Hydrogen 101:

Frequently Asked Questions About Hydrogen for Decarbonization

Hydrogen is emerging across the world as a potential low-carbon energy carrier that can provide an alternative to fossil fuels. With the increasing deployment of renewable energy, the role of low-carbon power generation in hydrogen production through electrolysis is expected to increase. Hydrogen can also play a role in reducing carbon emissions in several sectors such as chemicals, iron, steel, and long-haul transport like heavy-duty trucks and shipping. As a result of these possibilities, many countries have included hydrogen as a central part of their energy strategies. For example, the International Partnership for Hydrogen and Fuel Cells in the Economy now includes 20 countries, and the European Commission is collaborating on research, development, demonstration, and deployment challenges to advance hydrogen technologies. Likewise, many other developing countries and multiple government-industry research partnerships are exploring opportunities for hydrogen within their economies. This growing interest has led to many questions among various stakeholders, including policymakers, planners, regulators, system operators, utilities, and investors. This fact sheet provides answers to some of the most frequently asked questions (FAQs) related to hydrogen production, transportation, storage, cross-sectoral utilization, and its role in power sector decarbonization. (See **Figure 1** for overview of processes involved in energy chain of hydrogen.)

Part A: Hydrogen Basics

What is hydrogen?

Hydrogen is a chemical element represented with the symbol H on the periodic table and atomic number 1. Hydrogen typically exists in molecular form (H_2) and is nontoxic at room temperature and pressure but can be condensed to a liquid form at very low temperatures (-423°F or -253°C). Elemental hydrogen is found in compounds like water (H_2O), ammonia (NH_3), and hydrocarbons such as natural gas, coal, and oil.

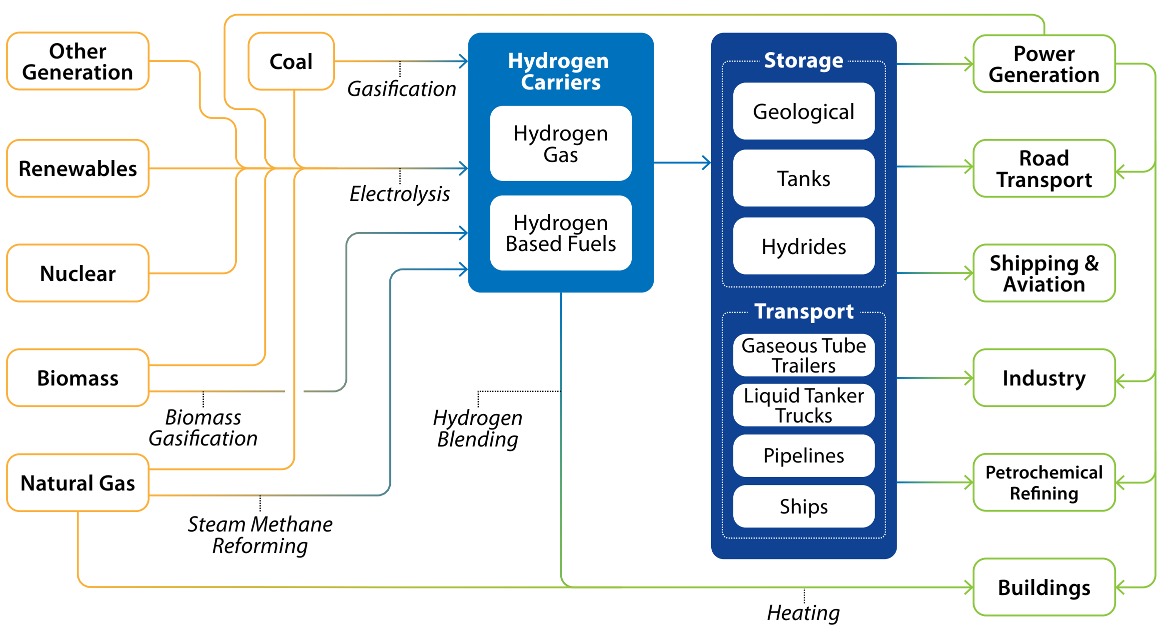

Figure 1. Energy process chain of hydrogen and its cross-sectoral linkages

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Table 1. Classification of Hydrogen Based on Energy Source and Carbon Intensity

Classification Based on Energy Source	Energy Source for Hydrogen Production	Classification Based on Carbon Intensity
Black Hydrogen	Bituminous coal	
Gray Hydrogen	Natural Gas or Methane	High Carbon Hydrogen
Brown Hydrogen	Lignite (brown coal)	
Blue Hydrogen	Natural Gas or Methane with CCUS	
Green Hydrogen	Electrolysis powered by renewable energy	Lower Carbon Hydrogen
Pink Hydrogen	Electrolysis powered by nuclear energy	

How is hydrogen used today?

Hydrogen is mainly used for industrial processes. This includes **oil refining** (~33%), **ammonia production** (~27%), **methanol production** (~27%), and **steel production** (~3%) globally (IEA 2019). In the United States, almost all the hydrogen produced is used for refining petroleum, ammonia production (as a precursor for fertilizer production), and methanol production; about 10% is used for treating metals, processing foods, and other applications (Connelly, Elgowainy, and Ruth 2019). Hydrogen can also be used as a fuel for **electricity production, transport,** and **building heating**. Such use is limited now but has a potential to lower global carbon emissions. These pathways are discussed later in this FAQ.

What does it mean for hydrogen to be an energy carrier?

Because hydrogen must be produced from other energy sources, it is considered an energy carrier rather than an energy source. Once produced, hydrogen can then be stored, transported, and later used in applications such as hydrogen fuel cells, ammonia production, biofuels, industrial metalworking and welding, and other applications.

Why is hydrogen commonly associated with colors like black, blue, gray, and green?

Hydrogen is a colorless, odorless, clean-burning gas. It is generally preferable to classify hydrogen based on the carbon emission intensity of the full production cycle for different production methods (e.g., high-carbon or low-carbon hydrogen). However, it is common for some people to refer to different colors of hydrogen. The colors are used to differentiate how the hydrogen was produced, and different colors are sometimes used to describe the greenhouse gas emissions intensity of the hydrogen production process. Some of the commonly used hydrogen colors are listed in **Table 1.**

It is important to note that there is no universal standard that defines the different colors of hydrogen. This can lead to miscommunications about the properties, environmental impacts, and trade-offs among different hydrogen production processes. For example, blue hydrogen, which uses natural gas as the feedstock and includes carbon capture and storage (CCUS) to minimize direct carbon dioxide emissions, is often referred to as a low-carbon process. However, blue hydrogen production can produce methane emissions, a potent greenhouse gas, from the production and transportation of natural gas. Rather than rely on the color-based classification, a more accurate classification based on carbon intensity is provided in **Table 1.**

Part B: Hydrogen Production, Storage, and Transportation

How is hydrogen produced today?

Hydrogen can be produced by separating it from its various compound forms. Around 80% of hydrogen supply currently comes from dedicated hydrogen production plants. The remaining 20% is produced as a byproduct of other processes (IEA 2020). The four most prevalent methods for hydrogen production are:

1. **Steam-methane reforming:** This is a widely used and mature method for hydrogen production using natural gas as the primary fuel source. Around three-quarters of the annual global production and about 95% of dedicated hydrogen production use this process in the United States. It involves three stages, wherein high-temperature steam (700°C–1,000°C) first reacts with methane in the presence of a catalyst to produce hydrogen, carbon monoxide, and a small amount of carbon dioxide in the first stage. Carbon monoxide and steam then reacts (water-gas shift reaction) using a catalyst to form carbon dioxide and hydrogen. Later, hydrogen gas is purified by removing carbon dioxide and other impurities (usually using pressure-swing adsorption). This process can also be done with other fuels such as ethanol, propane, or gasoline (IEA 2019; EERE 2022).
2. **Coal gasification:** The carbon-based matter in coal includes carbon, hydrogen, oxygen, nitrogen, and sulfur. To produce hydrogen, coal is partially burned in the presence of a catalyst to create the heat and chemical reactions necessary to produce carbon dioxide, which reacts with coal to form carbon monoxide. This carbon monoxide reacts with steam to produce hydrogen (water-gas shift), followed by purification processes similar to steam-methane reforming. This method accounts for around 23% of dedicated global hydrogen production (IEA 2019).

3. **Electrolysis:** This is a process of splitting hydrogen and oxygen from water molecules in a unit called an electrolyzer, which is operated by electricity (and heat, in some technologies). Currently, less than 0.1% of dedicated hydrogen production is via electrolysis (IEA 2021). An electrolyzer consists of an anode and a cathode in water and, in some technologies, an electrolyte. An electric current is applied to the cathode and passes through the water, causing the water molecules to split into hydrogen and oxygen. Today, there are three primary electrolysis technologies: alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis cells.

ISO 22734:2019 provides standards for hydrogen generators using electrolysis in industrial, commercial, and residential applications.

Note: This standard is being redeveloped to also include testing guidance for performing electricity grid services.

Other ISO standards related to hydrogen production, use, storage, and mobility are available here.

4. **Methane pyrolysis:** This is a new technology in which methane is thermally decomposed into hydrogen and solid carbon. Because most of the resultant carbon is solid, the carbon dioxide emissions can be lower than the steam methane reforming process. Research efforts are underway to overcome challenges such as the need for high process temperature, hydrogen gas purity, and separation of solid carbon from gaseous hydrogen.

Additional methods such as biomass gasification, reforming of renewable liquid fuels, biological processes, and direct solar water splitting processes can also be used for hydrogen production.[1]

What is the cost of hydrogen production from various sources?

The cost of hydrogen production depends on several factors such as the initial capital expenditure (i.e., capital cost), operation and maintenance expenses, operating efficiency, operating hours, and fuel cost and/or electricity cost to operate an electrolyzer. **Table 2** provides a comparison of cost estimates of different hydrogen production methods.

Although natural gas-based hydrogen production without CCUS (assuming no carbon pricing) is the least expensive method of hydrogen production today, it is highly dependent on the price of natural gas, which can contribute anywhere between 45%–75% of the total cost (IEA 2019). Currently, capital costs are responsible for around ~50% of the cost of coal- and electrolysis-based hydrogen production (IEA 2019), but research and development are underway to reduce those costs. Electrolysis powered by renewables is widely discussed as a lower-carbon alternative to traditional hydrogen production methods. Still, it is currently the costliest by a wide margin, which makes scale-up and commercialization challenging in the near-term.

What is the current state of electrolyzer technologies?

Around 300 megawatts (MW) of electrolyzer capacity was installed worldwide by mid-2021, with 18.5 MW installed and 602.6 MW firm planned capacity in the United States as on May 2022 (Arjona 2022, IEA 2021). Alkaline electrolyzer (61% of total installed capacity) is a mature technology, while solid oxide electrolysis cell electrolyzer is a relatively new but promising technology that has the potential to operate in reverse mode as a fuel cell as well, although this capability is yet to be demonstrated in a commercial application. PEM technology (31% of total installed capacity) is being used extensively in recent electrolyzer installations and has the potential to be operated more flexibly than alkaline electrolyzers. Over the past decade, deployments of PEM electrolyzers have increased from the kilowatt to megawatt scale, with higher capacity deployments (>10 MW) under development (IEA 2021).

Are there regions where hydrogen production is expected to be more cost-effective?

As mentioned above, the cost-effectiveness of hydrogen production largely depends upon the cost of energy inputs, which varies by location (i.e., the cost of coal or natural gas), as well as the availability of low-cost renewable energy resources. Regions with lower-cost natural gas would have a relatively lower cost for hydrogen production from the steam methane reforming process. Similarly, regions with abundant, low-cost renewable energy resources may have a relatively lower cost for electrolysis-based hydrogen production. IEA analysis suggests areas like South

Table 2. Costs of Different Hydrogen Production Methods

Hydrogen Production Method	Production Cost (U.S. Dollars/Kilograms)
Steam-methane Reforming Using Natural Gas Without CCUS	0.7–1.6
Steam-methane Reforming Using Natural Gas With CCUS	1.2–2.1
Coal Gasification	1.9–2.5
Coal With CCUS	2.1–2.6
Low-Temperature Electrolysis Powered by Renewables	4.2–6.3

Sources: IEA 2020; Vickers, Peterson, and Randolph 2020; NETL 2022

1. See IEA (2019) pages 38–54 and IRENA (2020) for more details on hydrogen production methods.

Asia, Australia, the Middle East, parts of the United States, parts of China, and Northern Africa may be promising for low-carbon hydrogen production from solar photovoltaics and wind resources.

How can hydrogen be stored?

Hydrogen can be stored directly or converted into hydrogen-based fuels. The selection of storage medium would depend upon the availability of geological sites and the duration and scale of storage and transportation requirements. For a smaller-scale application, storage tanks are useful. Geological storage sites, like salt caverns, are promising for large quantities of hydrogen. Because hydrogen has a low energy density by volume, more storage volume is needed for the same energy content compared to other fuels. To overcome this barrier, hydrogen can also be converted to hydrogen-based fuels and feedstocks such as ammonia, liquid organic hydrogen carriers, synthetic hydrocarbons, or synthetic liquid fuels, which can be stored in tanks and can be transported over long distances. This approach requires an additional step of hydrogen extraction if the end use requires pure hydrogen, impacting the efficiency and ultimately the cost of hydrogen as an energy carrier.

How can hydrogen be transported?

Currently, most hydrogen is produced and consumed at the same site or in close proximity. However, hydrogen in the various forms discussed above is also often transported in gaseous or liquid form, through gaseous tube trailers, liquid tanker trucks, or dedicated pipelines. The most viable approach to hydrogen delivery depends largely on the magnitude and stability of regional hydrogen demand. Gaseous tube trailers can typically store up to 1 ton of hydrogen, liquid tanker trucks can typically store 4–5 tons of hydrogen, and gaseous pipelines are commonly used when regional delivery requirements are hundreds of tons per day and are expected to remain stable for decades. Transport of hydrogen via shipping is not common today, but early deployments are underway in support of global hydrogen trade.

Challenges in Hydrogen Storage

- Compared to fossil fuels, the low energy density of hydrogen means more storage volume is needed for the same energy content.
- Limited availability of geological storage sites
- Additional cost of liquefaction or conversion to carriers

Part C: Hydrogen for Power Sector Decarbonization

How can hydrogen help in decarbonization of the power sector?

Hydrogen can be used for **long-duration energy storage**, which can be essential for power grids with high deployment of renewable energy. During times of excess renewable energy, for example in summer when solar resources are most abundant, electrolyzers can start or increase production of hydrogen. This hydrogen can then be used by regional industries or stored and used to supply power to the grid at times of the year when demand outpaces supply. Today, large-scale storage of hydrogen typically relies on geologic formations, such as salt caverns. These formations are limited in regional availability, and research is underway on geographically agnostic approaches. Technologies that can be used to produce power from hydrogen include:

1. **Hydrogen fuel cells** can be used to generate electricity by combining hydrogen with oxygen. Fuel cells could also be used for the purpose of providing backup power or providing electricity access at remote places as well as bulk power when it is needed. However, the cost of fuel cells is currently high in comparison to other sources of generation, but research, development, and demonstration activities are underway to reduce the cost of fuel cells.
2. Hydrogen can be used alone or blended with natural gas in **combustion gas turbines to produce electricity.** This pathway is being pursued on a commercial basis in some locations. However, there are limits to hydrogen blending in the gas network and existing combustion gas turbines need to be suitably modified for use with pure or high blends of hydrogen. Research and demonstration projects are also exploring turbines that can directly burn hydrogen in the form of ammonia.
3. Hydrogen in the form of ammonia can be used to **co-fire in coal-fired power plants and fuel cells.** This pathway is in the research, development, and demonstration phase. Although this pathway has lower CO_2 emissions than natural gas turbines, it may require site modifications to mitigate ammonia leakage, as ammonia is a toxic chemical, and to mitigate NOx emissions associated with burning ammonia.

What are the key barriers to deployment of hydrogen for power sector decarbonization and criteria for its commercialization?

Even though clean hydrogen has the potential to support decarbonization targets across the world, research and development is still needed to reduce costs toward parity with existing sources of energy. Direct use of hydrogen for large-scale electricity production is still at an early stage with some demonstration projects or small-scale commercial deployments. The cost-competitiveness of hydrogen production, storage, and transport also needs to improve for large-scale deployment of hydrogen technologies. Commercialization of hydrogen not only depends upon the cost of hydrogen technologies but also on region-specific costs for alternative decarbonization options. Technology

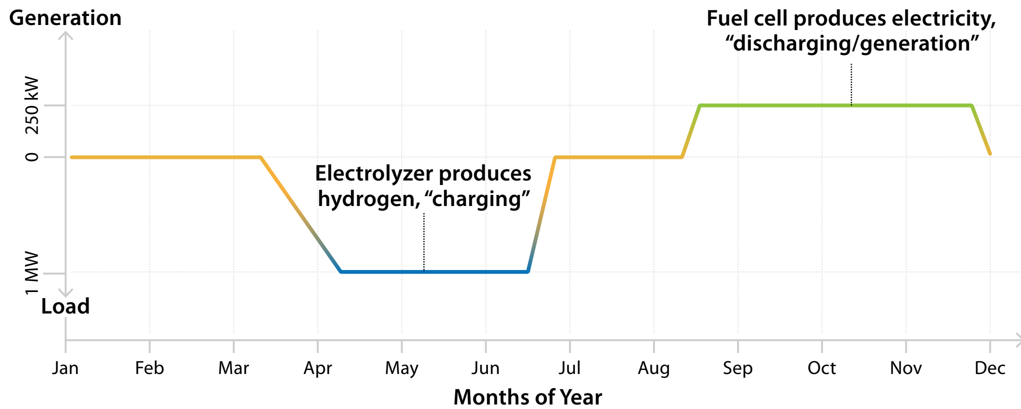

Figure 2. Conceptual diagram showing integrated operation of electrolyzer and fuel cell as hybrid energy storage

Source: Adapted from SDGE 2021.

improvements through research and development, greater economies of scale, and increasing utilization can help reduce the cost of hydrogen technology over time. Continued growth in awareness of safety best practices, codes, and standards is also to needed to enable deployments at scale.

What is a fuel cell?

A fuel cell is an electrochemical device where the chemical energy of a fuel can be converted into electricity. When hydrogen is used as fuel for the technology, a chemical reaction with oxygen (from air) produces electricity, emitting only water. Fuel cells have efficiency in the range of 40%–60% (DOE 2015). The operation of fuel cells is similar to batteries where a structure of anode, cathode, and electrolyte can produce electricity as long as the fuel is supplied. Fuel cells can be used for power generation and for vehicle transportation. Current research efforts for fuel cells in transportation are focused on the medium- and heavy-duty trucking sector, where fuel cells may have greater cost advantages over batteries.

How can hydrogen be used in energy storage applications?

Hydrogen-based systems can provide options for large-scale and long-term (i.e., seasonal) energy storage applications. During times of excess renewable energy generation, electrolyzers can be switched on or instructed to increase their production. The hydrogen gas generated in this process can be stored either in salt caverns, absorbed in liquid organic hydrogen carriers, or converted to other forms, such as methane or ammonia. Later, this hydrogen could be used in any other application or converted back to electricity through any of the pathways discussed above. **Figure 2** provides an example showing integrated operation of electrolyzer and fuel cell as hybrid energy storage. Stored hydrogen could also be traded around the world to manage seasonal changes in renewable energy. Currently, compressed hydrogen and ammonia are considered the more cost-effective long-duration storage options (IEA 2019). However, to date, the technology is not widely commercialized.

Examples of Real-World Applications of Hydrogen in Power Sector

Around 522 hydrogen projects have been announced as of 2021 to be developed between 2021 to 2030 (Statista 2021). Some examples of these projects are given below

- 485-MW Long Ridge Energy Generation Project facility in Ohio with a gas-fired combustion turbine will use 15%–20% carbon-free hydrogen initially, with transition to 100% hydrogen over time (LRET 2020).
- Intermountain Power Agency has planned to deploy 840 MW of natural gas turbines capable of burning blends of 30% hydrogen in the near term and 100% low-carbon hydrogen in the long term (EIA 2022).
- San Diego Gas and Electric power-to-gas-to-power project will use the electric grid to produce hydrogen via electrolysis and use it in a fuel cell to generate electricity (SDGE 2021).
- Equinor and Scottish utility SSE recently announced a plan to build a 1.8-gigawatt (GW) hydrogen-fired power station at Keadby in northeast England (Collins 2021).
- An 80-MW cogeneration project in São Paulo state, Brazil, is being commissioned to use byproduct hydrogen from a petrochemical refinery to provide power and heat back to the refinery (Collins 2021).
- Energy Australia's new Tallawarra B Power Station of 316 MW in New South Wales will run on a blend of natural gas and hydrogen (GE 2021).
- A 55-MW solar plant, along with 20MW/38MW-hour of battery storage, a 16-MW electrolyzer, and a 3-MW fuel cell, is being constructed in French Guiana (Collins 2021).

Can electrolyzers provide flexibility and grid services?

Yes, electrolyzers can provide grid flexibility services. PEM electrolyzers have been shown to be capable of grid response within sub-seconds (Eichman, Harrison, and Peters 2014). They have few moving components and use power electronics for operations and control, which makes them suitable to provide a range of grid services like fast frequency response, operational reserves, load following, and time shifting.

Part D: Cross-sectoral Applications of Hydrogen

What are the hydrogen consumption pathways of the future?

Hydrogen has potential applications in multiple sectors, including road transport, shipping, aviation, buildings, power, and industry. Some of these pathways are listed in **Table 3.**

Are there alternatives to hydrogen for decarbonization of the power sector and other sectors?

Biofuels and biogas are seen as low-carbon alternatives in transport, aviation, and shipping. Renewable energy and battery energy storage are widely commercialized and cost-competitive in the power sector, and through electrification, they have potential applications in transport and heat sectors as well. CCUS can help in the decarbonization of the power, heat, industry, and petrochemical sectors. All these alternatives are at different levels of maturity for different sectors.

Table 3. Application of Hydrogen in Different Sectors

Sector	Existing of Potential Applications of Hydrogen
On-Road Transport and Rail	• Fuel cell-based transport (cars, trucks, rail, etc.)
Buildings	• Hydrogen or a blend of natural gas and hydrogen for heating
Shipping and Aviation	• Ammonia and methanol as a fuel in shipping • Feedstock for liquid fuels (e.g., biofuels, synthetic fuels)
Power	• Fuel cell-based generation • Blending hydrogen with natural gas in combustion turbines • Combustion turbines designed to use 100% hydrogen • Co-firing coal-fired power plants with ammonia • Seasonal energy storage
Industries	• Hydrotreatment and hyrdocracking in crude oil refining • Ammonia and methanol production • Iron and steel production • Hydrogen or a blend of natural gas and hydrogen combustion in boilers and furnaces to produce high-temperature heat • Blending hydrogen with natural gas in combustion turbines

Note: These potential applications are at different levels of maturity and cost-competitiveness.

What can policymakers do to understand the potential value of hydrogen in their country?

Figure 3 summarizes the steps that policymakers can take to understand the potential value of hydrogen and also stimulate its deployment. Policymakers can first start with an assessment of hydrogen potential in their country. This could include opportunities in existing and new sectors and markets. Thereafter, policymakers can conduct economic, environmental, and energy justice assessments to understand various aspects associated with a hydrogen economy, including infrastructure requirements, investment, jobs, and climate impacts.

Examples of analyses that can help policymakers assess the value of hydrogen include:

1. NREL study on resource assessment for hydrogen production in the United States
2. NREL study on the technical and economic potential of the H2@ Scale concept within the United States
3. United States Department of Energy (DOE) Hydrogen Program Plan
4. Scottish Hydrogen Assessment
5. Opportunities for Hydrogen Energy Technologies Considering the National Energy and Climate Plans in France

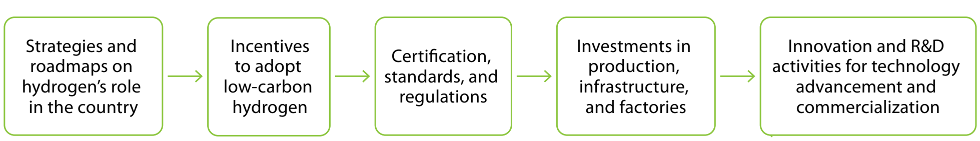

Figure 3. Steps that policymakers can take to stimulate growth of hydrogen deployment

This is only one suggested order of steps. Policymakers can take these steps in an alternate order as well.

Source: Adapted from IEA 2019

Are there any examples of policy directives to stimulate hydrogen deployment?

Many countries around the world published national strategies, road maps, or targets for hydrogen. Some countries are evaluating and assessing the role of hydrogen in their economy and are expected to come out with hydrogen-related plans soon. Some examples of policy initiatives are given in **Table 4.**

Table 4. Examples of Policy Directives to Stimulate Hydrogen Deployment

Country	Policy/Initiatives	Key Focus Area or Target
Australia	National Hydrogen Strategy	Outlines approach to quickly scale up hydrogen production and use
	H_2 Under 2	Target to produce hydrogen under $2 Australian dollars per kilogram
Canada	Hydrogen Strategy	30% of Canada's end-use energy from hydrogen by 2050
Chile	National Green Hydrogen Strategy	Set out ambition to become world's cheapest green hydrogen producer, leading exporter, and 25-GW green hydrogen via electrolysis capacity by 2030
Colombia	Hydrogen Roadmap	3-GW electrolysis capacity by 2030 and roadmap for development, generation, and use of hydrogen until 2050
European Union	Hydrogen Strategy for a Climate-neutral Europe	Phased approach for decarbonization and targets for renewable hydrogen electrolyzers (40 GW by 2030) and renewable hydrogen (10 million tonnes by 2030)
France	National Strategy for the Development of Decarbonized and Renewable Hydrogen in France	Investment in clean hydrogen infrastructure and research and development of 6.5-GW electrolyzers by 2030
Germany	The National Hydrogen Strategy	5-GW electrolyzer capacity by 2030
India	Green Hydrogen Policy	Incentives for green hydrogen and green hydrogen production Indian government has also set a target for 5 million tonnes of green hydrogen production annually by 2030
Japan	Green Growth Strategy	Strengthen hydrogen supply, transportation, and storage to reduce price of hydrogen and increase utilization
Netherlands	Dutch Hydrogen Strategy	Target for at least 30% and up to 50% energy consumption via gaseous energy carriers such as biogas and hydrogen
Norway	The Norwegian Government's Hydrogen Strategy	Expand use of hydrogen in maritime sector and promote innovation in subsea storage
Portugal	Portugal National Hydrogen Strategy	Aiming to increase the share of hydrogen in final energy consumption to 5% by 2030
South Korea	Hydrogen Economy Roadmap	Target of 6.2 million fuel cell electric vehicles and 15 GW of fuel cells for power generation by 2040
United Kingdom	Hydrogen Strategy	5 GW of low carbon hydrogen production capacity by 2030
United States	Hydrogen Program Plan	Plan to accelerate research, development, and deployment of hydrogen technologies in United States
	DOE National Clean Hydrogen Strategy (to be released soon)	Strategy for affordable clean hydrogen for a net-zero carbon future and a sustainable, resilient, and equitable economy

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