WHAT WE NEED TO KNOW ABOUT HYDROGEN?

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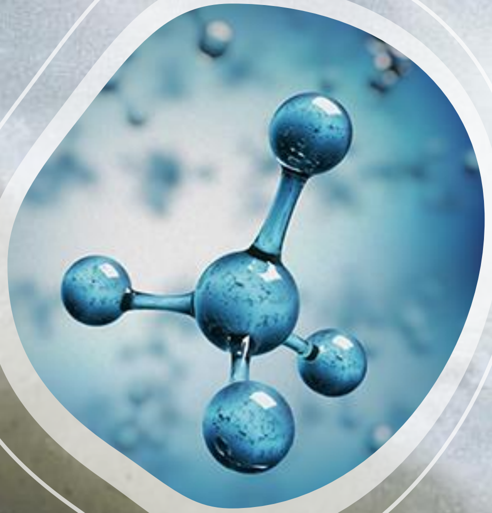
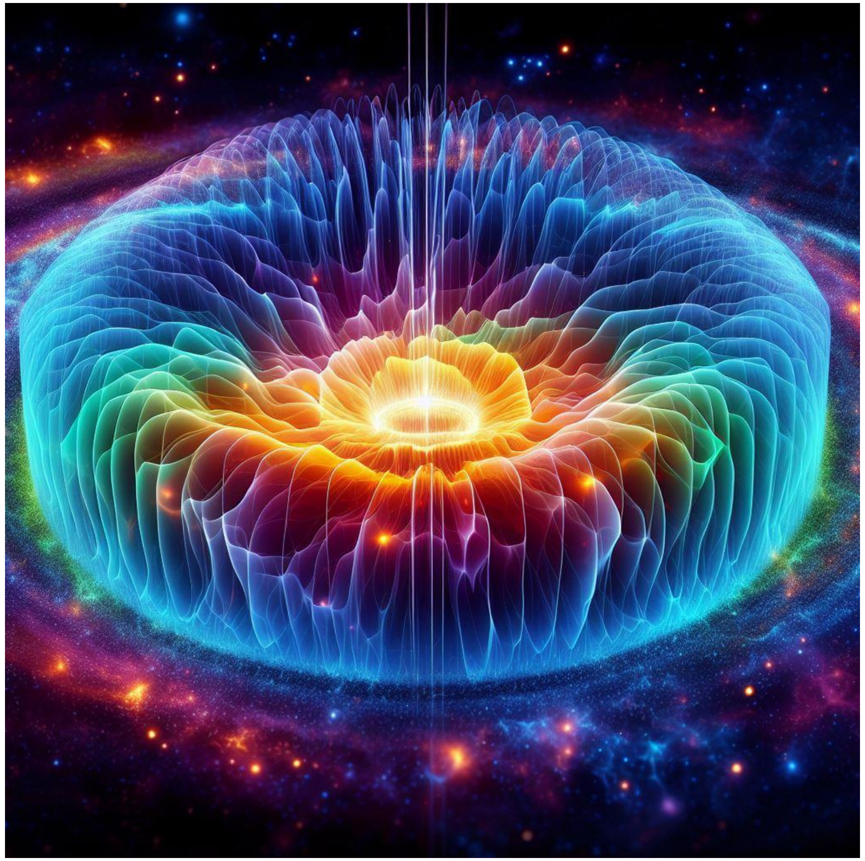


NEW TECHNOLOGIES – HYDROGEN AND HIS ROLE IN ENERGY TRANSITION

The history of the universe and the ORIGIN of hydrogen



Hydrogen was formed after the Big bang, a little over 13 billion years. It accounts for 75% of the matter in the Universe.

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Hydrogen was the first and most important element of the periodic table, accounting for 75% of the mass and 93% of the number of atoms in the Universe. It has a whole range of unique properties in various processes in physics, chemistry, and biology (R.1). Because, according to scientific theory, hydrogen has influenced the formation of the universe the most, it gives us light from the Sun, surrounds us with waters and clouds, and is ultimately part of our body it can also be called the "creator of nature."

How was hydrogen formed? Its formation is narrowly related to the formation of the universe or to the Big Bang of which is the closest link (R.1). The Big Bang is one of the theories of the formation of the universe. Others are known, such as: *Steady state Theory, Tired Light Aging, Multiverse Theory, Mirage of a Four-Dimensional Black Hole*, and others, but they are not as accepted in science as the Big Bang Theory.

The Big Bang theory was explained by Arno Alan Penzias and Robert Woodrow Wilson when, by measurements in 1964, they accidentally discovered the background of cosmic microwave background (CMB) and measured a temperature of 3.5 K with a Holmdel Horn antenna in New Jersey. It is a radio astronomy that significantly complements classical optical astronomy and is based on the fact that various objects in astronomy radiate in the form of radio waves. For this discovery and clarification of the Big Bang, they (in 1978) received the Nobel Prize in Physics. Scientists consider CBM to be an echo or "shock wave" of the Big Bang. Over time, this primordial light cooled down significantly and weakened. Therefore, the measured temperature was only 3.5 K. After the Big Bang, the universe began to expand rapidly from an infinitely dense and high-energy state called the singular state (an infinitely compacted state). According to the best measurements available, the Big Bang occurred 13.3 to 13.9 billion years ago. In the beginning after the bang, the Planck era comes, and in the shortest possible time of 10–32 seconds (Planck's time), an exponential expansion of the universe called the "period of cosmic inflation" was triggered. After one microsecond, the first baryons appeared, and 3 minutes later the first hydrogen nucleons, and 380,000 years later the first formed neutral hydrogen and helium-4 atom and the first appearance of monoatomic hydrogen. It is only 200 million years later that the first stars (dust and gas concentration) appear. The first galaxies appear in 400 million years. Thus, **Mother Nature celebrated the birth of children of the Big Bang. These are hydrogen atoms.**

After the appearance of hydrogen atoms, the material continued to merge into the first stars and finally into galaxies, quasars, clusters of galaxies and superclusters. Stars are composed predominantly of hydrogen in the plasma state. For the chemical evolution of stars, certain fusions with hydrogen are crucial. In interstellar space, hydrogen exists in the form of a separate molecule; Atoms and ions can form molecular clouds that differ significantly in size, density and temperature. Thus, the hydrogen atom is the direct and closest ancestor of the Big Bang. It is one of the oldest creations in the universe.

Discovery of hydrogen — chemical element No 1

Hydrogen was discovered by Henry Cavendish in 1766.

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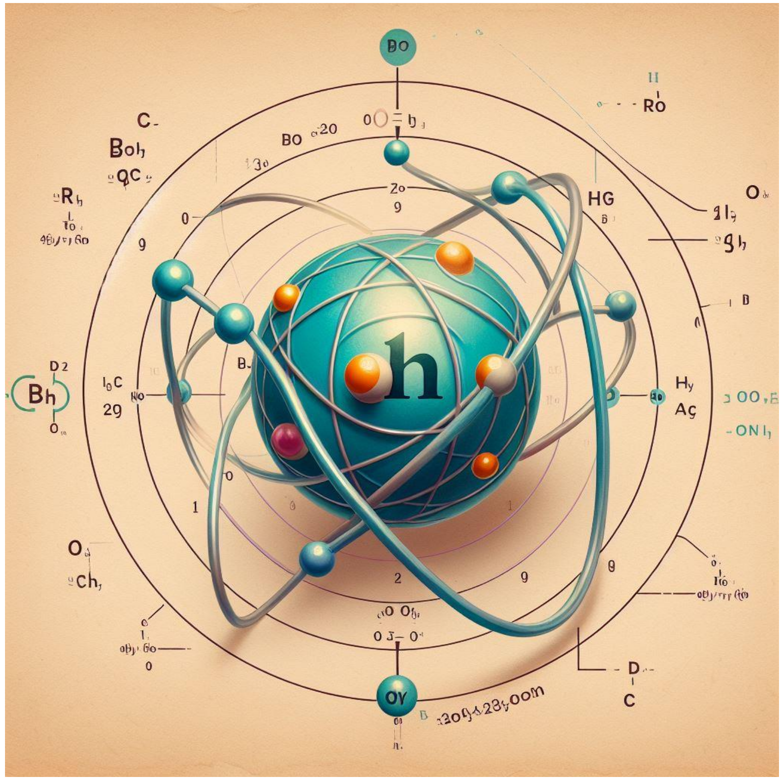
Hydrogen was discovered by Henry Cavendish (1731□1810) in 1766, but there are several earlier reports of the discovery of this flammable gas. This is understandable, since mineral acids (sulfuric and hydrochloric) and certain metals (iron, zinc, tin) have been known since the Middle Ages. Each of these metals reacts with acids to form hydrogen as the main gaseous product. Henry Cavendish first recognized it as an independent substance and called it "flammable air." Later, in 1781, he discovered that during his combustion water was formed. This property also gave it a name derived from the Greek: ὕδωρ (húdōr, "water") + γεννάω (gennáō, "birth"), Latin hydrogenium, hydrogen in English (R.2). Hydrogen is a chemical element with the symbol H, atomic number 1 and atomic mass 1.00794. In the monoatomic state (H), it is the most common chemical element in the universe, but it is almost absent in our atmosphere. Gaseous hydrogen (di-hydrogen or molecular hydrogen) is highly flammable and burns in air over a very wide concentration range of 4 to 75 % by volume. The auto-ignition temperature of hydrogen in the air is 500oC. It represents the third most common element on the Earth's surface but is rarely found alone in or on Earth. It is non-toxic but can also become very toxic if its concentration increases in the air.

Under normal atmospheric temperature and pressure conditions, gas is **colorless** and odorless and lighter than air (about 1/15 of the weight of air) and water (1/14 by weight of water). It is soluble in water up to 1.6 mg/l at 21 °C. Depending on temperature and pressure, it is located in different states of aggregation. It is often a component of various organic compounds and, of course, water. In the air, it burns with a pale blue, almost invisible flame. When released, it has the highest rate of combustion energy per unit weight among all common substances. Due to this property, it is used for fuel in the highest stage of multistage space rockets. It also has the lowest boiling point (-252.70C) of all elements except helium. However, it has a melting point at -259.2°C. When cooled to boiling, it becomes transparent, odorless, liquid. Liquid hydrogen is not corrosive or especially reactive. When converted from liquid to gas, hydrogen expands about 840 times. Due to its low boiling point and low density, liquid hydrogen spillage disperses rapidly. Stars, including our Sun, are mainly composed of hydrogen in the plasma state. Hydrogen also plays an important role in nuclear fusion – the most promising clean electricity technology. When used in fuel cells, it can generate electricity.

Hydrogen itself is considered not as an energy source, but as an energy carrier or vector, since energy is needed to obtain it. Hydrogen was used as early as the 18th century at the beginning of air transport. The first hydrogen filled balloon flew in 1783. Later, in 1910, the most famous promoter of hydrogen airship air transport was Ferdinand von Zeppelin, who organized scheduled flights. In 1919, they crossed the Atlantic for the first time and continued flights until the hydrogen airship accident in New Jersey in 1937.

Hydrogen has 7 isotopes, the first three of which (contradiction, deuterium, tritium) persist in nature, and the other 4 are unstable and obtained in the laboratory. The most common isotope of hydrogen is the opposite (99,985%) of one proton and one electron. Deuterium has another neutron in its nucleus besides a proton and is only 0.015% on Earth. Water enriched with molecules containing deuterium instead of hydrogen is called heavy water. Heavy water is used as a moderator and coolant in nuclear reactors. Deuterium is a fuel for planned fusion power plants.

Energy properties of hydrogen



Hydrogen has excellent energy characteristic in terms of mass (33-40 kWh/kg) and poor in terms of volume (2,8-3,5 kwh/m3) at 15 st. C and a pressure of 1 atm.

Source for image: AI Designer

The first expert article on the integration of hydrogen into the power system (R.5) appeared at the Cigre Session in Paris as early as 1974. This was the first time that a cross-sectoral connection of electron and molecules (electricity and gas) has been proposed. For the next two decades, hydrogen was a common topic at various power conferences, especially at IEEE PES (Power & Energy Society) conferences in the Hydrogen Economy section. Yet it took 50 years for a major investment cycle aimed at partially replacing fossil fuels with hydrogen as an energy carrier globally. By the end of May 2023, more than 1,000 large-scale hydrogen projects worth USD 320 billion of direct investment had been announced worldwide, of which around 36% in Europe. These projects are expected to achieve green hydrogen consumption of 38 Mt/year in 2030 compared to current consumption below 1 Mt/year (green hydrogen). Long-term plans for consumption by 2050 are as high as 800 Mt/year, which is the energy equivalent of 32,000 TWh. Here we are talking exclusively about green hydrogen (for definitions of colors, see the text for May). Global energy consumption in 2022 was around 170,000 TWh (14,600 MTEP), of which electricity was around 27,000 TWh. By 2050, global electricity consumption is projected to be around 40,000 TWh (according to Cigre Technical Brochure No. 775). The consumption of fossil energy significantly influences the increase in the concentration of greenhouse gases (GHG) in the atmosphere, which affects climate change on the Earth's surface. Since the Kyoto Agreement (February 2005), the global picture of CO2 emissions has only deteriorated. The greatest influence on this situation is the combustion of fossil fuels, which still represent ok. 80% of the fuel share. Therefore, a reasonable part of humanity is trying to stop global warming to 1.5-20C, in line with the Paris Agreement. One of the strategic objectives for halting global warming is the use of green hydrogen.

What should be the role of hydrogen in the energy transition strategy?

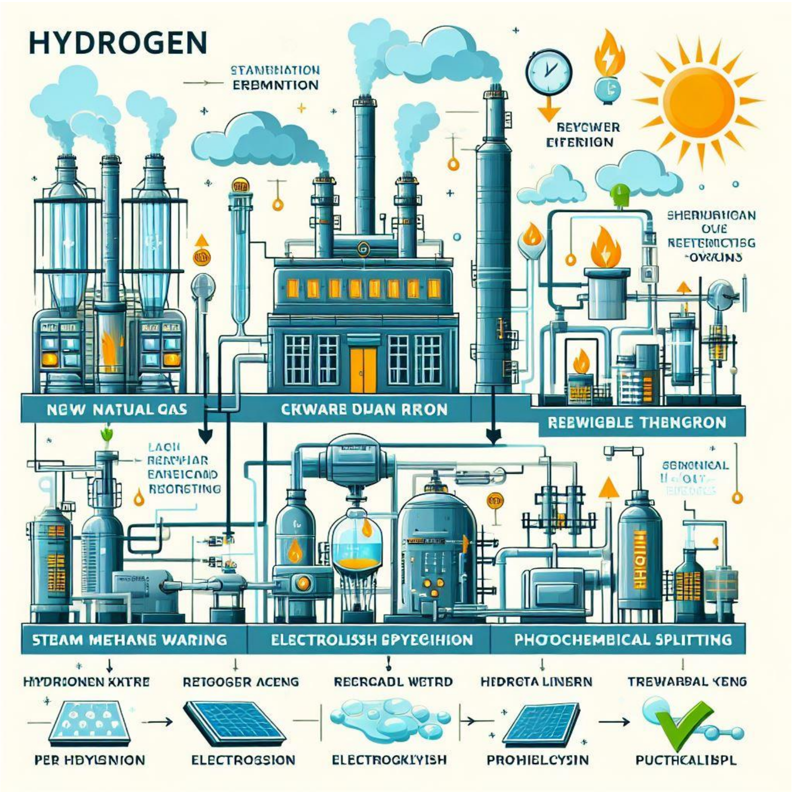
Hydrogen could replace existing "black/grey" hydrogen with "green hydrogen" in many industrial processes, fossil fuels in transport (ships, heavy trucks), help develop RES with support for different types of storage tanks, etc. Many of the predicted strategies for using hydrogen are based on significantly cheapening the production of "green" hydrogen produced by electrolysis, called P2G (electricity to gas), and vice versa G2P (gas to electricity) - using fuel cells.

The energy content of hydrogen is described by its calorific value (lower and higher). The lower calorific value of hydrogen can be expressed as 33,3 kWh/kg or 3 kWh/Nm³. The higher calorific value has 40 kWh/kg or 3.54 kWh/Nm³. A lower calorific value is usually used if hydrogen does not burn directly. The energy content of 1 Nm³ or 1000 Nl of hydrogen gas corresponds to 0.36 l of gasoline. The equivalent of 1 l of liquid hydrogen is equal to 0.27 l of gasoline, and 1 kg of hydrogen is the equivalent of 3.3 kg of gasoline (based on the lower calorific value). This shows that hydrogen has exceptional energy density properties by mass and very poor in volume. This means that it has much worse transport characteristics compared to natural gas. The same pipeline transports less energy per year with hydrogen than would be the case with natural gas.

The table shows the equivalence of 1 MWh of fossil fuel and hydrogen energy (R.7)

Energy (MWh)	Oil (boe)	Natural gas (scm)	Natural gas (MMBtu)	Coal (TCE)	Hydrogen (kg)
1	0,6	91,4	3,41	0,12	25
Boe… *barrel of oil* … = 159 liters of crude oil					
Scm … *standard cubic meter* … cubic meters of gas					
TCE … ton of coal equivalent … = 27,78 MMBtu					
MMBtu … one million British Thermal Units.					

Hydrogen production technologies



Today hydrogen is most often obtained by steam transformation of methane (SMR). In order to obtain 1 t of grey hydrogen, around 9 tons of Co2 is released into the atmosphere. In future, green hydrogen is to be produced by electrolysis.

Source for image: AI Designer

The most common process for hydrogen production is steam methane reforming (SMR) hydrocarbons, especially natural gas, which releases carbon dioxide (CO_2). To obtain one tone of hydrogen ("grey hydrogen"), about 9 tones of CO_2 are released into the atmosphere. 2.2 tons of methane, 4.9 tons of water and about 6.2 MWh of heat are required. The SMR process requires a lot of water, but consumption can be significantly reduced by using membrane technologies. Other methods for producing hydrogen are partial oxidation of hydrocarbons and coal, electrolysis of water and several thermo-chemical processes that are still under development.

The process of electrolysis of water, when water molecules are divided into hydrogen and oxygen with the help of electricity, does not contribute direct greenhouse gas emissions, so the focus of introducing hydrogen into the energy transition is on this process. The cheaper electrolysers (electrolysis installations) would be made cheaper and the cheap electricity of large solar and wind fields, as well as nuclear power plants in special circumstances, should be used. In research and development, there are several new processes for the production of hydrogen, which use heat or various thermo-chemical processes to generate hydrogen instead of electricity. Interestingly, hydrogen is produced in poorly insulated transformers, so often the first indicator of poorly insulated transformers is precisely the formation of hydrogen.

Looking at the advantages and disadvantages of hydrogen, we can classify them as follows:

Advantages:

1. Hydrogen is abundant and can be produced from renewable sources, reducing GHG emissions and reduce dependence on fossil fuels,
2. It can be transported by pipeline, truck, ship, or rail, increasing flexibility and security of supply,
3. Hydrogen can be used in a variety of sectors and applications, such as power generation, transport, industry, buildings and agriculture, creating new markets and opportunities.

Disadvantages:

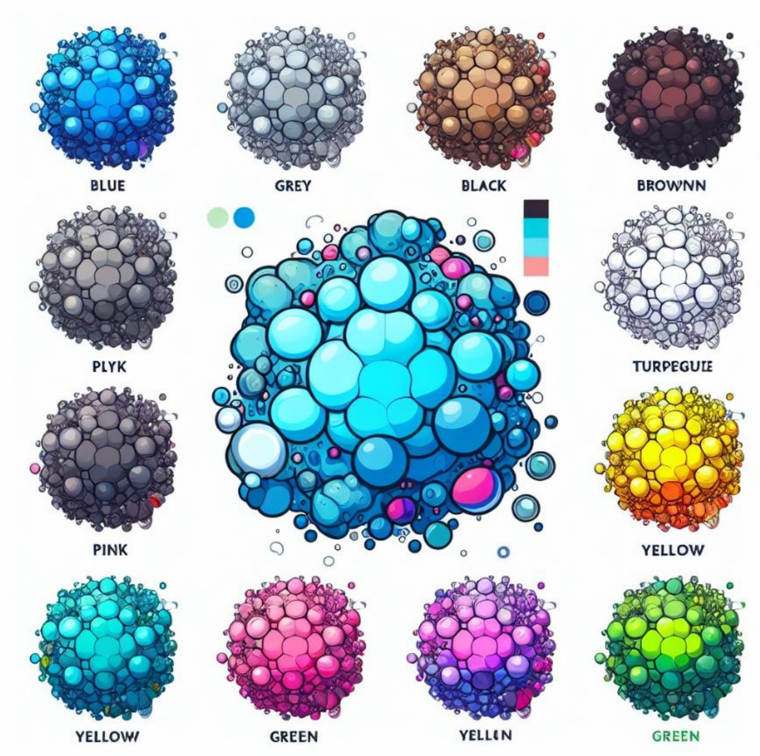
1. Hydrogen production is currently expensive and energy-intensive, especially in electrolysis and renewable production,
2. The storage and distribution of hydrogen requires high pressure tanks or cryogenic vessels, which increases safety and technical challenges,
3. Hydrogen infrastructure and end-to-end technologies remain underdeveloped and require more research, innovation, and investment to become competitive and reliable.

Where will hydrogen play an important role in the future? (R. 3)

- ❑ *Replacing existing "dirty" hydrogen (grey, black) with "clean" green hydrogen, which will reduce GHG emissions because existing hydrogen is produced 99% from fossil fuels.*
- ❑ *Replacing fossil fuels in various industrial processes with green hydrogen derivatives.*
- ❑ *Replacing fossil fuels with green hydrogen in long-distance transport (ships, heavy tractors, possibly aviation).*
- ❑ *Seasonal green hydrogen storage tanks in power systems for renewable energy balancing.*

The Hydrogen Council estimates that green hydrogen will be able to meet 16% of global energy needs in 2050. European organizations working on hydrogen strategies expect the share of green hydrogen in Europe to be between 8 and 24% in 2050. The widespread production, distribution and use of hydrogen will certainly require numerous innovations and investments in efficient and environmentally acceptable production, transport and storage systems and innovative applications for use.

Guide's colour definitions



The colours of hydrogen indicate the method of production according to sustainable tendencies. In the future, we want the most of green hydrogen.

Source for image: AI Designer

The interest in hydrogen increased during energy transition to a low-carbon society and hydrogen promoters started using hydrogen colors based on how it is produced and reduce the impact on greenhouse gases (GHGs). The idea of hydrogen colors is thought to come from the research of Danish physicist Niels Bohr (1885 -1962), who made important contributions in the field of quantum mechanics and many years ago developed a theoretical model of a hydrogen atom that explains its spectrum of emissions. According to this model, electrons travel in certain orbits around the nucleus and energies can be calculated. These vary depending on the photons emitted and absorbed. Quantized energy levels release specific bands of light with specific colors (wavelength 434 nm = blue, wavelength 656 nm = red, etc.). The idea was to switch from emission wavelengths to agreed RGB (standardized color model) color codes. This, of course, has nothing to do with colors visible to us, because hydrogen is colorless and invisible. The use of paints would determine the genres of hydrogen in conjunction with society's sustainable tendencies and the desire to reduce GHG emissions. Although there is no international standard (for now) setting rules on hydrogen colors, the following hydrogen colors have become a rule in the separation of hydrogen types in the international public and literature.

Grey hydrogen is produced from natural gas or methane by steam methane reforming (SMR) and causes GHG emissions from the process. Natural gas and steam are converted to hydrogen and CO2 at high temperature and pressure by a catalytic chemical reaction, which is endothermic and uses vapor at 700 to 1000 °C. It is currently the cheapest ($1/kg) and the most common form of hydrogen production, despite emissions of 6-10 tons CO2/tone of hydrogen.

Black or brown hydrogen is obtained by gasification of hard or brown coal. In the process of production, coal decomposes into chemical components, which include methane gas. Coal reacts with oxygen and steam at high temperature and steam, resulting in the formation of synthesis gas, a mixture of hydrogen, CO_2 and CO. This gas is hydrolysed to obtain more hydrogen. Extraction costs are lowest compared to electrolysis or natural gas, amounting to 1,2- 2,2 USD/kg in 2022. By 2030, is expected due to the low price to increase in production lead to a 60%, despite CO_2 emissions.

Blue hydrogen is produced in the same way as grey hydrogen using SMP process, but by devices CCS (carbon capture and storage) for CO_2 capture, where it is separated, stored or converted for further use. According to the IEA, the price of this hydrogen in 2019 was around USD 2.6/kg, which of course depends on the price of natural gas and CCS installations.

Pink hydrogen (sometimes called red hydrogen) is produced by electrolysis same as green hydrogen but with electricity from nuclear reactors. Americans predict favorable prices for this clean hydrogen ($1/kg in the next decade) with hybrid nuclear power plants (heat + electricity). The current price is 2-6 USD/kg, depending on the location. The Japanese did experiments and got a price of 2-3 USD/kg.

Turquoise (green blue) hydrogen is made by the process of methane pyrolysis (high temperature in the absence of oxygen). Thus, in addition to hydrogen, hard carbon is obtained. The process causes low GHG emissions because hard carbon can be stored permanently or further used. Currently, there is no significant production volume.

White hydrogen is a natural geological hydrogen found in underground sediments and formed by hydraulic fracturing. There are currently no strategies for the exploitation of this hydrogen. In the future, some hydrogen paints are likely to lose their relevance.

The electrolysers issues

There are three types of electrolysers: PEM, AE and SOEC. In future, PEM electrolysers are expected to be the most suitable for integration with intermittent energy sources (wind and solar power plants)

Source for image: AI Designer

All projects to expand green hydrogen production are based on significantly cheapening electrolyzes. Thus, the strategies predict a price decrease for 2030 to half of the current price. According to the IRENE study, this should be achieved by simplifying models, increasing efficiency, innovation, using materials that are not uncommon on Earth, increasing power per unit, increasing hydrogen production, standardization, etc.

There are three types of electrolysers: PEM (Proton Exchange Membrane), AE (Alkaline Electrolysis) and SOEC (Solid Oxide Electrolysis Cell). A feature of PEM is high current density and high price. AEs are cheaper at low current density. SOEC electrolysers have high efficiency (P2H) but belong to immature technologies. The energy efficiency of electrolysers is about 70% with a tendency to increase to 80%. For the power system, electrolysers are a nonlinear load due to the action of electrodes. Losses come from ohm resistance and electrodes. If we compare the energy efficiency of all three electrolysers, SOEC does not show a greater advantage over PEM and AE in terms of energy conversion efficiency, or may even be worse in conditions of poor energy supply.

Possible implementations of electrolysers for connection to sources of electricity generation:

- SOEC are better suited to situations with abundant resources, e.g. integration with a nuclear power plant.
- PEM has a wide load range and potential for integration with fluctuating energy sources, e.g. offshore wind farms.
- The advantage of AE is high performance and the lowest costs that can be used in scenarios with high hydrogen demand, e.g. in chemical engineering.

In the coming years, green hydrogen from electrolysers is expected to be cheaper than today's classic SMR grey hydrogen production process if regulation of penalizing CO2 emissions is introduced correctly. Various consulting companies (**Irena, IEA, Bloomberg NEF**) estimate that in 2030 the price of green hydrogen will be 2-4 USD/kg, and in 2050 it will be between 1 and 2 USD/kg. The condition for these prices is, of course, the essential cheapening of electrolysers and abundant renewable energy sources (RES).

Technical characteristics of electrolysers technologies according to (R.3)			
	AE	**PEM**	**SOEC**
Cost, service life, efficiency	-Typical capex is in the range of **700 €/kW$_e$** today and is expected to decrease slightly. -Efficiency ranges from **63% to 70%** and is expected to increase slightly over the next decade.	-Typical capex is **1200 €/kWe** today, but is anticipated to fall and be broadly similar to AE up to 2030. -Efficiency is in range of **61-70 %** and is expected to increase slightly in next decade.	- Typical capex is ca. **3000 €/kWe** and is expected to fall by more than 40 %. - Efficiency is in range of **74 do 91 %** and is expected to increase slightly in next decade.
Plant size	-Currently, Toshiba operates the largest alkaline electrolyser with a power of **10 MW**. -The future performance of the device should increase up to **200MW**.	-Air Liquide recently inaugurated **20 MW** PEM electrolyser. Future plant capacity is expected to increase up to **200 MW.**	-Currently, the largest SOEC electrolyser has a **capacity of 225 kW.** - Future plant capacity is expected to reach up to **100 MW.**
Flexibility	-The start-up time is in the range of **1 to 10 minutes.** - Ramp-up/down response is **0,2 to 20 % / second.**	- The start-up time is in the range of **1 secund to 5 minute.** - Ramp-up/down response is **100%/second**.	-There is very limited information on SOEC electrolyser characteristic about flexibility.
Size and flexibility are the main characteristics that influence electrolysers capability to provide system services.			

The importance of hydrogen in the energy transition

Green hydrogen, which does not produce GHG when burned, is to be used in transport and industry, as it can make a significant contribution to reducing GHG emissions.

Source for image: AI Designer

Clean (green) hydrogen is a powerful vector to achieve decarbonization for key sectors in heavy industry and transport where direct electrification is not yet possible. According to some world-renowned consulting firms, introducing clean hydrogen in the energy transition would compensate for about 30% GHG. As a result, many countries around the world have devised hydrogen deployment strategies and launched projects to develop hydrogen technologies and grow the hydrogen economy. According to many energy sectors, hydrogen offers the potential to reduce the carbon footprint and switch to more sustainable energy sources.

Where can the meaning of hydrogen be seen?

a) As a fuel carrier that does not emit carbon dioxide (CO2) when burned, it can be used in transport and industry where it can contribute to reducing greenhouse gas emissions.

b) When storing energy that can be produced by electrolysis from surpluses of renewable sources such as solar and wind. It can be stored and, if necessary, generate electricity through fuel cells.

Here it is important to remember when hydrogen infrastructure is being developed that it is not fully compatible with fossil natural gas infrastructure (large difference in volume energy density and size of molecules). It is also important to develop the hydrogen market, international cooperation and, above all, the cheapening of green hydrogen production, which will be possible by making electrolysers cheaper, increasing the volume of renewable sources, developing hydrogen storage tanks and systemic regulation. The price of green hydrogen can also be affected by network charges if the electrolysers are connected to the public electricity grid. Successful cooperation with local communities, environmental justice organizations and partnership is necessary to achieve market growth. Financial incentives and friendly legislation on investment in infrastructure and job creation are very important to kick-start the hydrogen market.

The energy transition will require a lot of work and change, especially in the development of hydrogen technologies, the development of new materials, innovation, and research. These require careful analysis when experimenting with the transitions of P2G (electricity to gas) and G2P (gas to electricity). In addition to technological approaches, socio-economic performance analyses and teamwork are needed for real lasting effects.

European hydrogen strategy and Slovenian projects

*The first Slovenian project „**Hydrogen valley of the Northern Adriatic**“, implemented in cooperation with Croatia and Italy, started operating in September 2023 and will be completed in 2032.*
Source for image: AI Designer

To decarbonize society and reduce dependence on imported fossil fuels, already in 2018, the EU started work on a strategy for the deployment of green hydrogen in all areas where this proves to be smart and cost-effective. Thus, in July 2020, the "Hydrogen Strategy for a climate-neutral Europe« was adopted. The Investment Agenda outlined 20 key policy actions – action points that were implemented up to 2022. They were divided into five areas: support for investment, support for production and demand, creation of the hydrogen market and infrastructure, research, and international cooperation. Hydrogen has been identified as a key priority for achieving the European Green Deal. **The strategy focuses on green hydrogen.** It includes the installation of 40 GW electrolysers in the EU by 2030. In this way, the EU is striving to become a leading industrial power in clean hydrogen. To achieve this goal, the Commission launched the Clean Hydrogen Alliance. Some EU countries expect to become major importers of hydrogen, while others are expected to become exporters or transit hubs. In July 2021, the "Fit-for-55" package presented a number of legislative proposals that translate the European hydrogen strategy into a concrete framework for European hydrogen policy. This includes proposals to set targets for the deployment of hydrogen from renewable sources in industry and transport by 2030, the hydrogen and decarbonized gas market package, which puts forward proposals to support the deployment of optimal and dedicated hydrogen infrastructure and an efficient hydrogen market. In 2020-2023, seven European studies have been produced addressing different views on hydrogen, such as the role of biomethane and hydrogen in trans-European infrastructure, green hydrogen production in the EU, costs and benefits of pan-European infrastructure, assessment of the potential of renewable liquid and gaseous transport fuels of non-biological origin, intended for transport use …

In September 2022, the European Union approved €5.2 billion for hydrogen financing projects, which is expected to unlock an additional €7 billion in private sector investments, or a total of €12.2 billion. In addition to the **EU strategy**, 17 EU countries have already published their national hydrogen strategies, according to Hydrogen Europe. In addition to them, Norway, and the United Kingdom as non-EU members.

So far, Slovenia has not published a national hydrogen strategy. Nevertheless, Slovenia is already participating in one of the European projects. It is a project called "**The Hydrogen Valley of the northern Adriatic**" and includes Slovenia, Croatia, and Friuli Venezia Giulia (Italy).
The project will address the entire chain of use of green hydrogen, from its production, storage, and distribution to final use in various sectors, notably industry, land, and maritime transport. The consortium involves 37 partners, and on the Slovenian side it is managed by Holding Slovenske elektrarne (HSE). It started in September 2023 and will last for 72 months (until September 2032) and will include 17 pilot projects. The project received the highest score among all hydrogen EU projects presented at the call. In the first phase of the Slovenian part of the project, a solar power plant (6 MW) and an electrolyser (2 MW) will be built, which will produce about 300 t of green hydrogen per year.
In the second phase, an even larger electrolyser (17 MW) will be upgraded for an annual production of 2700 t of green hydrogen and will be supplied with electricity from a floating solar power plant with a capacity of 140 MW, which will be installed on the lake near TPP Šoštanj. The project also foresees a hydrogen storage tank.

Hydrogen transport issues

Hydrogen has in accordance with an energy content of in the liquid or gas state only a third volume of the same unit of methane, so significantly less energy is transported during transport (pipeline, ship, or tank)

Source for image: AI Designer

Transport and storage play an important role in hydrogen strategies. Hydrogen can be transported as compressed gas by trucks on roads, railway, or by pipelines (distribution or transmission). It can also be transported in liquid form by trucks or specially designed ships. It is also possible to convert hydrogen to ammonia and transport it by truck or ship. This should be suitable for longer distances. Trucks transporting compressed or liquid hydrogen over short distances are the cheapest option. Here we must once again mention the fact that hydrogen has an energy density (by volume) 3 times lower than methane (natural gas), regardless of whether it is gaseous, compressed or liquid. Therefore, there is much less energy in a reservoir or when transporting it through a pipeline than transportation with methane. When transporting liquid hydrogen, it is necessary to constantly maintain a temperature of minus 253oC, which requires additional energy. Since the main goal of all hydrogen strategies is to reduce greenhouse gas (GHG) emissions and diversify sources, the use of green hydrogen, which is a carbon-free option, is being forced. When transporting hydrogen, the costs mainly depend on the amount of hydrogen and the transport distance. The table below presents the economics of hydrogen transport (H2) in terms of distance and quantity of pressurized or liquid hydrogen.

Economics of hydrogen transport (H2) in terms of quantity and distance under R.3

Quantity/Distance	1 to 10 km	10 to 100 km	100 to 1000 km	1000 to 10.000 km
100 to 1000 tH2/d	P/gas pipeline	P/gas pipeline	P/gas pipeline	Ship LH2 Ship NH3
10 to 100 tH2/day	Truck – LH2 D/gas pipeline	P/gas pipeline D/gas pipeline	P/gas pipeline D/gas pipeline	Ship NH3
1 to 10 tH2/day	Truck – CH2 D/gas pipeline	Truck – CH2 D/gas pipeline	Truck – NH3 D/gas pipeline	Uneconomical
0,1 to 1 tH2/day	Truck – CH2 D/gas pipeline	Truck – CH2 D/gas pipeline	Truck – CH2	Uneconomical

P…transmission pipeline, **D**…distribution pipeline, **LH2**… liquid hydrogen, **NH3**…ammonia, **CH2**…compressed hydrogen

It is evident that costs with larger quantities of hydrogen and longer distances are more favorable to shipping. Research into transporting large quantities of hydrogen over long distances (3000 km and more) also shows favorable solutions if hydrogen is converted into ammonia and transported as an energy carrier. It should be considered in mind that ammonia is toxic and very much care should be taken and standards should be full observed when handling ammonia. Hydrogen is flammable and must not come into contact with oxygen, but is less explosive than, for example, gasoline or natural gas. Therefore, strict adherence to standards is also necessary. It is mandatory to use detectors to detect a flame that is not visible or ventilation of the premises, electrical appliances must be properly grounded so as not to generate static electricity and, as a result, ignition …and other measures.

For gas pipelines built to transport natural gas (methane), some companies started with blending 5% and later 10% hydrogen while transporting natural gas. This is favorable in terms of reducing GHG, but this also means a decrease in energy transmission. For Slovenia, if we were to mix 10% of hydrogen with natural gas in gas pipelines, this would mean about 7% less energy transferred.
Green hydrogen is in some ways like electricity and is cheapest when used at the point of production (i. e. "hydrogen valleys") and at the time of production. If stored, transported, or converted into other energy products, it can increase cost up to 5 times.
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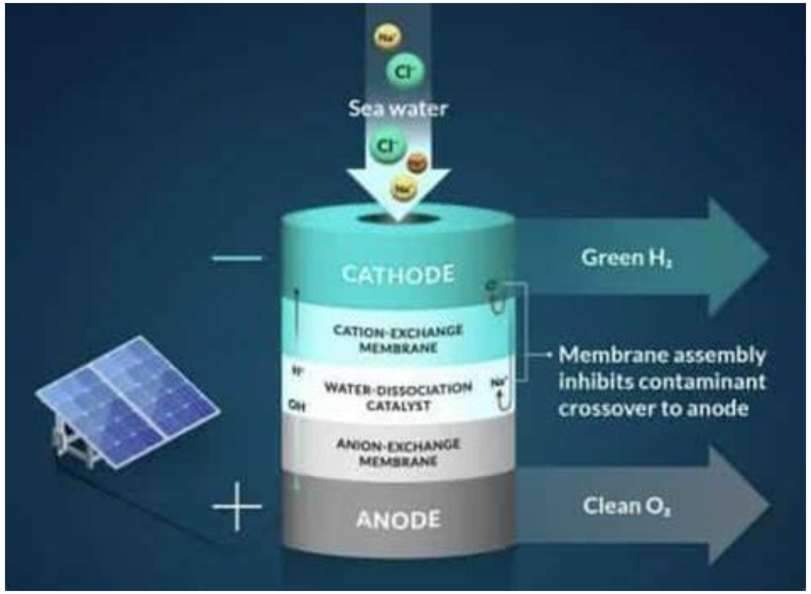
Innovation: extraction of hydrogen directly from the sea



Innovation to extract hydrogen directly from the sea is coming to commercial realization (USA, Australia, China).

Image credit: Nina Fujikawa / Stanford University, SLAC Laboratory, USA.

Innovation will play an important role in decarbonizing energy and introducing green hydrogen. Recently, there has been an increasing number of very interesting innovative approaches and proposals for hydrogen-bound solutions in professional publications. It seems that the widespread use of electrolysers, as predicted in many hydrogen strategies, would create major problems with drinking water supply, which would be the basis for obtaining green hydrogen. It is known that existing methods of electrolysis of water are based on highly purified water, which is a valuable resource. There is a shortage of drinking water in many parts of the world, and this fact represents a limitation to the implementation of the strategic objectives of obtaining cheap clean hydrogen. Therefore, it would be a good idea for electrolysers to act on seawater, which is abundant. Thus, already in 2019, researchers from Stanford University announced the first innovation to extract green hydrogen directly from the sea using electricity from solar power plants. When electrolysis of salt water, negatively charged chloride in salt of sea water causes corrosion of the anode and limits the life of the device. They, in turn, found a way to prevent the anode from breaking down by coating it with layers that repelled chloride and slowed down the decomposition of the anode. The service life of the anode in salt water is only 12 hours, and with a coating - several thousand hours. Soon, improvements also emerged from other universities. So, in November 2022, an article appeared in the scientific journal Natura about a membrane electrolyser of seawater for hydrogen production. It reports stable operation of the demonstration project at a current density of 250 mA/cm2 for more than 3,200 hours without failure. Here an important role is played by the choice of materials electrodes, catalysts, and membranes.

This and similar innovations are expected to be commercialized to solve the important challenge of large-scale production of green hydrogen by electrolysis. In Australia at RMIT University in Melbourne, too, they were engaged in innovation in direct production of hydrogen from seawater and developed an even cheaper method, a critical step towards a thriving green hydrogen industry. The researchers hope that further development could accelerate the establishment of a green hydrogen industry in Australia. Also in China, a device was developed for the direct production of hydrogen from salty sea water. Their membrane electrolyser of seawater is supposed to help solve lateral reaction and corrosion problems caused by brine even more successfully. All these innovations are expected to start soon actually working in many hydrogen valleys around the world.

When discussing electrolysis and obtaining green hydrogen to mitigate global warming, it is good to remember that the theory of electrolysis, as well as the first calculation of global warming (1897), was developed by the same man Swedish chemist **Svante A. Arrhenius** (1859-1927). He won the 1903 Nobel Prize in Chemistry for his electrolytic theory of dissociation. In greenhouse theory, he predicted that combustion of fossil fuels would double CO2 emissions in the atmosphere, causing the temperature on the Earth's surface to rise by 3 -4°C. He assumed that this would happen in 500 years' time, but, unfortunately, this is happening much faster. We are approaching its predicted temperatures on the surface of our planet after 137 years. But it may also happen, as predicted, if the current inhabitants of the Earth act intelligently and halt temperature rise at the agreed level after the Paris Agreement (1.5°C - 2 °C).

The use of hydrogen in industrial transition

In Slovenia, hydrogen is already used in the glass industry and „Steklarna Hrastnik“ is one of the European pioneers in the introduction of hydrogen with the aim of reducing GHG emissions.

Source for image: AI Designer

Hydrogen is now used in many industries, such as hydrogen. chemical industry (production of ammonia and other fertilizers), refineries/petrochemical industry (refining petroleum and derivatives, Sulphur removal), glass industry (as antioxidant or protective gas in combination with nitrogen), food industry (production of margarine, butter), welding (atomic hydrogen welding), semiconductor manufacturing, LED manufacturing, displays, methanol manufacturing, rocket engines, etc.

In 2020, the annual production of clean hydrogen (all commercial colours) was around 100 Mt. Most of them are in industry and in the production of synthetic nitrogen fertilizers. It can be said that hydrogen today is extremely important for the food industry, and this will remain but only green hydrogen. In energy, consumption was ultimately less than 1% due to excessive prices compared to fossil fuels. Yet there is great prospect for hydrogen in the energy transition. Especially in certain areas of industry where fossil fuels could be replaced.

Reputable global experts working on energy transition issues note that hydrogen will play the most important role in decarbonizing industry and partly in long-haul heavy truck transport. Today, the iron and steel industry is contributing around 9% globally with GHG emissions, and hydrogen-backed decarbonization holds great prospects. In steel production, hydrogen can contribute to partial decarbonization in blast furnaces and direct steel reduction. Steel produced using hydrogen is more expensive, but reducing GHG emissions will contribute to credit ratings and more favorable sustainable solutions in the long run, as well as a friendlier steel industry. In Europe, the use of hydrogen in steel production processes is actively being researched in steel production as part of efforts to reduce carbon emissions, such as the use of hydrogen in steel production processes, as example ArcelorMittal in Germany, in France, in Spain, as well as Voestalpine Linz, in Austria (known project H2Future) and TATA Ijmuiden, in the Netherlands (H2Ermes project).

The glass industry has also made the first projects for the use of hydrogen in the production process with the aim of reducing emissions. The **EU-funded H2Glass** project involving 23 partners from 8 European countries aims to decarbonise and make the glass industry more sustainable. The project started in January 2023 and will last until December 2026. The project has a budget of €33 million co-financed by the EU with €24 million. The project envisages replacing natural gas with green hydrogen and using oxy fuel combustion technology to avoid NOx emissions. The use of new technology is expected to reduce GHG emissions by 80% and generate an increase in revenues of up to 5 billion euros.

Among the participants of this project is also the **Slovenian company "Steklarna Hrastnik".** The second phase of the project is expected to produce up to 600 m3/hour of green hydrogen, reduce the share of fossil fuels by 33% and also reduce CO2 emissions by 20%. The final third phase is expected to increase green hydrogen production to 1800 m3/hour and reduce fossil fuel consumption by 100% and CO2 emissions by 65%.

The examples above show that the first steps have already been taken in the transition and introduction of hydrogen by industry in sectors where greenhouse gas emissions can be reduced. All beginnings are difficult and flawed, and prudence is needed, especially at the beginning of changes. The energy world will certainly change at an increasingly rapid pace.

Geopolitical effects of hydrogen in the energy transition

The geopolitical map of the world's energy sources will change with the entry of green hydrogen. In the world+s energy balances. The key role in this will be played by the price, which is predicted to be 1-2 Euro/kg for green hydrogen in 2050.

Source for image: AI Designer

If the forecasts of investors of billions invested in the development of green hydrogen come true, there will definitely be a change in energy markets and the geopolitical map of the world's energy products. As already mentioned, the share of hydrogen in 2050 is predicted from 8% to 24% of energy sources. Countries and regions with high renewable energy potential and low electricity costs can use their resources to become major producers of green hydrogen. The ability to produce cheap green hydrogen from different regions varies greatly. Africa, America, the Middle East and Oceania (Australia) are regions with the greatest technical potential. Europe and parts of highly populated Asia predict fewer opportunities. However, countries' potential for cheap renewable energy is not the only factor influencing the potential of large producers of green hydrogen. It is also important to reduce investment costs for electrolysers. There are many other factors, including existing infrastructure and 'soft factors' (e.g. government support, friendliness towards new businesses, political stability, development of the hydrogen market) as well as the current state of energy resources and industry in these areas. The table below shows the projected evolution of reducing the cost of producing green hydrogen by 2050:

Future path of reducing the cost of green hydrogen after R.7 (Table 6)

Year	Price of renewables USD/MWh	Electrolysers capacity implied GW	Electrolysers Capital cost USD/kW	Cost of green hydrogen USD/MWh	Cost of green hydrogen USD/kg
2010	360	Unknown	1500	600	24
2021	30-45	0,3	950	100-140	4-5,5
+5 years	20-35	25	330	45-70	2-3
+10 years	15-27	50	270	35-55	1,5-2
2050	10-13	more than 50	170	22-28	less than 1

The key to green hydrogen entering the energy balances of the future lies in lowering the price of green hydrogen to a level of 1-2 USD/kg. The well-known Italian energy expert Alessandro Clerici in R.11 points to a number of pitfalls when analyzing how to get cheap green hydrogen and also cites the impact of network charges when electrolysers operate on a public network. Network charges will not only be made when operating as a remote "hydrogen factory" next to a renewable source of electricity. In any case, the arrival of the era of green hydrogen is admirable for the cross-sectoral integration of electrons and molecules. Yet alternatives to development, in particular the use of green hydrogen, will need to be well considered. An EU study (Horizon 2020) shows a more favorable alternative by producing synthetic methane (from green hydrogen and captured carbon dioxide in CCS) to be used just like ordinary natural gas, and projections for 2050 point to costs €50-120/MWh, significantly more favorable than "burning" green hydrogen.

At the end it is also necessary to consider the thoughts of some experienced chemists who have been working with hydrogen for decades and do not see the economic viability of the vast majority of these hydrogen strategies in energy transition. The views of Canadian chemist **Paul Martin**, who is also an environmentalist and sees the future of hydrogen only in replacement in the production of grey hydrogen with blue or turquoise, are very well known, claiming that all other strategies have no future. In doing so, his company Zeton states that they do not support his views. Another such experienced chemist is **Samuel Furfari**, who wrote an interesting book on the subject (R.6), where he negates the enthusiasm for hydrogen's future in the transition of the energy sector.

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Thank you for your attention