Frequently Asked Questions About Hydrogen and Fuel Cells

June 2023 – Draft

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1. What is hydrogen used for?

Hydrogen is used as a chemical raw material (or feedstock) for industrial applications and as a fuel that can generate electricity and/or heat when either used in a fuel cell or combusted (e.g., in a turbine). Most of the hydrogen consumed in the United States today is used by industry for petroleum refining, fertilizer production, and the production of chemicals, such as methanol. These uses currently drive the demand for hydrogen, which is roughly 10 million metric tons in the United States and more than 90 million metric tons globally.[1]

In recent years, hydrogen has been used in new applications such as fuel cells to power forklifts, buses, cars, and generators for backup power, with substantial growth expected in many of these applications.[2] The long-term strategy laid out by the U.S. Department of Energy includes employing clean hydrogen for high-impact uses, particularly those hard-to-decarbonize applications like heavy-duty transportation, industrial needs like steel making, and for energy storage to support a renewable-powered grid. Many of the emerging applications employ fuel cells to generate electricity; however, hydrogen can also be combusted to generate high temperatures critical to several industrial applications.

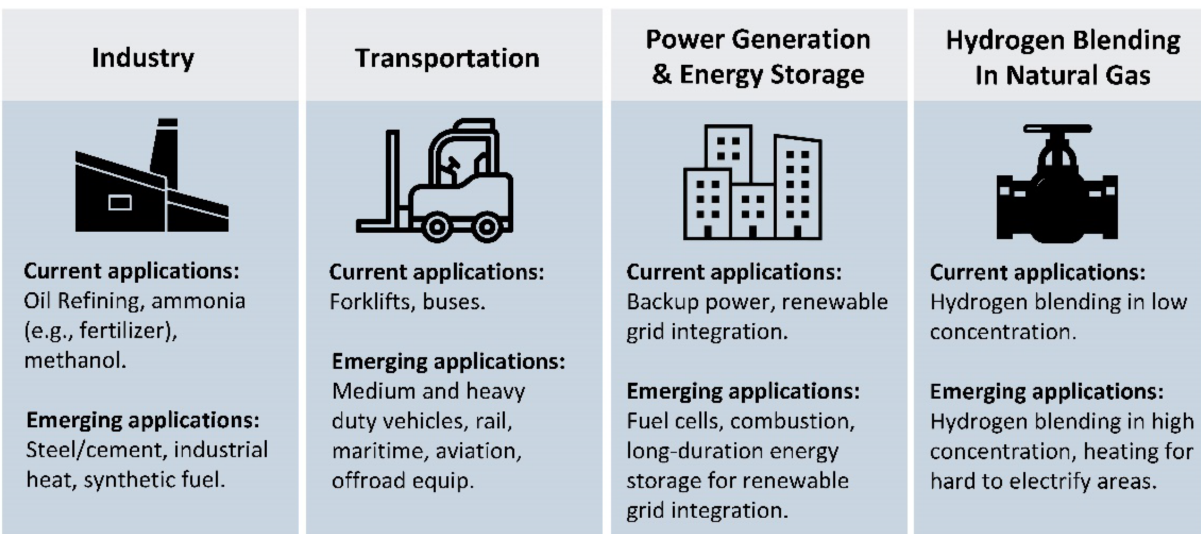

Figure 1: Examples of existing and emerging end uses for hydrogen

2. Why hydrogen?

Hydrogen is the most abundant element in the universe and can be produced from diverse energy resources, including renewables, nuclear power, and fossil fuels with carbon capture and storage. Once you produce hydrogen, which is a gas under normal temperature and pressures, it can then be directly used as a chemical feedstock[i] (e.g., to produce ammonia or methanol) and can also be used to generate energy with technologies like fuel cells or combustion turbines. It is one part of a comprehensive energy portfolio and offers versatility as a carbon-free fuel or feedstock to enable deep decarbonization as well as energy security,

[i] Feedstocks are starting materials that hydrogen can be produced from, also referred to as raw materials.

resiliency, and economic prosperity. In fact, many countries are recognizing that to meet their climate goals, they cannot rely on electrification alone and will need to import or produce carbon-free fuels like hydrogen, especially for hard-to-decarbonize applications such as heavy-duty transportation and industrial applications like producing fertilizer or manufacturing steel. Hydrogen can also be an enabler of renewables—it can store energy during peak power production from renewables such as solar and wind and then be used to produce electricity when wind and solar are not producing enough to meet demands. The stored energy can be controlled to precisely meet the needs of users (what the power industry calls "dispatchable" generation). Hydrogen can also support renewables and nuclear power by providing multiple alternate revenue streams—for example, in addition to being reconverted back into clean electricity, the hydrogen can also be sold for other uses. The entire life cycle (production, transportation, use) of hydrogen must be taken into consideration when evaluating its overall greenhouse gas (GHG) emissions for specific end uses. For more information on the GHG emissions from hydrogen see ***Is hydrogen a greenhouse gas?***, ***Are there carbon dioxide emissions associated with hydrogen?***, and ***What is life cycle assessment?***

3. Is hydrogen going to replace electrification efforts?

Hydrogen complements electrification efforts and will help expand the use of low emission alternatives in areas where electrification is typically infeasible or cost prohibitive. Long haul heavy-duty trucking is an example of an application where hydrogen may be advantageous over other decarbonization options. While heavy-duty trucks can also use batteries, there are certain market segments where hydrogen may be a lower-cost option—e.g., if the truck requires a range of >500 miles or requires rapid fill times (<5 minutes) (see ***Why should we care about fuel cell vehicles when we already have gas/diesel/electric vehicles?***). Also, hydrogen fuel cell vehicles are actually electric vehicles. They use an electric motor and do not have an internal combustion engine drive train, and therefore produce no greenhouse gas emissions or pollution from the tailpipe. Hydrogen will target "hard-to-decarbonize" areas, including heavy-duty transportation, industry (e.g., steel, ammonia), and long-duration energy storage. For more information on the U.S. Department of Energy's work in hard-to-decarbonize technology, see this presentation about decarbonization of heavy industries[3] and further details are in the U.S. National Clean Hydrogen Strategy and Roadmap[4] and DOE's Industrial Decarbonization Roadmap.[5]

4. Why should we care about fuel cell vehicles when we already have gasoline/diesel/electric vehicles?

Fuel cell electric vehicles (FCEVs)[6] are electric vehicles, where the energy is stored in hydrogen rather than batteries. In an FCEV, hydrogen and oxygen gases are passed through the fuel cell to generate electricity and power an electric motor. FCEVs are not intended to replace passenger electric vehicles or other low-carbon vehicle options and are instead intended to target areas where other low-carbon options are not as viable. Fuel cells have a role in the transportation sector, particularly for trucks, buses, trains, boats, and other "heavy-duty" vehicles. Fuel cell vehicles can target areas in the transportation sector where minimizing weight, increasing range, and lowering refueling/charging times are critical.[7] Compared with combustion engines, electric vehicles, whether powered by batteries or fuel cells, are quieter, more efficient, and do not directly generate distributed greenhouse gas emissions or other pollutants. Anticipated markets for battery electric vehicles and hydrogen-powered fuel cell electric vehicles are discussed in the U.S. National Blueprint for Transportation Decarbonization7. Also see the Hydrogen's Role in Transportation[8] webpage for more information.

Vehicle weight, range (how many miles per tank of gas or from a full charge), and refueling time are all important considerations when assessing decarbonization technologies in the transportation sector. For example, the weight of a truck is important for specific roads or terrains (e.g., the weigh stations for trucks before they pass over a bridge or section of road). Since trucks are significantly heavier than passenger vehicles, they require more power, especially when driving over mountain passes and steep terrain. Larger battery packs are required to meet these power requirements, which significantly increases the weight of the truck. Because the weight of the vehicle increases as battery packs get larger, the range of battery electric vehicles is often limited. In comparison, hydrogen is very light and contains much more energy per unit mass than a battery or fossil fuels. This means that the mass of additional hydrogen required to increase the range of a fuel cell vehicle is significantly less than the mass of a battery required to increase the range of a battery electric vehicle. Fuel cells are primarily targeting weight-limited applications in the transportation sector such as heavy-duty trucking or aviation.

Refueling or charging time is another important consideration for many applications in the transportation sector. Currently, light-duty electric vehicles take anywhere from 30 min to an hour[9] to charge with DC fast chargers, and technologies are being developed to decrease this charging time. However, many heavy-duty vehicles (e.g., long-haul trucks) may take significantly longer to charge and need to be able to rapidly refill or charge, especially if the vehicle suffers from a small range and needs to refill frequently. The time required to refill a hydrogen tank is typically comparable to refilling a traditional gas tank. This faster refilling combined with longer ranges makes fuel cells promising for these heavy-duty and/or long-haul applications.

5. Is hydrogen safe?

Hydrogen has been safely produced and used in industry for over a century. Like any other fuel, such as gasoline, diesel, or natural gas, hydrogen must be handled appropriately. The systems in use today have been engineered to reduce risk and enable the safe handling and use of hydrogen. Fuel cell vehicles and hydrogen fueling stations meet all the same rigorous safety standards as their gasoline/diesel counterparts. Hydrogen is also non-toxic and can diffuse or dissipate rapidly, rather than pooling, which can make it safer than other fuels. For example, if a hydrogen tank developed a leak, the gas would rapidly diffuse away, unlike liquid fuel sources (e.g., gasoline and diesel) which can accumulate on the ground and create a flammable or combustible pool.

Hydrogen tanks and pipelines are also designed, manufactured, and operated with special care, to mitigate risks related to "embrittlement," which can occur when hydrogen moves into metals, making them more prone to cracking. Special materials, thicker walls, shorter service lives, and/or more frequent inspections are all employed to manage embrittlement effects. Hydrogen tanks are typically subject to rigorous testing, including burst testing, drop testing, and even gunfire testing, before being placed in service.[10] DOE is funding ongoing research into safe hydrogen handling and storage practices, hydrogen-compatible materials,[11] and leak detection systems. See the Safe Use of Hydrogen webpage[12] and the Safety, Codes and Standards webpage[13] for more information about hydrogen safety. There is also significant ongoing research into hydrogen sensor development at the national labs,[14] and several recent funding opportunity announcements (FOAs) will provide funding into hydrogen sensor research. For information about ongoing research of hydrogen sensors, see the Hydrogen Safety R&D Projects webpage.[15] Additional information about hydrogen safety can be found at H2Tools,[16] and the Hydrogen Safety Panel.[17]

6. How is hydrogen produced?

Hydrogen can be produced using many different feedstocks, energy sources, and processes, and DOE funds research on many different ways of producing clean hydrogen (referred to as "production pathways"). Clean hydrogen is defined by DOE as producing less than 4 kg of carbon dioxide equivalents per kg of hydrogen over the entire production process, and this can be achieved via use of renewable resources, nuclear energy, and fossil fuels with carbon capture.

Currently, 95% of the hydrogen produced in the United States is generated using steam methane reforming (SMR), which generates carbon dioxide as a secondary product.[18] Methane is the primary component of natural gas. Facilities that use methane as a feedstock with carbon capture and storage systems are a crucial technology in the clean energy transition. SMR with carbon capture and storage will not require a massive investment in new infrastructure and will reduce GHG emissions in the near-term. Hydrogen can also be produced via water-splitting, which involves breaking of the chemical bonds of water molecules to produce hydrogen and oxygen gas and does not directly generate carbon dioxide emissions. Electrolysis is the only method for splitting water that is currently available, and it represents a rapidly expanding market. These hydrogen production pathways and other promising pathways are described in more detail below.

Electrolysis

Electrolysis uses electricity to split water into hydrogen and oxygen in a device called an electrolyzer. The water-splitting reaction is shown below:

Water + Electricity → Hydrogen + Oxygen

When powered by renewable or nuclear energy, electrolysis is a carbon-free hydrogen production method. Electrolysis is an important hydrogen production pathway for achieving the Hydrogen Energy Earthshot[19] goal of reducing the cost of producing carbon-free hydrogen to $1/kg. Carbon-free hydrogen is already being produced at commercial scale with electrolysis coupled with renewable energy, but the costs of electrolysis and renewable energy need to be reduced for this pathway to be cost competitive with SMR, as the current cost is $4–6/kg[20], which is currently about two to three times more expensive than SMR. There are several types of electrolyzers, with different capabilities and operation requirements that can serve diverse scenarios. To learn more about electrolysis and the types of electrolyzers being developed, see the Hydrogen Production: Electrolysis webpage.[21]

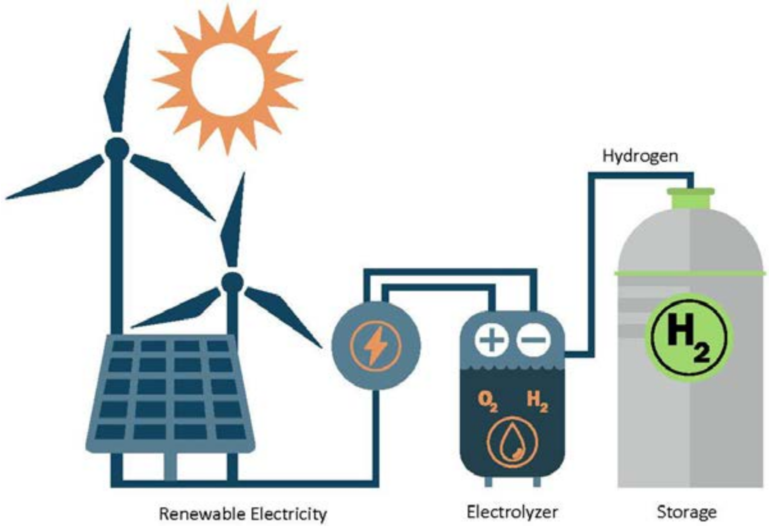

Figure 2: Electrolysis

Biomass Gasification and Pyrolysis

Biomass gasification uses heat, steam, and oxygen to convert biomass to hydrogen and other products. Biomass is a renewable organic resource that includes leftovers from agriculture, forestry, organic municipal solid waste, and animal waste. Gasification is a high temperature, non-combustion process (>700°C) that converts carbon-containing materials into carbon monoxide, hydrogen, and carbon dioxide using oxygen and/or steam. Another chemical reaction (called a water-gas shift reaction) can then be used to convert the carbon monoxide into more hydrogen and carbon dioxide. Biomass gasification is a mature technology with low carbon emissions because the carbon dioxide produced is offset by the carbon dioxide removed from the atmosphere when the biomass was grown. Biomass can also be converted to hydrogen using pyrolysis in the absence of oxygen, a process that produces solid carbon (charcoal) as a byproduct instead of carbon dioxide. This is a potential zero to negative carbon emissions hydrogen production pathway, meaning that over the entire life cycle of the materials, more carbon dioxide is consumed than produced. With the large availability of biomass in the United States and the ability of biomass to recycle carbon dioxide, DOE anticipates deployment of biomass gasification in the near future. See the Hydrogen Production: Biomass Gasification webpage[22] for more information.

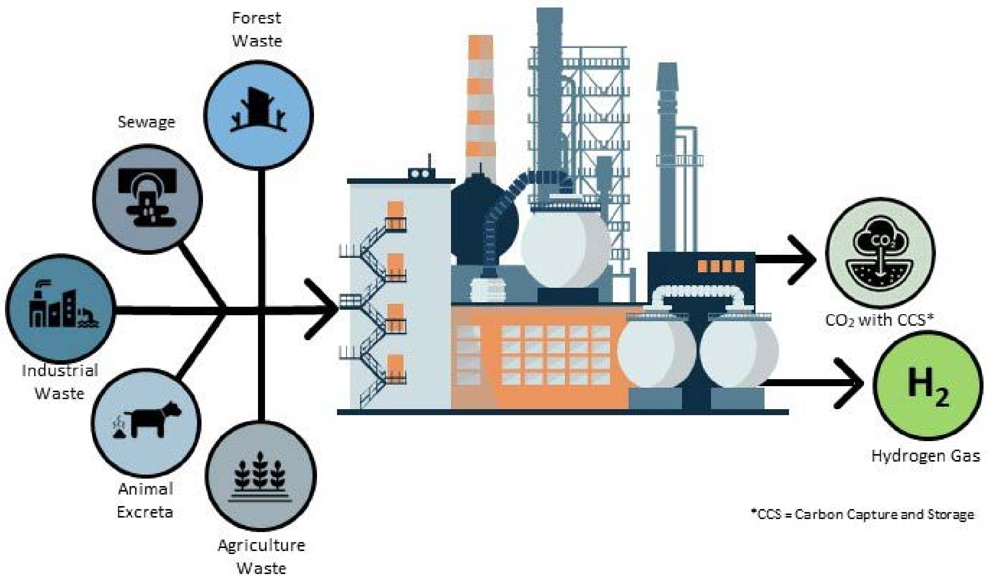

Figure 3: Biomass gasification

Steam Methane Reforming (SMR)

SMR currently generates 95% of the United States' hydrogen by converting natural gas or methane into hydrogen and carbon monoxide in the following steam methane reforming reaction:

Methane + Steam + Heat → Carbon Monoxide + Hydrogen

This process is performed with high temperature steam (700°C-1000°C) and high pressures and must be conducted in the presence of a catalyst.[ii] Once the SMR reaction is complete, a "water-gas shift" reaction is performed to convert the carbon monoxide and additional steam to carbon dioxide and hydrogen:

Carbon Monoxide + Steam → Carbon Dioxide + Hydrogen

Carbon dioxide and other impurities are then removed from the gas stream, leaving pure hydrogen. The overall carbon emissions associated with SMR are lower than gasoline combustion in an internal combustion engine; however, SMR facilities need to be coupled with carbon capture systems to generate clean hydrogen. The estimated cost of hydrogen produced from SMR with carbon capture is $1.64/kg, from a 2022 report.[23] For more information on steam methane reforming, see the webpage Hydrogen Production: Natural Gas Reforming.[24]

[ii] Catalyst is a material that improves the rate of the reaction without being consumed, often nickel-based for SMR.

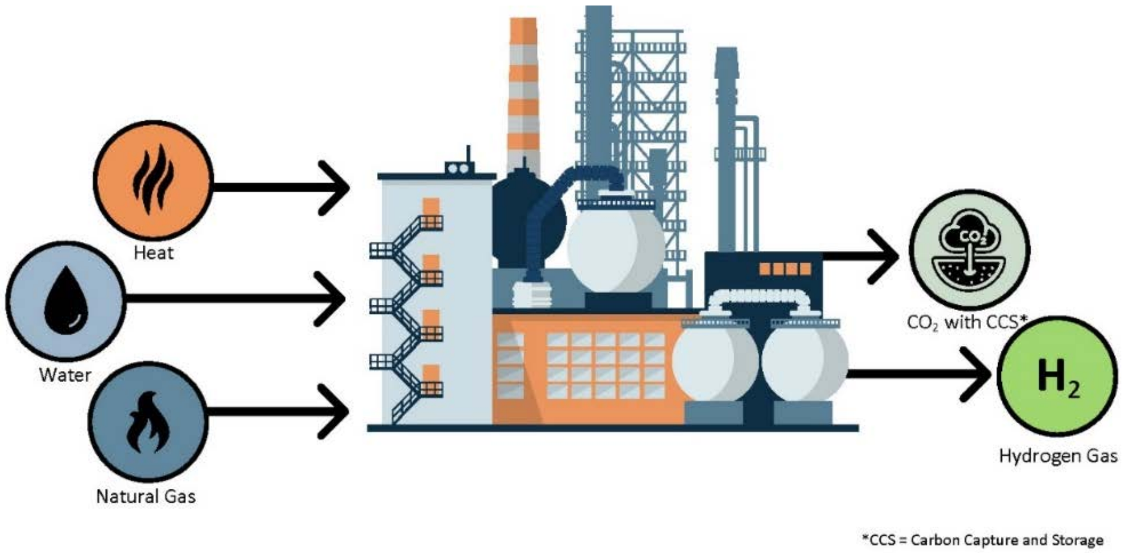

Figure 4: Steam methane reforming

Autothermal Reforming (ATR)

ATR is another commercial process for producing hydrogen from methane. The key difference between ATR and SMR is that the ATR process requires high-purity oxygen for a partial oxidation of methane. The net chemical reaction for the ATR process is:

Methane + Steam + Pure Oxygen → Carbon Monoxide + Hydrogen + Heat

Similar to SMR, the carbon monoxide undergoes a water-gas shift reaction to produce carbon dioxide and additional hydrogen.

Carbon Monoxide + Steam → Carbon Dioxide + Hydrogen

Because this reaction generates heat (it is "exothermic") unlike the SMR process which requires heat (an "endothermic" reaction), ATR has the potential for higher efficiency and lower operation costs. However, the air separation unit that provides high-purity oxygen gas requires a large amount of energy, which can offset some of the efficiency and cost benefits. A 2022 report estimates the cost of ATR with carbon capture is $1.59/kg, which is similar in cost to SMR.23

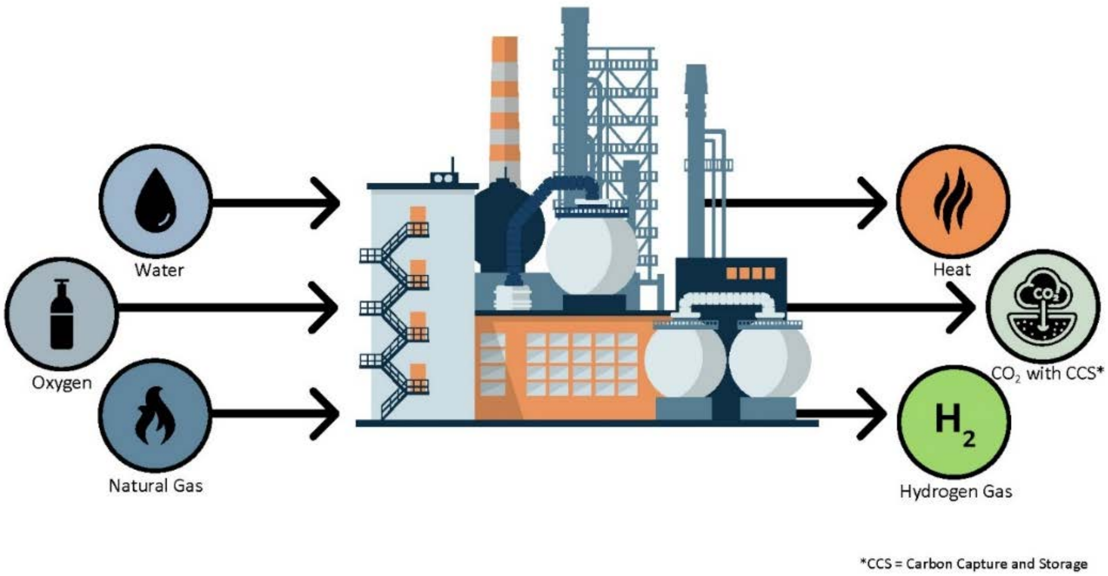

Figure 5: Autothermal reforming

Pyrolysis

Another pathway for producing hydrogen from methane and heat is with pyrolysis, which generates hydrogen and solid carbon, thereby mitigating carbon dioxide emissions.[25] Pyrolysis occurs in the following reaction:

Methane + Heat → Hydrogen + Solid Carbon

While carbon dioxide is not released in the pyrolysis process, like any other pathway that employs methane, methane leaks can have a large contribution to overall GHG emissions.

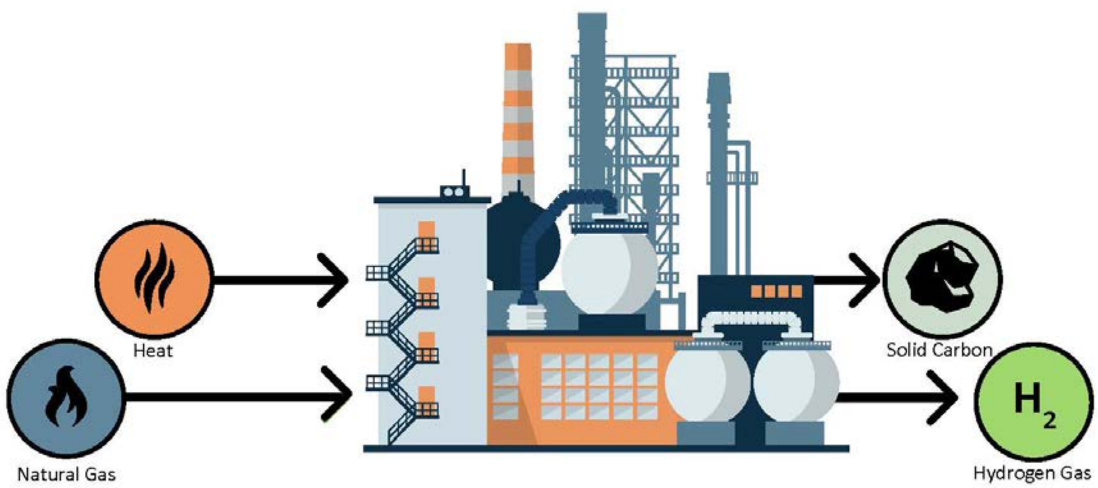

Figure 6: Pyrolysis

Advanced Pathways

DOE is also funding research into advanced hydrogen production pathways for potential deployment in the longer-term. These advanced pathways are not yet at the commercial scale but have potential for highly efficient clean hydrogen generation. Advanced pathways currently being pursued include photoelectrochemical water-splitting,[26] thermochemical water-splitting,[27] biological fermentation,[28] and photobiological hydrogen production.[29]

7. How does one kilogram of hydrogen compare with fossil fuels?

One kilogram of hydrogen has about the same energy content as a gallon of gasoline. When discussing cost or range of fuel cell vehicles, which use hydrogen to produce power, the price/kg or miles/kg can be roughly compared to price/gallon or miles/gallon of these other fuels.[30] So for example, $1 for 1 kilogram of hydrogen (the Hydrogen Energy Earthshot target) can be thought of as roughly $1 for 1 gallon of gasoline. However, it is important to note that a fuel cell is about twice as efficient as an internal combustion engine, so you would need half as much hydrogen as gasoline to travel the same distance. Also, the actual cost to the end user can vary considerably, depending on costs of transporting, storing, and dispensing the hydrogen.

8. What is the hydrogen economy?

The hydrogen economy is the vision of an energy infrastructure where clean hydrogen replaces other carbon-intensive fuels and feedstocks such as fossil fuels. The hydrogen economy is intended to complement electrification efforts by targeting hard-to-decarbonize end uses and it also supports a renewables-based electric grid. Hard-to-decarbonize end uses are energy intensive applications or industries, such as cement and steel manufacturing, that are difficult to power with renewable energy alone.

The U.S. Department of Energy and its national laboratories launched H2@Scale[31] in 2016 (see Figure 7, which outlines a vision for a hydrogen economy). In this vision, clean hydrogen can be produced via several pathways including from: water-splitting, fossil fuels with carbon capture, utilization, and storage (CCUS), nuclear energy, and biomass or waste

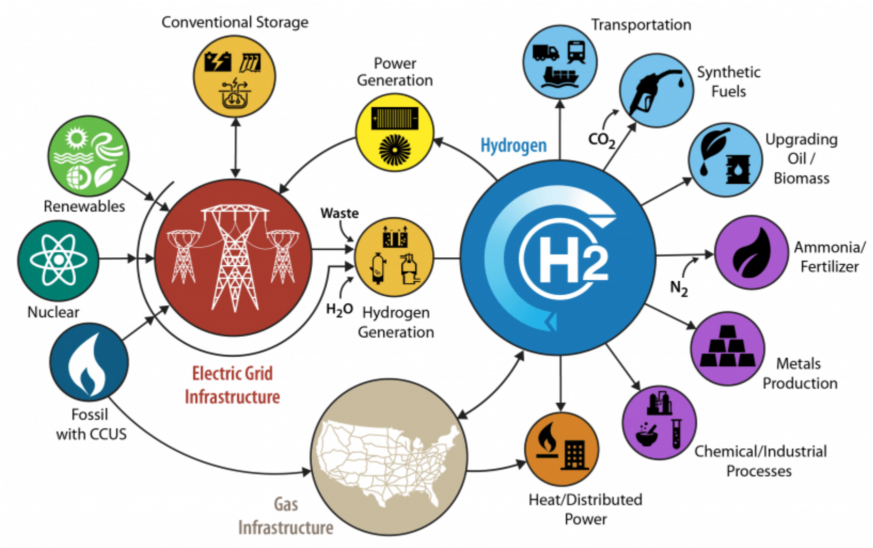

Figure 7: H2@Scale vision of the hydrogen economy

feedstocks[iii] (see ***How is hydrogen produced?*** for more information on hydrogen production pathways). Hydrogen can store excess energy produced by variable renewable resources (e.g., solar and wind) for short- or long-durations, and then be used when the demand for power is higher or solar/wind power generation is lower. Clean hydrogen can also be used to replace petroleum fuels for heavy-duty vehicles, ships, and aircraft, and as a chemical feedstock for metal refining and production of other chemicals (see ***What is hydrogen used for?*** for more information about hydrogen end-uses).

9. What is a fuel cell?

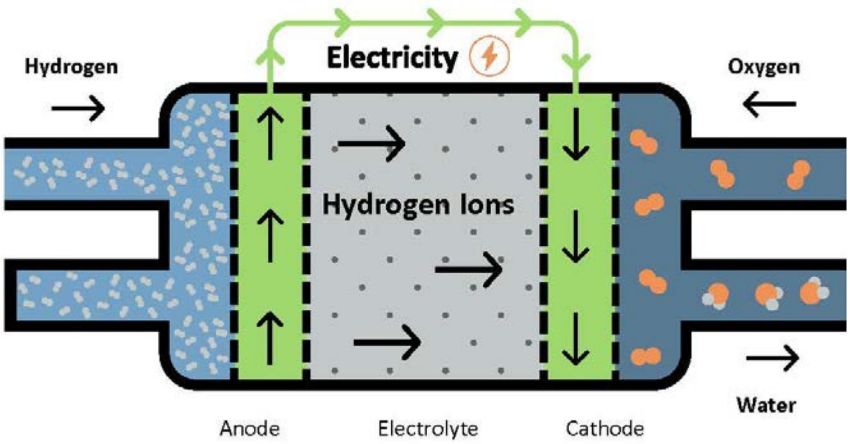

Figure 8: A diagram of a PEM fuel cell

A fuel cell is similar to a battery, except it is powered by an external fuel source, and therefore does not require charging. Like a battery, fuel cells have positive and negative electrodes where electrochemical reactions occur. A specific type of fuel cell that is commonly used in transportation applications is the proton exchange membrane (PEM) fuel cell, shown in Figure 8. With a PEM fuel cell, when hydrogen is fed to the negative electrode (or anode) and oxygen gas is fed to the positive electrode (or cathode), electricity, heat, and water are generated. In this example, hydrogen and oxygen (from air) are the external fuel sources. When hydrogen reaches the anode, the hydrogen molecule breaks apart and generates an electron (a negatively charged particle) and a proton (a positively charged particle). The electron moves through an external wire while the proton moves through the electrolyte (the fluid or material that separates the two electrodes). The movement of electrons through the external wire creates an electrical current, which can be used to power an electric motor, a generator, or a home—or this electricity can be fed into the grid. When the electrons and protons meet at the cathode, they recombine with the oxygen gas and produce water. Each electrode has a catalyst, where the reaction actually occurs. The catalyst, which can be made of materials such as nickel or platinum, lowers the amount of energy the reaction requires to proceed, thereby making the process more efficient.

The PEM fuel cell is just one type—there are many different fuel cell technologies, suited for different applications. For example, high temperature fuel cells are better for stationary applications that are rarely shut down such as data centers that need power 24/7. Low temperature fuel cells are better suited for transportation applications because they operate at closer to room temperature and can be turned on and off quickly. More details about different

iii Feedstocks are starting materials that hydrogen can be produced from, also referred to as raw materials.

types of fuel cells—such as PEM, solid oxide, alkaline, and molten carbonate—can be found on DOE's Types of Fuel Cells webpage.[32]

10. How is hydrogen stored and transported?

Currently, hydrogen is primarily transported and stored as a compressed gas at high pressures—250 bar (or atmospheres) and higher—or as a liquid at cryogenic temperatures (-253°C/-423°F). These approaches require heavy-duty tanks, and, in the case of liquid storage, they must be kept at very low temperatures. For certain high-demand applications, hydrogen can be stored in geologic salt caverns and transported via dedicated hydrogen pipelines. While these storage and delivery systems have functioned for decades in industrial applications, large-scale deployment of hydrogen as an energy carrier will require advancements in technology and infrastructure.

Delivery

Building a national hydrogen delivery infrastructure will require significant time, resources, and technological advancements. One major challenge of hydrogen delivery via steel pipelines is hydrogen embrittlement, which makes pipelines more prone to cracking and leaks. Embrittlement is caused by hydrogen (which is a very small molecule) diffusing into the metal structure, thereby creating pockets that weaken the pipeline. Currently, a 5% blend of hydrogen in natural gas is considered safe for delivery in existing natural gas pipelines. Other recent demonstrations have used 12% blends, and other countries have used a range of different concentrations safely.[33] Installation of fiber-reinforced polymer pipelines is one option for safe, large-scale delivery of hydrogen.[34] DOE is also funding efforts focused on mitigating embrittlement, preventing hydrogen leaks, and lowering delivery costs. Different materials are also being examined for their ability to act as "hydrogen carriers"—meaning that they can temporarily bond with hydrogen to make it easier to transport than compressed or liquid hydrogen. Efforts are also being made to co-locate hydrogen production sites with hydrogen end-uses to limit the delivery infrastructure required. See the Hydrogen Delivery webpage[35] for more information.

Storage

Advancement of hydrogen storage is critical to the large-scale deployment of hydrogen and fuel cell technologies. Because hydrogen is an extremely light molecule, it has the highest energy per unit mass of any fuel. However, hydrogen is much less dense than other fuels, which means it takes up more space (volume) than other fuels when comparing the same amount of energy stored (see Figure 9). The large volume required to store hydrogen presents challenges for many hydrogen applications. This is particularly challenging in the transportation sector, where space is often limited on board a vehicle, plane, etc. DOE is pursuing several pathways to address these challenges, with the near-term strategy focused on the development and cost reduction of fiber reinforced, high-pressure tanks capable of storing more hydrogen in less space (or increasing its "volumetric density"). The longer-term strategy focuses on two approaches—storing liquid hydrogen at higher pressures (cryo-compressed) to further increase volumetric density, and the development of materials-based hydrogen storage technologies such as sorbents, metal hydrides, and chemical hydrogen storage materials.[36] Like the "hydrogen carriers" mentioned above, these storage materials work by temporarily bonding to hydrogen, allowing for more hydrogen to be contained in a smaller space. For more information, see the Hydrogen Storage webpage.[37]

For bulk storage, hydrogen has historically been stored in salt caverns around the world. However, these geologic formations are not widely available in the United States. To advance the availability of geologic hydrogen storage, DOE is evaluating the viability, safety, and reliability of storing pure hydrogen or hydrogen/natural gas blends in other geologic formations such as depleted oil and gas wells and saline formations that are more widely available in the United States.[38]

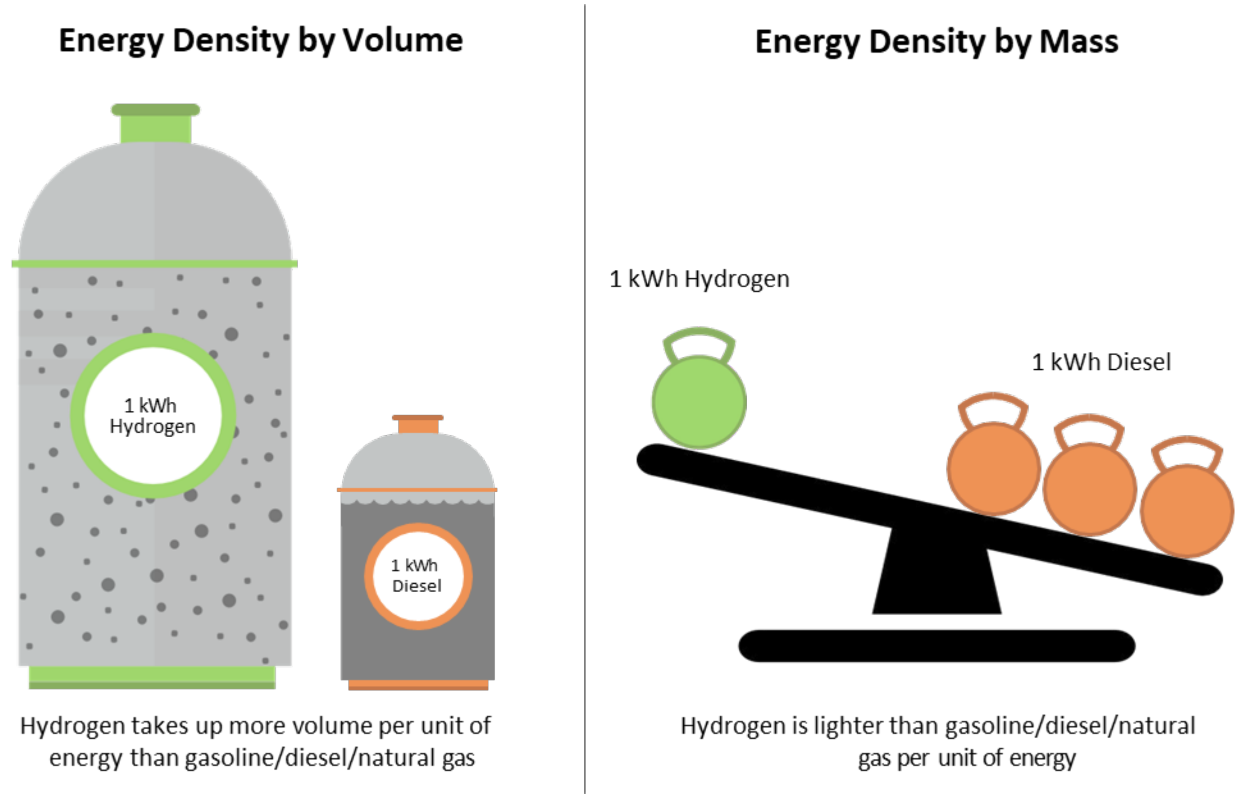

Figure 9: Energy densities of different fuels by mass and volume

11. Is hydrogen a greenhouse gas?

Greenhouse gases (GHG) are gases that get trapped in the atmosphere and cause the atmosphere to warm. GHGs typically retain heat better than other gases and often have long lifespans, thereby retaining more heat. Common GHGs are carbon dioxide, methane, and fluorinated gases. Hydrogen is not a GHG by itself. However, some early research suggests hydrogen released into the atmosphere can react with other atmospheric gases and subsequently extend the lifetime of GHGs in the atmosphere. Ongoing research is examining the impact of hydrogen on atmospheric GHGs, but the global warming potential of hydrogen is still significantly lower than that of methane. More research is necessary to fully understand the impacts of hydrogen released into the atmosphere; however, the benefits of clean hydrogen significantly outweigh these potential disadvantages,[39] especially when compared with the warming potential of natural gas. These benefits will be fully realized only once hydrogen is produced using clean pathways, such as electrolysis powered by renewable or nuclear energy, and dependence on methane as a feedstock is reduced.[40]

12. Are there carbon dioxide emissions associated with hydrogen? Other pollutants?

Because hydrogen does not contain any carbon atoms, there are no carbon emissions directly associated with its use. However, there can be carbon emissions associated with some hydrogen production pathways, and other pollutants associated with some uses.

Emissions from Hydrogen Production

Some hydrogen production pathways can generate carbon emissions. For example, carbon dioxide is generated when hydrogen is produced using steam methane reforming, and the electrolysis process can produce carbon dioxide emissions if the electricity comes from a fossil-fuel-powered grid (see ***How is hydrogen produced?*** question above). When natural gas is used for the hydrogen production process, it is also important to consider emissions associated with the extraction and transportation of the natural gas. As the industry moves toward producing clean hydrogen using electrolysis powered by clean energy—such as wind, solar, or nuclear power—hydrogen production will be an increasingly carbon-free process.

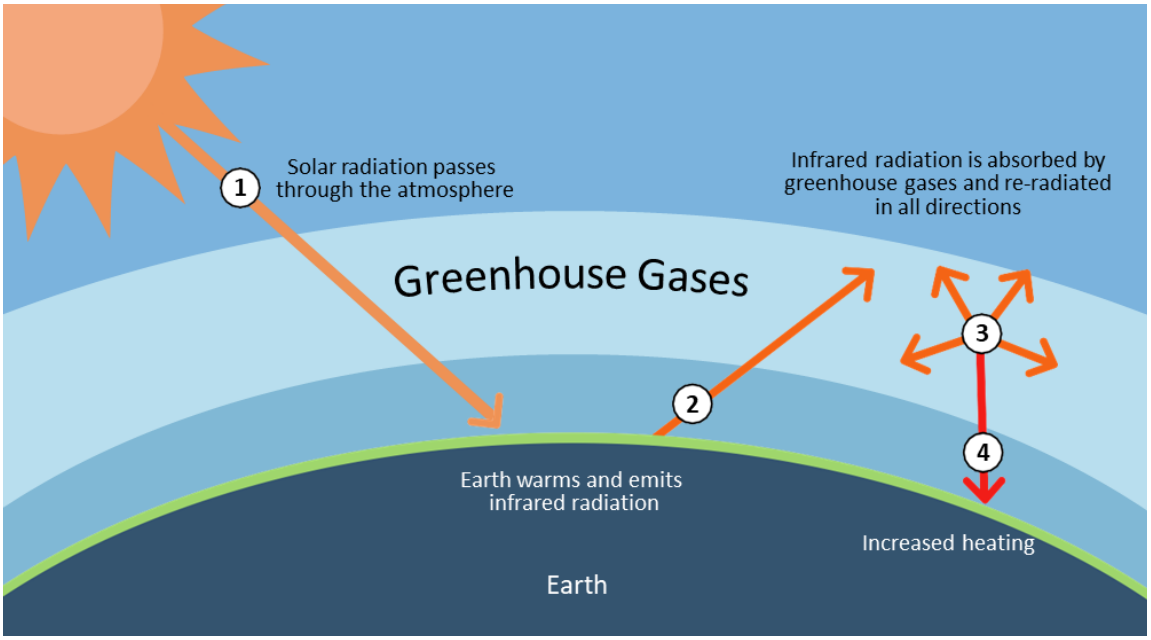

Figure 10: Diagram showing how greenhouse gases cause atmospheric warming

Emissions from Hydrogen Use

The use of hydrogen does not generate any carbon emissions directly, because a hydrogen molecule does not contain any carbon atoms. However, hydrogen combustion can indirectly create other pollutants, such as nitrogen oxides (NOx, which include nitric oxide, NO, and nitrogen dioxide, NO_2), which are criteria air pollutants.[41] NOx emissions are formed when a fuel (including gasoline, diesel, natural gas, and hydrogen) is burned at very high temperatures (>1500 °C), causing nitrogen and oxygen in the surrounding air to react and generate NOx. Because hydrogen burns at higher temperatures than natural gas, combustion of pure hydrogen may result in higher NOx emissions. However, hydrogen has a larger stable combustion temperature range, meaning a lower ratio of fuel to air can be used—and this additional air effectively dilutes the hydrogen, which cools off the flame and results in lower-temperature combustion, thereby reducing the amount of NOx emissions that are produced. Current research has shown that hydrogen combustion via turbines can achieve comparable performance and NOx emissions to those of today's turbines running on pure natural gas.[42]

If NOx is produced during hydrogen combustion, its release into the atmosphere can be reduced using existing and emerging technologies. One existing technology to reduce NOx emissions is catalytic converters, which are currently integrated into gasoline- and diesel-powered vehicles to convert harmful emissions into less harmful compounds. Because hydrogen burns hotter than methane or gasoline, research into possible adaptations of existing NOx capture technologies is ongoing. Combustion in a hydrogen turbine is only one example of an end-use for hydrogen. Hydrogen can also be used in a fuel cell to generate electricity. Because fuel cells operate via a well-controlled electrochemical reaction instead of combustion, even high-temperature (≤800°C) fuel cells do not create NOx emissions. More information on NOx emissions can be found in the H2IQ Hour.[43]

13. What is GREET?

GREET, or Greenhouse Gases, Regulated Emissions, and Energy use in Technologies, is a model developed by Argonne National Laboratory that provides a publicly accessible, comprehensive platform for assessing the life cycle emissions, water consumption, and energy consumption of different technologies and fuels. GREET can calculate emissions of greenhouse gases (GHG) such as carbon dioxide, methane, and nitrous oxide. GREET can also be used to calculate pollutant emissions including carbon monoxide, NOx, and particulate matter. This tool is central to determining the life cycle GHG emissions from different transportation and energy pathways, including hydrogen production pathways.[44] This tool also assesses emissions produced upstream of the site of production as well as water consumption in the different hydrogen production pathways. For more information on how GREET works, see Argonne National Laboratory's GREET Workshops.[45] This tool has been cited in the Inflation Reduction Act for use in determining eligibility for the hydrogen production tax credit. It is also used by DOE in many programs to help select projects for funding based on the projected emissions.

14. What is life cycle assessment?

Life cycle assessment (LCA)[46] is a tool scientists use to measure the impact a product has on the environment over its entire lifetime or part of its lifetime. A typical product life cycle includes 5 steps: 1) raw material extraction, 2) manufacturing and processing, 3) transportation, 4) usage and retail, and 5) disposal. LCA typically assesses a number of factors, including greenhouse gas emissions, other pollutant emissions, materials that end up in landfills versus getting recycled, overall energy and resources used, water consumption and contamination, and others. Conducting an LCA on a product should provide information on specific steps, or "hot spots", in its life cycle that result in high emissions or energy usage, thereby helping identify which steps need improvement.

The DOE Hydrogen Program is interested in the LCA of hydrogen from different production pathways and end-uses. For example, an LCA of greenhouse gas emissions for hydrogen produced from SMR and used to power a fuel cell will take into consideration emissions associated with the entire process. This includes emissions from methane extraction, methane leaks throughout the entire process, the entire SMR process, transportation of methane and hydrogen, materials extraction for fuel cell development, fuel cell manufacturing, use of hydrogen in the fuel cell, disposal of any materials used in the process, etc.

DOE emphasizes well-to-gate emissions in the assessment of clean hydrogen production. Well-to-gate is a life cycle assessment that starts at the feedstock[iv] and goes through the point of production (to the "gate" of the production plant). Well-to-gate assessments typically include:

- Upstream emissions associated with the generation and processing of feedstocks and energy sources—such as natural gas (including methane leakage), water, electricity, etc.
- Emissions associated with the hydrogen production process
- Any emissions associated with carbon capture, utilization, and storage.

Well-to-gate assessments do ***not*** include the end use of hydrogen or emissions associated with processes involved in manufacturing hydrogen equipment.

Some of these values are difficult to measure accurately and are often dependent on the models employed. For example, estimated emissions from upstream methane leakage can vary widely. The GREET model (see ***What is GREET?*** question above) is often used for life cycle assessments and to determine if clean hydrogen is being produced. Sources considered in an LCA for hydrogen is shown in Figure 11 below.[47]

[iv] Feedstocks are starting materials that hydrogen can be produced from, also referred to as raw materials.

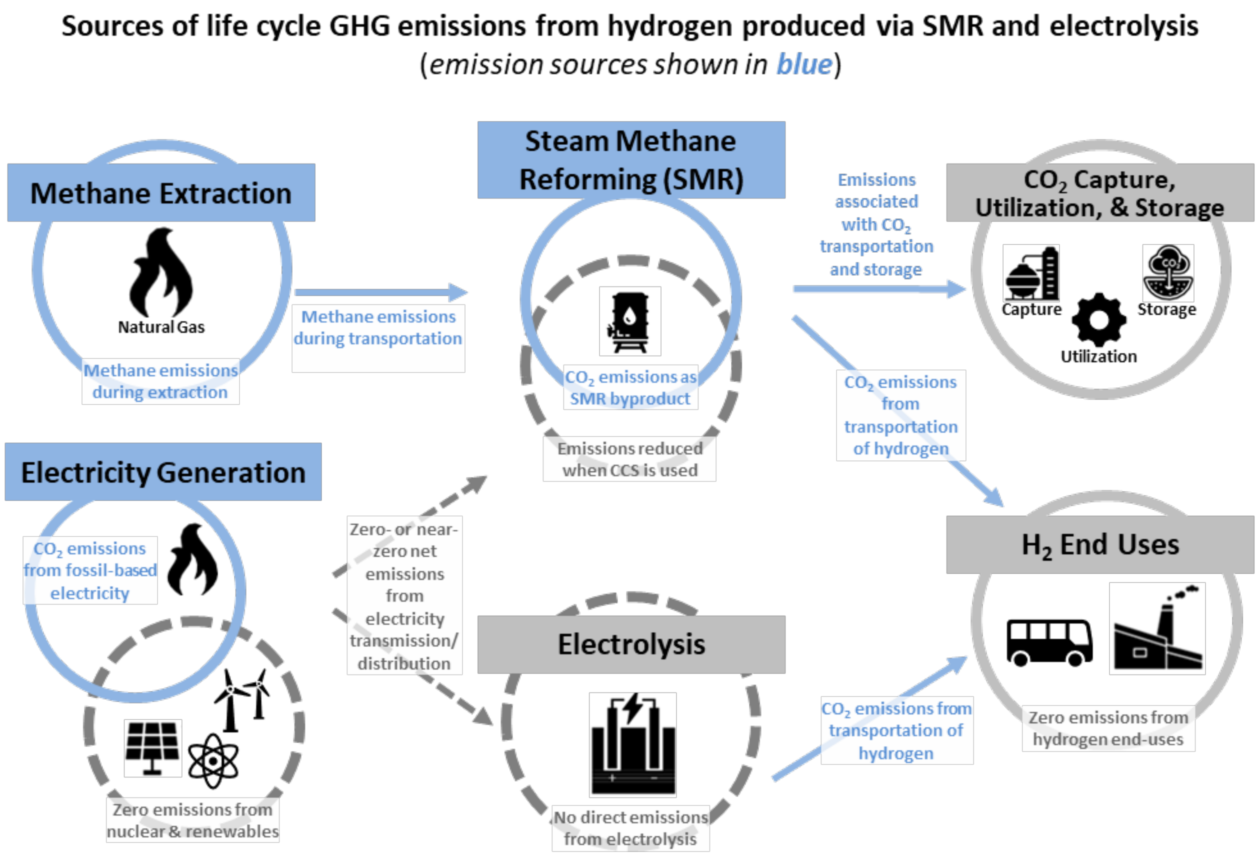

Figure 11: Examples of factors considered in life cycle assessment of hydrogen production

15. How much water does electrolysis consume?

The amount of fresh water consumed by electrolysis is an important consideration, especially when deploying large-scale hydrogen production in water-scarce regions. According to the Greenhouse Gases, Regulated Emissions, and Energy use in Technologies (GREET)44 tool, about 40 liters (L) of water is consumed for every 1 kg of hydrogen produced using solar/wind electrolysis, and about 30 L of water are consumed for every kg of hydrogen produced by SMR with CCS.[v] It is important to note that, on a national scale, these levels of water consumption are not expected to substantially strain annual freshwater supplies. For instance, production of 10 million metric tons of hydrogen (the amount of hydrogen currently produced in the U.S. each year) from electrolysis would only consume between <0.03%–0.6% of the annual freshwater withdrawal in the United States, depending on the type of electricity used.[48] However, given that water availability can vary widely by region, deployments should be optimized to account for regional water supply, particularly when located in regions with scarcity.

[v] For crude oil recovery, about 80 L of water is consumed per MMBtu of crude oil produced.

To enable sustainability in future deployments, DOE is funding analyses to better estimate water consumption using different methods of hydrogen production, encouraging the inclusion of sustainability planning in hydrogen deployments (e.g., encouraging applicants to DOE's Regional Clean Hydrogen Hubs to exercise water-consumption reduction strategies), and funding ongoing research into electrolyzers that can tolerate impure water sources and minimize the consumption of clean fresh water.[49,50] Strategies that producers can utilize to mitigate consumption include sourcing water from regions with abundance, accounting for regional impacts when siting projects, and/or coupling electrolyzers with desalination plants, which can generate fresh water from salt water while only increasing the overall cost of hydrogen by $0.06/kg or less.[51]

16. What are the Bipartisan Infrastructure Law and the Inflation Reduction Act, and how do they relate to hydrogen?

The Bipartisan Infrastructure Law (BIL)—sometimes referred to as the Infrastructure Investment and Jobs Act—and the Inflation Reduction Act (IRA) are laws passed by Congress. The BIL is a comprehensive law that is helping shape infrastructure changes within the United States, specifically in the energy sector. The BIL specifically designated $8 billion to create Regional Clean Hydrogen Hubs, $1 billion for a Clean Hydrogen Electrolysis Program, and $500 million for Clean Hydrogen Manufacturing and Recycling. More details about hydrogen-related provisions in the BIL can be found in the DOE announcement and requests for information.[52] The IRA is the single largest investment in tackling the climate crisis in our nation's history, and it provides incentives for various energy technologies over a ten year plan. More details can be found in the Inflation Reduction Act of 2022 explanatory video.[53] Regarding hydrogen, the IRA provides a tax credit for clean hydrogen production, up to $3/kg when less than 0.45 kg of life cycle greenhouse gases are emitted per kg of hydrogen produced. The amount of tax credit received is determined by the amount of emissions produced, where hydrogen production pathways with lower GHG emissions qualify for higher tax credits. There are several other incentives related to hydrogen and fuel cells that can be found here: Hydrogen and Fuel Cell Incentives.

17. What are the Regional Clean Hydrogen Hubs?

The Regional Clean Hydrogen Hubs are planned networks of clean hydrogen producers, consumers, and local connecting infrastructure located in close proximity to help accelerate large-scale production and use of clean hydrogen. The Regional Clean Hydrogen Hubs will be deployed throughout the United States as a key provision of the Bipartisan Infrastructure Law. DOE released the funding opportunity announcement for the Hubs in September 2022.[54] DOE envisions that the Regional Clean Hydrogen Hubs will demonstrate low-carbon-intensity deployment of hydrogen using sustainable business models that can replace existing carbon-intensive processes. The Hubs are intended to be located where resources exist for clean hydrogen production and where there is an existing demand for hydrogen, thereby limiting the need for extensive hydrogen storage and delivery infrastructure. Each Regional Clean Hydrogen Hub will be expected to: produce clean hydrogen; demonstrate end uses; generate training opportunities and well-paying union jobs; reduce emissions and pollution; and tangibly benefit local communities. More information can be found in the [What are Regional Clean Hydrogen Hubs video][55] and the [Regional Clean Hydrogen Hubs] webpage.[56]

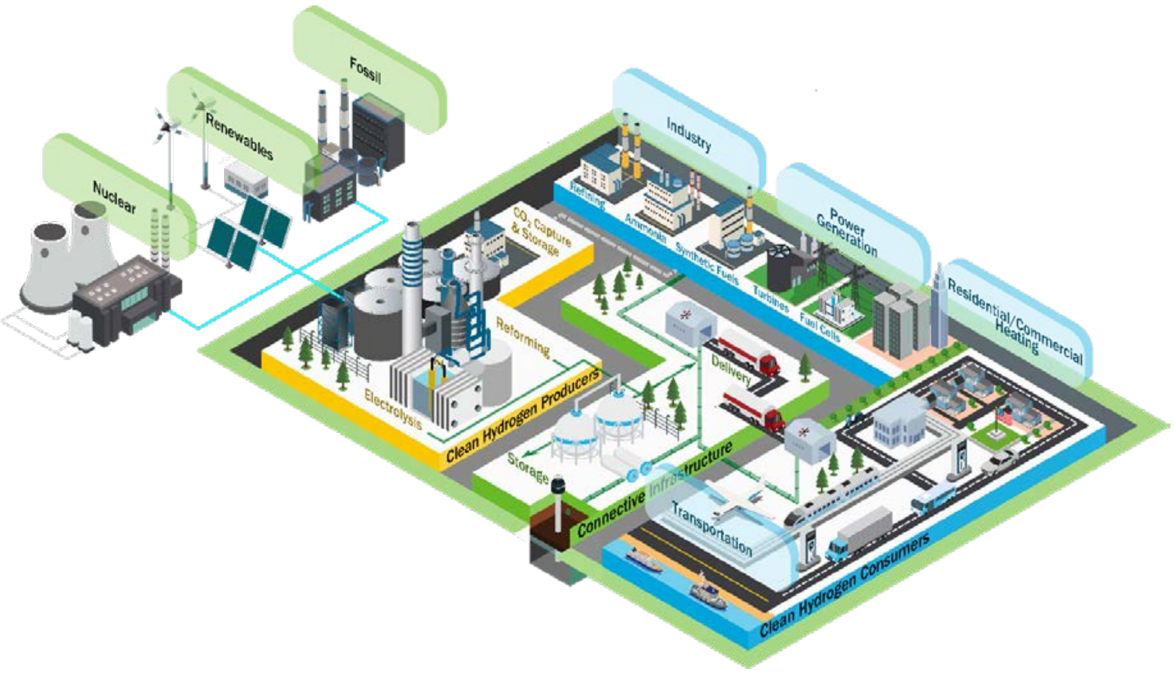

Figure 12: An example diagram of a Regional Clean Hydrogen Hub

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