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Hydrogen Production: Overview and Issues for Congress

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SUMMARY

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Lexie Ryan
Analyst in Energy Policy

Hydrogen Production: Overview and Issues for Congress

Various hydrogen production methods, or *pathways*, can use energy to extract hydrogen from *feedstocks* such as fossil fuels, biomass, and water. Hydrogen molecules can then be used in functional purposes. Today, hydrogen is predominantly used for industrial processes, including petroleum refining and ammonia production. Emerging and potential future applications include storing energy, heating, and replacing natural gas in certain functions.

The choice of feedstock and production pathway can have implications for the cost and environmental impact of hydrogen production. The most widespread hydrogen production pathway in the United States and globally is steam methane reforming (SMR), which uses natural gas as the hydrogen feedstock. A less widespread but still commercially mature hydrogen production pathway is gasification of coal. Most hydrogen is currently produced with fossil fuels: 95% of hydrogen produced in the United States is produced by SMR of natural gas, and 4% is produced by gasification of coal. Carbon-based feedstocks like fossil fuels and biomass may also be converted to hydrogen via pyrolysis, autothermal reforming (ATR), or partial oxidation (PO_X); in these processes, the carbon is typically converted to carbon dioxide (CO_2) as a byproduct.

Carbon capture and storage (or sequestration), known as CCS, has the potential to lower emissions from hydrogen production pathways that use fossil fuels. Incorporating CCS may increase the cost of making hydrogen, by over 50% according to one study from the National Energy Technology Laboratory. Hydrogen produced using fossil fuels is usually considered low-emission or "clean" hydrogen only when CCS is used. Hydrogen produced using fossil fuels with CCS makes up almost all of the current production of low-emission hydrogen. CCS does not mitigate emissions that may come at other points in the supply chain. For pathways that use natural gas, such emissions can include venting, leaking, and flaring methane.

Electrolysis is another potentially low-emission way to produce hydrogen. In electrolysis, electricity splits hydrogen from water in an electrolyzer. Electrolysis may be low-emissions if the electricity source is nonemitting (e.g., renewables or nuclear energy). However, electrolysis is considered low-emissions only if CCS is used when burning the fossil fuels to generate the electricity.

Electrolysis is not in widespread use compared with production pathways that use fossil fuels: approximately 1% of hydrogen produced in the United States is from electrolysis, and most of this electrolytic hydrogen uses electricity from fossil fuels. Electrolysis capacity may increase: in the United States, almost six times the current electrolyzer capacity is under construction, and over 30 times the current electrolyzer capacity is planned.

Congressional support for hydrogen production pathways includes funding and tax credits for projects that decrease emissions, lower costs, and support diversity in feedstock and geography compared with current conditions. Current congressional support for hydrogen production includes the Clean Hydrogen Production Tax Credit (45V); research and development activities, such as those for clean hydrogen electrolysis; and demonstration programs, such as the Regional Clean Hydrogen Hubs. Members have debated the level of support for hydrogen production pathways that use fossil fuels plus CCS. Some Members see SMR plus CCS as a viable option to produce low-emission hydrogen, while other Members oppose measures that support hydrogen production pathways that use natural gas due to emissions associated with natural gas production, which CCS does not mitigate. Congress may consider maintaining, expanding, or decreasing existing support for low-emission hydrogen production. Congress may also consider supporting specific pathways, or withdrawing support for hydrogen production entirely.

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Introduction

Hydrogen is the most abundant element in the universe but occurs naturally on Earth mostly in compound form with other elements. Pure molecular hydrogen (H_2) can be extracted by decomposing or by chemically reacting *hydrogen feedstocks*—sources of hydrogen such as fossil fuels, biomass, and water. Once hydrogen molecules are extracted, they can be used for functional purposes. For decades, technologies such as steam methane reforming (SMR) and coal gasification have used fossil fuels as hydrogen feedstocks for the manufacture of ammonia, fertilizers, and petroleum products and for other industrial processes.[1] Emerging and potential future applications for hydrogen include storing energy, heating, and replacing natural gas in certain functions.[2]

Almost all current hydrogen production in the United States uses fossil fuels as feedstocks and directly emits carbon dioxide (CO_2). Recent legislation has authorized and appropriated billions of dollars in grants and has established incentive programs for producing hydrogen, focusing on decreasing CO_2 emissions, lowering costs of technologies using alternative feedstocks, and encouraging geographic and feedstock diversity. In addition, this legislation has defined "clean hydrogen" relative to the emissions generated during its production. Most hydrogen produced today does not qualify as "clean" according to definitions established by legislation such as the Infrastructure Investment and Jobs Act (P.L. 117-58).[3]

Programs including the Regional Clean Hydrogen Hubs and incentives such as the Clean Hydrogen Production Tax Credit (45V) support lower-emission hydrogen pathways when compared with production using fossil fuels as hydrogen feedstocks. These pathways may include *electrolysis*, in which electricity splits water into oxygen (O_2) and H_2 in an electrolyzer; production methods that use biomass; and production methods that use fossil fuels in conjunction with carbon capture and storage (CCS). Developing these production pathways has been a point of focus for Congress in recent legislation.

This report describes the current production of hydrogen, including methods, emissions, costs, and availability. The most widespread hydrogen production pathways use fossil fuels as hydrogen feedstocks and include SMR, coal gasification, and autothermal reforming (ATR). Less widespread pathways use technologies such as electrolysis or use energy sources such as nuclear power and biomass.

Hydrogen Production Today

Hydrogen is currently produced both intentionally (*on-purpose hydrogen*) and as a byproduct of other processes. On-purpose hydrogen produced and sold to a consumer is known as *merchant hydrogen*, while on-purpose hydrogen produced by a consumer for internal use is called *captive*

[1] Elizabeth Connelly, Amgad Elgowainy, and Mark Ruth, *Current Hydrogen Market Size: Domestic and Global*, U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Record no. 19002, October 2019, p. 4. https://www.hydrogen.energy.gov/pdfs/19002-hydrogen-market-domestic-global.pdf, hereinafter Connelly, Elgowainy, and Ruth, *Current Hydrogen Market Size*.

[2] For more on potential applications, see CRS Report R47487, *The Hydrogen Economy: Putting the Pieces Together*, by Martin C. Offutt.

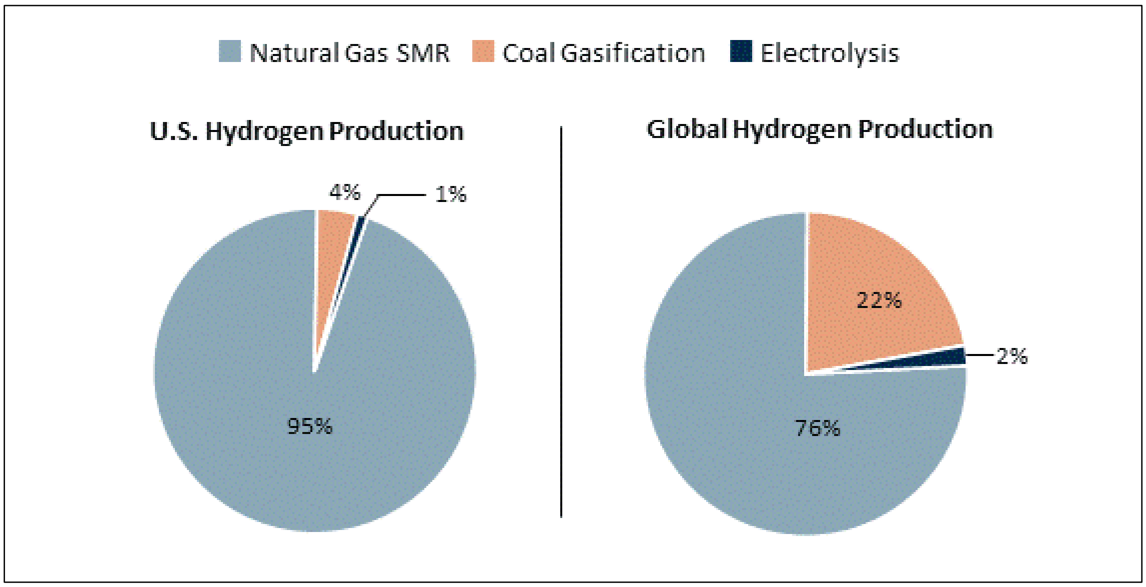
[3] For example, 42 U.S.C §16166 defines "clean hydrogen" as "hydrogen produced with a carbon intensity equal to or less than 2 kilograms of carbon dioxide-equivalent produced at the site of production per kilogram of hydrogen produced."

hydrogen.[4] On-purpose hydrogen differs from *byproduct hydrogen*, which is the result of processes that are not for the express purpose of producing hydrogen. Examples include processes for producing chlorine and sodium hydroxide. Estimates of hydrogen production may cover on-purpose hydrogen, or they may cover both on-purpose and byproduct hydrogen combined.

A U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Record published in 2019 estimates that about 10 million metric tons (MMT) of on-purpose hydrogen is produced in the United States annually (**Figure 1**). Production in the United States accounts for approximately 14% of total hydrogen produced worldwide, which is around 70 MMT.[5]

Figure 1. U.S. and Global Hydrogen Production

(percent by production pathway)



Sources: Elizabeth Connelly, Amgad Elgowainy, and Mark Ruth, *Current Hydrogen Market Size: Domestic and Global*, U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Record no. 19002, October 2019, https://www.hydrogen.energy.gov/pdfs/19002-hydrogen-market-domestic-global.pdf; and DOE, Office of Fossil Energy, *Hydrogen Strategy: Enabling a Low-Carbon Economy*, July 2020, p. 5, https://www.energy.gov/sites/default/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf.

Note: SMR = steam methane reforming.

Most of the hydrogen produced globally—and almost all of the hydrogen produced in the United States—comes from natural gas. Natural gas SMR accounts for 95% of hydrogen produced in the United States and 76% of hydrogen produced globally (**Figure 1**). Coal gasification produces 4% of hydrogen in the United States and 22% of hydrogen globally. Electrolysis accounts for approximately 1% of hydrogen production in the United States and 2% globally.

[4] For more about on-purpose, merchant, captive, and byproduct hydrogen, see Connelly, Elgowainy, and Ruth, *Current Hydrogen Market Size*.

[5] The DOE Hydrogen and Fuel Cells Program Record explains that some hydrogen production estimates do not include byproduct hydrogen, while others do include byproduct hydrogen. The Program Record uses sources that estimate annual U.S. production to be between 9 and 15 MMT and annual global production to be between 65 and 100 MMT; the estimates vary in part due to variations in whether and to what extent the estimates include byproduct hydrogen. Connelly, Elgowainy, and Ruth, *Current Hydrogen Market Size*; and DOE, Office of Fossil Energy, *Hydrogen Strategy: Enabling a Low-Carbon Economy*, July 2020, p. 5, https://www.energy.gov/sites/default/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf, hereinafter DOE, Office of Fossil Energy, *Hydrogen Strategy*.

Selected Hydrogen Production Pathways and Associated Technologies

Commercially mature hydrogen production pathways in use today include SMR, electrolysis, gasification, ATR, partial oxidation (PO_X), and pyrolysis (**Table 1**). Many emerging hydrogen production pathways are outside the scope of this report.[6] Reforming technologies such as SMR, ATR, and PO_X use carbon-based hydrogen sources as feedstocks. These carbon-based feedstocks typically include fossil fuels, but may also include biomass. Carbon-based hydrogen feedstocks may also produce hydrogen via *gasification*, which reacts the feedstocks with steam in a high-temperature environment with some oxygen, or *pyrolysis*, which gasifies the feedstocks without oxygen present. Fossil fuels may also be used in the hydrogen production process to generate heat or electricity. Water may be used as a hydrogen feedstock in electrolysis. This is sometimes referred to as *green hydrogen*, if the electricity comes from nonemitting energy sources (see more on hydrogen "colors" in **Appendix A**). Hydrogen production pathways that use fossil fuels can emit greenhouse gases like CO_2 and air pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and other pollutants.

Table 1. Selected Hydrogen Production Technologies

Pathway	Hydrogen Feedstocks
Steam methane reforming (SMR), also called *natural gas reforming*	• Natural gas • Less commonly, other light hydrocarbons, liquefied petroleum gas and naphtha, or biomass
Autothermal reforming (ATR)	• Natural gas • Less commonly, other light hydrocarbons, liquefied petroleum gas and naphtha, or biomass
Partial oxidation (PO_X)	• Coal • Fuel oil • Less commonly, liquid mixture of ground coal with water, or biomass
Pyrolysis	• Hydrocarbons or biomass
Gasification	• Coal • Less commonly, solid biomass
Electrolysis	• Water

[6] Emerging production pathways may involve biological or geologic processes, decomposition of methane, and algae/cyanobacteria. These pathways offer long-term potential for hydrogen production with low or no greenhouse gas emissions. Many are in early stages of development with years before expected widespread commercial deployment. They may also be more expensive than pathways that use carbon-based fuels as feedstocks. See DOE Office of Energy Efficiency and Renewable Energy (EERE), "Hydrogen Production Pathways," https://www.energy.gov/eere/fuelcells/hydrogen-production-pathways, accessed September 14, 2023, hereinafter DOE, EERE, "Hydrogen Production Pathways"; National Energy Technology Laboratory (NETL), "7.3. Technologies for Hydrogen Production," https://www.netl.doe.gov/research/carbon-management/energy-systems/gasification/gasifipedia/technologies-hydrogen, accessed September 14, 2023, hereinafter NETL, "7.3. Technologies for Hydrogen Production"; and Table 2 in Mohamed Nasser et al., "A Review of Water Electrolysis-Based Systems for Hydrogen Production Using Hybrid/Solar/Wind Energy Systems," *Environmental Science and Pollution Research*, vol. 29 (October 2022), pp. 86994-87018, https://doi.org/10.1007/s11356-022-23323-y, hereinafter Nasser et al., "A Review of Water Electrolysis-Based Systems."

Source: Tables 1-3 in National Energy Technology Laboratory, "7.3. Technologies for Hydrogen Production," https://www.netl.doe.gov/research/carbon-management/energy-systems/gasification/gasifipedia/technologies-hydrogen.

Producing Hydrogen from Carbon-Based Feedstocks

Carbon-based compounds such as fossil fuels and biomass can be used as feedstocks to produce hydrogen. They can also be used as energy sources to make the heat or electricity needed for hydrogen production. As noted, commercially available processes that use carbon-based feedstocks include SMR, ATR, partial oxidation, and gasification. In these processes, a carbon-based feedstock is reformed by a chemical reaction driven by heat in the presence of a catalyst. The reaction converts the hydrogen—which is chemically bound to carbon in the feedstock—into H_2. Reforming, oxidation, and gasification may include a second separate step, known as the *water-gas shift reaction*, to increase the overall yield of hydrogen. Typically, the carbon is converted to carbon dioxide (CO_2) as a byproduct.

Approximately 99% of the 10 MMT of hydrogen produced annually in the United States is sourced from fossil fuels (**Figure 1**).

Steam Methane Reforming (SMR)

As shown in **Figure 1**, approximately 95% of hydrogen produced in the United States, and 76% of hydrogen produced globally, comes from natural gas by a sequence of steps collectively referred to as *steam methane reforming* (SMR), also known as *natural gas reforming*. This process is widely used at petroleum refineries, where hydrogen is used to reduce the sulfur content of crude oil and to break heavier hydrocarbon molecules into lighter molecules. These refineries may produce hydrogen on-site or purchase hydrogen from merchant suppliers.[7]

The name *steam methane reforming* derives from the first step in the process: the reaction of natural gas with high-pressure (3 to 25 bar), high-temperature (7,200°C to 10,000°C) steam over a catalyst, typically nickel-based.[8] This reaction breaks the natural gas, which is principally methane (CH_4), into a mixture of mostly H_2 and carbon monoxide (CO). In addition to acting as the hydrogen feedstock, natural gas is also typically combusted externally to the process stream to create the high temperature needed. A water-gas shift may then react the CO with steam over a catalyst to produce a gaseous stream that is mostly H_2 and CO_2.[9] To produce high-purity hydrogen, a process called *pressure swing adsorption* (PSA) may be used. PSA removes impurities (such as CO_2) from the gaseous stream.[10] See **Figure 2** for a visual representation of SMR with PSA.

Although costs may fluctuate based on the price of natural gas, SMR is generally among the least expensive hydrogen production pathways in the United States. One study from DOE's National Energy Technology Laboratory (NETL) models that hydrogen produced from SMR without CCS would cost about $1.06/kilogram (kg) H_2, and hydrogen produced from SMR with CCS would

[7] Peter Gross and Matthew Skelton, "U.S. Gulf Coast Refinery Demand for Hydrogen Increasingly Met by Merchant Suppliers," *Today in Energy*, U.S. Energy Information Administration (EIA), March 15, 2019, https://www.eia.gov/todayinenergy/detail.php?id=38712.

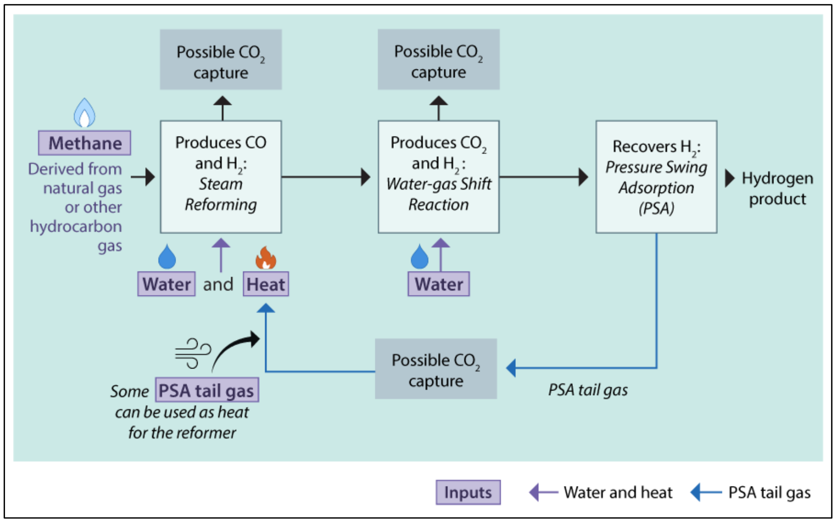
[8] A bar is a unit of pressure. One bar is slightly less than atmospheric pressure at sea level.

[9] For more on water-gas shift reactions, see NETL, "6.2.6. Water Gas Shift & Hydrogen Production," https://netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/water-gas-shift, accessed May 7, 2024.

[10] DOE, EERE, "Hydrogen Production: Natural Gas Reforming," https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming, accessed September 14, 2023, hereinafter DOE, EERE, "Hydrogen Production: Natural Gas Reforming."

cost about \$1.64/kg H_2.[11] See **Figure B-1** for price comparisons of production methods that use fossil fuels, with and without CCS.

Figure 2. Schematic of Steam Methane Reforming (SMR) with Pressure Swing Adsorption (PSA)



Source: Figure created by CRS, based on Vince White, "World Scale Hydrogen Production," Air Products, IMechE/IChemE Evening Seminar: 2019 Hydrogen Event, March 2, 2019, p. 7, https://www.icheme.org/media/9638/vince-white-world-scale-hydrogen-production.pdf; and U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, "Hydrogen Production: Natural Gas Reforming," https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming.

Notes: Pressure swing adsorption is typically used after steam reforming and water-gas shift reaction to produce high-purity hydrogen.

SMR produces greenhouse gases (GHGs). According to the International Energy Agency (IEA), the direct GHG emissions from SMR are around 9 kg CO_2-equivalent (CO_2e) per kg H_2. This measure (kg CO_2e/kg H_2) is referred to as the *emissions intensity* of a process. (See **Figure B-2** for emissions intensity comparisons of hydrogen production methods.[12]) Emissions could be lower if carbon capture technology is used, as discussed below. Another emerging option to reduce emissions from SMR involves using electrically heated reformers (instead of combusting natural gas for heat) in a process called electrified SMR or ESMR.[13] No ESMR plants currently produce hydrogen; an ESMR demonstration facility in Denmark began production of methanol in 2021. The company says that the ESMR technology used at the plant may also be able to produce hydrogen and other products.[14]

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[11] Eric Lewis et al., *Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies*, NETL, April 12, 2022, Exhibit 5-9, p. 277.

[12] Direct emissions reported in **Figure B-2** account only for those produced during the production process. They do not include emissions from producing and transporting fuel or feedstock, or from transporting, storing, and using hydrogen after production. International Energy Agency (IEA), *Towards Hydrogen Definitions Based on Their Emissions Intensity*, April 2023, p. 39, https://www.iea.org/reports/towards-hydrogen-definitions-based-on-their-emissions-intensity, hereinafter IEA, *Towards Hydrogen Definitions Based on Their Emissions Intensity*.

[13] For more on electrified SMR, see IEA Greenhouse Gas R&D Programme (IEAGHG), *Low-Carbon Hydrogen from Natural Gas: Global Roadmap*, August 2022, https://ieaghg.org/publications/low-carbon-hydrogen-from-natural-gas-global-roadmap/.

[14] Ulrik Frohlke, "Topsoe Puts Demonstration Plant into Operation for Production of Sustainable Methanol from (continued...)

Steam reforming can also use other light hydrocarbons (e.g., ethanol, propane, the molecules in gasoline), biomass, or, less frequently, liquefied petroleum gas and naphtha as feedstocks for hydrogen production.[15] These alternative feedstocks are not commonly used because natural gas is typically the most economical and widely available feedstock.

Partial Oxidation (PO_X) and Autothermal Reforming (ATR)

Hydrocarbons can be converted to hydrogen through two other reforming pathways: partial oxidation (PO_X) and autothermal reforming (ATR).[16] Both are already used in the chemical industry.

PO_X is used to produce hydrogen or synthesis gas (syngas) in refineries. In the PO_X process, liquids or gases react with a small amount of oxygen, typically from air, at a temperature greater than 1,000 degrees Celsius (°C) in a reactor.[17] Neither catalysts nor steam are required in PO_X. The resulting syngas contains primarily hydrogen and carbon monoxide, and a smaller amount of CO_2 and other compounds. A subsequent water-gas shift reaction can react the carbon monoxide with water to form carbon dioxide and more hydrogen. Compared with SMR, PO_X is faster and requires a smaller reactor vessel, and it does not require a catalyst for the reaction. PO_X is not widely used to produce hydrogen outside of refineries.

ATR is already used to produce hydrogen for the chemical industry (such as for ammonia production). In ATR, gasification and a water-gas shift occur in the same reactor in the presence of pure oxygen and at a temperature greater than 1,000°C. Like SMR, ATR typically uses light hydrocarbons—most commonly natural gas—as feedstocks. Less frequently, ATR uses liquefied petroleum gas and naphtha. The CO_2 produced by the ATR process is more highly concentrated than the CO_2 produced by SMR and therefore may be easier to capture. However, ATR produces less hydrogen per unit of input fuel than SMR, and SMR may be more economical at scale.[18] Further, ATR requires pure oxygen, which may add costs.

Coal Gasification

Hydrocarbons can be converted into hydrogen via gasification. Coal or another solid hydrogen source is typically used as the feedstock in gasification, though petroleum and biomass may also be gasified. In 2020, coal gasification produced 4% of hydrogen in the United States and 22% of hydrogen globally (**Figure 1**). Much of the world's coal gasification capacity is in China, where

Biogas-Significant Global Carbon Emission Reduction Potential," Topsoe press release, October 13, 2021, https://www.topsoe.com/press-releases/topsoe-demonstration-plant-operation.

[15] NETL, "7.3. Technologies for Hydrogen Production."

[16] For a comparison of reforming processes (SMR, PO_X, and ATR), see Joydev Manna, "Chapter 1.1 – Hydrogen Economy and International Hydrogen Strategies," in *Towards Hydrogen Infrastructure: Advances and Challenges in Preparing for the Hydrogen Economy*, ed. Deepshikha Jaiswal-Nagar, Viney Dixit, and Sheila Devasahayam (Elsevier, 2024), pp. 3-38, https://doi.org/10.1016/B978-0-323-95553-9.00009-1; and Duane B. Myers et al., *Cost and Performance Comparison of Stationary Hydrogen Fueling Appliances*, Directed Technologies, Department of Energy Grant No. DE-FG01-99EE35099, 2002, https://www.nrel.gov/docs/fy02osti/32405b2.pdf.

[17] DOE, EERE, "Hydrogen Production: Natural Gas Reforming."

[18] DOE, EERE, "Hydrogen Production: Natural Gas Reforming."

the technology has been used for decades to produce ammonia and methanol.[19] According to the IEA, about two-thirds of China's hydrogen production in 2020 used coal.[20]

During coal gasification, a limited amount of oxygen (that is, not enough to completely oxidize the feedstock) and steam react with the coal at a high temperature to produce syngas containing CO. A water-gas shift reaction produces H_2 with slag (i.e., residue) and CO_2 as byproducts.

According to the IEA's *Global Hydrogen Review 2023*, hydrogen production from coal gasification results in 22-26 kg CO_2e/kg H_2 of total emissions, with over 80% of the emissions from coal gasification associated with direct emissions from the production plant. The IEA projects that capturing these direct emissions from the production plant with CCS may reduce emissions to 2.6-6.3 kg CO_2e/kg H_2.[21] See **Figure B-2** for emissions intensity comparisons of hydrogen production methods.

Another way to reduce emissions from coal gasification is co-gasification with a feedstock associated with lower lifecycle emissions, such as biomass. A 2022 report from NETL found only two examples of commercial facilities that have co-gasified coal with an alternative feedstock. Neither produce hydrogen as an end-product. One decommissioned power plant co-gasified coal and woody biomass in the Netherlands from 1994 to 2013. Another facility began co-gasifying coal and waste plastics to make new plastic in Tennessee in 2024.[22]

Hydrogen Purity

Hydrogen purity is determined by the levels of contaminants such as CO_2, CO, hydrogen sulfide (H_2S), ammonia (NH_3), water (H_2O), oxygen (O_2), and others. Different uses of hydrogen require different grades of hydrogen purity. Some petroleum refining processes may use hydrogen that is between 80% and 90% pure. Fuel cell electric vehicles (FCEVs) require hydrogen at about 99.97% purity.[23] Even small amounts of contaminants may decrease the lifespan and performance of fuel cells in FCEVs.[24]

Hydrogen is typically (but not always) purified at the point of production by a process called *pressure swing adsorption* (PSA).[25] Because hydrogen delivery may introduce impurities, further purification may be required during transportation, storage, and distribution for applications that require high levels of purity.[26]

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[19] DOE, Office of Fossil Energy, *Hydrogen Strategy*; IEA, *Global Hydrogen Review 2022*, September 2022, p. 87, https://www.iea.org/reports/global-hydrogen-review-2022, hereinafter IEA, *Global Hydrogen Review 2022*. For more about ammonia, see CRS In Focus IF12273, *Ammonia's Potential Role in a Low-Carbon Economy*, by Lexie Ryan.

[20] IEA, *Opportunities for Hydrogen Production with CCUS in China*, November 2022, https://www.iea.org/reports/opportunities-for-hydrogen-production-with-ccus-in-china.

[21] According to the IEA, the remaining less than 20% of emissions associated with coal gasification is from coal mining, processing, and transportation. IEA, *Global Hydrogen Review 2023*, September 2023, p. 88, https://www.iea.org/reports/global-hydrogen-review-2023, hereinafter IEA, *Global Hydrogen Review 2023*.

[22] Eric Lewis et al., *Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies*, NETL, April 12, 2022, p. 18; NETL, "8.6.3. Nuon Power Buggenum IGCC Plant," https://netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/nuon, accessed August 2, 2024; and "Kingsport, Tennessee, site," Eastman, accessed August 2, 2024, https://www.eastman.com/en/sustainability/environmental/circularity/site-locations/tennessee-site.

[23] U.S. DRIVE, *Hydrogen Delivery Technical Team Roadmap*, June 2013, https://www.energy.gov/eere/fuelcells/articles/hydrogen-delivery-roadmap.

[24] James M. Ohi, Nicholas Vanderborgh, Gerald Voecks Consultants, *Hydrogen Fuel Quality Specifications for Polymer Electrolyte Fuel Cells in Road Vehicles*, report to the Safety, Codes and Standards Program, Fuel Cell Technologies Office, DOE, November 2, 2016, https://www.energy.gov/sites/prod/files/2016/11/f34/fcto_h2_fuel_quality_specs_pem_fc_road_vehicles.pdf.

[25] Ibid.

[26] U.S. DRIVE, *Hydrogen Delivery Technical Team Roadmap*, June 2013, https://www.energy.gov/eere/fuelcells/articles/hydrogen-delivery-roadmap.

Purification processes can add costs, especially capital costs, to hydrogen production. One DOE study on SMR+PSA found that the capital cost contribution of the hydrogen production unit (which includes the fuel processor, processor, and purifier) accounted for 11% of the delivered hydrogen cost, and the PSA unit represented roughly 6% of the delivered hydrogen cost.[27] For comparison, the same study found that the feedstock accounted for 34% of delivered hydrogen cost. Other costs may be associated with maintaining purity, including costs for testing, storage, and transportation.

Methods to decrease emissions from hydrogen production using coal may increase costs. One study from NETL modeled that hydrogen produced from coal gasification without CCS would cost about \$2.58/kg H_2. Hydrogen produced from coal gasification with CCS was modeled to cost \$3.09/kg H_2. Hydrogen produced from co-gasification of coal and biomass was modeled to cost \$3.64/kg H_2.[28] See **Figure B-1** for price comparisons of production methods that use fossil fuels, with and without CCS.

Pyrolysis

Pyrolysis is the gasification through heat of methane sources (natural gas or biogas) without oxygen.[29] In this process, high-temperature heat splits methane into hydrogen and solid carbon with no direct release of CO_2 into the atmosphere. Solid carbon, sometimes known as *carbon black*, can be used to manufacture rubber, tires, inks, catalysts, plastics, and other industrial materials.[30]

According to the IEA, pyrolysis results in emissions ranging from 2 to 16 kg CO_2e/kg H_2 depending on upstream and midstream emissions from the feedstock (usually natural gas) and electricity supply.[31] Under certain optimized conditions, pyrolysis using biogas or biomethane as the feedstock could result in net negative emissions.

Although pyrolysis is a commercially mature technology, hydrogen production through pyrolysis is not widespread. Pyrolysis is used today to produce carbon black or syngas rather than on-purpose hydrogen. In 2021, DOE's Loan Programs Office (LPO) announced a conditional commitment to finance the first commercial-scale methane pyrolysis project. The project is located in Nebraska and intends to produce hydrogen for ammonia.[32] A 2022 report from NETL notes that pyrolysis is currently considered more as a production route for carbon black than as a method of hydrogen production.[33]

[27] James M. Ohi, Nicholas Vanderborgh, Gerald Voecks Consultants, *Hydrogen Fuel Quality Specifications for Polymer Electrolyte Fuel Cells in Road Vehicles*, report to the Safety, Codes and Standards Program, Fuel Cell Technologies Office, DOE, November 2, 2016, pp. 48-49, https://www.energy.gov/sites/prod/files/2016/11/f34/fcto_h2_fuel_quality_specs_pem_fc_road_vehicles.pdf.

[28] Eric Lewis et al., *Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies*, NETL, April 12, 2022, Exhibit 5-9, p. 277.

[29] DOE, EERE, "Hydrogen Production: Biomass Gasification," https://www.energy.gov/eere/fuelcells/hydrogen-production-biomass-gasification, hereinafter DOE, EERE, "Hydrogen Production: Biomass Gasification."

[30] DOE, *U.S. National Clean Hydrogen Strategy and Roadmap*, June 2023, pp. 43-44, https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap, hereinafter DOE, *U.S. National Clean Hydrogen Strategy*.

[31] IEA, *Towards Hydrogen Definitions Based on Their Emissions Intensity*, p. 48.

[32] Jigar Shah, "Open for Business: LPO Issues New Conditional Commitment for Loan Guarantee," Loan Programs Office, DOE, December 23, 2021, https://www.energy.gov/lpo/articles/open-business-lpo-issues-new-conditional-commitment-loan-guarantee.

[33] Eric Lewis et al., *Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies*, NETL, April 12, 2022.

Use of Biomass in the Hydrogen Production Process

Biomass can be converted to hydrogen through several methods. Biomass solids can be gasified or pyrolyzed. Liquid biomass can be converted to hydrogen in a process similar to SMR called *biomass-derived liquid reforming*.[34] SMR and ATR may also replace some natural gas with biogas from organic landfill matter, sewage, or agricultural waste to produce hydrogen.[35] Biomass can also be blended with coal and other hydrocarbons in some existing plants—for example, some coal gasification plants.[36]

According to the IEA, the first commercial biomass-gasification-to-hydrogen plant may be operational in 2025.[37] Biomass is already used as a hydrogen source at several fuel cell power plants, which generate electric power by combining hydrogen and oxygen. As of December 2022, these fuel cell power plants include one that uses landfill gas and four that use biogas from wastewater treatment.[38] In February 2024, DOE's Office of Fossil Energy and Carbon Management announced a funding opportunity for carbon dioxide removal, including pilot projects that focus on producing hydrogen from biomass.[39]

Congress has specified that biomass should be considered a renewable energy resource for the purposes of DOE's clean hydrogen research and development program.[40] Also, DOE's Office of Energy Efficiency and Renewable Energy states, "Because growing biomass removes carbon dioxide from the atmosphere, the net carbon emissions of this method can be low, especially if coupled with carbon capture, utilization, and storage in the long term."[41] While biomass feedstock may be abundant and cheap, feedstock impurities and seasonal availability may lead to fluctuating hydrogen yields and require further purification. (See the "Hydrogen Purity" text box above.)

Hydrogen Production and Carbon Capture Technologies

One method that may mitigate greenhouse gas emissions from hydrogen produced from carbon-based feedstocks is carbon capture and storage (or sequestration), known as CCS. CCS is a greenhouse gas mitigation process intended to capture anthropogenic (human-generated) CO_2 at its source, transport it to a storage or sequestration site, and store it permanently underground or convert it into commercially valuable products. CCS is sometimes referred to as CCUS—carbon capture, *utilization*, and storage. Utilization refers to the use of CO_2—in lieu of storing it—as a means of mitigating CO_2 emissions. Utilization involves converting captured CO_2 into chemicals,

[34] DOE, EERE, "Hydrogen Production: Biomass-Derived Liquid Reforming," https://www.energy.gov/eere/fuelcells/hydrogen-production-biomass-derived-liquid-reforming, accessed September 14, 2023.

[35] DOE, *U.S. National Clean Hydrogen Strategy*, p. 45.

[36] NETL, "7.3. Technologies for Hydrogen Production."

[37] IEA, *Global Hydrogen Review 2022*, p. 87.

[38] As of December 2022, about 205 fuel cell electric power generators operate in the United States; the majority use natural gas as the hydrogen feedstock. EIA, "Hydrogen Explained: Use of Hydrogen," https://www.eia.gov/energyexplained/hydrogen/use-of-hydrogen.php, last updated June 23, 2023.

[39] DOE, EERE, "U.S. Department of Energy Announces up to $100 Million for Pilot-Scale Testing of Advanced Carbon Dioxide Removal Technologies; Includes Funding for Projects to Produce Carbon-Negative Hydrogen from Biomass," February 15, 2024, https://content.govdelivery.com/accounts/USEERE/bulletins/38acc22; "Opportunity: Carbon Negative Shot Pilots," issue date March 28, 2024, DE-FOA-0003082.

[40] 42 U.S.C. §16154 (e).

[41] DOE, EERE, "Hydrogen Production: Biomass Gasification."

cements, plastics, and other products.[42] This report uses the term CCS except in cases where utilization is specifically discussed.

CCS has the potential to lower emissions from hydrogen production pathways that use fossil fuels by capturing CO_2 emissions that occur during the production process. CO_2 may be produced at a hydrogen production plant through the chemical reaction that produces hydrogen, when combusting fuel for heat and during purification (for example, see **Figure 2**); these CO_2 emissions are known as *direct emissions* from hydrogen production. According to the IEA, CCS has the potential to recover more than 90% of direct emissions.[43] (See **Figure B-2** for emissions intensity comparisons of production methods with and without CCS.)

Upstream, Midstream, and Downstream Emissions

CCS does not necessarily mitigate CO_2 emissions that may come at other points in the hydrogen supply chain besides production. These emissions may occur before hydrogen production (*upstream* emissions); during—but external to—the production process (*midstream* emissions); or after hydrogen is produced and reaches end use (*downstream* emissions).

For hydrogen produced from SMR, upstream and midstream emissions may come from natural gas production, storage, transportation, and processing. They may include direct emissions—such as from venting, leaking, and flaring methane—and indirect emissions, such as emissions that occur when generating electricity used to compress natural gas.[44] The IEA has found that between 1 and 5 kg CO_2e/kg H_2 may be produced by upstream and midstream emissions for hydrogen production that uses natural gas (see **Figure B-2** for emissions intensity comparisons of production methods, including upstream and midstream emissions).[45]

For hydrogen produced by renewable electrolysis, upstream emissions may come from manufacturing materials used to generate renewable energy technologies (e.g., wind turbines). The IEA estimates that lifecycle emissions from producing electrolytic hydrogen are approximately 0.9-2.5 kg CO_2e/kg H_2 for hydrogen production using solar photovoltaic modules and 0.4-0.8 kg CO_2e/kg H_2 for hydrogen production using onshore wind energy.[46]

Downstream emissions may occur during transportation and storage of hydrogen, boil-off (evaporation), and possible processing before end use (such as further purification, if necessary). Some research suggests that hydrogen may also act as an *indirect* GHG if it leaks downstream, meaning it may increase the lifetime or amount of other GHGs in the atmosphere.[47]

Besides CCS, other methods to reduce emissions may involve replacing fossil fuels that are burned to generate heat for the reformer. Electrified SMR, a variant on SMR, may reduce CO_2 emissions by using electricity to heat the reformer. Another option could be to use byproduct heat from nuclear power to generate steam to heat the reformer.[48]

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[42] For more on carbon capture technologies, see CRS Report R44902, *Carbon Capture and Sequestration (CCS) in the United States*, by Angela C. Jones and Ashley J. Lawson.

[43] The IEA has found that advanced technologies may produce capture rates of above 90% for direct emissions, but no plants with these technologies are in operation. IEA, *Towards Hydrogen Definitions Based on Their Emissions Intensity*, p. 9. The *Towards Hydrogen Definitions* report does not explain what kinds of CCS technologies are considered advanced CCS technologies. An IEA web page explains, "While the most advanced and widely adopted capture technologies are chemical absorption and physical separation, other separation technologies under development include membranes and looping cycles (such as chemical looping and calcium looping)." IEA, "Carbon Capture Utilisation and Storage," last updated April 25, 2024, https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage.

[44] IEA, *Towards Hydrogen Definitions Based on Their Emissions Intensity*, p. 39.

[45] IEA, *Towards Hydrogen Definitions Based on Their Emissions Intensity*, p. 39.

[46] IEA, *Towards Hydrogen Definitions Based on Their Emissions Intensity*, Box 2.2, p. 42.

[47] For example, see Maria Sand et al., "A Multi-Model Assessment of the Global Warming Potential of Hydrogen," *Communications Earth & Environment*, vol. 4, article no. 203 (June 7, 2023), https://doi.org/10.1038/s43247-023-00857-8.

[48] DOE, Office of Nuclear Energy, "Could Hydrogen Open New Markets for Nuclear?" June 24, 2020, https://www.energy.gov/ne/articles/could-hydrogen-open-new-markets-nuclear.

CCS can increase the cost of hydrogen production compared with producing hydrogen without CCS. One study from NETL estimated that the levelized cost of hydrogen (LCOH)[49] produced from SMR systems with CCS is around 54% more than SMR systems without CCS (without accounting for a federal tax credit—see discussion in the section "The Clean Hydrogen Production Tax Credit (45V) and Emissions").[50] See **Figure B-1** for price comparisons of production methods that use fossil fuels, with and without CCS.

Hydrogen generated through processes associated with low CO_2 emissions is currently mostly produced through fossil fuel feedstock combined with CCS. The IEA defines hydrogen as having "low emissions" when it is produced by electrolysis using renewable or nuclear energy or if it is produced using biomass or fossil fuels with CCS.[51] The IEA has found that almost all of the nearly 1 MT of global low-emissions hydrogen production in 2022 used fossil fuels with CCS.[52]

According to the IEA Hydrogen Projects Database, as of October 2023 five operational U.S. facilities produced hydrogen using CCUS: one oil with CCUS, one coal with CCUS, and three SMR with CCUS.[53]

DOE's *Pathways to Commercial Liftoff: Clean Hydrogen* report identifies challenges with relying on CCS as an option for developing large amounts of clean hydrogen production.[54] According to the *Liftoff* report, currently around 25 MMT CO_2 is captured and sequestered in the United States. The report's scenarios of clean hydrogen production project that generating this hydrogen from fossil fuels combined with CCS would result in an additional 2-20 MMT of CO_2 captured and sequestered annually by 2030; 100-225 MMT by 2040; and 175–425 MMT by 2050.[55] According to DOE, such an increase may require "significant further investment in CO_2 infrastructure and coordination to manage environmental and safety considerations."[56]

[49] The study used 2018 dollars and defined levelized cost of hydrogen (LCOH) as follows: "The LCOH is the amount of revenue required per kilogram of H_2 produced during the plant's operational life to meet all capital and operational costs." Eric Lewis et al., *Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies*, NETL, April 12, 2022, pp. 48-49.

[50] The study analyzed six configurations of hydrogen production from fossil fuels: two SMR cases (with and without CCS), one ATR case (with CCS), two coal gasification cases (with and without CCS), and one coal/biomass co-gasification case (with CCS). The study found that adding CO_2 capture technologies increased the levelized cost of hydrogen by 54% for SMR and 20% for coal gasification. Eric Lewis et al., *Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies*, NETL, April 12, 2022, pp. 276-277.

[51] IEA, *Global Hydrogen Review 2023*, p. 169.

[52] IEA, *Global Hydrogen Review 2023*, pp. 64-65.

[53] The five operational U.S. facilities producing hydrogen with CCS named in the database are Coffeyville fertilizer plant, Great Plains Synfuel Plant and Weyburn-Midale, PCS Nitrogen-Geismar Plant (LA), Port Arthur, and Enid fertiliser. These results are from Country – "USA"; Status – "Operational"; Technology – "Coal w CCUS, NG w CCUS, Oil w CCUS." Other projects listed in the database using carbon-based feedstock technologies produce hydrogen in feasibility study and concept projects. IEA, Hydrogen Projects Database, October 2023, https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database.

[54] Hannah Murdoch et al., *Pathways to Commercial Liftoff: Clean Hydrogen*, DOE, March 2023, https://liftoff.energy.gov/wp-content/uploads/2023/05/20230523-Pathways-to-Commercial-Liftoff-Clean-Hydrogen.pdf, hereinafter Murdoch et al., *Pathways to Commercial Liftoff: Clean Hydrogen*.

[55] The report explains its estimations: "Range is based on the Net Zero 2050 – high RE and Net Zero 2050 – low RE scenarios, 70-90% capture rates, 8-11 kg CO_2e/kg H_2 pre-capture carbon intensity, and 2 kg CO_2e/kg H_2 upstream methane emissions." Footnote 137, Murdoch et al., *Pathways to Commercial Liftoff: Clean Hydrogen*, p. 58.

[56] More challenges are listed in the report. See "Chapter 4: Challenges to Commercialization and Potential Solutions" in Murdoch et al., *Pathways to Commercial Liftoff: Clean Hydrogen*, pp. 57-68.

Producing Hydrogen from Water

All commercial hydrogen production technologies use water, and some use water as a hydrogen feedstock. Several different production pathways can split water (H_2O) into hydrogen and oxygen. These pathways may use different energy sources, including electricity, solar, and heat. Many of these pathways are in early stages of development. Some pathways using these technologies have the potential for zero emissions during production. The most commercially available of these pathways is electrolysis, although, as shown in **Figure 1**, electrolysis is not in widespread use compared with production pathways that use fossil fuels. Pathways that use water as a hydrogen feedstock are typically more expensive than pathways that use carbon-based feedstocks. Efforts to lower costs are an area of continuing development.

Water Electrolysis

In electrolysis, an electric current splits water in an electrolyzer, producing hydrogen. An electrolyzer consists of two electrodes (an anode and a cathode) joined by an electrical circuit but separated by an electrolyte membrane. The electricity that passes through the circuit can be produced from a variety of dedicated, on-site sources, or it can be drawn from the electric grid (which gets electricity from a combination of sources).

The source of the electricity largely determines the level of greenhouse gas emissions associated with production of electrolytic hydrogen. Electrolysis using electricity from nonemitting sources—such as renewables or nuclear energy—may produce no direct greenhouse gas emissions and low total lifecycle emissions.[57] Emissions may be higher if electricity is sourced from fossil fuels. For example, the IEA found that using the current average global grid emissions intensity results in a lifecycle emissions intensity for electrolytic hydrogen of about 24 kg CO_2e/kg H_2.[58] This is almost equal to the emissions intensity for producing hydrogen from unabated coal gasification (23 kg CO_2e/kg H_2). See **Figure B-2** for emissions intensity comparisons of production methods.

Electrolytic hydrogen is generally more expensive than hydrogen produced by SMR or coal gasification. A DOE Hydrogen Program Record estimates the levelized cost of hydrogen produced via water electrolysis, without subsidies or tax incentives, at around \$5-\$7/kg H_2.[59]

Approximately 1% of hydrogen produced in the United States is produced via electrolysis (**Figure 1**).[60] Significant planned electrolyzer capacity has been announced (**Figure 3**). DOE's Hydrogen Program Record on U.S. electrolyzer installations reports that current combined installed capacity of electrolyzers in the United States is approximately 116 MW (0.116 GW) as

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[57] DOE, EERE, "Hydrogen Production: Electrolysis," https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis, accessed September 14, 2023, hereinafter DOE, EERE, "Hydrogen Production: Electrolysis."

[58] The IEA calculated the current average global CO_2 intensity at 460 g CO_2e/kWh. The average global grid emissions intensity is affected by coal-fired power plants across countries; other countries may have different grid emissions intensities than the United States. IEA, *Towards Hydrogen Definitions Based on Their Emissions Intensity*, p. 40.

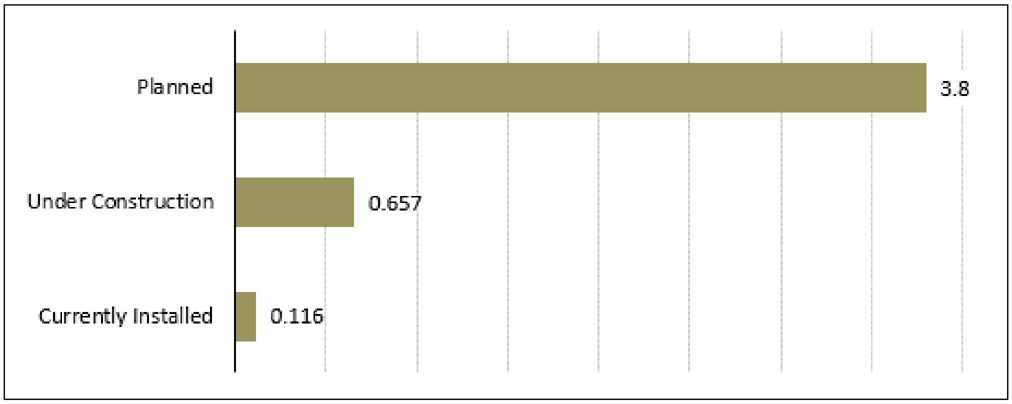
[59] Cost is estimated in 2022 dollars for hydrogen "produced from renewable electricity using currently available proton exchange membrane (PEM) technology and various renewable energy sources." Cost does not include costs incurred after hydrogen production (such as costs for compression, storage, distribution, and dispensing). McKenzie Hubert et al., *Clean Hydrogen Production Cost Scenarios with PEM Electrolyzer Technology*, DOE Hydrogen Program Record no. 24005, May 20, 2024, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24005-clean-hydrogen-production-cost-pem-electrolyzer.pdf. For more information on the cost of delivery and dispensing, see Mariya Koleva and Neha Rustagi, *Hydrogen Delivery and Dispensing Cost*, DOE Hydrogen Program Record no. 20007, August 25, 2020, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/20007-hydrogen-delivery-dispensing-cost.pdf.

[60] DOE, Office of Fossil Energy, *Hydrogen Strategy*; DOE, EERE, "Hydrogen Production: Electrolysis."

of May 2024. Approximately 657 MW of additional capacity (almost six times the current capacity) is under construction, and 3,800 MW of additional capacity (over 30 times the current capacity) is planned.[61]

Figure 3. Electrolyzer Capacity in the United States: Planned, Under Construction, and Currently Installed, as of May 2024

(in gigawatts)



Source: Figure created by CRS. Data from McKenzie Hubert and Vanessa Arjona, *Electrolyzer Installations in the United States*, U.S. Department of Energy (DOE) Hydrogen Program Record no. 24001, May 4, 2024, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24001-electrolyzer-installations-united-states.pdf.

Notes: Includes DOE categories "planned," "planned/under construction," "installed/commissioning," and "installed/operational" plants. Electrolyzers include polymer electrolyte membrane (PEM), solid oxide electrolysis cell (SOEC), and alkaline systems with capacity of 120 kW or greater. The full list of current or planned installations, with location, power (kW), and status, is available at the source cited above. According to the source, "this Record focuses on plants that have been funded (e.g., DOE projects or other financing already in place)."

Some of these projects are expected to take years to construct, and some may never go into operation. The IEA has found that 4% of global "large-scale projects for the production of low-emission hydrogen" that have been announced are under construction or have enough committed financial resources for the project to move to construction.[62]

Nuclear Power

Nuclear power can provide process heat, electricity, or both for commercial hydrogen production.[63] For electrolysis, nuclear power can generate the electricity needed to split water in an electrolyzer. Nuclear power may also generate the heat for high-temperature electrolysis, such

[61] Projected capacity is calculated based on under-construction and planned (firm commitments) projects. Totals exclude installations (planned, under construction, or current) with less than 120 kW capacity. McKenzie Hubert and Vanessa Arjona, *Electrolyzer Installations in the United States*, DOE Hydrogen Program Record no. 24001, May 4, 2024, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24001-electrolyzer-installations-united-states.pdf.

[62] IEA, *Towards Hydrogen Definitions Based on Their Emissions Intensity*, p. 7.

[63] For more information on nuclear power in hydrogen production, see DOE, Office of Nuclear Energy, "Infographic: Clean Hydrogen Powered by Nuclear Energy," November 9, 2022, https://www.energy.gov/ne/articles/infographic-clean-hydrogen-powered-nuclear-energy; and Section 2.2.2, "Hydrogen Production," in Shannon M. Bragg-Sitton et al., *Integrated Energy Systems: 2020 Roadmap*, DOE, Idaho National Laboratory, September 2020, pp. 15-18, https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_26755.pdf.

as electrolysis using a solid oxide electrolysis cell. For SMR and other reforming processes, nuclear energy can provide high-quality steam to replace natural gas boilers.[64]

The IEA has estimated emissions from electrolytic hydrogen using electricity from nuclear energy at 0.1-0.3 kg CO_2e/kg H_2.[65] This takes into account emissions from the mining and processing of uranium, which the IEA estimates at 2.4-6.8 g CO_2e/kWh, and the emissions-free process of creating nuclear energy at a power plant. See **Figure B-2** for emissions intensity comparisons of production methods.

The International Atomic Energy Agency (IAEA) developed its Hydrogen Calculator (HydCalc) and Hydrogen Economic Evaluation Program (HEEP) to estimate the cost of nuclear hydrogen production. One study using HydCalc and HEEP estimated the cost of electrolytic hydrogen production with nuclear power to be between $1.70/kg H_2 and $3.90/kg H_2.[66] Results from the study suggest that cost varies depending on the electricity price, the cost of operating the nuclear power plant, and the hydrogen production rate.

Nuclear hydrogen production is in the development stage in the United States. DOE's Office of Energy Efficiency and Renewable Energy and Office of Nuclear Energy are working with utilities to support nuclear hydrogen demonstration projects.[67] Nine Mile Point Nuclear Station began producing hydrogen in February 2023, becoming "the first-of-its-kind in the United States to generate clean hydrogen using nuclear power," according to DOE.[68]

Issues for Congress

Congressional support for hydrogen production pathways includes grants and tax credits. Current funding prioritizes projects that decrease emissions, lower costs, and support diversity in feedstock and geography compared with current production. These three priorities are outlined in the hydrogen provisions of P.L. 117-169, commonly known as the Inflation Reduction Act of 2022 (IRA), and P.L. 117-58, the Infrastructure Investment and Jobs Act (IIJA). In addition, the IIJA specifies that priority be given to hydrogen production projects that support domestic supply chains for materials and components; that partner with "tribal energy development organizations, Indian Tribes, Tribal organizations, Native Hawaiian community-based organizations, or territories or freely associated States"; that reduce imports; that improve energy efficiency; and that are located in natural gas-producing regions.[69]

[64] DOE, Office of Nuclear Energy, "Could Hydrogen Open New Markets for Nuclear?" June 24, 2020, https://www.energy.gov/ne/articles/could-hydrogen-open-new-markets-nuclear.

[65] IEA, *Towards Hydrogen Definitions Based on Their Emissions Intensity*, p. 40.

[66] The study cited estimates the cost of hydrogen using HydCalc and compares the result with similar studies that used HEEP. The levelized costs obtained using IAEA's HydCalc and HEEP, respectively, were compared as follows: Korea Advanced Power Reactor 1400 MW electricity costs are $2.60/kilogram (kg) (HydCalc) and $3.18/kg (HEEP); Russian VVER-1200 costs are $3.80/kg and $3.44/kg; Nine Mile Point NPP in New York costs are $1.70/kg and $4.85/kg; Davis-Besse Nuclear Power Plant (NPP) in Ohio costs are $3.90/kg and $3.09/kg; Arizona Public Service's Palo Verde NPP costs are $3.50/kg and $4.77/kg; and Prairie Island NPP in Minnesota costs are $3.63/kg and $0.69/kg. Reuben Joseph Soja et al., "Comparative Analysis of Associated Cost of Nuclear Hydrogen Production Using IAEA Hydrogen Cost Estimation Program," *International Journal of Hydrogen Energy*, vol. 48, no. 61 (July 19, 2023), Table 4, pp. 23373-23386, https://doi.org/10.1016/j.ijhydene.2023.03.133.

[67] DOE, Office of Nuclear Energy, "3 Nuclear Power Plants Gearing Up for Clean Hydrogen Production," November 9, 2022, https://www.energy.gov/ne/articles/3-nuclear-power-plants-gearing-clean-hydrogen-production.

[68] DOE, Office of Nuclear Energy, "Nine Mile Point Begins Clean Hydrogen Production," March 7, 2023, https://www.energy.gov/ne/articles/nine-mile-point-begins-clean-hydrogen-production.

[69] 42 U.S.C. §16161c.

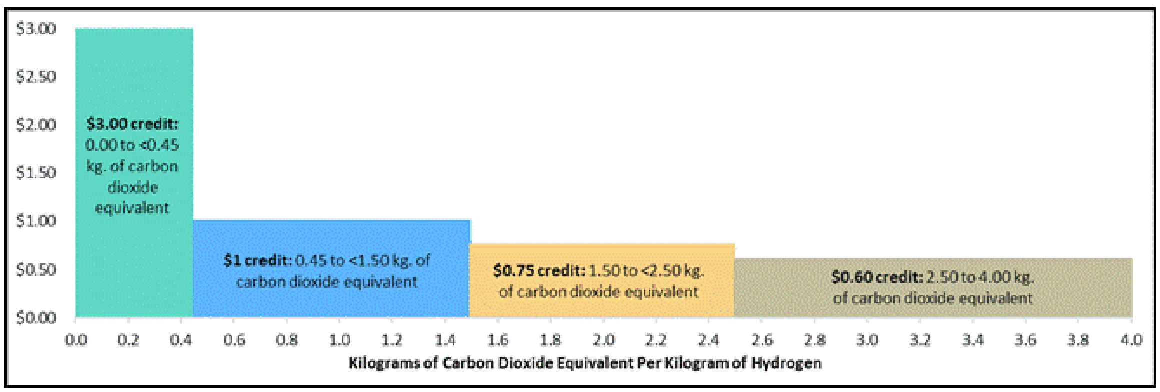
The IRA and IIJA provisions primarily support electrolysis and reforming pathways with CCS, as discussed below. Congress could consider maintaining, expanding, or decreasing existing support for low-emission hydrogen production. Congress could also consider supporting only certain pathways, or withdrawing support entirely.

The Clean Hydrogen Production Tax Credit (45V) and Emissions

One policy aimed at promoting the production of hydrogen is the so-called 45V tax credit. The tax credit was established by P.L. 117-169.[70] The value of the credit for qualifying facilities varies by the CO_2 emissions intensity of the hydrogen production pathway. To qualify for the tax credit, a facility must produce hydrogen with a lifecycle greenhouse gas emissions rate of no greater than 4 kg CO_2e/kg H_2 (referred to as *qualified clean hydrogen*, or QCH). The value of the tax credit increases with decreasing emissions intensity, as shown in **Figure 4**. To measure emissions, statute requires the use of the most recent Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model to assess emissions through the point of production (also known as *well-to-gate*).[71]

Figure 4. Value of the Clean Hydrogen Production Tax Credit

(dollars per kilogram of hydrogen produced)



Source: CRS analysis of 26 U.S.C. §45V. CRS In Focus IF12602, *The Clean Hydrogen Production Credit: How the Incentives are Structured*, by Nicholas E. Buffie and Martin C. Offutt.

Notes: Values of credits displayed are before any reductions for the use of tax-exempt bonds. Credits shown are for firms meeting applicable wage and apprenticeship requirements.

The structure of the 45V emissions rate functions as a series of "credit cliffs." The value of the credit may rise or fall based on small changes in CO_2e emissions at the edge of a cliff. However, away from the edge of the cliff the credit value remains constant even with further small emissions reductions. Eliminating the "credit cliffs" could incentivize incremental emissions reductions. If Congress is interested in incentivizing more incremental emissions decreases, it could consider requiring the tax credit value to increase or decrease gradually.

[70] For further discussion, see CRS In Focus IF12602, *The Clean Hydrogen Production Credit: How the Incentives are Structured*, by Nicholas E. Buffie and Martin C. Offutt.

[71] The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model is developed by DOE's Argonne National Laboratory to assess lifecycle environmental effects by simulating the energy use and emissions outputs of various process and fuel combinations. This includes emissions associated with feedstock growth, processing and transportation, fuel combustion, and hydrogen production facility processes. DOE, *Guidelines to Determine Well-to-Gate Greenhouse Gas (GHG) Emissions of Hydrogen Production Pathways Using 45VH2-GREET 2023*, December 2023, p. 7, https://www.energy.gov/sites/default/files/2023-12/greet-manual_2023-12-20.pdf.

Some have expressed concern that the GREET model may not accurately measure the full scope of emissions associated with hydrogen production. For example, the National Petroleum Council (NPC), an advisory committee to the Secretary of Energy, pointed out that the version of GREET used to calculate emissions for the tax credit, 45VH2-GREET, automatically sets the level of fugitive methane emissions for production methods that use natural gas; however, as the NPC notes, some studies have shown that fugitive methane emissions are highly variable.[72] If the fugitive methane emissions set in GREET do not reflect actual emissions, some hydrogen producers may receive higher or lower credits than they have earned, and the overall emissions picture may be distorted. Some Members of Congress have also pointed out this discrepancy.[73]

Congress has shown interest in measuring emissions that occur before production. For FY2024, the Senate Appropriations Committee recommended up to $3 million in funding to examine upstream methane leakage and other components of hydrogen production lifecycle emissions.[74]

Congress could require GREET updates to include more inputs relating to methane, such as the natural gas field, the pipeline network or transportation method used, and proximity to the field. Updates designed to capture a fuller scope of emissions could also require inputs for emissions created by other upstream and midstream processes such as manufacturing technology. For renewable electrolysis, this may include manufacturing solar panels or wind turbines. On the other hand, data uncertainties may cause difficulties in verifying inputs.

Federal Research and Development (R&D) Activities

Federal research and development (R&D) activities support many hydrogen production pathways that include fossil fuels, renewable energy, biomass, and nuclear power as feedstocks and energy sources. Congress could consider maintaining, increasing, or decreasing support for these pathways.

Congress funds R&D programs for hydrogen production through several DOE offices, including the Office of Energy Efficiency and Renewable Energy (EERE), the Office of Fossil Energy and Carbon Management (FECM), the Office of Nuclear Energy (NE), and the Office of Science. The Hydrogen Program, led by the Hydrogen and Fuel Cell Technologies Office (HFTO, an office within EERE), includes more than 400 projects with more than 200 companies and universities and 15 National Labs.[75]

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[72] The National Petroleum Council cites two studies that found higher averages: "For example, Alvarez et al., 2018, found a 2.3% national average, while Vallejo et al., 2023, points to a leakage rate of approximately 1% in the Marcellus Basin and 4% in the Permian Basin." National Petroleum Council, "Chapter 6 – Policy and Regulation," in *Harnessing Hydrogen: A Key Element of the U.S. Energy Future* (draft), April 23, 2024, p. 15, https://harnessinghydrogen.npc.org/files/H2-CH_6-Policy-2024-04-23.pdf; Ramón A. Alvarez et al., "Assessment of Methane Emissions from the U.S. Oil and Gas Supply Chain," *Science*, vol. 361, no. 6398 (June 21, 2018), pp. 186-188, https://doi.org/10.1126/science.aar7204; Sandra Valeria Vallejo Vargas, "Geospatial Life Cycle Assessment of Blue Hydrogen Production Pathways: Case Study of the Marcellus Shale and Permian Basin" (master's thesis, University of Texas at Austin, 2023).

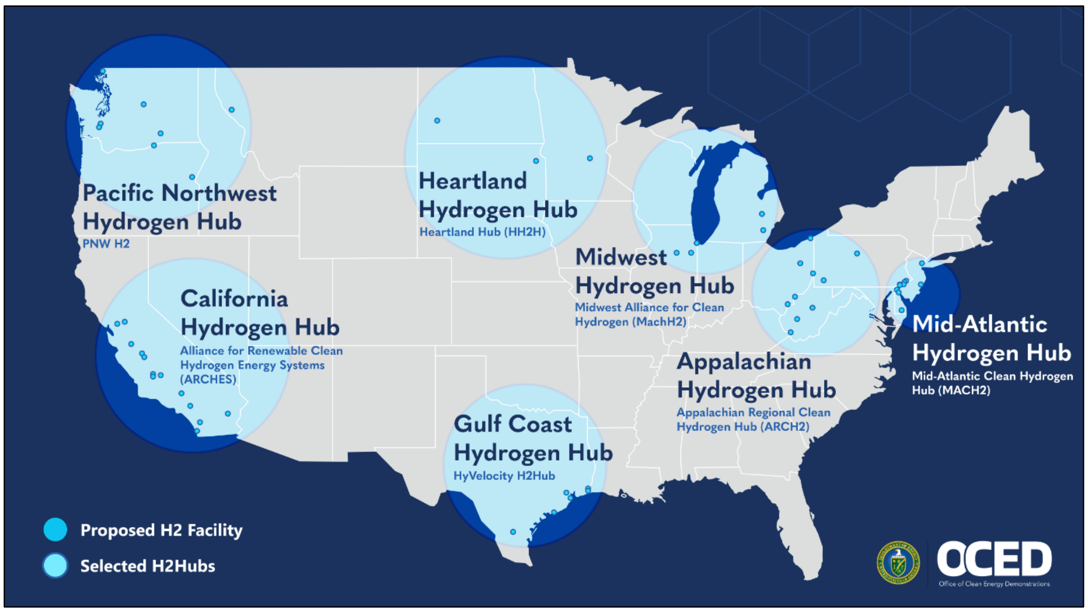
[73] For example, see Letter from Sen. Robert P. Casey, Jr., to President Joseph R. Biden, May 24, 2024, https://www.casey.senate.gov/imo/media/doc/45v_implementation_letter_.pdf; Letter from Rep. Jamie Raskin et al. to Janet Yellen, Secretary of the U.S. Department of the Treasury, and Ethan Zindler, Climate Counselor, U.S. Department of the Treasury, December 7, 2023, https://raskin.house.gov/_cache/files/f/3/f3cdbda3-b4e6-4894-b5f0-fd22e8c8dce6/948623656BCC3E1C5F54ACF203659467.letter-to-treasury-on-strong-climate-standards-in-45v-implementation-raskin-beyer.pdf.

[74] S.Rept. 118-72, as incorporated by reference in the joint explanatory statement to the Consolidated Appropriations Act, 2024 (P.L. 118-42).

[75] Sunita Satyapal, Director, Hydrogen and Fuel Cell Technologies Office, *2022 AMR Plenary Session*, June 6, 2022, https://www.energy.gov/sites/default/files/2022-06/hfto-amr-plenary-satyapal-2022-1.pdf.

The IIJA established the Regional Clean Hydrogen Hubs program.[76] Hydrogen hubs are emerging centers of activity involving hydrogen production, transport, delivery, and end use to provide energy services, such as mobility, goods movement, and heat for manufacturing processes. Selection criteria ensured pathway and geographic diversity. Statute mandated that at least one regional clean hydrogen hub use fossil fuels, at least one use renewable energy, and at least one use nuclear energy as feedstocks. Selection criteria for the Regional Clean Hydrogen Hubs program were designed to encourage location of hubs in different regions of the country. The statute required that at least two hubs be located in regions with natural gas resources.[77] The seven finalists for the initial $7 billion are shown in **Figure 5**. According to DOE's Office of Clean Energy Demonstrations page for the hub selections, three finalists plan to incorporate natural gas into hydrogen production processes: the Appalachian Hydrogen Hub, the Gulf Coast Hydrogen Hub, and the Midwest Hydrogen Hub.

Figure 5. Selected Regional Clean Hydrogen Hubs



Source: U.S. Department of Energy, Office of Clean Energy Demonstrations, "Regional Clean Hydrogen Hubs Selections for Award Negotiations," https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations, accessed June 5, 2024.

Notes: H2 = hydrogen. There are no regional hubs in Alaska or Hawaii.

In hearings during the 117th Congress, some Members expressed concern over the cost of hydrogen, particularly when produced by electrolysis, and expressed support for cost-competitive clean hydrogen.[78] Congress has sought to address the cost of clean hydrogen with the Clean

[76] See CRS Report R47289, *Hydrogen Hubs and Demonstrating the Hydrogen Energy Value Chain*, by Martin C. Offutt.

[77] P.L. 117-58, §40312 (3)(D).

[78] These include U.S. Congress, House Committee on Science, Space, and Technology, *H2success: Research and Development to Advance a Clean Hydrogen Future*, hearings, 117th Congress, 2nd sess., February 17, 2022; U.S. Congress, Senate Committee on Energy and Natural Resources, *Opportunities and Challenges in Using Clean Hydrogen in the Transportation, Utility, Industrial, Commercial, and Residential Sectors*, hearings, 117th Congress, 2nd sess., February 10, 2022, S.Hrg.117-274; U.S. Congress, House Select Committee on the Climate Crisis, *Manufacturing a Clean Energy Future: Climate Solutions in America*, hearings, 117th Congress, 2nd sess., February 2, (continued...)

Hydrogen Electrolysis Program. Created by the IIJA (P.L. 117-58, §816; 42 U.S.C. §16161d), the program established a goal of reducing the cost of electrolytic hydrogen to less than $2/kg by 2026 and to $1/kg by 2031 (compared with an estimated $5-$7/kg in 2023[79]). The IIJA provided $1 billion for FY2022-FY2026 for the program. Under the program, DOE is directed to fund research for AEC and PEM and high-temperature electrolyzers, among other technologies. DOE has established further clean hydrogen[80] cost goals, including the Hydrogen Shot goal of "$1 per 1 kilogram in 1 decade," or "$1/kg H_2 by 2031," not including delivery and dispensing, for production using electrolyzers.[81] In its 2020 Hydrogen Program Plan, DOE lists "reduce costs and improve the performance and durability of hydrogen production, delivery, storage, and conversion systems" as an activity focus.[82]

Fossil Fuel Pathways

Major R&D programs mentioned in this report include funding for hydrogen production pathways that use fossil fuels. The 45V tax credit applies to "clean hydrogen" produced "from any fuel source."[83] Similarly, the Regional Clean Hydrogen Hubs program requires diversity in feedstock.

Some debate concerns the appropriate level of support for pathways using fossil fuels plus CCS. Some climate and environmental groups oppose any use of fossil fuels to produce hydrogen.[84] Some Members of Congress have also expressed concern that facilities using fossil fuels to produce electrolytic hydrogen may qualify for the 45V tax credit.[85] On the other hand, some

2022; U.S. Congress, Senate Committee on Energy and Natural Resources, *The President's Budget Request for the Department of Energy for Fiscal Year 2022*, hearings, 117th Congress, 1st sess., June 15, 2021, S.Hrg. 117-140.

[79] The 2023 electrolytic hydrogen cost estimate is from DOE, EERE, *Hydrogen and Fuel Cell Technologies Office Multi-Year Program Plan*, May 2024, Table 1.1, p. 15, https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office-multi-year-program-plan.

[80] Section 40315 of the IIJA creates a new Section 822 of the Energy Policy Act of 2005, "Clean Hydrogen Production Qualifications," and defines "clean hydrogen" as hydrogen produced with 2 kg or less of CO_2e per kg of hydrogen (≤2 kg $CO_2e/kg\ H_2$). The IIJA authorized the Secretary of Energy to publish an initial standard for the "carbon intensity of clean hydrogen production" (the Clean Hydrogen Production Standard, or CHPS). DOE finalized the standard in June 2023 and established the initial standard at 4 kg $CO_2e/kg\ H_2$. DOE is required to update the standard within five years of setting it initially.

[81] DOE, EERE, "Hydrogen Shot," https://www.energy.gov/eere/fuelcells/hydrogen-shot, accessed March 5, 2024.

[82] DOE, *Department of Energy Hydrogen Program Plan*, November 2020, p. 14, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/hydrogen-program-plan-2020.pdf.

[83] "The terms 'clean hydrogen' and 'hydrogen' mean hydrogen produced in compliance with the greenhouse gas emissions standard established under section 822(a), including production from any fuel source." P.L. 117-58, §40312(1).

[84] Examples include the Sierra Club and Earthjustice. Cara Fogler, "Hydrogen: Future of Clean Energy or a False Solution?" Sierra Club, January 4, 2022, https://www.sierraclub.org/articles/2022/01/hydrogen-future-clean-energy-or-false-solution; Earthjustice, "Earthjustice Statement on DOE's Regional Hydrogen Hub Announcement," press release, October 13, 2023, https://earthjustice.org/press/2023/earthjustice-statement-on-does-regional-hydrogen-hub-announcement.

[85] For example, see Letter from Rep. Jamie Raskin et al. to Janet Yellen, Secretary of the U.S. Department of the Treasury, and Ethan Zindler, Climate Counselor, U.S. Department of the Treasury, December 7, 2023, https://raskin.house.gov/_cache/files/f/3/f3cdbda3-b4e6-4894-b5f0-fd22e8c8dce6/948623656BCC3E1C5F54ACF203659467.letter-to-treasury-on-strong-climate-standards-in-45v-implementation-raskin-beyer.pdf; and Letter from Sen. Sheldon Whitehouse et al. to Janet Yellen, Secretary of the U.S. Department of the Treasury, et al., September 11, 2024, https://www.whitehouse.senate.gov/wp-content/uploads/2024/09/Letter-to-Biden-Administration-re-45V-Hydrogen-Tax-Credit-09-11-2024.pdf.

Members see SMR plus CCS as a viable option for producing low-emission hydrogen.[86] Some have encouraged expanding federal support, such as the 45V tax credit, to pathways that use fossil fuels other than natural gas[87] or to hydrogen production methods not currently covered under the tax credit, such as geologic hydrogen.[88] Other Members oppose measures that support hydrogen production pathways that use natural gas, sometimes because of the emissions associated with upstream natural gas production and transportation.[89]

If Members are interested in prioritizing specific feedstocks, they could consider changing funding for different feedstocks or production technologies. Members could also consider changing the hydrogen production tax credit by expanding access to more pathways or increasing support for specific pathways.

Feedstock Supply

Another aspect that Congress may consider regarding specific hydrogen production pathways is the supply security of feedstocks. Considerations may include planning for geographic availability of resources—for example, locating production sites near feedstocks and a water source—and making decisions about resource use, that is, how to use (or conserve) fossil fuels, electricity, and water.

Congress established as one of the purposes of the IJIA "developing a robust clean hydrogen supply chain and workforce by prioritizing clean hydrogen demonstration projects in major shale gas regions."[90] Statute does not define the characteristics that determine a "region"; such characteristics could include size, proximity to resources, and proximity and availability of upstream and midstream infrastructure.

For electrolysis, an emerging concern is anticipated increased electricity demand around the country and the potential that new demand could outpace development of new supply.[91]

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[86] For example, see Sen. Sherrod Brown, "Brown Announces Nearly $1.5 Million for The Ohio State University to Advance Clean Hydrogen Technology," press release, August 23, 2023, https://www.brown.senate.gov/newsroom/press/release/sherrod-brown-announces-nearly-15-million-the-ohio-state-university-advance-clean-hydrogen-technology; Letter from Rep. Chris Deluzio to President Joseph R. Biden, December 12, 2023, https://deluzio.house.gov/media/press-releases/rep-deluzio-calls-president-biden-support-blue-hydrogen-and-union-jobs-western; and Sen. Joe Manchin, "West Virginia Wins the $1 Billion Hydrogen Hub," https://www.energy.senate.gov/services/files/DE8A0005-92F0-441E-82B5-A3137C183AD3.

[87] For example, see Letter from Sen. Robert P. Casey, Jr., to President Joseph R. Biden, May 24, 2024, https://www.casey.senate.gov/news/releases/casey-pushes-for-changes-to-proposed-hydrogen-production-tax-credit.

[88] *Geologic hydrogen* generally refers to two sources of hydrogen: (1) deposits of hydrogen naturally confined in underground reservoirs (sometimes referred to as *white hydrogen*) and (2) hydrogen that may be produced underground by stimulating specific types of rocks to break down water. Geologic hydrogen was discussed during U.S. Congress, Senate Committee on Energy and Natural Resources, *Full Committee Hearing to Examine the Opportunities and Challenges Associated with Developing Geologic Hydrogen in the United States*, hearings, 118th Cong., 2nd sess., February 28, 2024.

[89] For example, see Letter from Sen. Sheldon Whitehouse et al. to Janet Yellen, Secretary, U.S. Department of the Treasury, October 16, 2023, https://www.whitehouse.senate.gov/wp-content/uploads/imo/media/doc/letter_to_treasury_on_45v_hydrogen_tax_credit.pdf.

[90] IIJA; P.L. 117-58, §40322 (b)(4).

[91] For example, former Federal Energy Regulatory Commission Commissioner Allison Clements reportedly said, "Given that new energy-intensive customers are 'already making decisions about where they're going to locate based on whether or not there is available capacity on the grid, we have to think really hard about how we model and try to put parameters around that uncertainty.'" Daniel Moore, "Hydrogen's Power Demand Calls for Grid Planning, Regulator Says," *Bloomberg Law*, June 12, 2024, https://news.bloomberglaw.com/environment-and-energy/hydrogens-power-demand-calls-for-grid-planning-regulator-says. For an example of an assessment that finds potential future (continued...)

Electrolyzers may be competing with other new electricity users, such as data centers, manufacturing centers, transportation, and other industries that may undergo electrification. This competition could result in reliability and affordability concerns, as well as other potential concerns from affected communities.

All current hydrogen production pathways use water. Hydrogen production sites may compete for water resources with other purposes, such as irrigation, public drinking water, energy production, recreation, conservation, and other industries and uses. This may especially be an issue should hydrogen be produced in high-water-stress regions, such as regions in drought or with little annual rainfall. Congress could consider the best use or conservation of water resources, with input from communities impacted, or consider supporting the use of nonfreshwater resources (e.g., treated wastewater, desalinated seawater).

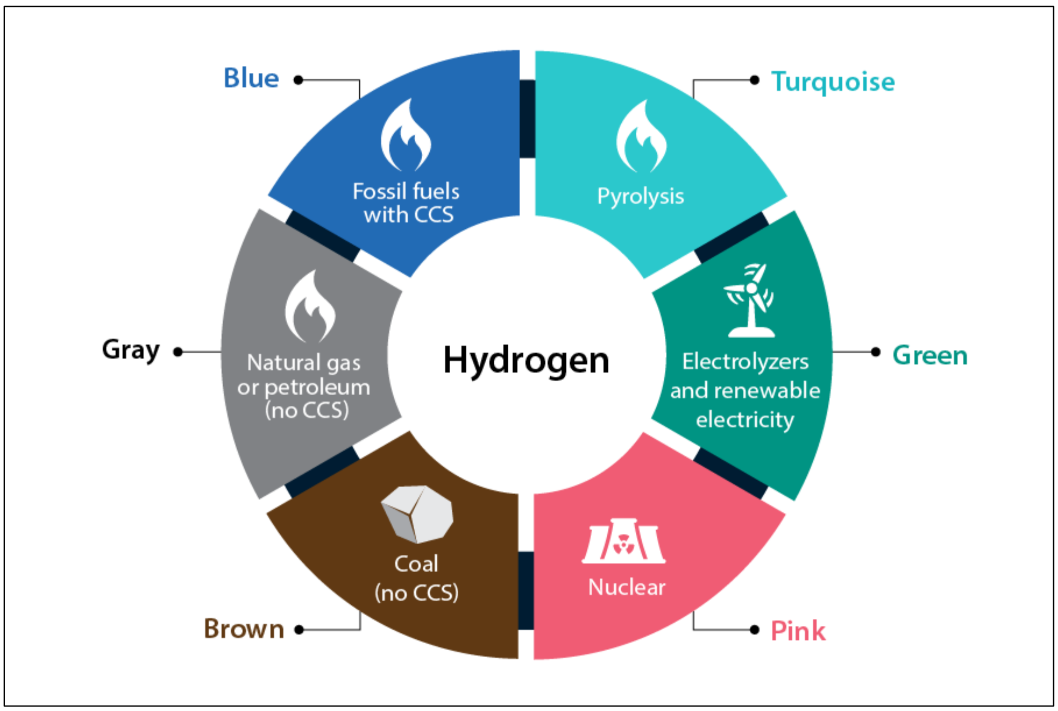
electricity shortages, see North American Electrical Reliability Corporation, *2023 Long-Term Reliability Assessment*, December 2023, https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_LTRA_2023.pdf.

Appendix A. Coding Hydrogen: Hydrogen "Colors" and "Clean" Hydrogen

Hydrogen "Colors"

Some hydrogen producers, marketers, governments, and other organizations refer to hydrogen using a color spectrum (see **Figure A-1**). The labels are not standardized.[92] Hydrogen produced via electrolyzers using electricity from renewable energy sources is generally referred to as "green hydrogen"; some stakeholders only support the production of "green hydrogen."[93] Some refer to hydrogen produced from fossil fuels (typically SMR) as "blue hydrogen," if the produced carbon dioxide is captured and sequestered. If CCS is not used, hydrogen produced from coal may be referred to as "brown hydrogen" and hydrogen produced from natural gas or petroleum may be referred to as "gray hydrogen."[94] "Pink hydrogen" may refer to hydrogen produced with nuclear energy. "Turquoise hydrogen" may refer to hydrogen produced by pyrolysis of hydrocarbons. Some pathways do not have a "color"—for example, electrolysis with fossil fuels.

Figure A-1. Hydrogen "Colors"



Source: Figure created by CRS.

[92] For discussion of the implications of not having standardized labels, see IEA, *Towards Hydrogen Definitions Based on Their Emissions Intensity*, pp. 11-12.

[93] For example, "the Sierra Club only supports the use of green hydrogen—hydrogen made through electrolysis that is powered by renewable energy." Cara Fogler, "Hydrogen: Future of Clean Energy or a False Solution?" Sierra Club, January 4, 2022, https://www.sierraclub.org/articles/2022/01/hydrogen-future-clean-energy-or-false-solution.

[94] CRS Report R46436, *Hydrogen in Electricity's Future*, by Richard J. Campbell; EIA, "Hydrogen Explained: Production of Hydrogen," https://www.eia.gov/energyexplained/hydrogen/production-of-hydrogen.php, last updated June 23, 2023.

Notes: "Colors" of hydrogen are not standardized. Some pathways do not have a "color"—for example, electrolysis with fossil fuels.

What Is "Clean" Hydrogen?

Congress has used CO_2 emissions intensity as a measure to define "clean" hydrogen. P.L. 117-169, commonly known as the Inflation Reduction Act of 2022, defines hydrogen that qualifies for the 45V tax credit as "hydrogen which is produced through a process that results in a *lifecycle* greenhouse gas emissions rate of not greater than 4 kilograms of carbon dioxide equivalent (CO_2e) per kilogram of hydrogen" (emphasis added). See "The Clean Hydrogen Production Tax Credit (45V) and Emissions" for further discussion.

The Infrastructure Investment and Jobs Act (IIJA; P.L. 117-58) defines clean hydrogen for the purposes of producing hydrogen from "renewable, fossil fuel with carbon capture, utilization, and sequestration technologies, nuclear, and other fuel sources using any applicable production technology" as "hydrogen produced with a carbon intensity equal to or less than 2 kilograms of carbon dioxide-equivalent produced *at the site of production* per kilogram of hydrogen produced" (emphasis added). DOE's Clean Hydrogen Production Standard (CHPS), developed to meet the IIJA requirements, establishes a target of 4.0 kg CO_2e/kg H_2 for *lifecycle* greenhouse gas emissions.[95] CHPS is not a regulatory standard, but Regional Clean Hydrogen Hubs funded through the IIJA are required by the law to "demonstrably aid achievement" of CHPS by mitigating emissions as much as possible.

Clean hydrogen, as defined for these policies, is not limited to a specific production pathway but is rather defined by emissions intensity. Through the Regional Clean Hydrogen Hubs, Congress has called for the establishment of clean hydrogen hubs that use a variety of pathways: fossil fuels (paired with carbon capture), renewable energy, and nuclear energy.

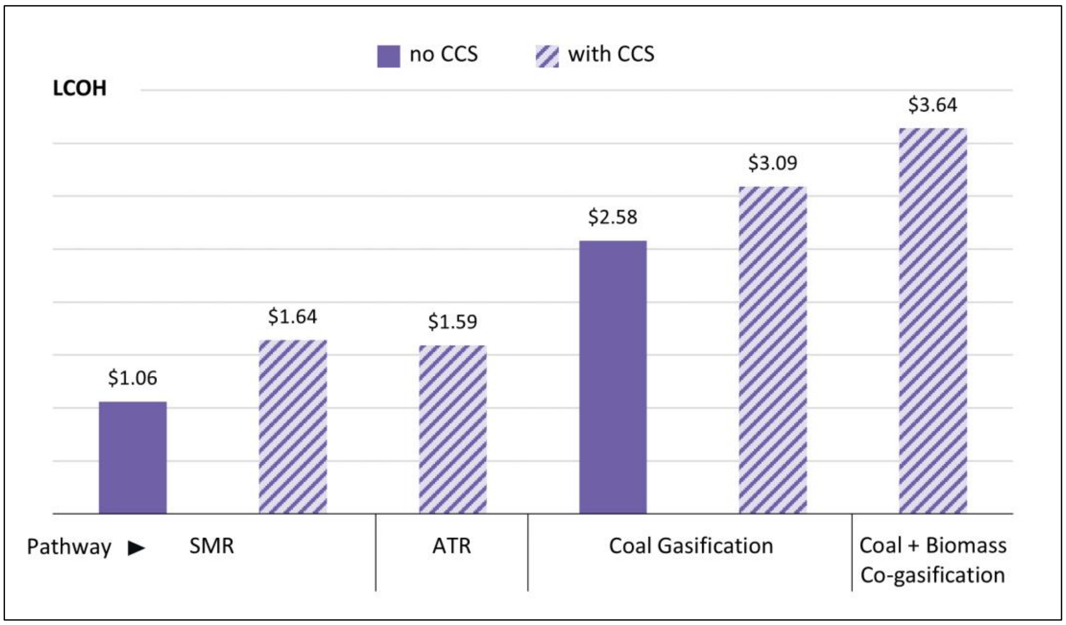
[95] DOE, "Clean Hydrogen Production Standard Guidance," https://www.hydrogen.energy.gov/library/policies-acts/clean-hydrogen-production-standard, accessed November 22, 2023.

Appendix B. Comparing Hydrogen Production Pathways

Figure B-1 compares the levelized cost of hydrogen (LCOH) produced using fossil fuels as the hydrogen feedstocks, with and without CCS, as estimated by researchers at the National Energy Technology Laboratory (NETL). The NETL report analyzed six hydrogen production pathways: two SMR cases (with and without CCS), one ATR case (with CCS), two coal gasification cases (with and without CCS), and one coal/biomass co-gasification case (with CCS). Each case analyzed in the report recovered greater than 90% of the CO_2 entering the plant boundary (direct emissions).

Figure B-1. Levelized Cost of Hydrogen (LCOH) of Selected Fossil Fuels

(dollars per kilogram H_2)



Source: Figure created by CRS. Data from Eric Lewis et al., *Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies*, National Energy Technology Laboratory, April 12, 2022, Exhibit 5-9, p. 277.

Notes: SMR = steam methane reforming. ATR = autothermal reforming. The cost of the carbon capture and storage (CCS) pathways includes transport and storage of CO_2, which is assumed to be $10 per metric ton of CO_2. Hydrogen production plants are assumed to be located at a generic plant site in the midwestern United States; costs for specific facilities may vary. Lewis et al. do not specify whether they consider tax credits or other incentives.

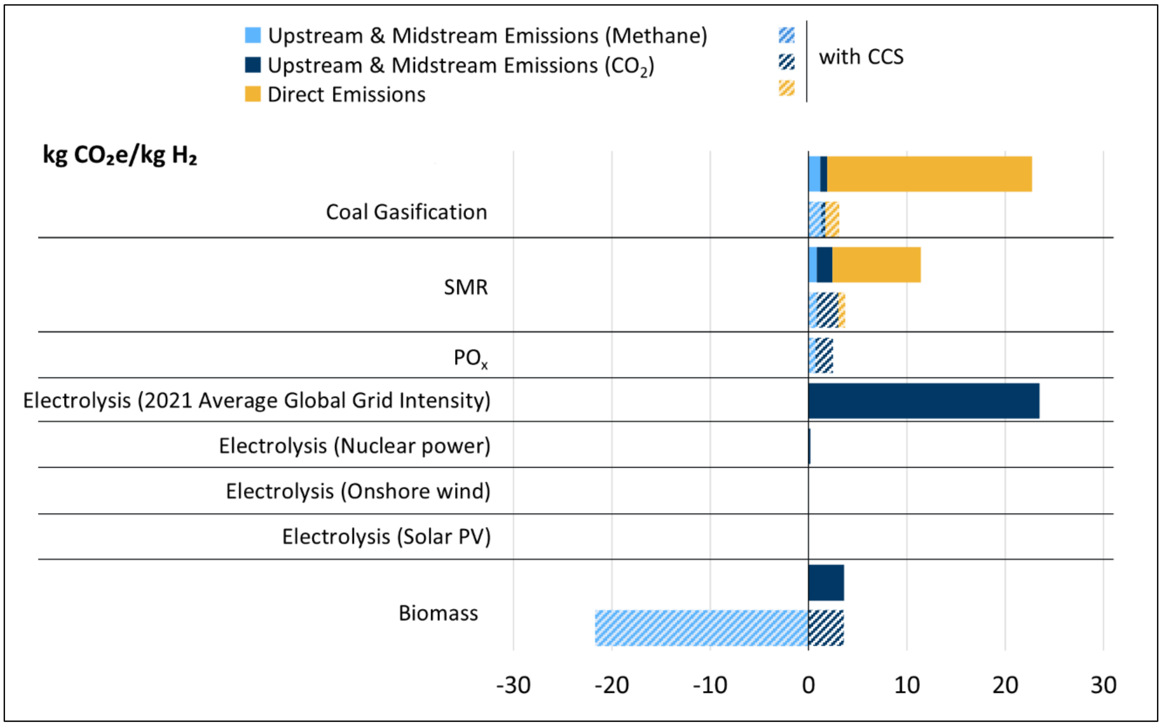
Figure B-2 compares estimated emissions from different parts of the value chain of select hydrogen production pathways based on International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) methodology.[96] IPHE upstream and midstream emissions estimates include median emissions of CO_2 and methane occurring during the extraction, processing, and supply of fuels (coal, natural gas) or production, processing, and transport of biomass. Direct emissions are from the hydrogen production plant. According to IPHE methodology, onshore wind, solar

[96] IPHE is an international intergovernmental organization promoting hydrogen technologies by, among other things, harmonizing codes and standards between members. The United States is a member.

photovoltaic, hydropower, and geothermal energy are considered to have zero upstream and direct emissions; therefore, electrolytic hydrogen produced via these pathways is considered to have zero emissions.[97]

Figure B-2. Estimated Upstream, Midstream, and Direct Emissions from Hydrogen Production

Figure is interactive in the HTML version of this report.



Source: Figure created by CRS. Data from International Energy Agency (IEA), "Comparison of the Emissions Intensity of Different Hydrogen Production Routes, 2021," charts, last updated June 29, 2023, https://www.iea.org/data-and-statistics/charts/comparison-of-the-emissions-intensity-of-different-hydrogen-production-routes-2021.

Notes: kg = kilogram. CO_2e = carbon dioxide equivalent. CCS = carbon capture and storage. PV = photovoltaic.

[97] IEA, *Towards Hydrogen Definitions Based on Their Emissions Intensity*, p. 40.

Appendix C. Glossary of Selected Terms

45V – Section 45V of the Internal Revenue Code, which provides a tax credit for hydrogen production meeting specified greenhouse gas emissions limits; *see "The Clean Hydrogen Production Tax Credit (45V) and Emissions"*

alkaline electrolysis cell (AEC) – electrolytic hydrogen production process that occurs in a liquid alkaline solution; sometimes referred to as *alkaline water electrolysis* (AWE)

alkaline water electrolysis (AWE) – electrolytic hydrogen production process that occurs in a liquid alkaline solution; sometimes referred to as *alkaline electrolysis cell* (AEC)

autothermal reforming (ATR) – hydrogen production method in which gasification and a water-gas shift occur in the same reactor in the presence of pure oxygen and at a temperature greater than 1,000°C; most commonly uses natural gas as the hydrogen feedstock; *see "Partial Oxidation (POX) and Autothermal Reforming (ATR)"*

bar – unit of pressure

biomass – organic matter that can be converted into energy

biomass-derived liquid reforming – process similar to SMR that can convert liquid biomass into hydrogen

byproduct hydrogen – hydrogen produced as a result of processes that are not for the purpose of producing hydrogen, such as processes for producing chlorine and sodium hydroxide

captive hydrogen – hydrogen that is produced by a consumer for internal use

carbon capture and storage (or sequestration) (CCS) – process intended to capture anthropogenic (human-generated) CO_2 at its source, transport it to a storage or sequestration site, and store it permanently underground; *see "Hydrogen Production and Carbon Capture Technologies"*

carbon capture, utilization, and storage (CCUS) – process intended to capture anthropogenic (human-generated) CO_2 at its source, potentially transport it, and convert it into chemicals, cements, plastics, and other products[98]

carbon dioxide equivalent (CO_2e) – the number of metric tons of CO_2 emissions with the same global warming potential as one metric ton of another greenhouse gas

CHPS – Clean Hydrogen Production Standard; standard for the "carbon intensity of clean hydrogen production"[99]

Clean Hydrogen Production Tax Credit (45V) – *see "The Clean Hydrogen Production Tax Credit (45V) and Emissions"*

coal gasification – process producing hydrogen from coal; *see "Coal Gasification"*

co-gasification – gasification of multiple solid feedstocks

electrolysis – process by which electricity splits water into oxygen (O_2) and H_2 in an electrolyzer; *see "Water Electrolysis"*

[98] For more on CCS and CCUS, see CRS Report R44902, *Carbon Capture and Sequestration (CCS) in the United States*, by Angela C. Jones and Ashley J. Lawson.

[99] See note 80.

electrolyzer – consists of two electrodes (an anode and a cathode) joined by an electrical circuit but separated by an electrolyte membrane

ESMR – electrified steam methane reforming (SMR); SMR process that uses electrically heated reformers (instead of combusting natural gas for heat)

GREET – Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation; model for assessing emissions through the point of production

HEEP – Hydrogen Economic Evaluation Program; developed by the International Atomic Energy Agency to estimate the cost of nuclear hydrogen production

HydCalc – Hydrogen Calculator; developed by the International Atomic Energy Agency to estimate the cost of nuclear hydrogen production

hydrogen feedstocks – sources of hydrogen such as water, fossil fuels, and biomass

hydrogen hubs – centers of activity involving hydrogen production, transport, delivery, and end use to provide modern energy services such as mobility, goods movement, heat for manufacturing processes, and other services

kt – kilotons (1,000 tons)

kW – kilowatt (1,000 watts)

kWh – kilowatt-hour

levelized cost of hydrogen (LCOH) – "the amount of revenue required per kilogram of H_2 produced during the plant's operational life to meet all capital and operational costs"[100]

merchant hydrogen – hydrogen that is produced and sold to a consumer

MMT – million metric tons

MW – megawatt (1 million watts)

natural gas reforming – *see* steam methane reforming

on-purpose hydrogen – hydrogen that is produced intentionally

PEM – polymer electrolyte membrane; sometimes referred to as *proton exchange membrane*

PO_X – partial oxidation

pressure swing adsorption (PSA) – process that removes impurities (such as CO_2) from a gaseous stream, resulting in a stream of high-purity hydrogen; used in hydrogen production processes that use carbon-based feedstocks

pyrolysis – the gasification through heat of methane sources (natural gas or biogas) without oxygen; *see "Pyrolysis"*

qualified clean hydrogen (QCH) – hydrogen that is "produced through a process that results in a lifecycle greenhouse gas emissions rate not greater than four kilograms of CO_2e per kilogram of hydrogen" (as defined in Section 45V of the Internal Revenue Code)

slag – solid waste/residue

[100] Eric Lewis et al., *Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies*, NETL, April 12, 2022, pp. 48-49.

steam methane reforming (SMR) – process for producing hydrogen from natural gas; also called *natural gas reforming*; *see "Steam Methane Reforming (SMR)"*

syngas – synthesis gas

water-gas shift reaction – chemical reaction used that reacts carbon monoxide (CO) with steam over a catalyst to produce a gaseous stream that is mostly H_2 and CO_2;[101] used in hydrogen production pathways that use carbon-based feedstocks

Author Information

Lexie Ryan
Analyst in Energy Policy

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Disclaimer

[101] For more on water-gas shift reactions, see NETL, "6.2.6. Water Gas Shift & Hydrogen Production," https://netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/water-gas-shift, accessed May 7, 2024.