Value chain

"If you can't describe what you are doing as a process, you don't know what you are doing"
W. Edwards Deming[26]

The hydrogen value chain involves a large number of actors along its three stages (Production, Transport and Storage, and Consumption), although some of them may be vertically integrated in various parts of the chain. Figure 6 summarizes the main stages of this chain.

Production

Hydrogen can be extracted from water or fossil fuels. The latter are used in 95% of current hydrogen production[27] and are responsible for CO_2 emissions in the process. As described in the previous section, there are different origins according to their mode of production.

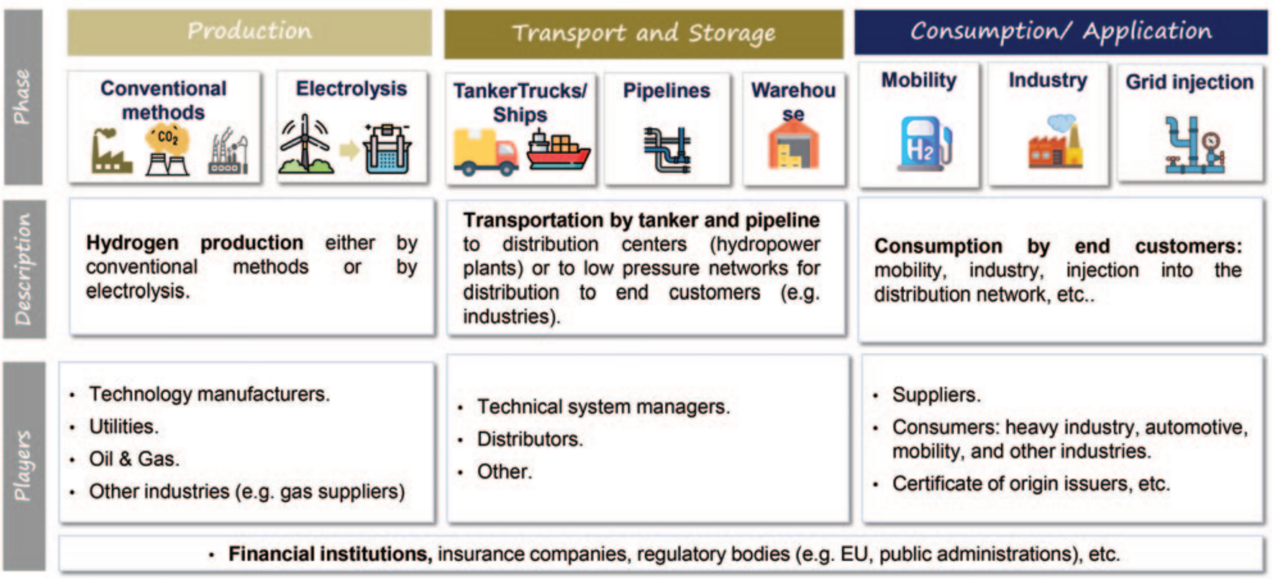
a) Hydrogen from fossil fuels.

Hydrogen obtained from fossil fuels comes mainly from natural gas, followed by oil and coal. The most common thermochemical production routes are reforming (steam reforming, partial oxidation and autothermal reforming) and gasification, the method by which gray hydrogen is obtained, which can become blue if carbon emissions are captured in the process (CCUS).

[26] W. Edwards Deming was an American statistician who revolutionised the manufacturing industry. He is famous for his 14 points of management and the PDCA (Plan, Do, Check, Act) Cycle, which focused on continuous process improvement to increase quality and reduce costs.

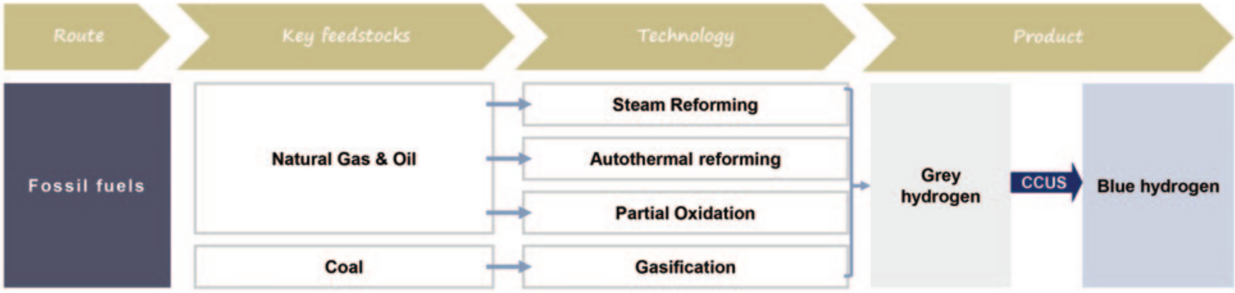
[27] IRENA, "Geopolitics of the Energy Transformation: The Hydrogen Factor" (2022).

Figure 6. Hydrogen value chain differentiated into three stages: production, transportation and storage, and consumption/application.



Source: Own elaboration.

Figure 7. Hydrogen production pathways from fossil fuels.



Source: Own elaboration.

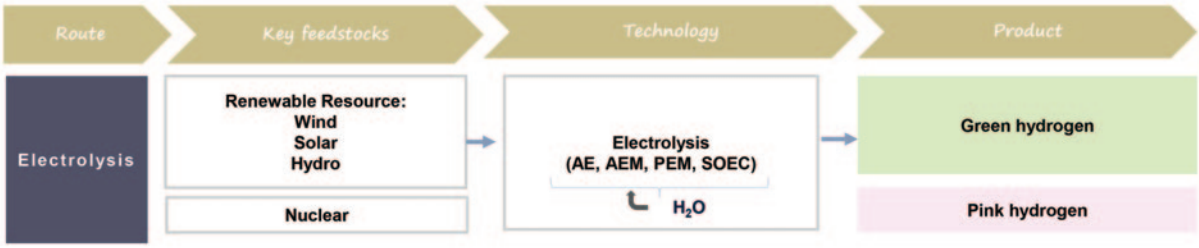
b) Hydrogen from renewable sources.

Electrolytic hydrogen.

The other main hydrogen production route is water electrolysis, an electrochemical technology consisting of the decomposition of water into its constituent elements, hydrogen and oxygen, by passing an electric current through water in an electrolyzer. This process can be carried out without emitting greenhouse gases as long as it can be integrated with renewable sources that provide the energy needed to split the water molecule. However, hydrogen production by electrolysis is much more expensive technologically and economically than producing the same hydrogen using thermochemical processes based on fossil fuels, although there is room for improvement to make current water electrolysis technologies more efficient and hence less expensive. The most widely used electrolyzer technologies to date are:

- Alkaline electrolysis (Alkaline Electrolysis, AE). An alkaline solution is used as the electrolyte.
- Polymer Membrane Electrolysis (Proton Exchange Membrane, PEM). A polymeric membrane is used to separate hydrogen and oxygen ions during electrolysis.
- Solid Oxide Electrolysis Cell (SOEC). A solid ceramic electrolyte is used for electrolysis, with a high temperature input.

Figure 8. Hydrogen production pathways from renewable resources.



Source: Own elaboration.

Hydrogen from biomass

Conversion of biomass into hydrogen can be achieved through two basic techniques: hydrogen production by thermochemical processes (pyrolysis and gasification) and/or by biological conversion (fermentation and biophotolysis).

- Thermochemical processes: One of the most common methods is pyrolysis, which produces pure hydrogen gas from biomass by heating it in the absence of air. On the other hand, hydrogen can also be produced by gasification of biomass through partial oxidation at high temperatures.
- Biochemical conversion: All processes under this umbrella are considered zero-emission; therefore, the final product is green hydrogen. Among the biological conversion techniques, the most relevant are biomass fermentation and biophotolysis.

In the production stage, the involvement of different stakeholders is of special relevance:

- Technology developers are engaged in researching and improving existing technology by lowering costs or improving performance through either research institutes or R&D departments.
- Technology manufacturers are leading developers of electrolyzers, components for wind farms and solar photovoltaic parks, compressor manufacturers, etc.
- Feedstock suppliers: In the short and medium term, feedstock suppliers are needed to provide the necessary resources for the manufacturing of hydrogen. In the long term, however, hydrogen is expected to be green, which will negate the need for feedstock suppliers.

Figure 9. Hydrogen electrolysis technologies.

	AE	PEM	SOEC
	Alkaline electrolysis is the most **mature**, the most **efficient** and has the **lowest CAPEX** of the existing electrolysis technologies, which makes it ideally suited for large and continuous demand for hydrogen. However, it has limited scope for improvement.	Membrane technology has **great development potential thanks to synergies with PEM fuel cells**. Its rapid response to load changes allows it to provide grid services and adapt to fluctuating renewable energy prices..	SOECs are the **most promising electrolysis technology** due to their **high energy efficiency** and ability to operate in reverse mode **like fuel cells**. Lifetime and high CAPEX are the main barriers to commercial scale-up of the technology.
Electrolyte	KOH or NaOH	Polymeric membrane	Metal oxide membrane
Electrode	Nickel-plated steel	Platinum or iridium	Níquel, LSM-YSZ
Temperature	70-90 °C	80-100 °C	650-1000°C
Useful life	60000 -90000 h	30000-90000h	10000-30000 h
Efficiency (%)	63-70 %	56-60 %	**74-81%**
CAPEX (€/kWe)	445 – 1190 €/kW$_e$	980 – 1600 €/kW$_e$	2500 – 5000 €/kW$_e$
Pros	• **Commercial scale.** • **High durability.** • **Low cost.**.	• Solid electrolyte. • Ability to function as a **fuel cell**.	• Solid electrolyte. • **High efficiency**. • Ability to function **as a fuel cell**.
Cons	• **Corrosive** electrolyte. • The hydrogen produced needs to be purified..	• **High costs** associated with the electrode and membrane. • High water requirements.	• **Need for high investment (CAPEX).** • **Short lifetime.**

Source: Own elaboration.

- Utilities and Oil & Gas companies are strategically positioning themselves in the hydrogen market in order to initiate their energy transitions more quickly.

Transportation and storage

Hydrogen transportation will represent a major challenge in the coming years, as the connection method between producer and consumer may vary depending on the transport distance and the intended end use. There are several transportation options, such as pipeline transport and transport in liquid or gaseous form via ships or tankers. The choice of the most appropriate option will depend on the specific circumstances of each case.

Hydrogen can be stored in different ways, including in gaseous or liquid form, in solid form, or in liquid organic carriers. Each of these forms of storage is discussed below.

Storage in gaseous or liquid state.

Hydrogen can be stored physically as either a gas or a liquid.In gaseous storage, given the low density of hydrogen, it must be compressed and stored in very high pressure tanks. If large volumes are to be stored, salt caverns, reconditioned natural gas fields or aquifers could be used. On the other hand, liquid storage requires the hydrogen to first undergo a liquefaction process at -253ºC.

Solid storage.

Another way to store hydrogen is through intermediate compounds, such as metal hydrides, by reversible chemical processes. In these processes, hydrogen is absorbed by a metal through heat input and then released by lowering the pressure of the metal hydride below the equilibrium pressure[28,29]. Solid storage offers higher density and lower risk of leakage, although it is still under development and requires additional chemical processing.

Storage in liquid organic carriers.

Finally, another way to store hydrogen temporarily is by means of liquid organic hydrogen carriers that are formed from hydrogen and another compound. Both generate a third substance that is stored and transported. Once the hydrogen is to be released, the chemical reaction is reversed, and both the hydrogen and the initial compound are recovered. This type of storage provides a solution to the instability of hydrogen and its transport but involves the need for chemical inversion to recover the hydrogen and may have a lower energy yield.

In the transport and storage phase, the involvement of different agents such as hydrogen distributors, transporters and technical managers is of particular relevance.

[28]Pressure at which the reaction rates of formation and decomposition of the compound are equal.
[29]NATURGY. "Hydrogen: Energy vector of a decarbonized economy" (2020).

Hydrogen transport mechanisms.

Pipeline

One of the most common forms of XX transportation is the use of the natural gas transmission network. Today, the transmission network has 1.2 million km installed worldwide, to which an additional 200,000 km under construction or in the bidding phase should be added[1]. In order to reuse these facilities, it would be necessary to reconfigure the existing pipeline system to adapt it to the new gas. The cost of this reconfiguration is estimated to be 50% to 80% less than the cost of installing a new hydrogen supply network[2]. In the short term, there is the option of blending as an alternative until pipelines are fully adapted. This method consists of introducing a low percentage of hydrogen into the gas network, together with natural gas. However, blending presents several challenges, such as the incompatibility of materials in the network, safety requirements (hydrogen is highly flammable and explosive), the need for hydrogen quality assurance systems and the different transport pressure of one and the other gas. In this context, some initiatives are working to upgrade gas transmission networks to allow their use for hydrogen, such as the HyReady initiative or the European Hydrogen Backbone (EHB).

One of the main problems with blending hydrogen and natural gas is that, due to its lower density, hydrogen requires a higher transport pressure. To achieve a proper mixing of both gases in the transport network it may be necessary to increase the pressure of the gas in the network or reduce the pressure of the hydrogen before blending. Typically, natural gas is transported at pressures between 5 and 100 bar, while higher pressures are used for hydrogen. This difference can cause, among other things, hydrogen pockets to appear during the injection process, not integrating properly with the natural gas.

Other alternatives could be the so-called repurposing (adapting the existing natural gas network to hydrogen conditions in order for natural gas to be replaced with hydrogen) or building greenfield hydroproducts in parallel to the existing network taking advantage of available land and rights-of-way (see section Hydrogen transport infrastructure).

Ship

This means of transport is intended for long distances, as it is more expensive than transport by hydro-ducts. The state in which hydrogen is transported will vary depending on the type of storage and the use to which it is to be put, and may be liquid, in the form of ammonia or as an organic carrier. The transport of liquid hydrogen is similar to the transport of liquefied natural gas, except that the boiling point of liquid hydrogen is considerably lower (-253°C for hydrogen compared to -162°C for natural gas). Therefore, in order to achieve the cooling of gaseous hydrogen at such low temperatures, a large amount of energy is required. The main advantage of transporting hydrogen in this state is that a higher purity of hydrogen is achieved for consumption, which is necessary for some applications.

With regard to ammonia transport, it would be possible to take advantage of the experience and infrastructures already in place for the manufacture of fertilizers, thus reducing the need for additional investment.

Finally, hydrogen could also be transported absorbed in organic components, called liquid organic hydrogen carriers (LOHC[3]). These substances do not require refrigeration and, due to their physical properties, could be stored in oil tankers.

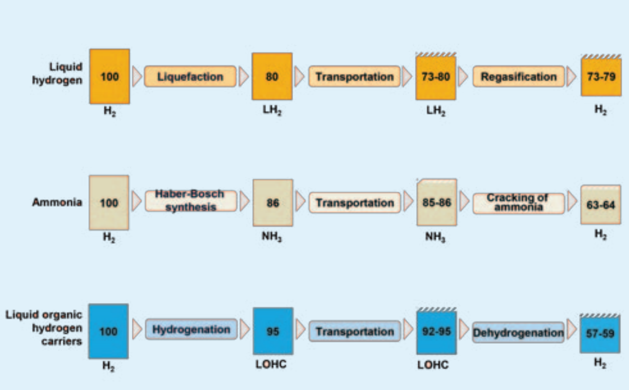
Figure 10 shows the numerical values representing the percentage amount of energy subtracted from hydrogen as a function of the transport used, along the supply chain, assuming that, at each stage of transport, the energy needs are covered with hydrogen itself or some fuel derived from it.

Truck

Due to their high cost, trucks are usually used for short distances and whenever there is no hydro-duct system. Compressed or liquid hydrogen is transported in special containers.

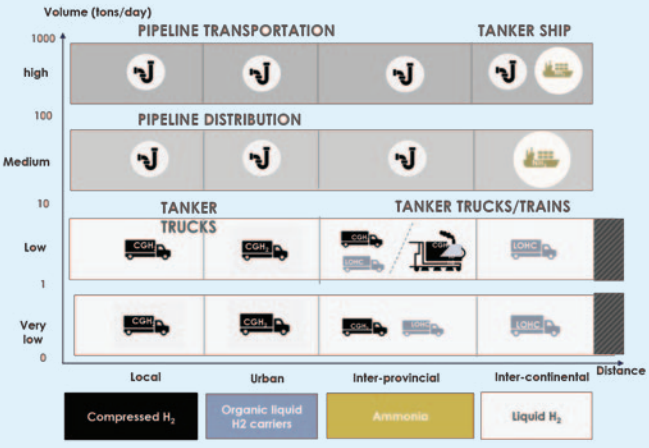
[1] IEA. "Global Hydrogen Review 2022" (2022).
[2] Íbid.
[3] LOHC: Liquid organic hydrogen carriers.

Figure 10. Energy available along the conversion and transport chain in hydrogen equivalent terms.



Source: IEA. "Global Hydrogen Review" (2022).

Figure 11. Comparison of different types of hydrogen transport according to volume and distance.



Source: BloombergNEF. "Hydrogen Economy Outlook" (2020).

Marketing (Consumption/Application)

Hydrogen has applications in four main areas:Industry, Transportation, Energy and Other fields.

Industrial application

Currently, the sector that consumes the most hydrogen is industry. The three main hydrogen consuming industries are petroleum refining, the chemical industry (particularly in the production of ammonia and methanol), and the metallurgical industry. Virtually all of this hydrogen is gray, although it could be replaced by green hydrogen from renewable resources. In addition, the use of hydrogen as a substitute for fossil fuels in high-temperature industrial applications is being evaluated.

Transport application

In transportation, there are two main lines of technological development for hydrogen: (i) direct use as a power source in fuel cell vehicles and (ii) e manufacture of renewable fuels (RFNBO - Renewable Fuel of Non-Biological Origin) or 'e-fuels' with zero net emissions, to replace ordinary gasoline or diesel.

Currently, road vehicles considered as heavy transport are the main source of hydrogen demand in transportation. Most of it is consumed in trucks and buses due to their high annual mileage, heavy weight and need for autonomy, compared to fuel cell electric cars. It is also presented as a solution for rail transport, as it allows the decarbonization of diesel lines when electrification is difficult and distances are too long to be covered by battery electric trains[30]. In addition, interest is growing in the use of hydrogen and hydrogen-derived synthetic fuels in the maritime and aviation sectors, although these are less mature technologies than those described above.

Application in Energy.

Renewable energies need s generation to maintain grid stability. Conventional generation assets such as gas turbine power plants are key in balancing supply and demand. While they are currently necessary, they are being considered for elimination in a future carbon-free energy system. This opens up an opportunity to include hydrogen and other low-carbon fuels in power generation, as they can be used to balance such variability[31]. This implies the possibility of producing and storing hydrogen during periods of surplus renewable energy production for later use during periods of high energy demand. However, it should be noted that the efficiency of this type of storage will depend directly on the electrolyzer technology. In this case, there will be two ways in which renewable variability can be balanced:

- Power to Power: the renewable surplus is used to produce H2 through electrolyzers, which is then stored and converted into electricity through hydrogen fuel cells.
- Power to Gas: the renewable surplus is used to produce H2 through electrolyzers, which is then stored and injected into the gas grid.

Application in construction and other fields.

The possibility of being able to use hydrogen in the domestic and tertiary sector, inside buildings, as a flexible, adapted and continuous energy supply is being studied. This use would be a possible alternative to fossil fuels for district heating, for example.

[30]IEA. "Future of Rail" (2019).
[31]Shell. "Shell Scenarios – Sky: Meeting the goals of the Paris Agreement" (2018).

However, the entry of new energies into these areas is complex, as it depends on multiple factors such as the type and location of buildings or general convenience, which reinforces the likelihood that, in the future, various energy sources and technologies will coexist in this sector.

Oxygen produced by electrolysis is also being used for rocket propulsion, as part of the oxidant in combustion.

In the consumption phase, end users include:

- Consumers: mainly industry, the transport sector (e.g. automotive sector), the energy sector (e.g. Oil & Gas companies), and other applications where its use will depend on the development of the sector.

- Hydrogen marketers: over the years, they will experience significant growth and consolidate their position as key players in the industry.

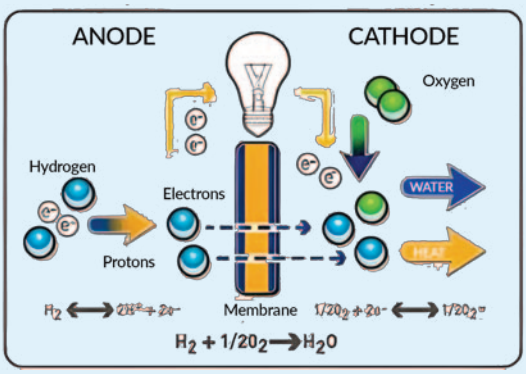
- Hydrogen plant managers: specialized in the design, construction, operation and maintenance of hydrogen refueling stations for fuel cell vehicles.

Hydrogen fuel cells

Hydrogen fuel cells (Fuel Cell) are devices in which a reverse process to that carried out by electrolyzers is performed: the chemical energy of hydrogen and oxygen is converted into electrical energy and water through an electrochemical reaction. As can be seen in Figure 12, hydrogen is introduced into the anode and separated into protons and electrons through the oxidation reaction. The electrons move to produce electrical energy (heat in Figure 12), while the protons move through the electrolyte to the cathode, where they combine with oxygen to form water.

Hydrogen fuel cells have certain advantages over battery electric cars, such as shorter recharge times and lower vehicle weight due to smaller batteries. In addition, hydrogen has a higher energy density than batteries and allows more autonomy and smaller vehicle footprint, especially at high pressures or liquefied. However, it is important to keep in mind that the energy efficiency of hydrogen fuel cells is lower than that of battery electric cars, and that the production and distribution of hydrogen requires an energy input.

Figura 12. Proceso químico por el cual funciona una pila de combustible de hidrógeno.



Source: Biodisol. "Clean energy potential of fuel cells".

RFNBO

"RFNBO" means renewable liquid and gaseous fuels of non-biological origin. It is a product group of renewable fuels defined in the Renewable Energy Directive (Art. 2.36). These fuels are produced from renewable energy sources other than biomass. Therefore, gaseous renewable hydrogen produced by feeding electricity based on renewable energy through electrolysis is considered a RFNBO. At the same time, liquid fuels, such as ammonia, methanol or e-fuels (synthetic fuels), are considered RFNBOs when produced from renewable hydrogen[1].

Renewable hydrogen that is produced from biomass sources (such as biogas) is not considered an RFNBO, but is covered by the Renewable Energy Directive under the definition of 'biomass fuels'. RFNBOs will only count towards the EU's renewable energy target if they deliver more than 70% greenhouse gas emission reductions compared to fossil fuels, which is the same standard that applies to renewable hydrogen produced from biomass.

[1]European Commission: EU Delegated Acts on Renewable Hydrogen.