050-Research.” Reuters. April 26, 2021. https://www.reuters.com/business/energy/15-trillion-global-hydrogen-investment-needed-2050-research-2021-04-26/.

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