Introduction to Hydrogen's Role in a Low-Carbon Future

Hydrogen production, use, and benefits

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Introduction to Hydrogen

Many stakeholders are increasingly eyeing hydrogen—a colorless, odorless gas—for its potential to help meet long-term climate and net-zero greenhouse gas (GHG) targets set by governments and businesses. Hydrogen has two main characteristics that make it attractive for this purpose. First, hydrogen is an extremely versatile energy source, with potential applications across several different sectors; and secondly it produces no GHG emissions or air pollution when created from renewable sources. In the first instance, hydrogen can be used as an energy carrier, energy storage medium, or feedstock. It can be used to create energy through traditional combustion methods such as internal combustion engines, furnaces, or gas turbines or through fuel cells to produce electricity. It can also be stored as a liquid or gas or converted into other chemical compounds (e.g., ammonia or synthetic natural gas). These characteristics make hydrogen an attractive candidate to help decarbonize energy systems across the economy, including natural gas networks, power generation, industry, and transportation.

While hydrogen produces no GHG emissions at the point of use, the true climate benefit of hydrogen is highly dependent on how it is produced. To have benefits to the environment, hydrogen must be renewable or low carbon. Today, only a small fraction of the hydrogen consumed globally is produced via a low-carbon or renewable process; the rest is produced via emissions-intensive processes using fossil fuels. This is due to a variety of factors such as the established industry that currently produces hydrogen from fossil fuels without carbon capture, higher costs of producing clean hydrogen and renewable hydrogen that is not yet at scale in comparison to those produced by fossil fuels. These costs are expected to decline in the coming years.

In recognition of clean hydrogen’s potential to contribute to decarbonization, governments and industry are ramping up investments globally. Hydrogen’s capability to reduce GHGs and contribute to decarbonization depends on widescale deployment of clean hydrogen production in favor of existing emissions-intensive pathways. Doing so requires even more investment and collaboration to achieve scales that would make clean hydrogen a cost-effective commodity for multiple sectors of the economy.

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This MJB&A Issue Brief is the first in a two-part series on hydrogen and the role it can play in a low-carbon future. It summarizes hydrogen production processes, describes current and future hydrogen applications, and explores the potential benefits of widespread clean hydrogen deployment.

A companion brief provides a deeper dive into hydrogen applications, discusses the economics of hydrogen, and highlights current clean hydrogen pilot projects.

Hydrogen Production

The U.S. currently produces and consumes approximately ten million metric tons of hydrogen annually, equivalent to just over one quadrillion British thermal units (Btus) per year (or roughly one percent of total U.S. energy consumption).[i]

Hydrogen can be produced using a range of energy sources and technologies, and the GHG impacts and costs of these different pathways vary significantly. The different pathways have traditionally been communicated by use of a series of colors that correlate to a specific hydrogen production pathway. For example, "green" hydrogen is produced by renewable electricity and therefore creates zero (or near-zero) life cycle GHG emissions.[1] However, several stakeholders have recently transitioned to a focus on "clean hydrogen" to distinguish between more and less emissions-intensive forms of hydrogen, regardless of their production pathway.

Table 1 reviews the main hydrogen production pathways and their associated emissions intensity.

Table 1: Key Hydrogen Production Pathways and GHG Impact

	Description of Hydrogen Production Pathway	Carbon Intensity (kg CO_2 per kg H_2)
	Green hydrogen is produced by extracting hydrogen from water using electrolysis powered by renewable electricity (such as wind and solar), which is non-emitting.	0
	Pink hydrogen is produced by extracting hydrogen from water using electrolysis powered by electricity from nuclear generation, which is also non-emitting.	0
	Yellow hydrogen is produced by extracting hydrogen from water using electrolysis powered by grid electricity (commonly a mixture of clean and emitting sources, depending on the location).	~17.0 - 39.0*
	Grey hydrogen is produced by extracting hydrogen from natural gas using thermal processes such as steam methane reformation (SMR).[2] CO_2 is emitted as a byproduct.	9.27
	Blue hydrogen is produced by extracting hydrogen from natural gas and using carbon capture technology to capture most remaining CO_2 emissions (commonly 80 to 90 percent or higher).[3]	0.93 - 1.8
	Brown hydrogen is produced via the gasification of coal. CO_2 is emitted as a byproduct.	20.0
	Turquoise hydrogen is produced by extracting hydrogen from natural gas via methane pyrolysis; solid carbon is produced as a byproduct.	0

Source: IEA, The Future of Hydrogen (2019) and MJB&A analysis. * = Utilizes world average electricity mix.

1 The emissions associated with hydrogen production from zero-emitting resources are zero. However, some small life cycle emissions may be attributable to construction (e.g., of the electrolyzer).
2 Autothermal reforming (ATR) is another process to produce hydrogen from natural gas, although less common.
3 Partial oxidation captures more than 90 percent of CO_2 emissions and can therefore reduce the carbon intensity to 1 kg CO_2 per kg H_2.

Hydrogen can be produced from organic biomass as well as from renewable natural gas (RNG) derived from biogenic waste. There are no established colors for these types of hydrogen. The emissions intensity of these production pathways varies considerably by feedstock and production pathway but is generally lower than that of grey hydrogen. For certain organic feedstocks such as animal waste, the emissions intensity may even be net-negative on a life cycle basis. Emissions reductions increase further if paired with carbon capture.

Today, nearly all hydrogen consumed globally is grey or brown, with roughly three-fourths grey hydrogen and just under one-fourth brown hydrogen.[ii] These forms of hydrogen offer no climate benefit, due to the GHGs emitted when producing hydrogen. However, with current production costs of approximately $1.00 per kilogram (kg) of hydrogen or lower, these forms of hydrogen are significantly less expensive than other forms of hydrogen.[iii] Due to its lower costs, the abundance of feedstock (natural gas), and the large number of SMR facilities in operation today, grey hydrogen is expected to remain the dominant technology for large-scale hydrogen production in the near term.[iv]

The green, pink, blue, and turquoise forms of hydrogen are lower-emitting or emissions-free and offer the greatest opportunity to decarbonize end uses across sectors. However, using current technology, these forms of hydrogen without the scale of their fossil counterparts are more expensive than their more carbon-intensive counterparts: for example, current estimates of green and blue hydrogen range from $2.50 to $4.50 per kg and $1.30 to $2.70 per kg, respectively.[v] As a result, these forms of hydrogen currently constitute a small portion of existing demand. For example, only about 0.1% of today's global hydrogen production is green.[vi] There is significant room for cost reductions across each of these forms of hydrogen production. Costs for both electrolysis and carbon capture technology are expected to decline, with further investment, scale and demand. Turquoise hydrogen is in the most nascent hydrogen production pathway and requires more research and development than other lower-emitting pathways. For production pathways that utilize electrolysis (e.g., green, pink, and yellow hydrogen), the electricity mix used is a key factor in assessing GHG impacts. While green and pink hydrogen are emissions-free, a 2019 report by the International Energy Agency (IEA) found that producing hydrogen with either gas- or coal-fired electricity generation emits more CO_2 emissions than hydrogen produced by SMR without CCS.[vii]

There has been a shift in recent months in how some stakeholders delineate between different types of hydrogen. Many recent clean energy tax incentive proposals and industry communications are focusing instead on "clean hydrogen," defined as hydrogen produced at or below a specified carbon intensity.[viii] There is no universal standard of "clean hydrogen" although several have identified a threshold of 2 kg CO_2 per kg H_2. Regardless of the exact definition, the concept represents a shift toward a focus on the life cycle emissions intensity of hydrogen, rather than its "color" or production pathway. This allows for a more holistic and source-specific accounting and curtails discussions about feedstocks or linkages to electricity supplies.

Blue Hydrogen: The Role of Carbon Capture in Hydrogen Production

Blue hydrogen is produced via the same method as grey hydrogen (via SMR using natural gas), but with added carbon capture technologies. The rate of carbon capture (i.e., the proportion of emissions that are captured and stored) directly influences the carbon intensity of the resulting hydrogen.

With 95 percent of today's hydrogen produced using SMR without carbon capture, the potential exists to retrofit these grey hydrogen facilities into blue hydrogen production by adding carbon capture technologies. Due to the high cost of carbon capture technologies, blue hydrogen is currently more expensive than its grey counterpart. For example, IEA finds that in the U.S., hydrogen production costs using natural gas commonly increase by 50 percent with carbon capture (e.g., from $1 per kg H_2 to $1.5/kg H_2.[1] However, blue hydrogen is less expensive than green hydrogen and is less emissions-intensive than its grey or brown counterparts. Some stakeholders assert that retrofitting today's existing large-scale SMR plants to incorporate CCS technology could allow for relatively low-cost hydrogen while waiting for anticipated cost reductions in green hydrogen technologies.

Ultimately, it is expected that many types of clean hydrogen will contribute to the decarbonization of the U.S. and global economies. The growth and ultimate impact of each will be determined by policy decisions, technology development, cost effectiveness, and investor decisions.

[1] IEA, The Future of Hydrogen (2019).

Hydrogen Use

Hydrogen can either be used in its "pure" form (i.e., 100 percent hydrogen) or blended with existing gaseous and liquid fuels to lower their carbon intensity. Further, pure hydrogen can either be used in fuel cells to create electricity or combusted. In all cases, a notable characteristic of hydrogen is that it produces no carbon emissions at the point of use (only water vapor and heat when used in fuel cells and nitrogen oxide, or NOx, when combusted).

Today, the bulk of hydrogen is used in various industrial processes, including petroleum refining, ammonia production and fertilizers, metals production, methanol production, electronics manufacturing, and food processing. Global demand for pure hydrogen, largely for these industrial purposes, is approximately 70 million metric tons per year. For hydrogen in mixed gases (such as synthetic gas and ammonia), global demand is approximately 40 million metric tons per year.[ix]

Emerging Uses

Hydrogen—whether in its pure form or blended with other applications— can also replace fossil fuels for various applications, including in buildings, electricity, industry, and transportation.

- **Buildings:** Hydrogen can be blended with natural gas to lower the GHG emissions of building heating needs (e.g., in space and water heating, among other end uses), while allowing customers to use the same appliances.[4] In its pure form, it can be used to provide heat and power to other appliances (i.e., hydrogen boilers, fuel cell heat pumps) or generate electricity using a fuel cell.
- **Electricity:** Similarly, hydrogen can be blended with natural gas in certain turbines to reduce the GHG emissions of electricity generation, although turbine modifications are needed to reduce NOx emissions. Equipment manufacturers, electric utilities, and technology providers are engaged in ongoing research and development for new gas turbines and retrofits to existing turbines that can tolerate higher levels of hydrogen blending (and up to 100 percent hydrogen). Turbine manufacturers like GE are producing turbines that can work with up to 50 percent hydrogen blending. GE, for example, has more than 70 gas turbines worldwide using hydrogen and associated fuels for power generation, with about 6 million operating hours in aggregate.[x]
- **Storage:** Also in the electric power sector, hydrogen can play a key role in an increasingly renewable electric grid mix: by using an electrolyzer to convert excess renewable electricity to green, pink, or yellow hydrogen (a process called "Power-to-Gas"), hydrogen can be used for long-term (seasonal) energy storage at the terawatt-hour scale to help balance electric supply and demand while complementing renewables such as wind and solar generation.[xi] The resulting renewable hydrogen can then be used either on-site or transported to decarbonize other sectors of the economy.
- **Transport:** Hydrogen can be used in fuel cell vehicles, whether light-duty vehicles, heavy-duty freight, aviation, or mass transit vehicles. Hydrogen is especially being considered within the medium- and heavy-duty sector (specifically for long-haul trucking) because of its fuel economy advantage, longer travel time on a single tank when compared to a battery and its rapid fueling capabilities. Hydrogen also has significant potential in marine and rail applications where electrification poses more challenges.[xii]

[4] While more research is needed, higher blending levels of hydrogen are likely tolerable with minor changes to appliances. See the "Transportation and Storage" section of this Issue Brief for more information.

- **Industry:** Hydrogen can be used directly or blended with fossil fuels in several industrial processes. Hydrogen holds value in its ability to create high-temperature process heat that is required by many industrial processes, such as iron and steel production.

Several studies have noted that the use of hydrogen across multiple sectors will help to achieve further cost declines and efficiencies, which in turn will help to achieve widespread commercial deployment.

Transportation and Storage

Widespread production and use of hydrogen across the economy requires a robust transportation and storage network. There are several ways to transport and store hydrogen—it can be transported by truck, rail, ship, or dedicated hydrogen pipelines, as well as blended safely with natural gas into existing gas pipelines. It can also be chemically converted into another form for easier transportation such as Liquid Organic Hydrogen Compound (LOHC) utilizing larger molecules, ammonia, or synthetic natural gas. There are advantages and disadvantages to each of these options.

- **Trucking, rail, and shipping:** Similar to natural gas, pure hydrogen can also be transported by rail, truck, or ship in compressed or liquified form. Compressed or liquified hydrogen is considered more stable for transport, but this chemical conversion incurs energy losses and increases total costs. It can also increase lifecycle GHG emissions.

- **Dedicated hydrogen pipelines:** The U.S. currently has approximately 1,600 miles of dedicated hydrogen pipelines, largely located near large industrial users of hydrogen.[xiii] Widespread hydrogen deployment may require further build-out of this infrastructure. Alternatively, in the long term, it may be possible that the existing natural gas pipeline network could be repurposed to transport, distribute, and store 100 percent pure hydrogen, rather than natural gas, or that twin hydrogen pipelines could be installed at existing locations. Expanding and establishing dedicated hydrogen pipelines will require significant capital investments. However, one analysis of such infrastructure in Europe projected that such costs would be only 10 to 20 percent of the delivered cost of energy.[xiv] Total capital costs of dedicated hydrogen transmission infrastructure may also be significantly lower cost on a per-mile basis than other alternatives, such as high voltage electric transmission lines.[xv]

- **Blending into natural gas distribution systems:** Existing research indicates that at low levels (e.g., up to 20 percent by volume), hydrogen can be blended with fossil natural gas and delivered to customers using existing distribution infrastructure with no or minor adverse impacts to customers or infrastructure.[xvi,5] Gas distribution systems are well suited to receive hydrogen blends sooner than gas transmission lines, as they are lower pressure and have large amounts of polyethylene (plastic) pipes, which mitigate adverse effects of hydrogen embrittlement. Local gas distribution companies can also be selective in introducing blends: they can target newer areas, away from customers whose appliances are known to not be compatible with blends, or to large customers whose equipment can be converted to receive large amounts of hydrogen. Of note, the emissions reductions associated with increasing percentages of hydrogen blending are non-linear (see Call Out box).

  Higher levels of hydrogen blending may introduce challenges such as pipeline embrittlement, compression, safety, compatibility with other end uses, impacts on heating value of pipeline natural gas, and customer meters. To help avoid some of the technical challenges associated with blending hydrogen in natural gas pipelines and potential impacts on end use appliances, hydrogen can be

[5] Hydrogen blending at low levels may require minor changes to infrastructure, equipment, and end use appliances, if changes are needed at all. Pipeline materials have varying degrees of tolerance for hydrogen blend volumes. Research is underway to better understand the impact of hydrogen blending on natural gas infrastructure and end-use equipment.

combined with CO_2 through methanation to produce pipeline quality synthetic natural gas. While this conversion increases overall costs, the life cycle GHG emissions are lower than those from conventional natural gas and can be further reduced if the methanation process utilizes CO_2 from a waste stream.[6]

- **Conversion to Other Forms:** Hydrogen can also be chemically converted into energy carriers such as LOHC's and ammonia. While this can make it easier to transport, this again results in energy losses and potentially higher costs.

The most cost-effective choice will likely vary according to geography, distance, scale, and the required end use of hydrogen.

Hydrogen Blending and Emissions Reductions

The relationship between hydrogen blends and carbon emission reductions in non-linear: because hydrogen is lighter and less energy-dense on a volumetric basis than natural gas, more hydrogen is required to achieve the same amount of delivered energy as natural gas. This is because on a volumetric basis, hydrogen has approximately one third the energy content of natural gas. This increase in hydrogen used creates non-linear GHG emission reductions when higher volumes of hydrogen are utilized. For example, blending 10 percent of hydrogen by volume results in less than 3 percent emissions reduction; a 60 percent blend results in a 31 percent emissions reduction.[1]

[6] Hydrogen can be converted into ammonia (NH_3) when reacted with nitrogen or into synthetic natural gas (CH_4) when reacted with CO_2. Synthetic natural gas is an artificially produced version of natural gas that can have lower life cycle GHG emissions than conventional natural gas, depending on the method of hydrogen production.

Hydrogen and the Potential Role of the Natural Gas Distribution Networks

Given the multiple emerging applications for hydrogen across sectors, many researchers and stakeholders are evaluating how the natural gas distribution networks can play a role in transporting hydrogen to these different end users. Existing gas transmission and distribution networks are not suited for transporting pure hydrogen. However, many are exploring hydrogen blending, or the injection of hydrogen into existing natural gas pipeline networks to reduce the GHG emissions associated with the end use of geologic natural gas, as well as methanating hydrogen to remove material compatibility and energy dilution effects. While investment in hydrogen injection facilities would be needed, hydrogen blending would generally offer a relatively efficient way to transfer hydrogen supplies to end users, offer mass reduction in carbon across a large customer base and enable an interface with the electrical grid.

Research and demonstration projects, which have largely been conducted in the United Kingdom and the European Union, indicate that (for natural gas distribution systems) up to 20 percent hydrogen (by volume) could be blended with fossil natural gas and/or biomethane and delivered by LDCs to their customers using existing infrastructure without adverse impacts to pipelines or customer appliances.* While less research on hydrogen blending has been conducted in North America to date, the National Renewable Energy Laboratory (NREL) announced in late 2020 that it will lead a new multi-year collaborative research and development project, HyBlend™, to address technical barriers to blending hydrogen in natural gas pipelines.

By repurposing and utilizing existing infrastructure, multiple sectors can begin to deploy low-carbon fuels while avoiding significant upfront investments in transmission and distribution.

[1] IEA, Future of Hydrogen (2019).

Hydrogen Co-Benefits

Hydrogen, when produced via low-carbon forms of energy, offers GHG benefits compared to emitting alternatives. This characteristic, combined with its versatility, makes clean hydrogen suitable to help decarbonize several energy sectors, including natural gas networks, power generation, and difficult-to-abate sectors such as industry and heavy-duty transportation.[7]

Low-carbon forms of hydrogen can also offer several additional benefits beyond its role in decarbonization:

- **Improved Local Air and Noise Quality:** Unlike fossil alternatives, hydrogen produces significantly fewer air pollutants at the point of combustion. When used in a fuel cell, hydrogen results in zero air pollutants (only water vapor) and no noise pollution. When hydrogen is used to replace on-site fossil fuel combustion, such as in a vehicle or at a natural gas turbine, this leads to improved air and noise quality and public health benefits.[8]

- **Seasonal Storage Complement to Intermittent Renewables:** Jurisdictions at the local, state, and federal level are planning for an increasingly electrified future and are enacting policies to decarbonize their electric grid by mid-century or sooner. Meeting increased electric demand in a low-carbon future requires vastly expanding electric generating and grid infrastructure, as well as an electricity mix that is largely comprised of intermittent renewables, such as wind and solar. Today, jurisdictions with increasing renewable penetration (e.g., California but increasingly other states as well) are curtailing excess renewable electricity to balance electric supply with demand. The need for renewable curtailment increases as the local electric mix becomes more comprised of intermittent renewables.

  Here, green hydrogen can play an important role in helping to cost-effectively balance electric supply and demand from these renewable resources. Rather than curtailing excess renewable electricity, that electricity can power an electrolyzer to create green hydrogen which can be stored for future use. This electricity can then be used on site, sold to other end users, or stored and distributed when most advantageous. Unlike today's battery storage technology, hydrogen can store large quantities of energy over long periods of time. By helping to address intermittency concerns, hydrogen can help to reduce the need for expansion of electric generation and transmission infrastructure, thereby reducing costs. The natural gas system offers a low cost of capital per kilowatt hour (kWh) for hydrogen storage, the cost of which is primarily driven by the electrolyzer connection cost to gas systems) and is significantly lower than alternative storage technologies such as pumped hydro and batteries.[xvii]

- **Net-Negative CO_2 Emissions:** While all clean hydrogen has no or low GHG emissions, hydrogen produced using certain organic feedstocks such as animal waste can be net carbon-negative on a life cycle basis, meaning that their production *reduces* CO_2 emissions. Emissions reductions increase further if paired with carbon capture.

- **Economic Development:** Growth in hydrogen economy is expected to create new jobs throughout the hydrogen life cycle. This includes new economic opportunities in hydrogen production, transportation, storage, and end-use technologies. Repurposing today's natural gas networks to supply

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7 However, as discussed, only a small fraction of the hydrogen produced today is derived from low-carbon sources. Scale-up of these forms of hydrogen are needed to unlock the decarbonization potential of hydrogen at a wider scale.

8 Hydrogen combustion (compared to hydrogen use within a fuel cell) can lead to increased levels of NOx pollution if no additional measures are taken to reduced NOx emissions. Further RD&D is necessary to understand turbine modifications and other emissions control measures to reduce NOx pollution during hydrogen combustion.

hydrogen and other low-carbon fuels can also maintain existing jobs and utilize existing infrastructure, all while reducing emissions. A coalition of energy and industry companies collaborated to develop an industry-led roadmap on the potential for hydrogen production in the U.S. The roadmap report concluded that by 2050, the U.S. hydrogen economy could lead to an estimated $750 billion in revenue and a cumulative 3.4 million jobs.[xviii] This enables a just transition to a low carbon economy, as existing skilled labor can participate in hydrogen development and deployment.

Path Forward for Hydrogen

The potential for hydrogen to enable cross-sector decarbonization is being recognized globally, with investments by government and industry ramping up in many countries. In the U.S., the Department of Energy (DOE) is investing up to $100 million over five years to advance research and development for hydrogen and fuel cell technologies.[xix] DOE estimates that by 2050, the U.S. could see a two- to four-fold increase in total hydrogen demand, assuming research and development success in key areas.[xx] Pilots and demonstration projects are also in the works, testing hydrogen production, storage, transport and end use (see MJB&A's companion Issue Brief for more details).

Emerging policy and market drivers are also helping to spur increased deployment. For example, large corporate (industrial) customers, particularly those for which electrification is not a viable decarbonization strategy, are showing increased interest in hydrogen and other low-carbon fuels to meet their company-wide sustainability and emission reduction targets. Certain states are pursuing Renewable Gas Standards for gas utilities (similar to Renewable Portfolio Standards for electric utilities), which would create a demand signal and investment certainty for project developers and investors that are able to provide hydrogen and other low-carbon gases for gas utilities and end-use customers.

Significant challenges still need to be addressed, such as the high input and resulting cost of clean hydrogen relative to its emissions-intensive counterparts. However, cost declines across the hydrogen life cycle are expected as scale is achieved. For example, Bloomberg New Energy Finance forecasts that declines in electrolyzer costs could lead to green hydrogen production for about $0.80 to $1.60 per kg before 2050 (below current costs of $2.50 to $4.50 per kg).[xxi] Hydrogen's capability to contribute to decarbonization depends on widescale deployment of clean hydrogen production in favor of existing emissions-intensive pathways. Widespread low-hydrogen deployment will also require supportive policies to incentivize its use across sectors. The growth and ultimate contribution of each type of clean hydrogen to decarbonization will ultimately be determined by policy decisions, technology development, cost-effectiveness, and investor decisions.

Widescale deployment of clean hydrogen will require even more investment and collaboration to achieve scales that would make clean hydrogen a beneficial commodity for multiple different sectors. This will require sustained engagement of multiple stakeholders, including policymakers, environmental NGOs, environmental justice communities, natural gas utilities, and hydrogen producers.

i U.S. Department of Energy (DOE), Current Hydrogen Market Size: Domestic and Global (October 1, 2019), https://www.hydrogen.energy.gov/pdfs/19002-hydrogen-market-domestic-global.pdf/

ii IEA, The Future of Hydrogen (June 2019), https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf; U.S. DOE, Current Hydrogen Market Size: Domestic and Global.

iii IEA, Hydrogen Production Costs Using Natural Gas in Selected Regions, 2018 (last updated March 12, 2020), https://www.iea.org/data-and-statistics/charts/hydrogen-production-costs-using-natural-gas-in-selected-regions-2018-2.

iv IEA, The Future of Hydrogen.

v Bloomberg New Energy Finance, Hydrogen Economy Outlook (March 30, 2020), https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf.

vi IEA, The Future of Hydrogen.

vii IEA, The Future of Hydrogen.

viii *See;* https://www.congress.gov/bill/117th-congress/senate-bill/1807.

ix IEA, The Future of Hydrogen.

x GE, News, https://www.ge.com/news/post-category/8782.

xii U.S. DOE, Hydrogen Program Plan (2020), https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf.

xiii U.S. DOE, Hydrogen Pipelines, https://www.energy.gov/eere/fuelcells/hydrogen-pipelines.

xiv Guidehouse, European Hydrogen Backbone,

xv James et al., "Analysis of Advanced H2 Production & Delivery Pathways," Strategic Analysis, June 2018, https://www.hydrogen.energy.gov/pdfs/review18/pd102_james_2018_p.pdf.

xvi IEA, The Future of Hydrogen.

xvii Pacific Northwest National Laboratory, Energy Storage Technology and Cost Characterization Report, U.S. DOE, July 2019, https://www.energy.gov/sites/prod/files/2019/07/f65/Storage%20Cost%20and%20Performance%20Characterization%20Report_Final.pdf.

xviii Fuel Cell and Hydrogen Energy Association, Road Map to a US Hydrogen Economy, https://www.fchea.org/us-hydrogen-study.

xix U.S. DOE, DOE Announces New Lab Consortia to Advance Hydrogen and Fuell Cell R&D (June 23, 2020), https://www.energy.gov/articles/doe-announces-new-lab-consortia-advance-hydrogen-and-fuel-cell-rd.

xx U.S. DOE, Hydrogen Program Plan.

xxi Bloomberg New Energy Finance, Hydrogen Economy Outlook (March 30, 2020).

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