Harnessing solar power and storing it as green hydrogen via PEM electrolysis – Alessandro Teixeira Neto, July 2026

Captura da energia solar e sua armazenagem como hidrogênio pela eletrólise PEM – Alessandro Teixeira Neto, julho 2026

Sumário

Este documento apresenta uma investigação breve e abrangente sobre a captura da energia solar e sua armazenagem como hidrogênio verde (H2) pela eletrólise da água usando a tecnologia PEM (membrana de troca de prótons). O foco principal está em apresentar algumas referências correlatas ao tema visando conhecer o estado da arte e as perspectivas de sucesso para um eventual desenvolvimento tecnológico e de produtos neste sentido. A captura da energia solar é feita por sistemas fotovoltaicos usando rastreadores. A planta de captação solar pode ser montada em terra firme (para uma maior praticidade) ou mesmo em plataforma flutuante (podendo levar a algumas vantagens de performance e a utilização direta da água de reservatórios artificiais para a produção do hidrogênio). A vantagem mais evidente de se integrar soluções contemporâneas de sistemas PV (fotovoltaicos) com a eletrólise PEM é a produção econômica e o armazenamento local da energia na forma de hidrogênio verde. O H2 armazenado encontra ampla aplicação em indústrias de transformação, na geração de energia, no balanceamento de grid (de longa ou de curta duração) e transporte pesado de carga (aviação, marítimo, por trem ou caminhões). O hidrogênio verde é importante vetor energético para complementar a eletricidade, como parte da estratégia de médio a longo prazo para reduzirmos as emissões dos gases de efeito estufa. Sob o ponto de vista da maturidade tecnológica, estamos atualmente na transição entre a fase II (transição da tecnologia para o mercado) e a fase III (expansão do mercado e da infraestrutura), estando os sistemas de potência H2 e de eletrólise PEM já disponíveis no mercado. Por isto tudo explicado acima, este momento mostra-se bastante adequado e auspicioso às iniciativas de desenvolvimento tecnológico e de produtos integrados para captura da energia solar e sua armazenagem como hidrogênio verde (H2) pela eletrólise da água usando a tecnologia PEM.

References:

https://en.wikipedia.org/wiki/Photovoltaic_system "A photovoltaic system, also called a PV system or solar power system, is an electric power system designed to supply usable solar power by means of photovoltaics. It consists of an arrangement of several components, including solar panels to absorb and convert sunlight into electricity, a solar inverter to convert the output from direct to alternating current, as well as mounting, cabling, and other electrical accessories to set up a working system. Many utility-scale PV systems use tracking systems that follow the sun's daily path across the sky to generate more electricity than fixed-mounted systems."

https://en.wikipedia.org/wiki/Floating_solar "Floating solar or floating photovoltaics (FPV), sometimes called floatovoltaics, are solar panels mounted on a structure that floats. The structures that hold the panels usually consist of plastic buoys and cables. They are then placed on a body of water (e.g., Reservoirs, quarry lakes, irrigation canals or remediation and tailing ponds)."

"The systems can have advantages over photovoltaics (PV) on land. Water surfaces may be less expensive than the cost of land, and there are fewer rules and regulations for structures built on bodies of water not used for recreation. Life cycle analysis indicates that foam-based FPV have some of the shortest energy payback times (1.3 years) and the lowest greenhouse gas emissions to energy ratio (11 kg CO2 eq/MWh) in crystalline silicon solar photovoltaic technologies reported. FPV can be used to generate electricity for any application as well as to make green hydrogen via electrolysis on the same water they are floating on."

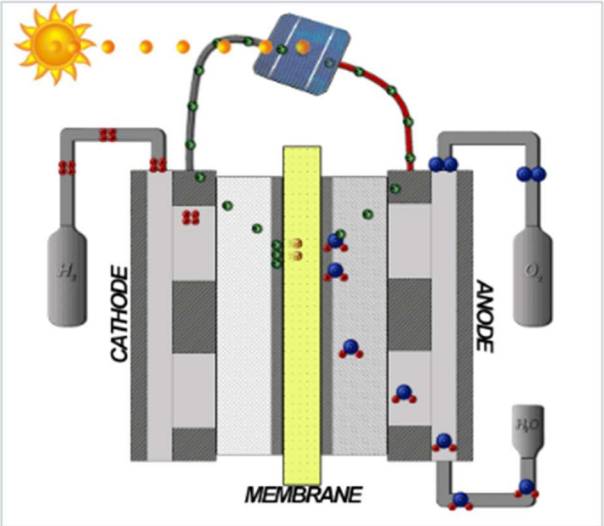
https://en.wikipedia.org/wiki/Green_hydrogen "Green hydrogen (GH2 or GH2) is hydrogen produced by the electrolysis of water using renewable electricity. Production of green hydrogen causes significantly lower greenhouse gas emissions than production of grey hydrogen, which is derived from fossil fuels without carbon capture."

"Green hydrogen's principal purpose is to help limit global warming, reduce fossil fuel dependence by replacing grey hydrogen, and provide for an expanded set of end-uses in specific economic sectors, sub-sectors and activities. These end-uses may be technically difficult to decarbonize through other means such as electrification with renewable power. Its main applications are likely to be in heavy industry (e.g. high temperature processes alongside electricity, feedstock for production of green ammonia and organic chemicals, as direct reduction steelmaking), shipping, and long-term energy storage."

"As of 2024, low-emission hydrogen, including both blue and green hydrogen, accounted for less than 1% of global hydrogen production, with green hydrogen only making up around 12% of all low-emission hydrogen production. Green hydrogen is more costly to produce compared to all other methods of hydrogen production, however, with new technological developments as well as the increasing cost of natural gas, the cost gap is expected to narrow by 2030."

"Most commonly, green hydrogen is defined as hydrogen produced by the electrolysis of water, using renewable electricity. In this article, the term green hydrogen is used with this meaning."

"Precise definitions sometimes add other criteria. The global Green Hydrogen Standard defines green hydrogen as "hydrogen produced through the electrolysis of water with 100% or near 100% renewable energy with close to zero greenhouse gas emissions." In integrated cases water can also provide services back to the renewable energy source such as when water cools floatovoltaics (floating solar photovoltaics) to improve efficiency of solar energy conversion, which in turn is used to generate green hydrogen from the water."



Animated schematic of a proton exchange membrane (PEM) electrolyzer showing water inlet, proton exchange membrane, and hydrogen/oxygen outlets.

https://en.wikipedia.org/wiki/Proton_exchange_membrane_electrolysis "Proton exchange membrane (PEM) electrolysis is the electrolysis of water in a cell equipped with a solid polymer electrolyte (SPE) that is responsible for the conduction of protons, separation of product gases, and electrical insulation of the electrodes. The PEM electrolyzer was introduced to overcome the issues of partial load, low current

density, and low pressure operation currently plaguing the alkaline electrolyzer. It involves a proton-exchange membrane."

"Electrolysis of water is an important technology for the production of hydrogen to be used as an energy carrier. With fast dynamic response times, large operational ranges, and high efficiencies, water electrolysis is a promising technology for energy storage coupled with renewable energy sources. In terms of sustainability and environmental impact, PEM electrolysis is considered as a promising technique for high purity and efficient hydrogen production since it emits only oxygen as a by-product without any carbon emissions. The IEA said in 2022 that more effort was needed. The availability of iridium may be a constraint for the widespread adoption of PEM technology."

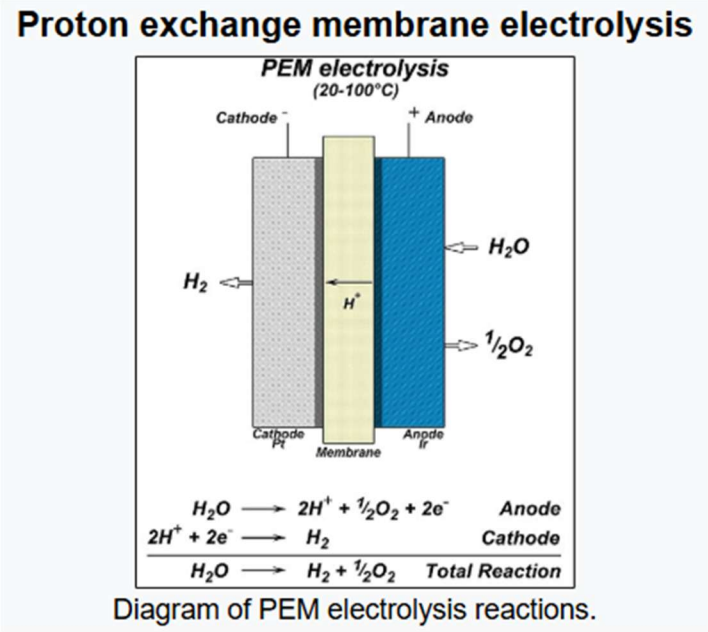


Diagram of PEM electrolysis reactions.

"One of the largest advantages to PEM electrolysis is its ability to operate at high current densities. This can result in reduced operational costs, especially for systems coupled with very dynamic energy sources such as wind and solar, where sudden spikes in energy input would otherwise result in uncaptured energy. The polymer electrolyte allows the PEM electrolyzer to operate with a very thin membrane (~100-200 μm) while still allowing high pressures, resulting in low ohmic losses, primarily caused by the conduction of protons across the membrane (0.1 S/cm) and a compressed hydrogen output."

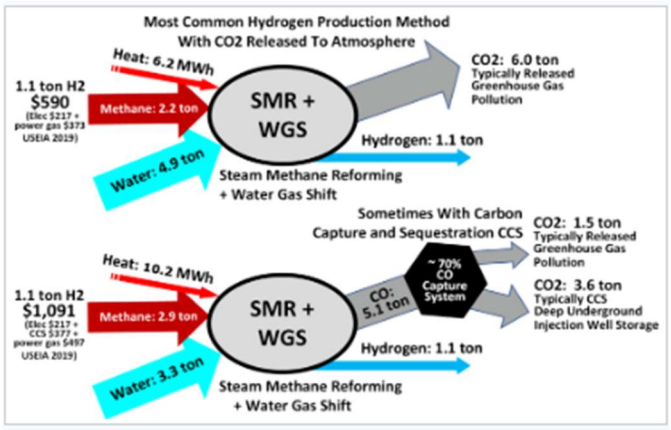
"The polymer electrolyte membrane, due to its solid structure, exhibits a low gas crossover rate resulting in very high product gas purity. Maintaining a high gas purity is important for storage safety and for the direct usage in a fuel cell. The safety limits for H2 in O2 are at standard conditions 4 mol-% H2 in O2."

"An electrolyzer is an electrochemical device to convert electricity and water into hydrogen and oxygen, these gases can then be used as a means to store energy for later use. This use can range from electrical grid stabilization from dynamic electrical sources such as wind turbines and solar cells to localized hydrogen production as a fuel for fuel cell vehicles. The PEM electrolyzer utilizes a solid polymer electrolyte (SPE) to conduct protons from the anode to the cathode while insulating the electrodes electrically. Under standard conditions the enthalpy required for the decomposition of water is 285.9 kJ/mol. A portion of the required energy for a sustained electrolysis reaction is supplied by thermal energy and the remainder is supplied through electrical energy."

"The ability of the PEM electrolyzer to operate, not only under highly dynamic conditions but also in part-load and overload conditions is one of the reasons for the recently renewed interest in this technology. The demands of an electrical grid are relatively stable and predictable, however when coupling these to energy sources such as wind and solar, the demand of the grid rarely matches the generation of renewable energy. This means energy produced from renewable sources such as wind and solar benefit by having a buffer, or a means of storing off-peak energy. As of 2021, the largest PEM electrolyzer is 20 MW."

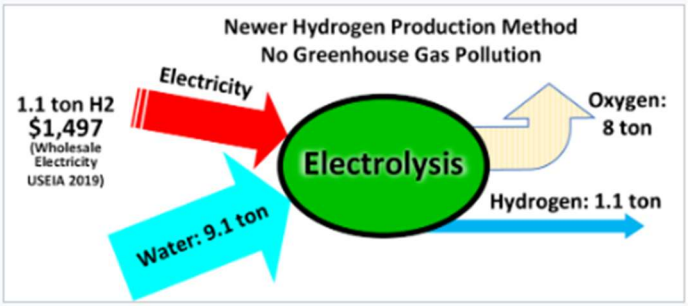
"PEM electrolysis has an electrical efficiency of about 80% in working application, in terms of hydrogen produced per unit of electricity used to drive the reaction. The efficiency of PEM electrolysis is expected to reach 82-86% before 2030, while also maintaining durability as progress in this area continues at a pace."

https://en.wikipedia.org/wiki/Hydrogen_production "Hydrogen gas is produced by several industrial methods. Nearly all of the world's current supply of hydrogen is created from fossil fuels. Most hydrogen is gray hydrogen made through **steam methane reforming**. In this process, hydrogen is produced from a chemical reaction between steam and methane, the main component of natural gas. Producing one tonne of hydrogen through this process emits 6.6–9.3 tonnes of carbon dioxide. When carbon capture and storage is used to remove a large fraction of these emissions, the product is known as blue hydrogen."



Illustrating inputs and outputs of steam reforming of natural gas, a process to produce hydrogen and CO_2 greenhouse gas that may be captured with CCS

"Green hydrogen is usually understood to be produced from **renewable electricity via electrolysis of water.** Less frequently, definitions of green hydrogen include hydrogen produced from other low-emission sources such as biomass. Producing green hydrogen is currently more expensive than producing gray hydrogen, and the efficiency of energy conversion is inherently low. Other methods of hydrogen production include biomass gasification, methane pyrolysis, extraction of underground natural hydrogen, and in situ hydrogen synthesis."



Illustrating inputs and outputs of simple electrolysis of water, for production of hydrogen.

"As of 2023, less than 1% of dedicated hydrogen production is low-carbon, i.e.; blue hydrogen, green hydrogen, and hydrogen produced from biomass."

"In 2020, roughly 87 million tons of hydrogen was produced worldwide for various uses, such as oil refining, in the production of ammonia through the Haber process, and in the production of methanol through reduction of carbon monoxide. The global hydrogen generation market was fairly valued at US$155 billion in 2022, and expected to grow at a compound annual growth rate of 9.3% from 2023 to 2030.

Color	Production source	Process / method / chemistry	Greenhouse gas footprint[27]	Notes	References
Green	Renewable electricity: wind, solar, hydro, tidal, geothermal. May also include electricity from low-emission sources such as biomass.	Electrolysis of water $2\ H_2O \rightarrow 2\ H_2 + O_2$	Minimal		[7]
Blue	Fossil hydrocarbons: natural gas	Gas reforming with carbon capture and storage 1st stage: $CH_4 + H_2O \rightarrow CO + 3\ H_2$ 2nd stage: $CO + H_2O \rightarrow CO_2 + H_2$	Low	CCS networks required	[28]:28
Gray	Fossil hydrocarbons: natural gas	Steam reforming of natural gas 1st stage: $CH_4 + H_2O \rightarrow CO + 3\ H_2$ 2nd stage: $CO + H_2O \rightarrow CO_2 + H_2$	High	CO_2 produced	[28]:28 [30]:10 [29]:2
Yellow	Solar photovoltaics	Electrolysis $2\ H_2O \rightarrow 2\ H_2 + O_2$	Minimal		[25]

https://en.wikipedia.org/wiki/Electrolysis_of_water

Efficiency

"Electrolyzer vendors provide efficiencies based on enthalpy. To assess the claimed efficiency of an electrolyzer it is important to establish how it was defined by the vendor (i.e. what enthalpy value, what current density, etc.)."

"Conventional alkaline electrolysis has an efficiency of about 70%. Accounting for the accepted use of the higher heating value (because inefficiency via heat can be redirected back into the system to create the steam required by the catalyst), average working efficiencies for PEM electrolysis are around 80%. This is expected to increase to between 82 and 86% before 2030. Theoretical efficiency for PEM electrolysers are predicted up to 94%."

Cost

"Calculating cost is complicated, and a market price barely exists. Considering the industrial production of hydrogen, and using current best processes for water electrolysis (PEM or alkaline electrolysis) which have an effective electrical efficiency of 70–80%, producing 1 kg of hydrogen (which has a specific energy of 143 MJ/kg) requires 50–55 kW·h (180–200 MJ) of electricity. At an electricity cost

of $0.06/kW·h, as set out in the US Department of Energy hydrogen production targets for 2015, the hydrogen cost is $3/kg. Equipment cost depends on mass production, and the cost of electrolyzers rose 50% between 2021 and 2024. Operating cost depends on electricity cost for about half of the levelised product price."

Comparison with steam-methane-reformed (SMR) hydrogen

"With the range of natural gas prices from 2016 as shown in the graph (Hydrogen Production Tech Team Roadmap, November 2017) putting the cost of steam-methane-reformed (SMR) hydrogen at between $1.20 and $1.50, the cost price of hydrogen via electrolysis is still over double 2015 DOE hydrogen target prices. The US DOE target price for hydrogen in 2020 is $2.30/kg, requiring an electricity cost of $0.037/kW·h, which is achievable given 2018 PPA tenders for wind and solar in many regions. This puts the $4/gasoline gallon equivalent (gge) H2 dispensed objective well within reach, and close to a slightly elevated natural gas production cost for SMR."

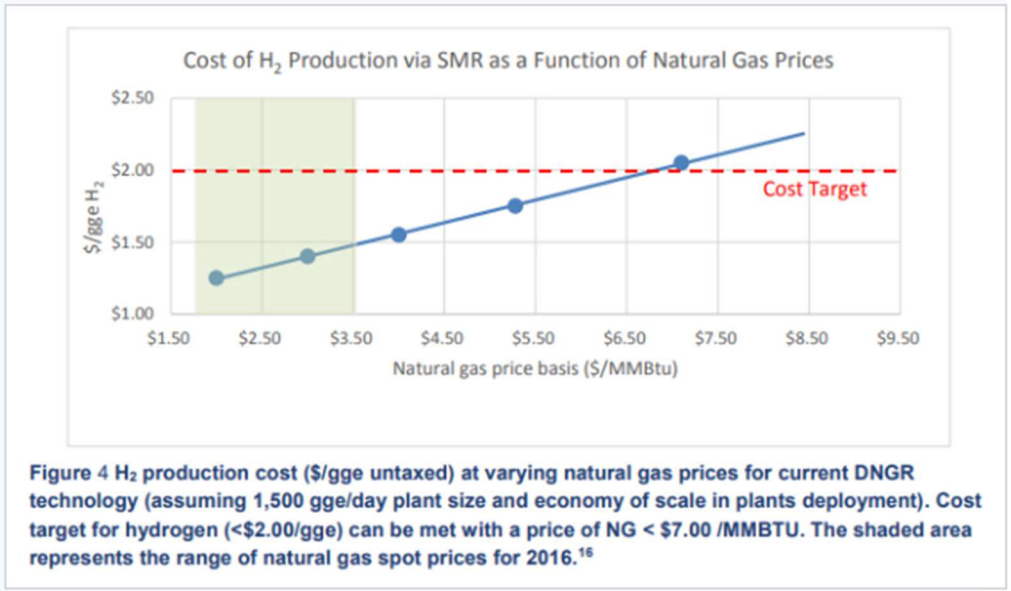


Figure 4 H_2 production cost ($/gge untaxed) at varying natural gas prices for current DNGR technology (assuming 1,500 gge/day plant size and economy of scale in plants deployment). Cost target for hydrogen (<$2.00/gge) can be met with a price of NG < $7.00 /MMBTU. The shaded area represents the range of natural gas spot prices for 2016.[16]

H_2 production cost ($-gge untaxed) at varying natural gas prices

"In other parts of the world, the price of SMR hydrogen is by between $1–3/kg on average. This makes production of hydrogen via electrolysis cost competitive in many regions already, as outlined by Nel Hydrogen and others, including an article by the IEA examining the conditions which could lead to a competitive advantage for electrolysis. The large price increase of gas during the 2021–2022 global energy crisis made hydrogen electrolysis economic in some parts of the world."

"In 2021, the US DOE established the Hydrogen Energy Earthshot (Hydrogen Shot) with a target of $1 (USD) for 1 kg of hydrogen in 1 decade, i.e., $1/kg by 2031 (known as "1 1 1"). This low price was selected to be competitive with the price of hydrogen

from natural gas in the United States which is approximately $1.50/kg. In comparison, the cost baseline for hydrogen from electrolysis in 2020 was approximately $5/kg, requiring an 80% cost reduction to meet the Hydrogen Shot goal."

"The report by IRENA.ORG is an extensive factual report of present-day industrial hydrogen production consuming about 53 to 70 kWh per kg could go down to about 45 kWh/kg H2."

"The thermodynamic energy required for hydrogen by electrolysis translates to 33 kWh/kg, which is higher than steam reforming with carbon capture and higher than methane pyrolysis. One of the advantages of electrolysis over hydrogen from steam methane reforming (SMR) is that the hydrogen can be produced on-site, meaning that the costly process of delivery via truck or pipeline is avoided."

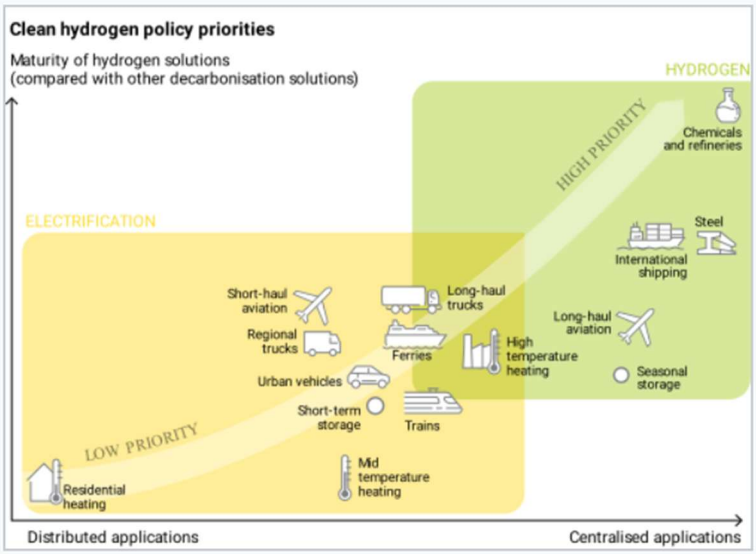
https://en.wikipedia.org/wiki/Hydrogen_economy The hydrogen economy is a term for the role hydrogen as an energy carrier to complement electricity as part of a long-term option to reduce emissions of greenhouse gases. The aim is to reduce emissions where cheaper and more energy-efficient clean solutions are not available. In this context, hydrogen economy encompasses the production of hydrogen and the use of hydrogen in ways that contribute to phasing-out fossil fuels and limiting climate change.

"Hydrogen can be produced by several means. Most hydrogen produced today is gray hydrogen, made from natural gas through steam methane reforming (SMR). This process accounted for 1.8% of global greenhouse gas emissions in 2021. Low-carbon hydrogen, which is made using SMR with carbon capture and storage (blue hydrogen), or through electrolysis of water using renewable power (green hydrogen), accounted for less than 1% of production. Of the 100 million tonnes of hydrogen produced in 2021, 43% was used in oil refining and 57% in industry, principally in the manufacture of ammonia for fertilizers, and methanol."

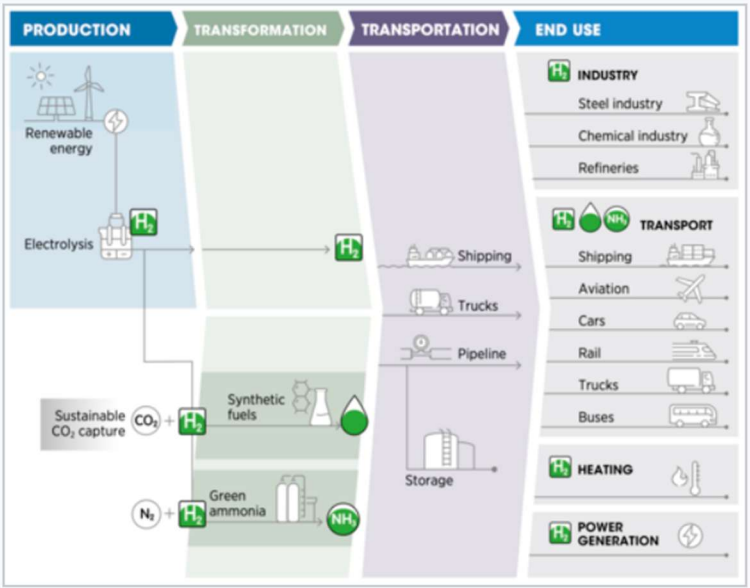
"To limit global warming, it is generally envisaged that the future hydrogen economy replace gray hydrogen with low-carbon hydrogen. As of 2024 it is unclear when enough low-carbon hydrogen could be produced to phase-out all the gray hydrogen The future end-uses are likely in heavy industry (e.g. high-temperature processes alongside electricity, feedstock for production of green ammonia and organic chemicals, as alternative to coal-derived coke for steelmaking), long-haul transport (e.g. shipping, and to a lesser extent hydrogen-powered aircraft and heavy goods vehicles), and long-term energy storage. Other applications, such as light duty vehicles and heating in buildings, are no longer part of the future hydrogen economy, primarily for economic and environmental reasons. Hydrogen is challenging to store, to transport in pipelines, and to use. It presents safety concerns since it is

highly explosive, and it is inefficient compared to direct use of electricity. Since relatively small amounts of low-carbon hydrogen are available, climate benefits can be maximized by using it in harder-to-decarbonize applications."

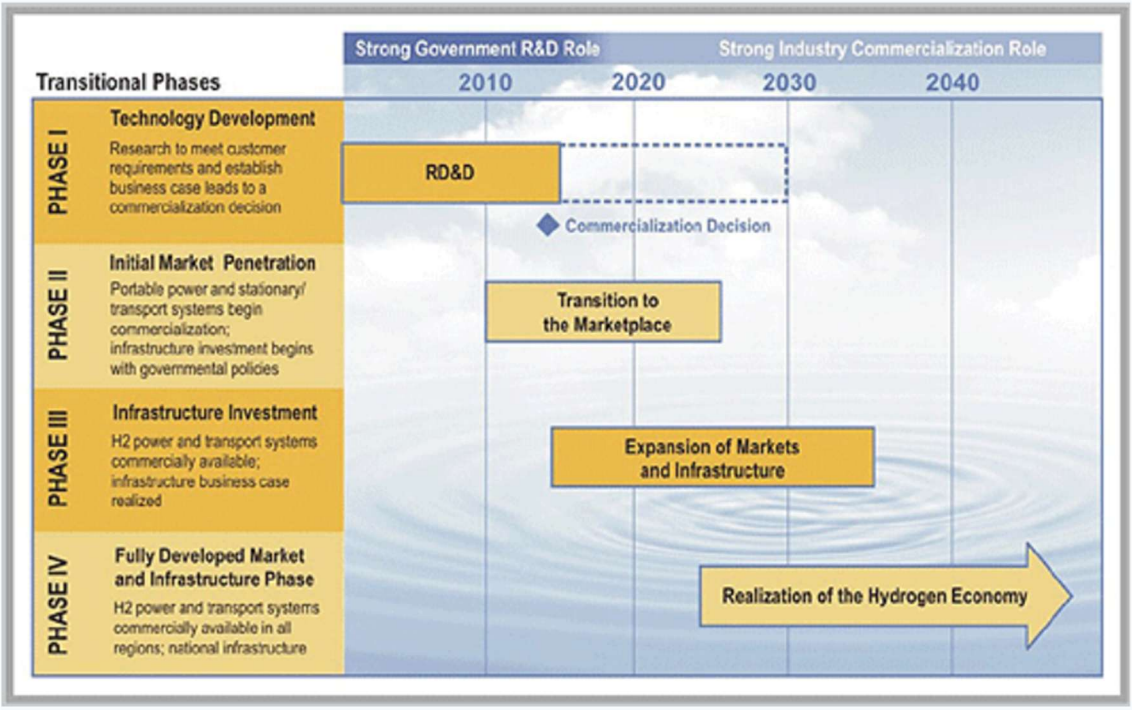
"As of 2023 there are no real alternatives to hydrogen for several chemical processes in which it is currently used, such as ammonia production for fertilizer. The cost of low- and zero-carbon hydrogen is likely to influence the degree to which it will be used in chemical feedstocks, long haul aviation and shipping, and long-term energy storage. Production costs of low- and zero-carbon hydrogen are evolving. Future costs may be influenced by carbon taxes, the geography and geopolitics of energy, energy prices, technology choices, and their raw material requirements. The U.S. Department of Energy's Hydrogen Hotshot Initiative seeks to reduce the cost of green hydrogen drop to $1 a kilogram by 2031, though the cost of electrolyzers rose 50% between 2021 and 2024."



Hydrogen has the most potential to reduce greenhouse gas emissions when used in chemical production, refineries, international shipping, and steelmaking[1]



Technology leadership opportunities in green hydrogen value chains according to the International Renewable Energy Agency in 2022[23]:55



Hydrogen strategy phases