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Hydrogen in Electricity's Future

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SUMMARY

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Richard J. Campbell
Specialist in Energy Policy

Hydrogen in Electricity's Future

The U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) describes hydrogen as an "energy carrier," as it allows the transport of energy that can be later converted to other forms of useful energy. Moreover, due to its high energy content and clean-burning properties, hydrogen is being investigated for its potential to replace or reduce the use of fossil fuels and to reduce greenhouse gas (GHG) emissions.

Natural gas is currently the fuel most used for electric power generation in the United States, and the DOE's Energy Information Administration expects it to be the predominant fuel for the production of electricity well into the 2040s. Natural gas is a fossil fuel that when burned to produce electric power, results in carbon dioxide (CO_2) emissions, varying from 42% to 63% of the CO_2 emissions of coal. When potential climate impacts are considered by electric utilities, increasing renewable sources of electricity and switching to natural gas generation from coal have been strategies that a number of companies have followed. Total CO_2 emissions have increased with increased electricity production from natural gas-fired generation.

If reducing or eliminating fossil fuel use is a goal for the electric power sector, then the expanded use of hydrogen due to its potential to decarbonize the sector could be an option. Combustion turbines capable of burning hydrogen could be used in order to increase power generation on a large scale, and could potentially replace natural gas-fired generation. There are technical and cost issues with how such a transition could be accomplished. Another potential option for the use of hydrogen is as a fuel for electricity production in fuel cells, as water and heat are the only by-products.

Hydrogen gas can be produced in a variety of ways, but it must be extracted from the various compounds containing hydrogen, using appropriate technologies. An increased use of hydrogen in the electric power sector for power generation would likely require an increased, more economical supply of hydrogen. With U.S. prices for natural gas currently below $2 per million BTU in several markets and projected to stay low, this presents a long-term challenge to the cost effective use of hydrogen. Other challenges are generally focused on two areas: the storage of hydrogen, and the transportation of hydrogen. Storing hydrogen requires the input of external energy to compress the gas. Building new pipelines for hydrogen transportation faces technical barriers beyond the initial high capital costs of pipeline construction, with embrittlement and escape of hydrogen (the smallest element) via permeation among known issues. According to one report, developing a system for hydrogen storage and transportation to provide the same utility as the natural gas system would require a significantly large, coordinated program of infrastructure upgrades and construction. Another article proposed using the existing natural gas pipeline system, and decarbonizing natural gas on-site as one way to avoid much of the need for hydrogen transport and storage.

A recent analysis by the U.S. Global Change Research Program found that if GHG emissions continued at forecast rates and adaptation actions were not undertaken, climate change impacts would damage U.S. infrastructure, communities, and the economy. If Congress chooses to pursue further GHG emissions reduction, then addressing carbon dioxide emissions from natural gas may be an option. Congress may examine the question of whether and how to lower the costs of producing and using hydrogen for power generation. Alternatively, Congress may consider how to address the unaddressed negative externalities of carbon dioxide emissions, with a tax or some other limit on CO_2 emissions as a potential option. Congress may also consider further research, development, demonstration, and deployment to facilitate the economic use of hydrogen for electric power, including the use of tax incentives or credits for such purposes.

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Introduction

Hydrogen is the simplest, and one of the most abundant elements on the Earth. The hydrogen atom is composed of a proton and an electron, and combines with other elements to form a number of common compounds including water (H_2O), and methane (CH_4), the primary constituent of natural gas.[1]

> Hydrogen is a commercially important element. Large amounts of hydrogen are combined with nitrogen from the air to produce ammonia (NH_3) through a process called the Haber process.… Liquid hydrogen is used in the study of superconductors and, when combined with liquid oxygen, makes an excellent rocket fuel.[2]

The U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) describes hydrogen as an "energy carrier," as it allows the transport of energy that can be later converted to other forms of useful energy (such as mechanical work or heat (or thermal) energy used for physical or chemical processes).[3] Hydrogen (with an energy density of about 142 megajoules per kilogram (MJ/kg))[4] also has one of the highest energy density values per unit of mass,[5] containing more than three times the energy of most hydrocarbon fuels.[6]

Hydrogen gas is highly flammable, requiring a small amount of energy to ignite and burn, and when hydrogen is burned with oxygen, it burns cleanly with the only by-products being heat and water.[7] Because of its high energy content and clean-burning properties, hydrogen is being investigated for its potential to replace fossil fuels and reduce greenhouse gas[8] (GHG) emissions. Freeing hydrogen from its compound forms requires the application of energy, and it can take more energy to produce hydrogen than it provides "when it is converted to useful energy. However, hydrogen is useful as an energy source/fuel because it has a high energy [density]."[9]

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[1] Thomas Jefferson National Accelerator Facility, *The Element Hydrogen*, 2020, https://education.jlab.org/itselemental/ele001.html.

[2] Ibid.

[3] DOE, Office of Energy Efficiency and Renewable Energy, *Hydrogen: A Clean, Flexible Energy Carrier*, February 21, 2017, https://www.energy.gov/eere/articles/hydrogen-clean-flexible-energy-carrier.

[4] For conversion to U.S. units: 1 MJ/kg = 430 British thermal units per pound (Btu/lb).

[5] Futek Global Energy Technology-Japan, *Hydrogen Fuelled Electricity Generation*, 2020, http://www.futeklighting.net/images/Hydrogen%20Fuelled%20Electricity%20Generation.pdf.

[6] Energy density is the amount of energy stored in a given system, substance, or region of space per unit volume. It therefore has units of energy per length cubed or energy per mass. Arthur Golnik, "Energy Density of Gasoline," The Physics Factbook, 2003, https://hypertextbook.com/facts/2003/ArthurGolnik.shtml. (Energy density is a volume-based measurement. It is used colloquially to refer to energy per unit mass, however the appropriate tem for energy per unit mass is "specific energy.")

For example, the energy density of methane is 55.5 MJ/kg, natural gas is 47.2 MJ/kg, and gasoline is 45.8 MJ/kg. Dr. Jean-Paul Rodrigue, *The Geography of Transport Systems*, Department of Global Studies and Geography, Hofstra University, Energy Content of some Combustibles, 2020, https://transportgeography.org/?page_id=5837.

[7] Michelle Fung, "Energy Density of Hydrogen," The Physics Factbook, 2005, https://hypertextbook.com/facts/2005/MichelleFung.shtml.

[8] According to the Environmental Protection Agency (EPA), greenhouse gases are any gas that absorbs infrared radiation in the atmosphere. There are six greenhouse gases addressed by EPA regulatory actions: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases—sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). Carbon dioxide is the most prevalent GHG produced by combustion of fossil fuels. See https://www.epa.gov/ghgemissions/overview-greenhouse-gases.

[9] Energy Information Administration, "Hydrogen Explained," January 21, 2020, https://www.eia.gov/energyexplained/hydrogen/.

Interest in reducing GHG emissions from electric power generation to mitigate climate change risks has increased the focus on the potential use of hydrogen to produce electricity. While renewable energy technologies (e.g., wind and solar power) are seeing increased deployment at utility scale, these technologies are generally intermittent or variable in their production of electricity, and are often backed up by electricity generated from fossil fuels (primarily natural gas). While increased deployment of energy storage devices and better forecasting techniques may help renewable electricity to become power "on-demand" resources, the economics and deployment of grid battery storage resources are still developing.[10] In the meantime, GHG emissions from natural gas-fired generation are rising from increasing natural gas utilization for power generation.[11]

This report is focused on the current and potential sources of hydrogen, and several of the various technologies and processes for its economic production and use. Replacing fossil fuels with hydrogen for the generation of electricity may provide one potential avenue for reducing GHG emissions. However, hydrogen production and technologies to use hydrogen as a fuel for power generation currently present higher cost options, if the potential negative externalities[12] of carbon dioxide emissions are not considered.

Why Hydrogen Is Being Discussed for Electric Power

According to the U.S. Department of Energy's Energy Information Administration (EIA), natural gas is currently the fuel most used for electric power generation in the United States,[13] and it is expected to be the predominant fuel for the production of electricity well into the 2040s.

EIA projects that coal as a source of electricity generation will continue to decline in share until about 2025, when power generation from coal is expected to stabilize at about 13% of annual U.S. generation.[14] This is due to EIA's expectation that the remaining coal plants will be "more efficient and continue to operate throughout the projection period." EIA also projects renewable electricity will overtake natural gas in the 2040s to 2050s.[15] Given that renewable generation from wind and solar sources is intermittent and variable, to balance these changing levels of generation, fast ramping generation (capable of quickly increasing or decreasing output) is used that today is typically fueled by natural gas.

However, natural gas is a fossil fuel that when burned to produce electric power results in various air emissions including carbon dioxide. Natural gas combustion for power generation generally results in about half the carbon emissions produced by burning coal per unit of energy output or

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[10] CRS Report R45980, *Electricity Storage: Applications, Issues, and Technologies*, by Richard J. Campbell.

[11] EIA, "EIA Projects U.S. Energy-Related CO2 Emissions Will Remain Near Current Level Through 2050," March 20, 2019, https://www.eia.gov/todayinenergy/detail.php?id=38773.

[12] "With a negative externality, like pollution, the market tends to over produce the relevant commodity. Too much electricity is produced using coal because the buyers of that electricity do not face the full costs of their actions. If they did, they would buy less." Stephen King, *Global Warming, Externalities and Government Failure*, June 24, 2013, http://economicstudents.com/2013/06/global-warming-externalities-and-government-failure/.

[13] U.S. Energy Information Administration, "Electricity Explained—Electricity in the United States," March 20, 2020, https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php.

[14] EIA, *Annual Energy Outlook 2020*, Electricity, January 29, 2020, https://www.eia.gov/outlooks/aeo/pdf/AEO2020%20Electricity.pdf.

[15] Ibid.

heat content.[16] The technology and process used can vary in efficiency for power production (e.g., a natural gas-fired combined-cycle power plant vs. a simple cycle combustion turbine), resulting in carbon dioxide emissions varying "anywhere from 42% to 63% of the CO_2 emissions of coal, depending upon the power plant technology."[17] Despite the lower per-unit emissions, the growth in overall natural gas power generation has made it the top source of CO_2 emissions in the sector.

> [I]n 2015, natural gas emissions surpassed coal emissions, and the [Annual Energy Outlook (AEO)] AEO2019 Reference case projects that natural gas CO_2 emissions will continue increasing as natural gas use increases. The U.S. electric power sector—now the largest consuming sector for natural gas—has added generating capacity from natural gas in recent years and has used those power plants more often.[18]

EPA has identified transportation and electric power generation as the two main sources of U.S. GHG emissions resulting from human activities:[19]

- Transportation (28.2% of 2018 anthropogenic greenhouse gas emissions). The transportation sector generated the largest share of anthropogenic greenhouse gas emissions. Greenhouse gas emissions from transportation primarily come from burning fossil fuel for cars, trucks, ships, trains, and planes. Over 90% of the fuel used for transportation is petroleum based, primarily gasoline and diesel.
- Electricity production (26.9% of 2018 anthropogenic greenhouse gas emissions). The production of electricity generated the second largest share of anthropogenic greenhouse gas emissions. Approximately 63% of U.S. electricity comes from burning fossil fuels, mostly natural gas and coal.
- Industry (22.0% of 2018 anthropogenic greenhouse gas emissions). Greenhouse gas emissions from industry primarily come from burning fossil fuels for energy, as well as greenhouse gas emissions from certain chemical reactions necessary to produce goods from raw materials.
- Commercial and Residential (12.3% of 2018 anthropogenic greenhouse gas emissions). Greenhouse gas emissions from businesses and homes arise primarily from fossil fuels burned for heat, and from the handling of waste.

The percentages above do not add to 100%, with the remaining balance coming from other sources.

Mitigation of Climate Change Impacts

There is a policy debate regarding the extent to which GHG emissions are responsible for climate change. However, a general consensus exists among most climate change scientists that "climate change is occurring, and rigorous scientific research demonstrates that the greenhouse gases emitted by human activities are the primary driver."[20] The question of how to reduce those

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[16] EIA, "How Much Carbon Dioxide Is Produced When Different Fuels Are Burned?," March 17, 2020, https://www.eia.gov/tools/faqs/faq.php?id=73&t=11.

[17] CRS Report R44090, *Life-Cycle Greenhouse Gas Assessment of Coal and Natural Gas in the Power Sector*, by Richard K. Lattanzio.

[18] EIA, *EIA Projects U.S. Energy-Related CO_2 Emissions Will Remain near Current Level Through 2050*, March 20, 2019, https://www.eia.gov/todayinenergy/detail.php?id=38773.

[19] EPA, "Sources of Greenhouse Gas Emissions," April 11, 2020, https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

[20] National Aeronautics and Space Administration, "Scientific Consensus: Earth's Climate Is Warming," June 26, 2020,

emissions therefore arises. One report has suggested that GHG emissions from these sectors could be mitigated with "aggressive" energy efficiency targets.[21]

However, when potential climate impacts are considered, some in the electric utility industry and others advocate wider actions to achieve a greater reduction in carbon dioxide emissions.[22] While increasing renewable sources of electricity and switching to natural gas generation from coal has been a strategy that a number of electric utilities have followed, EIA reports that CO_2 emissions have increased recently with the increased production of electricity using natural gas.[23]

Hydrogen, when burned in the presence of oxygen, produces only water as a by-product.

> [Hydrogen] is highly flammable, needing only a small amount of energy to ignite and burn. Hydrogen burns cleanly. When it is burned with oxygen, the only by products are heat and water.[24]

If reducing or eliminating fossil fuel use is a goal for the electric power sector, then the expanded use of hydrogen due to its potential to decarbonize the sector could be an option. Combustion turbines capable of burning hydrogen could be utilized in order to increase power generation on a large scale, and could potentially replace natural gas-fired generation. However, there are technical and cost issues with how such a transition could be accomplished, and several of these issues are discussed later in this report.

Another potential option would be to increase hydrogen as an energy carrier via an energy storage application:

> The solution, some propose, is to store energy chemically—in the form of hydrogen fuel.… This involves using devices called electrolyzers that make use of renewable energy to split water into hydrogen and oxygen gas.… It's an efficient energy carrier, and can be easily stored in pressurized tanks. When needed, the gas can then be converted back into electrical energy via a fuel cell and fed into the grid.[25]

Methods and Sources for Producing Hydrogen

Generally, large reserves of hydrogen do not occur naturally on Earth, being found mostly in compound form with other elements in liquids, gases, or solids.[26] Hydrogen is also found in biological organisms, and as a result, can be found in biomass and fossil fuels that originated from biological sources. Hydrogen must therefore be extracted from these various sources using

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https://climate.nasa.gov/scientific-consensus/.

[21] The report from the American Council for an Energy Efficient Economy concludes that, if pursued aggressively, energy efficiency can reduce energy-related carbon emissions in the U.S. in 2050 by as much as 57% relative to current projections. Steven Nadel and Lowell Ungar, *Halfway There: Energy Efficiency Can Cut Energy Use and Greenhouse Gas Emissions in Half by 2050,* American Council for an Energy-Efficient Economy, September 2019, https://www.aceee.org/research-report/u1907.

[22] For example, see Southern Company, *Climate*, 2020, https://www.southerncompany.com/corporate-responsibility/environment/air-and-climate.html?msclkid=1776f9920500144e9c26a70fa9e28039.

[23] EIA, "EIA Projects U.S. Energy-Related CO2 Emissions Will Remain near Current Level Through 2050," March 20, 2019, https://www.eia.gov/todayinenergy/detail.php?id=38773.

[24] Michelle Fung, "Energy Density of Hydrogen," The Physics Factbook, 2005, https://hypertextbook.com/facts/2005/MichelleFung.shtml.

[25] Sandy Ong, *Redox-Flow Cell Stores Renewable Energy as Hydrogen*, IEEE Spectrum, April 13, 2020, https://spectrum.ieee.org/energywise/energy/renewables/storing-renewable-energy-hydrogen-redoxflow-cell.

[26] Jordan Hanania, James Jenden, and Kailyn Stenhouse, et al., "Hydrogen," Energy Education, January 8, 2017, https://energyeducation.ca/encyclopedia/Hydrogen.

appropriate technologies. Some refer to hydrogen produced from fossil fuels as "blue hydrogen," if the separated carbon is captured and sequestered, and "gray hydrogen" if it is not; and hydrogen produced from renewable processes as "green hydrogen." An increased use of hydrogen in the electric power sector for power generation would likely require an increased, more economical supply of hydrogen than possible with current processes. This section summarizes the current methods and sources of hydrogen production.

Fossil Fuel Sources

According to DOE, over 95% of U.S. hydrogen production comes from steam-methane reforming (SMR). In this process, natural gas (which is principally methane) reacts with high pressure, high temperature steam, in the presence of a catalyst to produce a mixture of mostly hydrogen and carbon monoxide (i.e., a synthetic natural gas[27] or "syngas"). Further processing reduces the carbon monoxide, and results in a gaseous stream that is mostly hydrogen.[28]

Coal, an organic hydrocarbon, is another potential source of hydrogen. Hydrogen can be obtained from coal through gasification and other methods. Gasification is accomplished in a high-temperature pressure vessel. Coal gasification refers to a process where oxygen (or air) and steam would directly contact the coal causing a series of chemical reactions to occur that convert the feedstock to syngas, with some ash/slag (mineral residues) resulting.[29] Coal gasification offers the capability for CO_2 to be separated from the gaseous stream, allowing it to be potentially sequestered (e.g., carbon capture and sequestration) or reused (e.g., carbon capture, utilization, or storage).[30]

Renewable Sources

Hydrogen can be produced from renewable processes in several ways. According to one article, these pathways include:[31]

- Electrolysis—splitting water molecules into their elemental components, using electricity from a range of renewable sources;
- Biomass conversion—via either thermochemical or biochemical conversion to intermediate products that can then be separated or reformed to hydrogen; or fermentation techniques that produce hydrogen directly; and
- Solar conversion—by either thermolysis,[32] using solar-generated heat for high temperature chemical cycle hydrogen production or photolysis, in which solar

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[27] "Synthetic natural gas (SNG): (Also referred to as substitute natural gas) A manufactured product, chemically similar in most respects to natural gas, resulting from the conversion or reforming of hydrocarbons that may easily be substituted for or interchanged with pipeline-quality natural gas." EIA, "Glossary," 2020, https://www.eia.gov/tools/glossary/index.php?id=S.

[28] DOE, Office of Energy Efficiency and Renewable Energy, *Hydrogen Production: Natural Gas Reforming*, 2020, https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming.

[29] National Energy Technology Laboratory, "Gasification Introduction," 2020, https://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/intro-to-gasification.

[30] CRS In Focus IF11501, *Carbon Capture Versus Direct Air Capture*, by Ashley J. Lawson.

[31] Dale Gardner, "Hydrogen Production from Renewables," Renewable Energy Focus, January 1, 2009, http://www.renewableenergyfocus.com/view/3157/hydrogen-production-from-renewables/.

[32] Thermal decomposition, or thermolysis, is the splitting of water at very high temperatures. Ibid.

> photons are used in biological or electrochemical systems to produce hydrogen directly.

The article stated that the order of the listing of the technologies is "in general, also representative of the technological maturity of these pathways, and thus roughly the chronological order in which we might expect to see them commercially available."[33] This perspective aligns with that of the Department of Energy's expected time frames for these technologies (see **Figure 1**).

Nuclear Power for Hydrogen Production

Nuclear power plants could also be used to produce hydrogen through electrolysis and other methods. According to the Department of Energy,

> Nuclear power plants can produce hydrogen in a variety of methods that would greatly reduce air emissions while taking advantage of the constant thermal energy and electricity it reliably provides. Existing nuclear plants could produce high quality steam at lower costs than natural gas boilers and could be used in many industrial processes, including steam-methane reforming. However, the case for nuclear becomes even more compelling when this high-quality steam is electrolyzed and split into pure hydrogen and oxygen. A single 1,000 megawatt [MW] nuclear reactor could produce more than 200,000 tonnes of hydrogen each year. Ten nuclear reactors could produce about 2 million tonnes annually or one-fifth of the current hydrogen used in the United States.[34]

Exelon Corporation plans to install a one MW electrolyzer to demonstrate hydrogen production at one of its nuclear power plants. The installation would be a part of the DOE's H2@Scale initiative, a program that is exploring the potential for wide-scale hydrogen production and utilization in the United States.[35]

Commercial Readiness

Figure 1 presents the Department of Energy's perspective on the timing of commercial-readiness and production scales associated with various hydrogen production technologies. These technologies are summarized in the following paragraphs. More detail on several of the methods discussed below is provided in the **Appendix**.

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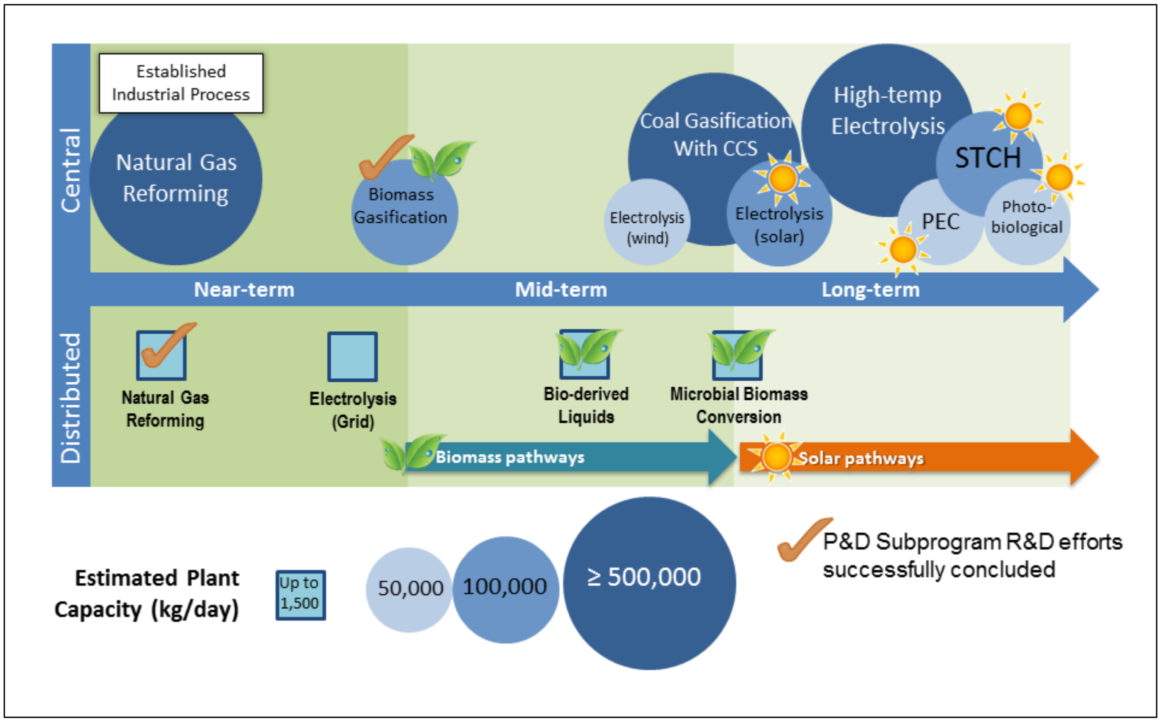
[33] Ibid.

[34] DOE, "Could Hydrogen Help Save Nuclear?," November 26, 2018, https://www.energy.gov/ne/articles/could-hydrogen-help-save-nuclear.

[35] S&P Global Market Intelligence, "Exelon Expects to Soon Name Nuclear Plant Getting Hydrogen Electrolyzer," June 9, 2020, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/exelon-expects-to-soon-name-nuclear-plant-getting-hydrogen-electrolyzer-58968111.

Figure 1. Hydrogen Production Technologies

Time frames and production scales



Source: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy at https://www.energy.gov/eere/fuelcells/hydrogen-production.

Notes: Solar thermochemical hydrogen (STCH); Photoelectrochemical (PEC); Carbon Capture and Sequestration (CCS); Production and Delivery (P&D); Research and Development (R&D).

Hydrogen for Large Scale Electric Power Generation

Hydrogen burned as a fuel could lower GHG emissions, since hydrogen combustion does not produce CO_2. The potential use of hydrogen as a fuel for electric power generation is based largely on its high energy density. According to DOE:

> Hydrogen has the highest energy per mass of any fuel; however, its low ambient temperature density results in a low energy per unit volume, therefore requiring the development of advanced storage methods that have potential for higher energy density…. On a mass basis, hydrogen has nearly three times the energy content of gasoline—120 [megajoules per kilogram (MJ/kg)][36] for hydrogen versus 44 MJ/kg for gasoline. On a volume basis, however, the situation is reversed; liquid hydrogen has a density of 8 [megajoules per liter (MJ/L)] whereas gasoline has a density of 32 MJ/L.[37]

Hydrogen has characteristics that may be useful as a power generation fuel, including its wide flammability limits (e.g., once a hydrogen stream is ignited, it is easy to maintain a hydrogen flame), a high spontaneous ignition temperature of 650° C (i.e., it needs a spark to ignite below

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[36] One megajoule per kilogram (MJ/kg) is approximately equivalent to 430 British thermal units per pound (Btu/lb).

[37] DOE, "Hydrogen Storage," 2020, https://www.energy.gov/eere/fuelcells/hydrogen-storage.

this temperature and so enhances safety), and the primary product of its combustion is water (as the hydrogen combines with oxygen to form H_2O) with little or no CO_2 emissions.[38]

Hydrogen-Fueled Combustion Turbines

Hydrogen has characteristics that make it an attractive choice as a fuel. However, shifting electric power generation from natural gas to hydrogen would likely require hundreds of billions of dollars of investment by the electric power industry.

Hydrogen's high flammability means that it burns at a high temperature that makes it unsuitable for use directly in the combustion turbines used to burn natural gas today. An article in 2019 addressed the question of what effect hydrogen would have on the furnace, flame, and exhaust in a natural gas combustion plant.[39] In addition to identifying several advantages of hydrogen, it cited several disadvantages as well:

- the higher flame speed, which increases the flame temperature locally, which can generate high levels of nitrogen oxides (NOx), pollutants which contribute to ozone formation (a precursor to smog);
- the wide flammability, which would require consideration in the safety assessments;
- hydrogen has a different Wobbe Index[40] than methane, which has to be taken into account in design; and
- hydrogen has a different combustion air requirement index (a measurement of the air required for a gas to ignite) compared to methane (and therefore would necessitate modifications to most combustion turbines to allow the use of hydrogen as a fuel).

Nevertheless, the article concluded that there "are many ways of accommodating high hydrogen fuel gases [e.g., fuel mixtures with a high proportion of hydrogen] whilst still keeping the flame cool enough to minimize [NOx] formation. The key is to slow down the rate at which the fuel and air mix."[41]

According to Bloomberg New Energy Finance (BNEF), since the 1990s, "there have been about 150 to 200 turbines globally that used gases with different amounts of hydrogen…. About 30 to 50 of the units likely operated with hydrogen making up more than 50% of the fuel volume."[42]

Another article in Power Engineering reported that today's natural gas-fired turbines would require modifications to the combustion elements to burn hydrogen. The compressor, turbine fans, and other auxiliary components would be expected to remain the same. However, due to the

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[38] Mike Menzies, *Hydrogen: The Burning Question*, September 23, 2019, https://www.thechemicalengineer.com/features/hydrogen-the-burning-question/.

[39] Ibid.

[40] "The Wobbe Index is a measure of the interchangeability of fuel gases and their relative ability to deliver energy. It gives an indication of whether a turbine or burner will be able to run on an alternative fuel source without tuning or physical modifications." Native Dynamics, "Wobbe Index," 2020, https://neutrium.net/properties/wobbe-index/.

[41] Mike Menzies, *Hydrogen: The Burning Question*, September 23, 2019, https://www.thechemicalengineer.com/features/hydrogen-the-burning-question/.

[42] Will Mathis and Akshat Rathi, "Green Hydrogen Could Price Gas Out of Power Markets by 2050," Bloomberg New Energy Finance, January 14, 2020, https://www.bloomberg.com/news/articles/2020-01-14/green-hydrogen-could-price-gas-out-of-power-markets-by-2050.

lower volumetric energy density of gaseous hydrogen, some piping and valves would have to be larger to accommodate the higher gas volumes necessary to produce the same energy content.[43]

One recent article estimates that replacing natural gas-fired power generation with hydrogen-fired power generation would require an investment of $637 billion by 2050 for hydrogen storage infrastructure alone to provide the same level of energy security.[44]

Some of the newer gas turbines currently in service may possibly be converted to burn a mixture of natural gas and hydrogen, while many older turbines may not be suitable for a retrofit.

> In the U.S., [Mitsubishi Hitachi Power Systems (MHPS)] recently was awarded a contract by Intermountain Power Agency to supply two of its M501JAC gas-fired turbines for a long-term hydrogen transition project in Utah. The M501JACs will utilize a 30-percent mix of hydrogen in only five years, with the long-term goal to burn 100 percent by 2045.[45]

Control of the flame temperature in combustion turbines burning a hydrogen-natural gas mixture is an issue that may need to be addressed to minimize NOx emissions. NOx control technologies are required for all fossil-fueled power generators, including natural gas-fired combustion turbines. However, current designs for hydrogen-fueled turbines "will emit the same NOx levels as natural gas-fired systems today, but will emit no sulfur dioxide, particulate matter, nor carbon dioxide and will only have a water byproduct."[46]

Advanced NOx emission technologies are being developed and deployed in new gas turbines.

> Using [dry low emissions (DLE)] burners, the flame temperature is controlled and kept the same. However, the more compact flame, near the burner tip, tends to raise NOx emission levels slightly. This latter can most likely be improved by tuning of the burner design but also mitigated by secondary NOx emission control systems.[47]

Fuel Cells for Hydrogen Power

Fuel cells use the chemical energy of hydrogen or another fuel "to cleanly and efficiently produce electricity."[48] If the fuel cell uses hydrogen as the fuel, "electricity, water, and heat are the only products." DOE states that fuel cells "can provide power for systems as large as a utility power station and as small as a laptop computer."[49]

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[43] Rod Walton, "Just What Goes into Converting a Gas-Fired Turbine to Hydrogen? The MHPS Perspective on Carbon-Free Thermal Power," *Power Engineering*, March 12, 2020, https://www.power-eng.com/2020/03/12/just-what-goes-into-converting-a-gas-fired-turbine-to-hydrogen-the-mhps-perspective-on-carbon-free-thermal-power/.

[44] "Hydrogen Economy Outlook," Bloomberg New Energy Finance, March 30, 2020, https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf.

[45] Rod Walton, "Hydrogen-Fired Power Promises Carbon-Free Future but Requires Nearly $800B Investment," *Power Engineering*, March 30, 2020, https://www.power-eng.com/2020/03/30/hydrogen-fired-power-promises-carbon-free-future-but-requires-nearly-800b-investment/.

[46] Rod Walton, "Just What Goes into Converting a Gas-Fired Turbine to Hydrogen? The MHPS Perspective on Carbon-Free Thermal Power," *Power Engineering*, March 12, 2020, https://www.power-eng.com/2020/03/12/just-what-goes-into-converting-a-gas-fired-turbine-to-hydrogen-the-mhps-perspective-on-carbon-free-thermal-power/.

[47] Gas Turbine World, "Working Toward 100% Hydrogen," March 20, 2020, https://gasturbineworld.com/working-toward-100-percent-hydrogen/.

[48] DOE, Energy Efficiency and Renewable Energy-Fuel Cell Technologies Office, "Fuel Cells," 2020, https://www.energy.gov/eere/fuelcells/fuel-cells.

[49] Ibid.

Fuel cells are classified according to the type of electrolyte they use, and are designed to meet different operating requirements. Fuel cells do not burn their fuel, but use an efficient electrochemical reaction to produce electricity.

> Fuel cells can operate at higher efficiencies than combustion engines, and can convert the chemical energy in the fuel to electrical energy with efficiencies of up to 60% [compared to existing fossil power plants with efficiencies about 40%]. Fuel cells have lower emissions than combustion engines. Hydrogen fuel cells emit only water, so there are no carbon dioxide emissions and no air pollutants that create smog and cause health problems at the point of operation.[50]

While fuel cells were first used in mostly niche applications, electric utilities are increasing their deployment of fuel cells.

> More homes, businesses and utilities are turning to fuel-cells to meet their power generation needs. Installing groups of modular fuel-cell systems to create small power plants ranging from 5 MW to 63 MW in size is a growing market…. In addition, fuel cells, which use hydrogen and oxygen to generate electricity, have no moving parts, making them inherently quiet and ideal for use in urban settings where the power is actually consumed. This limits the need for transmission and distribution lines, thus reducing the risk of power outages caused by ice storms and heavy winds…. Fuel cells are not a new technology. They have been long associated with the NASA space program and transportation vehicles. In recent years, though, the applications and markets for fuel cells have expanded. Fuel cells are being used for primary power, backup power, emergency power, and auxiliary power. They are used to power hotels, hospitals, universities, and data centers.[51]

Several large-scale fuel-cell power plants have been built in Connecticut, Delaware, and California.[52]

Energy Carrier to Fuel

Using an electrolyzer, hydrogen can be produced directly from water. Assuming GHG emissions are a consideration, the power for the process would be produced using low carbon or carbon-free energy such as wind, solar photovoltaic (PV), or nuclear power, and the hydrogen produced could be stored until a time of day when higher prices of electricity would favor the conversion of that hydrogen back to electricity. This has been described as the arbitrage opportunity for energy storage.[53] Electricity demand and production varies during the day, and the opportunity exists to store energy during low demand periods and use it during high demand periods. Electrolyzers can be used to supplement power generation at peak periods to avoid the need to build additional generation capabilities. Using this cycle, both hydrogen and electricity would be produced free of

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[50] Ibid.

[51] Russell Ray, "Fuel Cells to Play Important Role in Power Generation," Power Engineering, February 15, 2016, https://www.power-eng.com/2016/02/15/fuel-cells-to-play-important-role-in-power-generation/.

[52] Jeff St. John, "Bloom Energy and Power Secure Land Country's Biggest Fuel Cell Deployment to Date," Greentech Media, August 16, 2017, https://www.greentechmedia.com/articles/read/bloom-energy-and-powersecure-land-countrys-biggest-fuel-cell-deployment-to.

[53] "An arbitrage opportunity … exists under some circumstances to take advantage of power storage in regulatory regimes that attach value to such opportunities. Under such a scenario, electricity can be purchased from the grid and stored during times of lower demand. An energy storage system can be charged at this time so that the stored energy can be used or sold at another time when the price or costs are higher. Alternatively, energy storage can provide the opportunity to store excess energy production that may otherwise be curtailed from renewable sources such as wind or solar PV." See CRS Report R45980, *Electricity Storage: Applications, Issues, and Technologies*, by Richard J. Campbell.

GHG emissions. Producing and taking advantage of hydrogen for energy storage is the first step to taking advantage of the arbitrage opportunity. The second step is to use hydrogen to generate power, in this case using a fuel cell, to send power back to the grid. At present, two different devices are needed for the electrolyzer and power generation processes.[54]

Estimates of the Cost of Producing Hydrogen

Since hydrogen gas does not occur naturally in abundance on the Earth, it has to be produced from other hydrogen-containing compounds. **Table 1** summarizes recent estimates of the cost of producing hydrogen using selected technologies, and the estimated efficiencies of the selected processes are also summarized. The table shows how the efficiency of the steam reforming process using a low cost natural gas feedstock is a key factor in achieving the low cost of hydrogen production.

A report from BNEF in 2020 considered how to bring down the cost of producing hydrogen from renewable sources.[55] BNEF estimates the current cost of producing renewable hydrogen in 2018 dollars at about $2.50 to $4.50 per kg (or approximately $18.60 to $33.50 per million BTUs). This compares to BNEF's estimate of fossil fuel-derived hydrogen of $1.00 to $1.75 per kg (equating to approximately $7.40 to $13 per million BTUs).

By comparison, the per BTU price of hydrogen is much higher than the per BTU price of natural gas (currently below $2 per million in several markets). This cost difference presents a long-term challenge to the use of hydrogen as a substitute for natural gas.[56] BNEF's report suggested that one approach to addressing this challenge would be a tax on carbon emissions.[57] The report suggested a carbon price of $55 per ton of carbon dioxide by 2050, equating to a price of natural gas at least $6.50 per million BTU. BNEF estimates that by 2050, renewable hydrogen could be produced at prices between $0.80 to $1.60 per kg, if such policies were in place.[58]

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[54] "[C]ommercial electrolyzers and fuel cells use different catalysts to speed up the two reactions, meaning a single device can't do both jobs. To get around this, researchers have been experimenting with a newer type of fuel cell, called a proton conducting fuel cell (PCFC), which can make fuel or convert it back into electricity using just one set of catalysts." Robert F. Service, "New Fuel Cell Could Help Fix the Renewable Energy Storage Problem," *Science*, March 12, 2019, https://www.sciencemag.org/news/2019/03/new-fuel-cell-could-help-fix-renewable-energy-storage-problem.

[55] Will Mathis and Akshat Rathi, "Green Hydrogen Could Price Gas Out of Power Markets by 2050," Bloomberg New Energy Finance, January 14, 2020, https://www.bloomberg.com/news/articles/2020-01-14/green-hydrogen-could-price-gas-out-of-power-markets-by-2050.

[56] EIA, "Natural Gas Weekly Update," April 15, 2020, https://www.eia.gov/naturalgas/weekly/.

[57] Will Mathis and Akshat Rathi, "Green Hydrogen Could Price Gas Out of Power Markets by 2050," Bloomberg New Energy Finance, January 14, 2020, https://www.bloomberg.com/news/articles/2020-01-14/green-hydrogen-could-price-gas-out-of-power-markets-by-2050.

[58] Rod Walton, "Hydrogen-fired Power Promises Carbon-Free Future but Requires Nearly $800B Investment," *Power Engineering*, March 30, 2020, https://www.power-eng.com/2020/03/30/hydrogen-fired-power-promises-carbon-free-future-but-requires-nearly-800b-investment/.

Table 1. Selected Hydrogen Production Methods

Selected Factors for Comparison

Hydrogen Production Method	Feedstock Considered	Advantages	Disadvantages	Estimate of Process Efficiency (%)	Estimated Cost of H_2 (2018) $/kg
Steam Reforming	Natural Gas	Developed technology and existing infrastructure.	CO, CO_2 produced. Price volatility of natural gas can lead to feedstock supply issue.	74–85	1.80-2.27
Partial Oxidation	Petroleum coke	Established technology.	Along with H_2 production, heavy oils and soot can result depending on feedstock used.	60–75	1.48
Gasification	Coal or Biomass	Abundant, cheap feedstock.	Fluctuating H_2 yields due to feedstock impurities, and seasonal biomass availability. Formation of tar.	30–40	1.63–2.05
Pyrolysis	Biomass	Abundant, cheap feedstock.	Tar formation. Fluctuating H_2 yields because of feedstock impurities and seasonal availability.	35–50	1.59–1.70
Electrolysis	Water	Established technology Zero emissions. Existing infrastructure. O_2 as a byproduct.	Storage and transportation issues.	60–80	7.50-10.30

Source: CRS. Adapted from S. Shiva Kumar and V. Himabindu, "Hydrogen Production by PEM Water Electrolysis—A Review," Materials Science for Energy Technologies, vol. 2, no. 3 (December 2019), pp. 442-454, and Abdalla M.Abdalla, Shahzad Hossein, and Ozzan B. Nisfindy, et al., "Hydrogen Production,Storage, Transportation and Key Challenges with Applications: A Review," *Energy Conversion and Management*, vol. 165 (July 1, 2018), pp. 602-627. Will Mathis and Akshat Rathi, "Big Oil's Long Bet on Hydrogen Offers a Climate Lifeline," Bloomberg New Energy Finance, June 25, 2020, https://www.bloomberg.com/news/articles/2020-06-25/big-oil-s-long-bet-on-hydrogen-offers-a-climate-lifeline.

Notes: Cost is given per unit of mass (in kilograms (kg)) as of 2018. CO = Carbon monoxide. CO_2 = Carbon dioxide. H_2 = Hydrogen (molecular). O_2 = Oxygen (molecular). Efficiency estimates are from the Faradaic efficiency, defined as the ratio between experimentally evolved volume of gas value (hydrogen or oxygen) and theoretically calculated volume of gas value.

Further Electrifying the U.S. Economy

As of 2018, the transportation sector surpassed the power generation sector as the main source of U.S. GHG emissions.[59] If reducing GHG emissions is a goal for Congress, then Congress may consider measures focused on fossil fuel use in both sectors, as well as in the industrial sector. A transition from internal combustion engines in transportation to all-electric or fuel cell vehicles could contribute to further electrification of U.S. transportation. Such a transition may take into account the different ways that transportation and industry use fossil fuels, and consider what applications could economically and efficiently substitute electricity-based technologies for fossil fuels.

NREL's Electrification Futures Study

In 2017, the National Renewable Energy Laboratory (NREL) issued the first part in its Electrification Futures Study (EFS), which was intended to "develop and assess electrification scenarios designed to quantify potential energy, economic, and environmental impacts to the U.S. power system and broader economy."[60] This first report was focused on estimated cost and performance data for end-use technologies for the transportation, residential, and commercial buildings sectors through 2050.[61]

In 2018, NREL issued the second report from the study, and focused on how the potential for electrification might impact the demand side of the U.S. energy system. The report presented scenarios with various degrees of future electrification in all major end-use sectors of the U.S. energy system and quantifies impacts on the amount and shape of electricity demand.[62] The scenarios reflected electricity demand growth ranges through 2050 that resulted from "various electric technology adoption and efficiency projections in the transportation, residential and commercial buildings, and industrial sectors."[63]

Among the conclusions reached by the report (with emphasis added):

> The transportation sector experiences the greatest technology transition toward electric vehicles in the scenarios from this study…. These estimates foresee ranges of stock penetrations of plug-in electric vehicles in the 2050 light-duty fleet from roughly 11% in the Reference scenario to nearly 84% in the High scenario…. **This expansion is most pervasive in the High scenario, which is designed to include plug-in electric vehicle sales shares beyond many existing studies and where over 240 million light-duty electric cars and trucks, 7 million medium- and heavy-duty electric trucks, and 80,000**

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[59] EPA, "Sources of Greenhouse Gas Emissions," 2020, https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

[60] National Renewable Energy Laboratory, *Electrification Futures Study*, 2020, https://www.nrel.gov/analysis/electrification-futures.html.

[61] "These projections will be used in future EFS reports to present a range in comparative electricity use and cost across electrification scenarios, highlighting the uncertainty inherent in such values…. These costs can appropriately be used as rough initial approximations for the types of cost, the relative costs among options, and the order of magnitude of costs of end-use electrification." Paige Jadun, Colin McMillan, and Daniel Steinberg, et al., *Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections Through 2050,* National Renewable Energy Laboratory, 2017, https://www.nrel.gov/docs/fy18osti/70485.pdf.

[62] However, for this analysis, NREL focused only on direct electric technologies and the impacts of electrification: "[W]e make no attempt to compare a broader suite of technology or fuel (e.g., hydrogen- or biomass-based) options...." Trieu Mai, Paige Jadun, and Jeffrey Logan, et al., *Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States*, National Renewable Energy Laboratory, 2018, https://www.nrel.gov/docs/fy18osti/71500.pdf.

[63] Ibid.

electric transit buses are estimated to be on U.S. roads by 2050. For comparison, there were about 560,000 plug-in electric vehicles on U.S. roads by the end of 2016.…

The buildings and industrial sectors generally see less potential for transformational change nationwide, but electrification in these sectors could acutely affect certain regions and end uses. Still, a significant increase in building appliance manufacturing and adoption would be needed in our scenarios as the electric devices are found to provide up to 61% of space heating, 52% of water heating, and 94% of cooking services in the combined commercial and residential sectors by 2050 in the High scenario, compared with 17%, 26%, and 34%, respectively, in the Reference scenario.…

Electrification has the potential to significantly increase overall demand for electricity, although even in the High scenario, compound annual electricity consumption growth rates are below long-term historical growth rates. The Reference scenario has the most limited impacts from electrification, but continued growth in both population and the U.S. economy leads to a compound annual growth rate (from 2016 to 2050) in electricity demand of 0.65% and 4,722 terawatt-hours (TWh) of total consumption by 2050. In the Medium and High scenarios, total 2050 electricity demand is estimated to be 934 TWh (20%) and 1,782 TWh (38%) greater, respectively, than in the Reference. Compound annual growth rates are found to be 1.2% and 1.6% in these scenarios, respectively. These growth rates are well below the historical rate from 1950 to 2016 (4% per year), and fall below the 1.8% per year growth rate observed over the same duration (34 years, 1982–2016) as the study future period. **However, comparing absolute year-to-year changes in consumption (rather than compound annual growth rates) in the scenarios shows how widespread electrification can lead to historically unprecedented growth.** In the High scenario, the average increase (during 2016–2050) in annual electricity consumption is about 80 TWh per year, compared with 50 to 55 TWh per year over the prior 34 years. The vast majority of this increase occurs in the transportation sector. Building electrification leads to more-limited incremental growth in annual electricity consumption in part because of the high efficiency of heat pumps and their partial displacement of inefficient electric resistance heaters.…

In addition to growth in annual electricity consumption—driven to a large degree by greater adoption of plug-in electric vehicles—electrification has the potential to significantly shift load shapes, particularly due to increased reliance on electric heat pumps for space and water heating needs…. In 2015, all states excluding those in or near the Pacific Northwest are estimated to be primarily summer peaking, with a majority of the top 100 load hours falling in June, July, or August. Under the Medium and High electrification scenarios, growth in winter electricity consumption outpaces consumption in non-winter months in many regions, in large part because of greater adoption of electric air source heat pumps in the Midwest and Northeast regions, which have colder climates. Along with the shift in when peak demand occurs, the size of the peak also increases. The aggregate and coincident peak national hourly demand in 2050 is estimated to be 19% and 33% greater in the Medium and High scenario, respectively, than in the Reference scenario, where peak demand is estimated to reach 838 gigawatts (GW) in 2050…. **How electrification impacts load shape [i.e., hourly and seasonal demand] could have significant impact on electric utility planning, grid operations, reliability assessments, and electricity markets**.…

Widespread end-use electric technology adoption would result in substantial shifts in fuel, electricity, and total energy consumption. In 2050, electricity's share (of total final energy) increases to 32% in the Medium and 41% in the High scenario—significantly above the 23% in the Reference scenario and 19% in 2016…. The impacts to electricity share vary significantly by sector, with the largest growth found in transportation for the Medium and High scenarios and the least change occurring in industry. Consistent with observed trends since 1950 the buildings sectors remain the most electrified in all scenarios and with growing electricity shares of final energy. For example, the commercial buildings sector is

> nearly 75% electric under the High scenario. Electrification would also lead to reduced use of gasoline, diesel, and natural gas fuel. Demand-side fuel use reductions of 74% gasoline, 35% diesel, and 37% natural gas in 2050 are found in the High scenario, relative to the Reference. **It is possible that some of the reduced on-site natural gas use would be offset by greater gas-fired generation.**[64]

One possible assessment that may reasonably be made from the report is that electrification would increase demand for electricity, and natural gas use would likely increase. If no changes in environmental regulations occur in the timeframe to 2050, then it would be reasonable to follow EIA's reference projections (discussed earlier in this report) that natural gas and renewable sources would be the major generation sources by that time. NREL's study does not directly address the potential for climate change to drive electrification, instead positing environmental benefits as one of several purposes for the study:

> A second motivation for exploring electrification is the potential externality benefits of electrification, including security and environmental benefits. As electricity relies almost entirely on domestic generators and fuels in the contiguous United States, electrification may increase energy security. Recent studies also identify electrification as [a] key component of pathways to reducing greenhouse gas emissions. A related benefit is the overall higher energy efficiency of electric technologies, which could—all else being equal—reduce the negative impacts of energy use. However, the efficiency and environmental benefits of electrification ultimately depend on sources used to generate electricity.[65]

Challenges Associated with Hydrogen for Power

When hydrogen is discussed as a fuel for power generation, the technical challenges for its use generally are focused on two areas: the storage of hydrogen and the transportation of hydrogen. Due to its small molecular size, hydrogen gas is difficult to contain, which makes its storage or transportation more challenging. In addition, at room temperature and standard atmospheric pressure, hydrogen has low energy density per volume. Storing hydrogen requires the input of external energy to cool or compress the gas.

Transportation of Hydrogen

According to DOE, the existing hydrogen gas pipeline network provides a low-cost option for delivering large volumes of hydrogen.[66]

> Approximately 1,600 miles of hydrogen pipelines are currently operating in the United States. Owned by merchant hydrogen producers, these pipelines are located where large hydrogen users, such as petroleum refineries and chemical plants, are concentrated such as the Gulf Coast region.[67]

Beyond the initial high capital costs associated with pipeline construction, expanding the network of pipelines for hydrogen transportation presents unique technical barriers. DOE states that ongoing research is focusing on overcoming issues such as:

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[64] Ibid.

[65] Ibid.

[66] DOE-EERE, Office of Fuel Cell Technologies, "Hydrogen Pipelines," 2020, https://www.energy.gov/eere/fuelcells/hydrogen-pipelines.

[67] Ibid.

- the potential for hydrogen to embrittle the steel and welds used to fabricate the pipelines;
- the need to control the potential for hydrogen permeation[68] and leaks; and
- the need for lower cost, more reliable, and more durable hydrogen compression technology.[69]

DOE is investigating potential methods to address these issues, including the use of fiber reinforced polymer (FRP) pipelines for hydrogen distribution.[70] DOE estimates that the "installation costs for FRP pipelines are about 20% less than that of steel pipelines because the FRP can be obtained in sections that are much longer than steel, minimizing welding requirements."[71]

Adapting the natural gas delivery infrastructure to accommodate hydrogen may be another option, with natural gas pipelines prospectively carrying a blend of natural gas and hydrogen (e.g., up to about 15% hydrogen content). DOE expects that converting existing natural gas pipelines to deliver 100% hydrogen would likely require "more substantial modifications."[72]

Other existing elements on pipeline systems, such as compressors for long distance transmission and pressure reduction stations, may also be examined for the potential for leaks or "material integrity concerns."[73]

Hydrogen Storage

Hydrogen can be stored as either a gas or a liquid.

> Storage of hydrogen as a gas typically requires high-pressure tanks (350–700 bar [5,000–10,000 (pounds per square inch) psi] tank pressure). Storage of hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is −252.8 °C.[74]

Storing hydrogen therefore requires the input of energy to compress the gas. For electric power generation purposes, storage can potentially be accomplished in a large pressure vessel or a cavern. "Very large amounts of hydrogen can be stored in constructed underground salt caverns of up to 500,000 cubic meters at 2,900 psi, which would mean about 100 Gigawatt-hours (GWh) of stored electricity."[75]

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[68] "Hydrogen permeation is the diffusion of hydrogen ions through the thin metal isolation diaphragms used in pressure transmitters either through interstitial or substitutional (vacancy) mechanisms." Yokogawa Corporation of America, *Hydrogen Permeation*, 2018, https://www.yokogawa.com/us/library/resources/application-notes/hydrogen-permeation/.

[69] DOE-EERE, Office of Fuel Cell Technologies, "Hydrogen Pipelines," 2020, https://www.energy.gov/eere/fuelcells/hydrogen-pipelines.

[70] Ibid.

[71] Ibid.

[72] Ibid.

[73] Paul E.Dodds and Stéphanie Demoullin, "Conversion of the UK Gas System to Transport Hydrogen," *International Journal of Hydrogen Energy*, March 2, 2013, https://www.sciencedirect.com/science/article/pii/S0360319913006800.

[74] DOE-EERE, Office of Fuel Cell Technologies, *Hydrogen Storage*, 2020, https://www.energy.gov/eere/fuelcells/hydrogen-storage.

[75] Energy Storage Association, *Hydrogen Energy Storage*, 2020, https://energystorage.org/why-energy-storage/technologies/hydrogen-energy-storage/.

DOE further states that "[a] national hydrogen infrastructure could require geologic (underground) bulk storage to handle variations in demand throughout the year. In some regions, naturally occurring geologic formations, such as salt caverns and aquifer structures, might be used, while in other regions, specially engineered rock caverns are a possibility."[76]

Bulk storage of natural gas in salt caverns is a common practice, and there are four existing salt caverns used for hydrogen storage today.[77]

Estimate of the Cost of Hydrogen Storage and Transportation

Developing a system to transport and store hydrogen could entail substantial costs, whether for a completely new system or a gradually upgraded and modified system.

According to a report from BNEF, to develop a system for hydrogen storage and transportation to provide the same utility as the natural gas system that currently exists, "a huge, coordinated program of infrastructure upgrades and construction would be needed. For instance, 3-4 times more storage infrastructure would need to be built at a cost of $637 billion by 2050 to provide the same level of energy security as natural gas."[78]

Natural Gas Decarbonization On-Site

An article in 2018 looked at potential economic models for decarbonizing natural gas delivered to a power plant or industrial facility, and producing a syngas.[79] Under the scenarios presented in the article, facilities (e.g., potentially power plants) receive natural gas from the natural gas pipeline system and "transform it locally into hydrogen, capturing carbon, and eliminating the need for hydrogen transport and storage, as natural gas is the energy carrier vector."[80]

> The direct application of natural gas decarbonization to carbon capture [can be accomplished] in a natural gas combined cycle…. [N]atural gas enters a pyrolysis reactor operating at 1,200 °C achieving a molar conversion of methane into hydrogen close to 80%. The gas output from the reactor is a mixture of hydrogen and natural gas, which is almost 50/50 in weight.[81]

The author estimated that such a decarbonization and capture process would consume "[a]lmost 40% of the initial energy content of natural gas." A main benefit of the process is that the carbon emissions from natural gas combustion are avoided, and would avoid "the energy required for its further sequestration or reduction for CO_2 utilization."[82]

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[76] DOE-EERE, Office of Fuel Cell Technologies, "On-Site and Bulk Hydrogen Storage," 2020, https://www.energy.gov/eere/fuelcells/site-and-bulk-hydrogen-storage.

[77] Ibid.

[78] BNEF, "'Hydrogen Economy' Offers Promising Path to Decarbonization," March 30, 2020, https://about.bnef.com/blog/hydrogen-economy-offers-promising-path-to-decarbonization/.

[79] Alberto Abánades, "Natural Gas Decarbonization as Tool for Greenhouse Gases Emission Control," *Frontiers in Energy Research*, June 19, 2018, https://www.frontiersin.org/articles/10.3389/fenrg.2018.00047/full.

[80] Ibid.

[81] Ibid.

[82] Ibid.

Recent Legislation

A number of bills have been introduced in the 116th Congress proposing federal support for hydrogen transportation infrastructure. Several other bills addressed hydrogen for (smaller scale) energy storage applications. Also, a number of bills have been introduced that consider a goal of 100% renewable energy for electricity. However, these bills do not focus on hydrogen as a fuel for electric power generation. Accordingly, these bills are not included in this summary.

Bills in the 116th Congress

Several bills have been introduced that would provide tax credits for carbon capture. However, it may be unclear whether most of these would support hydrogen production. To the extent that a carbon capture facility uses a syngas process, a potential pathway could exist for such a facility to produce hydrogen gas. Two bills that explicitly include syngas processes are summarized below.

The Carbon Capture Improvement Act of 2019 (S. 1763), introduced in June 2019, would authorize the issuance of tax-exempt facility bonds for the financing of qualified carbon dioxide capture facilities. Carbon dioxide capture facilities in the bill would generally include any facility capturing carbon dioxide emissions from fuel combustion, gasification, bioindustrial, and fermentation processes, with certain exceptions.

The Carbon Capture Improvement Act of 2019 (H.R. 3861), introduced in July 2019, is a companion bill to S. 1763.

Issues for Congress

An analysis by the U.S. Global Change Research Program completed in November 2018 found that if GHG emissions continued at forecast rates and adaptation actions were not undertaken, climate change impacts would damage U.S. infrastructure, communities, and the economy.[83] With growing amounts of today's electricity coming from (generally GHG emissions-free) renewable sources, some stakeholders advocate a shift of U.S. national electric power generation to come from sources that do not emit carbon dioxide. However, natural gas for power generation is expected to increase, and fossil fuel-fired power often fills in for the variable generation from renewables.

If Congress chooses to pursue further GHG emissions reduction, then addressing carbon dioxide emissions from natural gas may be an option. Removing carbon from natural gas or replacing natural gas for electric power generation may not be easy or inexpensive, and if achieved, would likely be accomplished in a phased approach over several decades. Alternatively, Congress may examine how to lower the costs of producing and using hydrogen for power generation. In addition, Congress may consider how to address the unrealized negative externalities of carbon dioxide emissions, with a tax or some other limit on CO_2 emissions as a potential option.[84]

Congress may consider further research, development, demonstration, and deployment of electric power generation facilities that use hydrogen as a primary fuel, avenues for the transportation of hydrogen to power plants, and methodologies for the economic conversion of natural gas to

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[83] U.S. Global Change Research Program, *Fourth National Climate Assessment*, November 2018, https://nca2018.globalchange.gov/. See also CRS Insight IN11065, *An Electric Grid Based on 100% Renewable Energy?*, by Richard J. Campbell.

[84] CRS Report R45625, *Attaching a Price to Greenhouse Gas Emissions with a Carbon Tax or Emissions Fee: Considerations and Potential Impacts*, by Jonathan L. Ramseur and Jane A. Leggett.

hydrogen on-site at power plants. Congress may also consider avenues to accelerate a transition to hydrogen for electric power plants and infrastructure, using tax incentives or credits for such purposes.

Appendix. Sources of Hydrogen

Natural Gas Reforming

With steam-methane reforming (SMR), natural gas (which is principally methane) under pressure (3–25 bar),[85] reacts with high temperature steam (700°C–1,000°C) in the presence of a catalyst in the first part of a two-stage process. In the second stage, the gas mixture is passed through a water-gas shift reactor[86] with steam and a catalyst. This converts most of the carbon monoxide to carbon dioxide, and produces more hydrogen. Carbon dioxide and other impurities are removed from the resulting gas stream to leave mostly pure hydrogen.[87] The SMR process also can be used with other hydrocarbon fuels (e.g., ethanol, propane, gasoline) to produce hydrogen.[88]

Coal/Biomass Gasification

Coal is an organic hydrocarbon that can be used as a hydrogen source using gasification to extract the hydrogen.

> Specifically, hydrogen is produced by first reacting coal with oxygen and steam under high pressures and temperatures to form synthesis gas, a mixture consisting primarily of carbon monoxide and hydrogen. After the impurities are removed from the synthesis gas, the carbon monoxide in the gas mixture is reacted with steam through the water-gas shift reaction to produce additional hydrogen and carbon dioxide. Hydrogen is removed by a separation system, and the highly concentrated carbon dioxide stream can subsequently be captured and stored.[89]

Gasification would be accomplished in a gasifier, which is generally a high-temperature pressure vessel. Oxygen (or air) and steam would directly contact the coal causing a series of chemical reactions to occur that convert the feed to syngas, and ash/slag (mineral residues).[90]

Other feedstocks (such as forest or crop residues, and dedicated biomass crops) could potentially be gasified. However, each feedstock has its own challenges with respect to availability, and the degree of formation of undesirable materials (e.g., tars, CO and CO_2) that can impact production efficiency and facility maintenance.[91]

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[85] One bar = 14.5 pounds per square inch, or atmospheric pressure at sea level.

[86] The water-gas shift reactor converts the carbon monoxide present in syngas into carbon dioxide and generates more hydrogen.

[87] Air Liquide, *Steam Methane Reforming—Hydrogen Production*, 2020, https://www.engineering-airliquide.com/steam-methane-reforming-hydrogen-production.

[88] DOE, Office of Energy Efficiency and Renewable Energy, "Hydrogen Production: Natural Gas Reforming," 2020, https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming.

[89] DOE, Office of Energy Efficiency and Renewable Energy, "Hydrogen Production: Coal Gasification," 2020, https://www.energy.gov/eere/fuelcells/hydrogen-production-coal-gasification.

[90] National Energy Technology Laboratory, "Gasification Introduction," 2020, https://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/intro-to-gasification.

[91] DOE- Office of Fossil Energy, "Gasification Systems," 2020, https://www.energy.gov/fe/science-innovation/clean-coal-research/gasification.

Electrolysis of Water

Hydrogen can be produced directly from water. This can be accomplished using electrolysis, which involves passing an electrical current between positive and negative electrodes through water (containing various catalysts). Electrolysis breaks the chemical bonds present in the liquid water molecule, separating the hydrogen and oxygen atoms into individual gases.[92]

> The electrolysis process takes place at room temperature. A commonly used electrolyte in water electrolysis is sulfuric acid, and the electrodes are of platinum (Pt), which does not react with sulfuric acid. The process is ecologically clean because no greenhouse gases are formed, and the oxygen produced has further industrial applications. However, in comparison with the foregoing methods described, electrolysis is a highly energy-demanding technology.[93]

According to one article,[94] there are four main methods for electrolysis of water to produce hydrogen:

- Alkaline water electrolysis takes advantage of free ions in alkaline[95] water to conduct electricity for electrolysis to occur. Alkaline electrolyzers contain a water solution containing approximately 25% to 30% potassium hydroxide. Several megawatt industrial electrolyzers are used in industry for large-scale production of hydrogen.
- Solid oxide electrolyzer cells use a solid oxide fuel cell that achieves the electrolysis of water by using a solid oxide, or ceramic, electrolyte to produce primarily hydrogen gas and oxygen.
- Microbial electrolysis cells (MECs) use bacteria that thrive in an electrochemical environment to break down organic matter. When aided by the addition of a low voltage, MECs can produce hydrogen gas.
- Proton exchange membrane (PEM) water electrolysis uses a polymer electrolyte in the form of a thin, permeable sheet, and a platinum catalyst. In PEM water electrolysis, water is electrochemically split into hydrogen and oxygen at the respective electrodes (i.e., hydrogen at the cathode and oxygen at the anode).

Other Processes

Several other processes can be used to produce hydrogen from various fuel stock sources. These processes are either recently developed or are reported to be less productive in terms of the volumes of hydrogen produced. They include:

- Partial Oxidation. The process of partial oxidation reacts the methane and other hydrocarbons in natural gas with a limited amount of oxygen (typically from air) that is

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[92] Christos M. Kalamara and Angelos M. Efstathiou, *Hydrogen Production Technologies: Current State and Future Developments*, Hindawi, https://www.hindawi.com/journals/cpis/2013/690627/.

[93] Ibid.

[94] S. Shiva Kumar and V. Himabindu, "Hydrogen Production by PEM Water Electrolysis—A Review," *Materials Science for Energy Technologies*, December 2019, pp. 442-454, https://www.sciencedirect.com/science/article/pii/S2589299119300035#b0210.

[95] "The "alkaline" in alkaline water refers to its pH level. The pH level is a number that measures how acidic or alkaline a substance is on a scale of 0 to 14. For example, something with a pH of 1 would be very acidic and something with a pH of 13 would be very alkaline." See Healthline, "What Is Alkaline Water?," 2020, https://www.healthline.com/health/food-nutrition/alkaline-water-benefits-risks.

not enough to completely oxidize the hydrocarbons to carbon dioxide and water. With less oxygen available, the reaction products contain primarily hydrogen and carbon monoxide (and nitrogen, if the reaction is carried out with air rather than pure oxygen), and a relatively small amount of carbon dioxide and other compounds. In a subsequent water-gas shift reaction, the carbon monoxide reacts with water to form carbon dioxide and more hydrogen. It can be a faster process than steam reforming and requires a smaller reactor vessel. However, this process produces less hydrogen per unit of the input fuel than is obtained by steam reforming of the same fuel.[96]

- Pyrolysis. In this process, an organic material, such as biomass, is heated in the absence of oxygen. Because there is no oxygen present, the material does not combust but the biomass components (e.g., cellulose, hemicellulose, lignin) that comprise the material thermally decompose into combustible gases and charcoal. Pyrolysis of biomass produces three products: one liquid (bio-oil), one solid (bio-char), and one gaseous (syngas). The proportion of these products depends on several factors, including the composition of the feedstock and process parameters. The amount of syngas produced depends on these parameters, and may be in the range of 10% to 15% by weight.[97]

According to DOE, other technologies are being investigated to produce hydrogen.[98] These include direct solar water splitting (i.e., photolytic processes that use light energy to split water into hydrogen and oxygen), and photobiological processes.[99]

- Thermochemical Water Splitting. This process uses high temperatures—from concentrated solar power or from the waste heat of nuclear power reactions—and chemical reactions to produce hydrogen and oxygen from water. Thermochemical water splitting processes use temperatures of 500°–2,000°C to drive a series of chemical reactions that produce hydrogen. The chemicals used in the process are reused within each cycle, creating a closed loop that consumes only water and produces hydrogen and oxygen.
- Photoelectrochemical (PEC) Water Splitting. The PEC water splitting process uses semiconductor materials to convert solar energy directly to chemical energy in the form of hydrogen. The semiconductor materials used in the PEC process are similar to those used in photovoltaic solar electricity generation, but for PEC applications the semiconductor is immersed in a water-based electrolyte, where sunlight energizes the water-splitting process.
- Photobiological. With photobiological hydrogen production processes, microorganisms (such as green microalgae or cyanobacteria) use sunlight to split water into oxygen and hydrogen ions. The hydrogen ions can be combined through direct (e.g., using enzymes) or indirect (e.g., using catalyts) routes, and are released as hydrogen gas.

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[96] DOE, Office of Energy Efficiency and Renewable Energy, "Hydrogen Production: Coal Gasification," 2020, https://www.energy.gov/eere/fuelcells/hydrogen-production-coal-gasification.

[97] U.S. Department of Agriculture, "What Is Pyrolysis?," April 14, 2017, https://www.ars.usda.gov/northeast-area/wyndmoor-pa/eastern-regional-research-center/docs/biomass-pyrolysis-research-1/what-is-pyrolysis/.

[98] DOE, Office of Energy Efficiency and Renewable Energy, "Hydrogen Production Processes," 2020, https://www.energy.gov/eere/fuelcells/hydrogen-production-processes.

[99] Ibid.

- Photofermentative. Some photosynthetic microbes use sunlight as the driver to break down organic matter, releasing hydrogen.

Gas permeable membranes[100] are another potential technology for hydrogen separation, most likely from syngas.

> Membrane gas separation does not require moving parts; it has small footprint and it is a compact system; it provides operating flexibility to feed fluctuations; it demands comparatively lower energy requirement leading to lower operating costs; it does not involves chemicals, make-up, and solvents; it is easy start-up and shut-down; it requires minimal maintenance and operator attention; it allows a modular design; it requires minimal utilities; and it is easy to control. Among the main drawbacks, it can be mentioned no economy of scale due to the modular design; pretreatment of streams with particulates, organic compounds, or moisture can be difficult and/or expensive; sensitivity to chemicals can be problematic in some cases; requirement of electrical power for compression (high-quality energy).[101]

Author Information

Richard J. Campbell
Specialist in Energy Policy

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[100] "Gases with high solubility and small molecules pass through the membrane very quickly. Less soluble gases with larger molecules take more time to permeate the membrane. In addition, different membrane materials separate differently. The driving force needed to separate gases is achieved by means of a partial pressure gradient." Evonik Resource Efficiency GmbH, "Principle of Selective Permeation," 2020, https://www.sepuran.com/product/sepuran/en/pages/selective-permeation.aspx.

[101] Patricia L. Mores, Ana M. Arias, and Nicolás J. Scenna, et al., *Membrane-Based Processes: Optimization of Hydrogen Separation by Minimization of Power, Membrane Area, and Cost*, Molecular Diversity Preservation International, November 12, 2018, https://www.researchgate.net/publication/328932122_Membrane-Based_Processes_Optimization_of_Hydrogen_Separation_by_Minimization_of_Power_Membrane_Area_and_Cost.