



## Views &amp; Comments

## Hydrogen for a Net-Zero Carbon World

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## 1. Why hydrogen?

The concept of the “hydrogen economy” was first coined by Prof. John Bockris during a talk he gave in 1970 at the General Motors Technical Center. Bockris’s talk introduced the vision of a world economy in which energy was carried in the form of hydrogen, resulting in zero emissions at its point of use—be that as a chemical feedstock or as a fuel for industrial or domestic heating, for power generation in a gas turbine, or in a fuel cell “engine” for transport applications. Despite several waves of significant interest and investment, however, due to the relative costs and technological immaturity of hydrogen technologies, the hydrogen economy was never delivered at scale nor was there sufficient motivation to create the technology needed to overcome these hurdles.

But today, as the world seeks to transition to a truly net-zero carbon economy, hydrogen has returned to the fore as a key energy carrier—not as a hydrogen economy, but as “hydrogen in the economy,” synergistically working alongside low- to zero-carbon electricity to decarbonize those parts of the economy that are too expensive or too difficult to be directly decarbonized with electricity. These include:

- Transport applications in which large amounts of energy are needed on the vehicle, such as planes, trains, shipping, long-distance trucks, and heavy-duty vehicles;
- Industrial applications such as steelmaking and cement manufacturing;
- Long-term energy storage for days to weeks at a time;
- The production of green chemicals such as green ammonia and green methanol;
- Industrial (and potentially residential) heating.

## 2. The role of hydrogen today

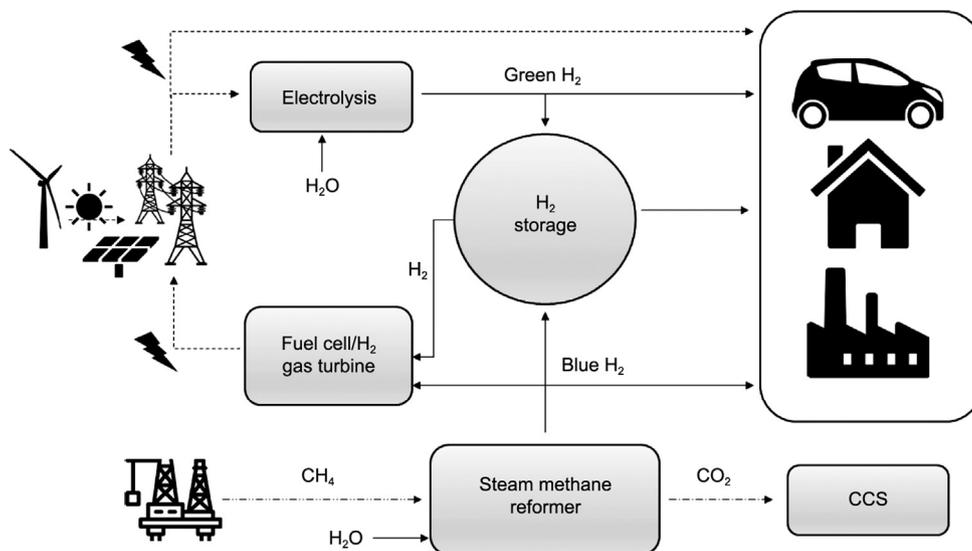
Three key points related to hydrogen must be kept in mind. First, hydrogen is an energy carrier rather than a source of energy; that is, energy is used to create hydrogen, either by stripping it from a fossil fuel such as natural gas, and then capturing and storing the hydrogen (blue hydrogen), or by splitting water

using electrolysis driven by renewable power (green hydrogen). Therefore, the carbon credentials of hydrogen depend on the route used to produce it. This concept is illustrated schematically in Fig. 1, which shows how green and blue hydrogen can be connected to hydrogen storage and to various end-use sectors, including the potential for long-term and large-scale energy storage [1].

The world today uses around 100 million tonnes of hydrogen a year, almost all of which is produced from fossil fuels such as natural gas and coal, without any form of carbon abatement, and almost all of which is used as a chemical feedstock for the petrochemical, fertilizer, and chemical industries. If hydrogen is to contribute to decarbonization, we must massively upscale this production and do so in a way that manages carbon emissions. Due to the increasing international focus on securing energy resilience while reducing dependence on imported fossil fuels such as natural gas, and the ensuing political implications of this shift, green hydrogen produced from local renewable resources is attracting ever-increasing interest on a global scale. Indeed, many governments have recently issued strategies to focus on the production, storage, distribution, and end use of low- to zero-carbon hydrogen.

Second, if hydrogen is made via electrolysis, then the hydrogen produced will always be more expensive per unit energy than the electricity used to produce it. Thus, zero-carbon electrons should be used whenever possible, with those electrons being converted into a zero-carbon molecule such as hydrogen only when it is too difficult and expensive to move the electricity to where it is needed (as hydrogen is much easier and cheaper to move in volume than electricity) or when electricity does not meet the functional requirements (e.g., long-distance air travel).

The third key point is that hydrogen is a hazardous gas with a propensity to leak, given its small molecular size. Recent work has shown that the global warming potential (GWP) of hydrogen is higher than previously thought, with recent work putting hydrogen’s GWP over 100 years (GWP-100) at  $(11 \pm 5)$  years [2] and its GWP over 20 years (GWP-20) at around 30 years [3]. Although hydrogen’s GWP is still much lower than that of methane, which



**Fig. 1.** Schematic illustration of how green and blue hydrogen can be produced and connected to end-use sectors, including large-scale and longer-term energy storage, alongside and in support of low-carbon electricity. CCS: carbon capture and storage.

has a GWP-100 of 27–30 years and a GWP-20 of 81–83 years, this finding highlights the need to ensure that the new hydrogen infrastructure is designed and built from the outset to minimize hydrogen leaks.

### 3. Key enablers for hydrogen

Let us now discuss the main technologies that must be established to enable a cost-effective and scalable role for hydrogen in net zero economies. Given the importance that green hydrogen will have in such a future, electrolysis is a key technology. Of course, electrolyzers are not new; alkaline electrolyzers have been used to produce hydrogen via electrolysis at scale for well over a hundred years. Today, these remain the lowest cost form of electrolyzer available, as well as the largest in the range of up to hundreds of megawatts. Alkaline electrolyzers are around 65% efficient, have a large footprint, do not deliver hydrogen at elevated pressure, and struggle to follow rapidly varying power sources. The polymer electrolyte membrane (PEM) or PEM electrolyzer is a newer technology that is available with a current range of tens of megawatts. These have a similar efficiency of around 65% but are more compact and produce hydrogen at high pressure. However, PEM electrolyzers require a relatively high content of iridium—a very rare and costly material—along with platinum and ruthenium, all of which are used as electrocatalysts. The solid oxide electrolyzer (SOE) is an emerging technology that electrolyzes steam rather than water; this approach provides important thermodynamic and kinetic advantages, enabling system electrical efficiencies of well above 90%. Furthermore, SOEs do not contain precious metals. Given that around 60%–80% of the cost of green hydrogen today is the cost of electricity, the significant efficiency advantage SOEs provide is clearly attractive. However, while they have great promise, SOEs are not yet commercially mature; they are being developed and tested at up to the megawatt scale today, so further work is needed to accelerate their development and manufacturing.

Once hydrogen is produced, we must be able to store and distribute it. While hydrogen storage has been the subject of an intensive global effort for many years, with the aim of increasing the mass of hydrogen that can be stored per unit volume/mass on a vehicle, the larger scale storage of hydrogen in solution-mined salt caverns or in lined rock caverns is already a mature technology that is used to provide strategic hydrogen storage for petrochemi-

cal or other facilities. There is now growing interest in utilizing this approach to enable electricity storage in the terawatt hour range, as will be needed to back up the large-scale penetration of wind energy, such as for periods of low windspeeds. The United Kingdom alone is likely to require tens of terawatt hour of storage to provide a few weeks' supply in the event of a low in winter windspeeds [4], which is a common occurrence in Northern Europe. Noting that 1 million tonnes of hydrogen contain around 33 TW-h of energy, and given that the United Kingdom and, indeed, many parts of Europe—has the geology needed to enable storage at the scale needed, then underground hydrogen storage offers a viable route to terawatt hour energy storage. There are also opportunities to produce and store hydrogen locally, such as using solar photovoltaics (PVs) with a coupled electrolyzer and local hydrogen storage to help decarbonize off-grid applications in order to replace liquid petroleum gas (LPG) tanks for cooking and heating.

In terms of distribution, hydrogen can be distributed at scale by pipeline; existing natural gas pipelines can be repurposed for hydrogen, provided they are suitably lined. Alternatively, for very long distances or international shipping, hydrogen can be converted into other green hydrogen carriers such as ammonia, or perhaps methanol with captured carbon dioxide, although care must be taken with the latter to ensure a completely closed carbon cycle.

It should be noted that hydrogen compression and liquefaction are both energy-intensive processes. For example, compression energy requirements from onsite production are approximately 5%–20% of the hydrogen lower heating value (LHV), where the LHV of hydrogen is  $33.3 \text{ kW}\cdot\text{h}\cdot\text{kg}^{-1}$ . Liquefaction energy requirements are even higher, typically the energy required to liquify hydrogen is  $10\text{--}13 \text{ kW}\cdot\text{h}\cdot\text{kg}^{-1}$ , depending on the scale of the liquefaction operation. Therefore, system and cost optimization are needed to determine the optimum means of hydrogen distribution.

Finally, the produced hydrogen must be used to produce heat or power, or as an input for industrial decarbonization. An immediate application would be to replace the fossil-derived hydrogen currently in use. Beyond that, the use of hydrogen in the direct reduction of iron (DRI) process in steelmaking is a rapidly emerging option for decarbonizing the global steel industry—an industry responsible for about one quarter of the world's industrial carbon emissions. Hydrogen can be used as a fuel for power generation in bespoke gas turbines and/or in fuel cells; the latter are already commercially available for distributed power applications in the

range of 10–100 kW and offer very high-efficiency power generation with zero noise, no vibration, and zero emissions. These attributes make fuel cells ideal for integration into buildings or urban environments in order to reinforce the electrical network as more power is needed for applications such as electric vehicles. Hydrogen can also be used for heat, including industrial heat and space heating; the latter application is attractive for older building stock that is difficult to equip with electrical heating via heat pumps.

The overall system efficiency of producing hydrogen via electrolysis, distributing it, and then converting it back to electricity in a fuel cell or gas turbine is the product of all the individual unit efficiencies. Thus, it falls in the range of around 30%–50%, depending on the technologies selected. It is hence essential to take a system view of the benefits hydrogen can bring. Hydrogen can support the electrification of other sectors, in terms of both managing peak energy demand and balancing the electricity system as a whole. It can couple together different parts of the economy, from transport to industry to heat, and this cross-sector coupling must be understood and valued. Finally, hydrogen is making an increasingly important contribution to energy resilience and security in both developed and developing economies.

#### 4. Conclusions

To conclude, the potential of hydrogen to lower the overall cost of the transition to net-zero carbon is clear. For that potential to be realized, we must take action to secure investment in manufacturing at scale, in deployment at scale, in the training of a skilled workforce, and in the co-creation of a hydrogen infrastructure for the production, storage, distribution, and end use of hydrogen and its carriers.

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