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Abbreviations

AC	Alternating current
BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CEL	Clean Energy Certificate
CHP	Combined Heat and Power Systems
CO2	Carbon Dioxide
DC	Direct current
DLE	Dry Low Emission system (turbines)
DLN	Dry Low NOx system (turbines)
ESOI	Energy Storage on Invested ratio
FC	Fuel cell
FCH-JU	Fuel Cell and Hydrogen Joint Undertaking
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gases Emissions
H_2	Hydrogen
HRS	Hydrogen Refuelling Station
IEA	International Energy Agency
MEA	Membrane-Electrode Assemble
NOx	Nitrogen oxides
PEM	Proton Exchange Membrane (Fuel cell or electrolyser)
PEMEX	Mexican Petroleum Company (state-owned oil and gas company)
PV	Photovoltaic power
SMR	Steam Methane Reforming (H2 production)
SOFC	Solid Oxide (Fuel cell or electrolyser)
WEC	World Energy Council

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Executive summary

Hydrogen as an energy carrier has more than five decades of research and development. In the last five years, it has been positioning as a viable alternative and a priority in many countries[1] energy agenda due to its decarbonization potential, the technological readiness it has reached, and the accelerated decrease of infrastructure costs.

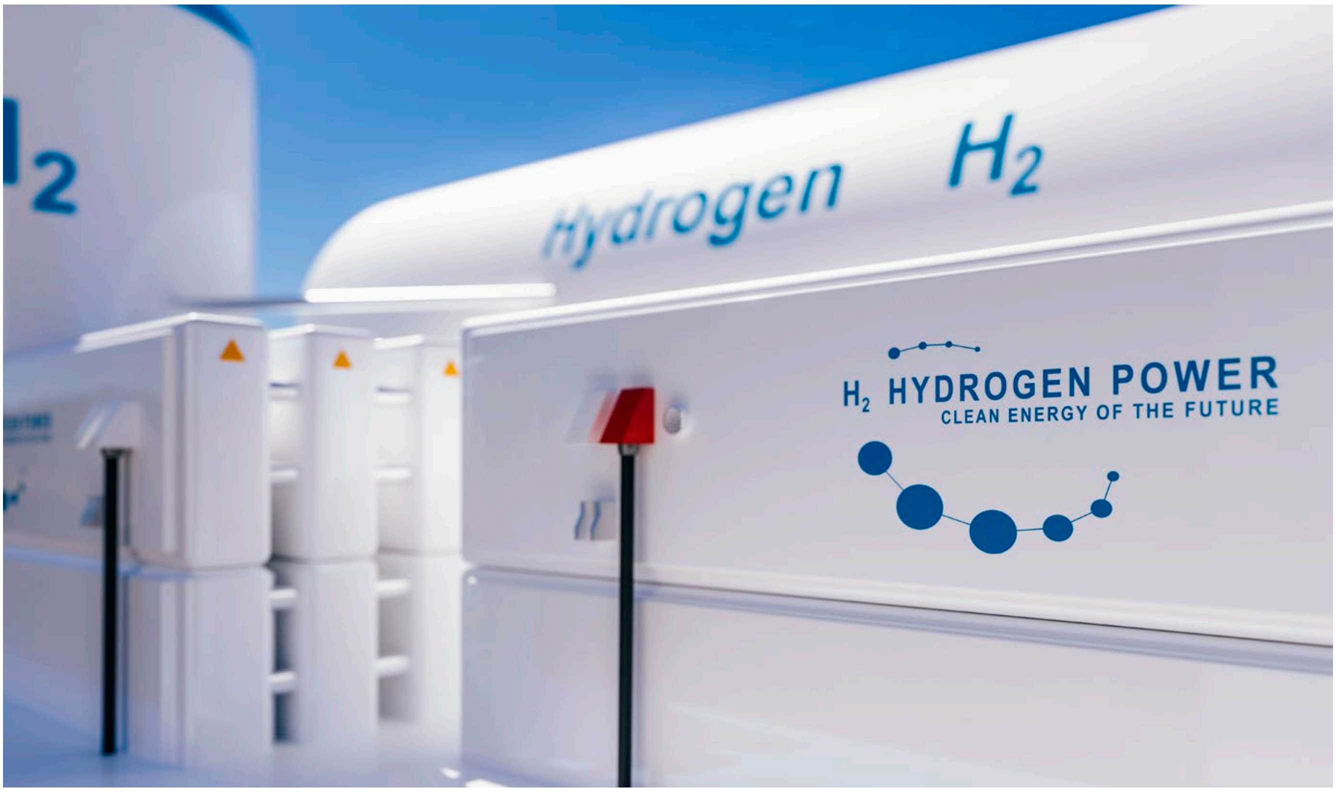
During the 20th century, the most extended hydrogen production technology was Steam Methane Reforming (SMR) because of its high production rates, low prices, and availability of feedstock (natural gas). Nowadays, SMR remains as the leader in hydrogen production technology, with 95% of the global share; nevertheless, SMR is a pollutant process (9 kilograms of CO_2 per kilogram of hydrogen), and cleaner methods are being developed and decreasing their costs, like pyrolysis and electrolysis.

To quickly identify the energy source, production technology and greenhouse gases emissions (GHG) related to hydrogen production, the international community has assigned "colors" to hydrogen, being **green hydrogen** (renewable energy with at least 60% less GHG emissions, according to CertifHy) the cleanest and the most searched to achieve climate change mitigation goals.

Today, green hydrogen is about 50 to 300% more expensive than gray hydrogen and other fossil fuels. However, the Hydrogen Council expects its costs to decrease up to 60% in the next 10 years.

By 2050, some countries like Russia, Korea, or Japan, with a low renewable energy potential, will have green hydrogen production costs (country average) above 4 USD/kg. In contrast, the Latin America region will have an average of 2-2.5 USD/kg, where the highest green hydrogen potential is in Chile, with a price forecast under 1.6 USD/kg, followed by Brazil, Peru, Argentina, and Mexico on the band of 1.6 – 2 USD/kg. Specific regions within countries like Mexico could achieve hydrogen costs as low as 1.2 USD / kg.

As of 2020, approximately 85% of global hydrogen production is captive , due to big consumers like petrochemical companies that incorporate hydrogen production plants into their process facilities. However, demand will grow mostly on new energy and transport applications. The Hydrogen Council foresees that 75% of H_2 demand by 2050 will be destinated to new uses of hydrogen.



1. Hydrogen markets can be classified into captive (hydrogen produced for self-consumption in industrial plants) and merchant (hydrogen produced by companies for sale in a s upply and demand free market).

New uses of hydrogen can be categorized as follows:

Renewable Energy Storage

Hydrogen in renewable energy storage is a circular process of splitting water on an electrolyser powered with renewable energy, storing hydrogen, and converting hydrogen back to electricity or to heat. This critical application could contribute to **12% of hydrogen demand in 2050.**

Electric Mobility

Hydrogen Fuel Cell Electric Vehicles (FCEV) will help decarbonize the transport sector, especially on heavy duty and intensive use segments, like freight trucks and public transport buses. Hydrogen mobility could make up for **28% of hydrogen demand by 2050.**

Green Chemicals

The chemical industry[2] consumed 90% of this hydrogen. Green hydrogen has the potential to reduce CO_2 emission from existing hydrogen demand, as well as from new chemical uses of hydrogen. **Hydrogen demand in 2050: 15-20%** (up to 598 million ton of CO_2)

Natural gas decarbonization

Hydrogen can be injected into natural gas grids to reduce the carbon footprint of natural gas combustion. Today, the maximum feasible hydrogen mix into natural gas is about 20%, on a volume basis, which can reduce natural gas's carbon footprint up to 10%. **Hydrogen demand in 2050: less than 5%**

Liquid synthetic fuels

Liquid synthetic fuels can be produced on processes mixing hydrogen with CO_2. Using green hydrogen and captured CO_2 results on a carbon neutral synthetic fuel. **Hydrogen demand by 2050: 5-10%**

100% renewable methane

Just as with liquid synthetic fuels, methane can be produced by mixing hydrogen with CO_2.

Buildings

Buildings can use hydrogen for power and heat generation using PEM fuel cells, which are devices that produce electricity and heat as a byproduct in temperatures suitable for residential applications (60-80°C). Hydrogen for buildings could contribute to **14% of hydrogen demand by 2050.**

Industrial heat and power

Hydrogen burners, turbines, and combined heat and power systems (fuel cells) can supply industries with their thermal and electric power needs. Hydrogen for industrial heat and power could contribute to **21% of hydrogen demand by 2050.**

2. Includes petrochemicals and oil refining.

Hydrogen is taking a leading role in the energy agendas of many countries around the world

As of September 2020, 19 countries (accumulating 44% of the World GDP) have a hydrogen roadmap or strategy in place. In many cases, hydrogen strategies are accompanied with investment funds for the development of pilot projects and enabling productive ecosystems.

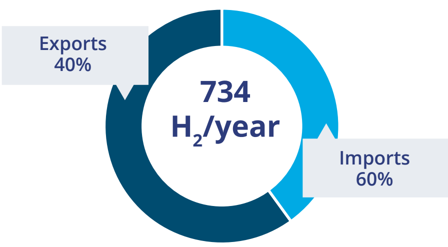
In Latin America, Chile is the leading country in terms of hydrogen developments. Its strategy was published by the end of 2020, and some pilot projects for high energy demand applications, like mining trucks and explosives manufacturing, are already in the planning phase. Chile's hydrogen state policy has four guidelines:

- Knowledge transfer and Innovation
- Support for the production, use, and exportation
- Regulation and normative
- Social and territorial development

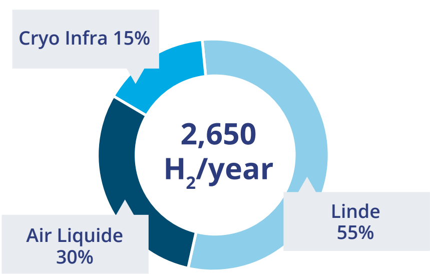
In Mexico, an existing hydrogen market is consuming more than 220,000 tons/year in 2020, of which 98.6% is captive in the hands of PEMEX, the state-owned oil, and gas company.

Figura 1-0. Mexican hydrogen market
(Secretaría de Economía, 2019 y Fortuna, 2020).

Mexican hydrogen international market



Mexican merchant hydrogen market



The production of merchant hydrogen in Mexico is approximately 2,650 tons per year, most of which is provided by Air Liquide, Linde, and Cryo-Infra.

There is a small international hydrogen trade balance in Mexico caused by private transactions. 40% represent exports mainly to Central America and the Caribbean, and 60% is imported from the United States. Most of the imports of hydrogen into Mexico respond to preventive and corrective shutdowns in gas plants, or unforeseen requests by customers of merchant hydrogen producers.

Mexico is in a privileged position to become a leader in the development of green hydrogen:

- The country has a well-distributed renewable energy potential
- Mexico has a well-developed energy infrastructure that could effectively enable green hydrogen developments
- There are at least a couple of international companies that have seen the potential for green hydrogen developments in Mexico and are already conceptualizing their first pilot projects in the country.
- The existing Energy Regulatory Framework allows the use of hydrogen as an energy vector
- Mexican universities and research centers have been working on hydrogen technologies since the 1990s. It means Mexico has the technical capacity to leverage for the development of industrial green hydrogen projects.

Regarding the Mexican stakeholder interviews conducted by Hinicio, most of the interviewed actors still observe how hydrogen develops in other latitudes and maintain an interest in the subject, but without active participation yet.

Without exception, the interviewed actors agree that Mexico has a high renewable potential and a wide territorial extension that could enable the development of green hydrogen in the country.

Regarding the barriers, the actors identify as the main barrier for green hydrogen, the current energy policy of the country and therefore, the adverse ecosystem of investment in renewable projects in Mexico.

The second most important barrier for hydrogen in Mexico is the lack of regulations aimed at meeting the goals of the Paris Agreement. This lack of regulation in terms of emissions has not made it necessary to issue technical regulations for new technologies, such as hydrogen production and use.

1.Hydrogen as energy vector: technologies and applications

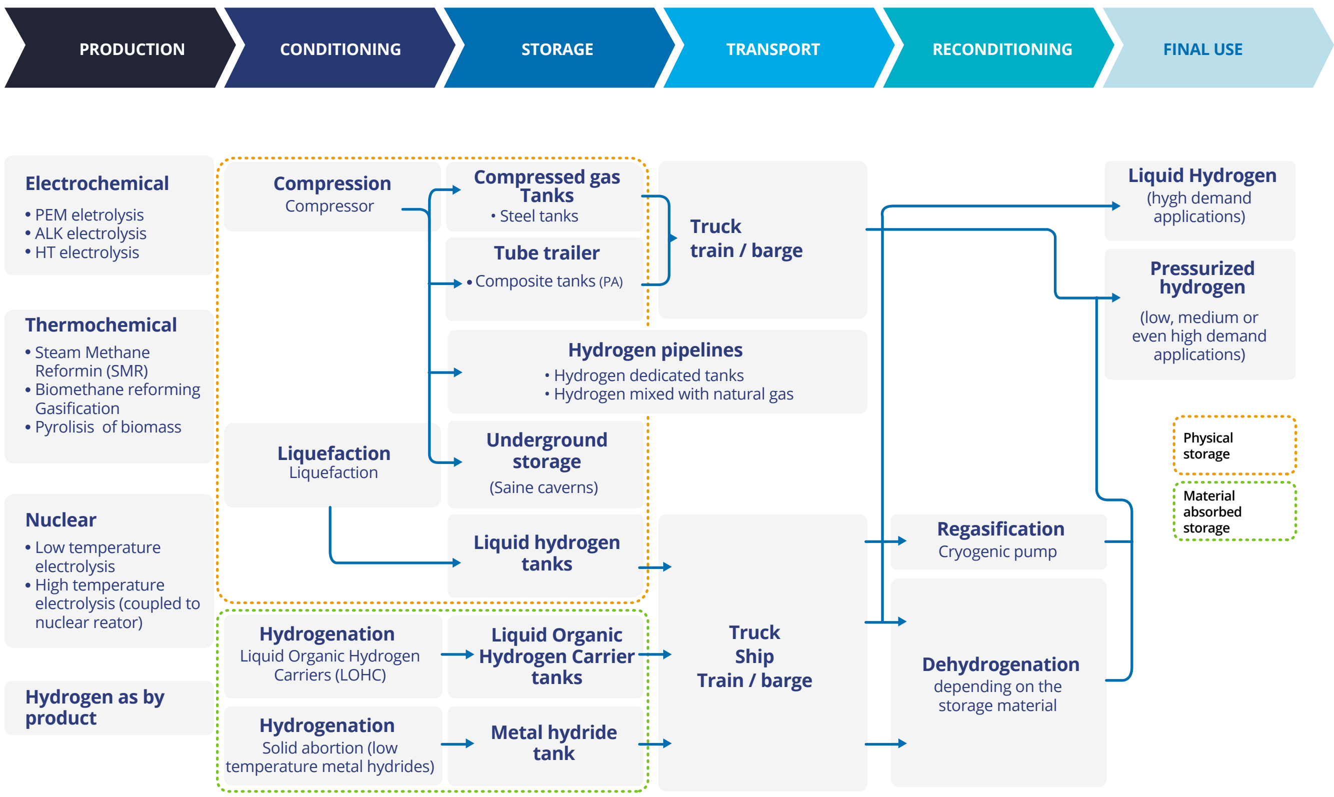
1.1. Green hydrogen context

Hydrogen is the first element in the periodic table; it is the simplest and most abundant element in the universe, in recent times it has attracted great interest due to its potential as an energy vector. Hydrogen is not found in a free state in the Earth, in the air, or mines. It is a substance that must be obtained by separating it from compounds such as hydrocarbons or water.

Since discovered in 1766 by Henry Cavendish, hydrogen has been used as a feedstock for many processes, especially for the petrochemical sector. Traditional uses include de-sulphuration of gasolines, addition to heavy organic molecules or chemical synthesis, like ammonia, the most important component of fertilizers.

During the 20th century, the most extended hydrogen production technology was Steam Methane Reforming (SMR) because of its high production rates, low prices, and availability of feedstock (natural gas). Nowadays, SMR remains as the leader in hydrogen production technology, with 95% of the global share, neverthe-less, SMR is a pollutant process (about 9 kilograms of CO_2 per kilogram of hydrogen). Cleaner methods for producing hydrogen are being developed (for instance pyrolisis, which consist on hydrogen production from thermal degradation of biomass. Inside high tempera-ture furnaces that as a result produce hydrogen and black carbon (in solid state) electrolysis: hydrogen production from water. The water molecule (H_2O) is splited into hydrogen and oxygen when an electric current hits the water.

Figure 1-1. Hydrogen value chain (Hinicio, 2020)



In order to easily identify the energy source, production technology and greenhouse gases emissions (GHG) related to hydrogen production, the international community has assigned “colors” to hydrogen, being green hydrogen the cleanest of all in terms of emissions reduction potential, as well as by-product generation.

Table 1. Hydrogen production technologies and colors (BMWi, 2020)

Hydrogen color	Energy Source	Feedstock	Production Technology	Production volumes	Contribution to decarbonization goals
Gray	Fossil fuels	Methane Coal	Steam methane reforming Gasification	100-600 ton H_2 /day	- High volumes of cheap hydrogen to test new H_2 consuming technologies. - No GHG emissions reduction.
Blue	Fossil fuels	Methane Coal	Steam methane reforming with carbon capture Gasification with carbon capure	100-600 ton H_2 /day	- High volumes of cheap hydrogen to test new H_2 consuming technologies. - 80 – 90% of GHG emissions reduction.
Turquoise	Renewable or carbon neutral energy	Methane or biomethane	Pyrolysis	Laboratory scale	- Expected to produce high volumes of H_2 - No GHG emissions but black carbon present
Pink	Nuclear power	Water	Electrolysis coupled with nuclear reactor cooling systems	0.1-2 ton H_2 /day	- Medium volume of hydrogen production expected - No GHG emissions but nuclear waste still present
Green	Renewable energy	Water	Electrolysis	0.1-2 ton H_2 /day	- Medium volume of hydrogen production expected - No GHG emissions or waste due to feedstock/energy processes.

According to the European program for Guarantees of Origin of Hydrogen, CertifHy (Hinicio, 2015), green hydrogen is produced using renewable energy and a GHG intensity at least 60% below hydrogen produced from natural gas.

Figure 1-2. World average production cost of H_2 by source, 2019 (IEA, 2019)

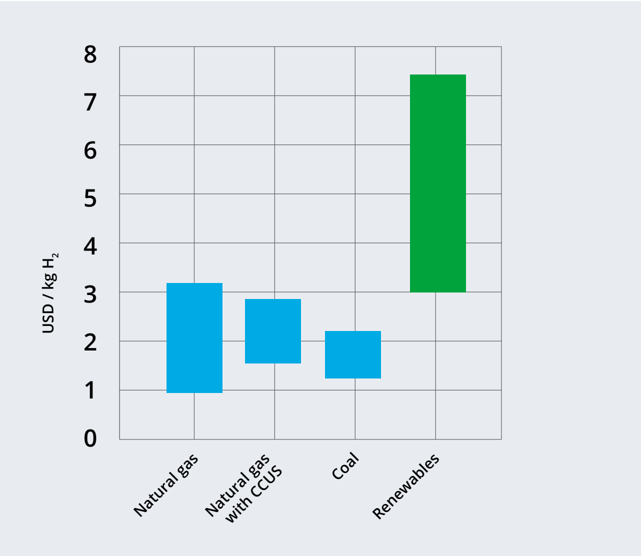
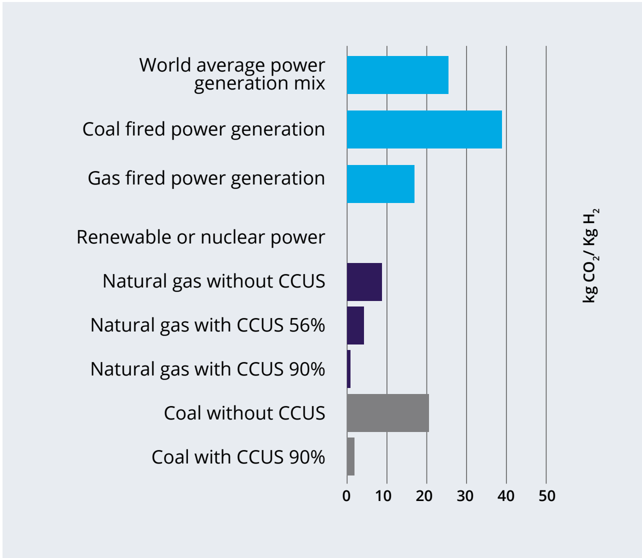


Figure 1-3. GHG intensity of hydrogen production (IEA, 2019)

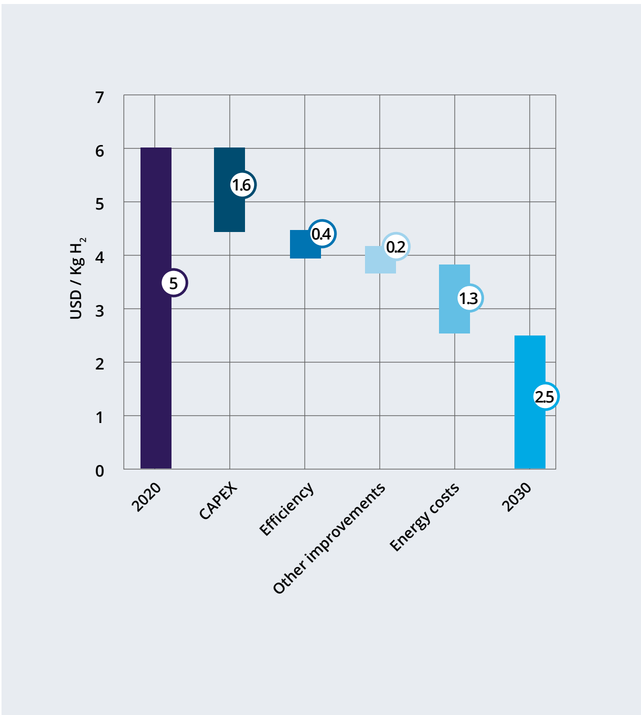


While green hydrogen is the cleanest hydrogen production pathway, it is still 50 to 300% more expensive than fossil fuel pathways. There are multiple reasons for this:

- **Efficiency and materials:** electrolysis is a mature technology; however, there is still potential for reducing material costs and improving efficiency.
- **Production scale:** there is still no mass-production of electrolysers as of 2020.
- **Supply chains:** still need to be optimized for the supply of green hydrogen.
- **Cost of energy and feedstock:** depending on the location, renewable energy could be more expensive than fossil-based energy.

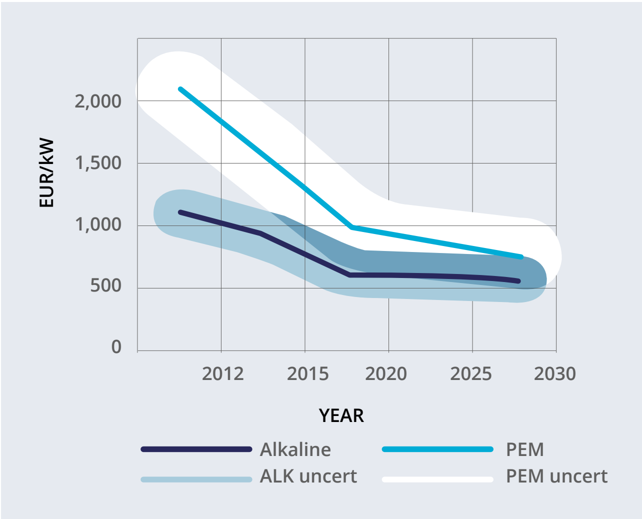
Efforts are being made across the world by private and public entities to close the gap between gray and green hydrogen. Climate change and energy security are the main drivers behind the desired adoption of green hydrogen.

Figure 1-4. Green hydrogen cost trajectory 2020-2030 (Hydrogen Council, 2020)



According to the Hydrogen Council, green hydrogen costs could fall up to 60% in the next 10 years driven by improvements in equipment CAPEX (includes supply chain, materials, and manufacturing), efficiency (meaning less energy consumption), energy costs, and other advances on the value chain. Just the CAPEX of electrolysers is expected to fall anywhere from 40 to 50% in the coming 10 years.

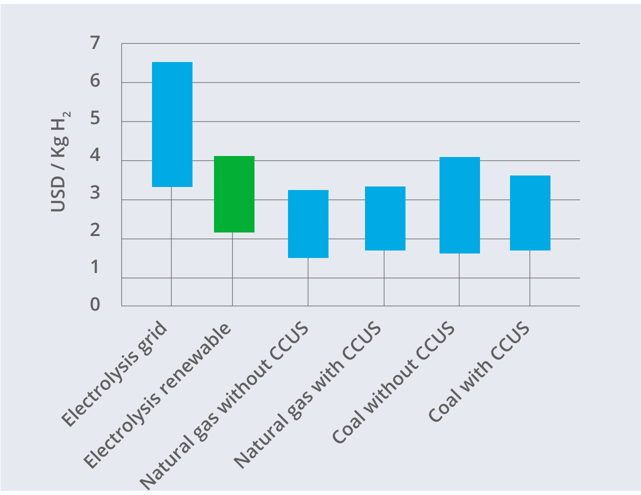
Figure 1-5. Forecast of CAPEX for electrolysis systems (FCH-JU, 2014)



The International Energy Agency estimates a global average cost of 2 – 4 USD/kg of green hydrogen by 2030, reaching parity with conventional technologies such as steam methane reforming and coal gasification with no carbon capture. Green hydrogen will be most competitive in markets with high carbon taxes, scarce fossil fuel resources, and high renewable energy potentials.

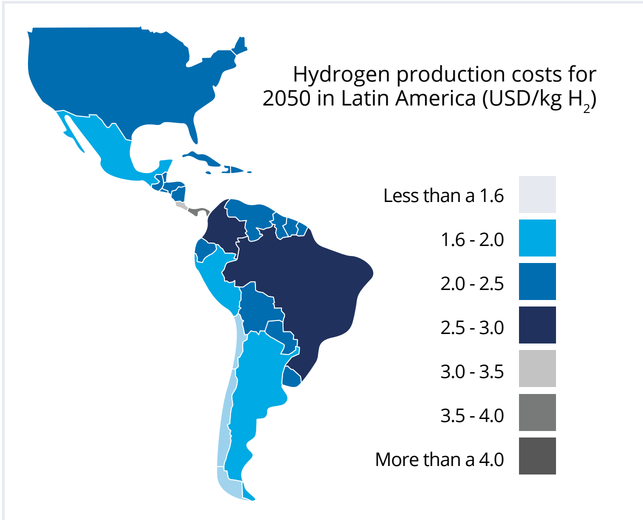
By 2050, countries with little renewable potential like Russia, Korea, or Japan, will produce hydrogen above 4 USD/kg. In contrast, the Latin American region is expected to reach prices around 2 to 2.5 USD/kg.

Figure 1-6. Forecast of global hydrogen production costs, 2030 (IEA, 2019)



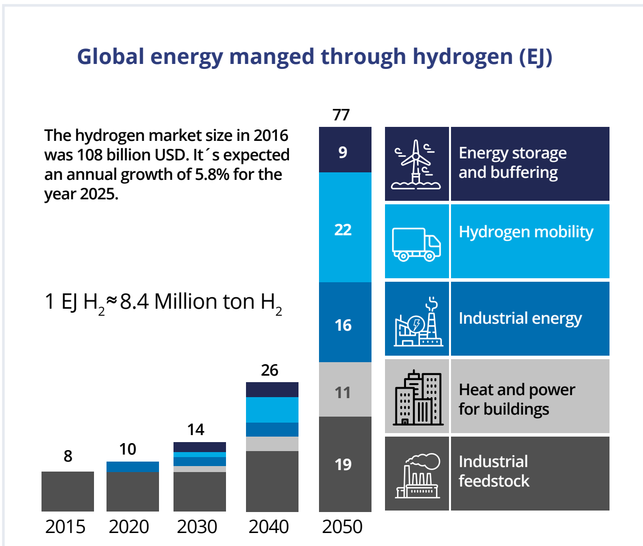
In Latin America, Chile will probably reach the lowest hydrogen production costs, at 1.6 USD/kg by 2050, followed by Brazil, Peru, Argentina, and Mexico on the range of 1.6 – 2 USD/kg.

Figure 1-7. Latin American hydrogen production costs (IEA, 2019)



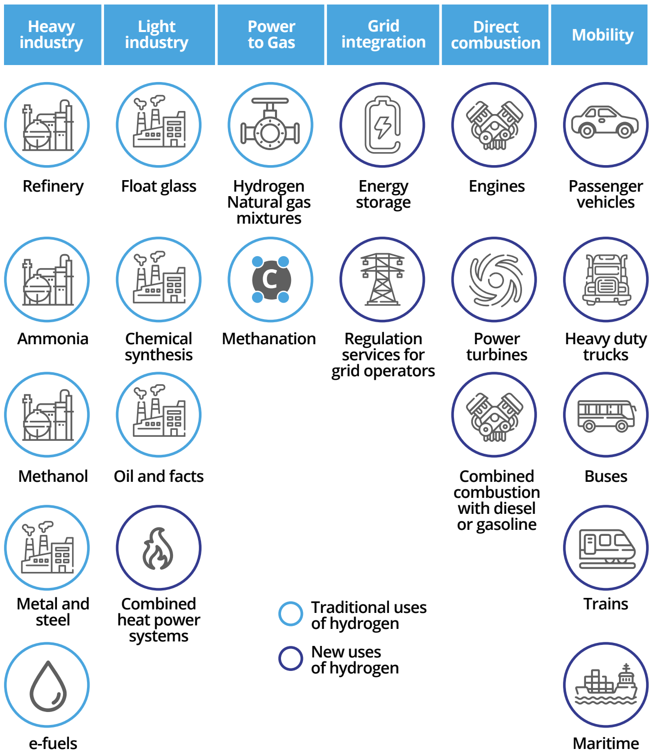
As of 2020, around 85% of global hydrogen production is captive, with on-site SMR installations at petrochemical plants. Merchant hydrogen is expected to gain market share due to its adoption in applications such as transportation and buildings, where many suppliers are expected to compete (just as happens today with liquid and gas fuels provision). Demand for hydrogen is expected to grow mainly in new applications such as energy storage, mobility, and energy for industries.

Figure 1-8. Hydrogen demand forecast (Hydrogen Council, 2017)



The transition from gray to green hydrogen will be a gradual process. Some innovative hydrogen projects are being developed with gray or blue hydrogen, allowing for the testing of concepts and development and strengthening of value chains in the so-called new "hydrogen economy". However, it is important to keep in mind that the ultimate goal of governments pushing for hydrogen development is to migrate to green hydrogen, for traditional and innovative H_2 uses alike. Gray and blue hydrogen can support the early steps of the transition, but only green hydrogen will lead the world to the decarbonization goals laid out in the Paris Agreement.

Figure 1-9. Traditional and new uses of hydrogen (Hinicio, 2020)



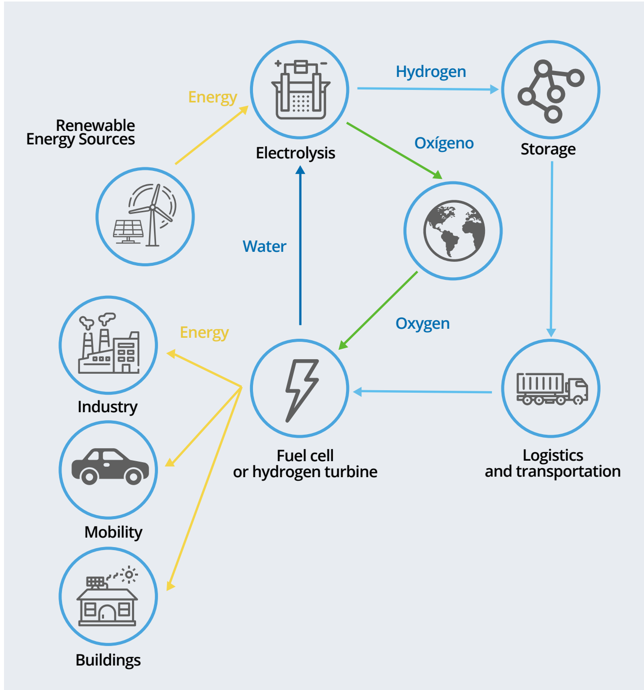
Hydrogen is not a primary energy source; it is an energy carrier. Renewable energy from photovoltaic, wind, geothermal, or hydroelectric plants can be stored and transported as hydrogen from split water molecules (electrolysis).

Electrolysers and fuel cells are key technologies for the new hydrogen economy, as they allow for intermittent renewable energy to be stored in the form of hydrogen, and then used as such (for industrial or transport applications) or converted back into electricity to inject to the electricity grid.

The concept of power-to-x refers to the possibility of transforming (renewable) electrical energy into a chemical molecule that can be transported, used to generate heat, power, or feedstock.

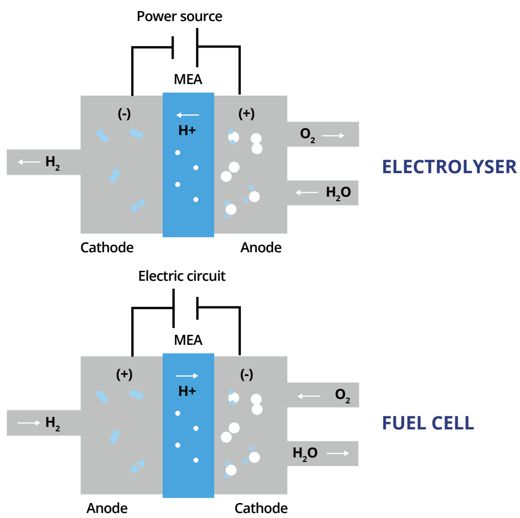
Hydrogen coupled to renewable energy is a circular process of splitting water, storing hydrogen and converting hydrogen back into electricity or heat.

Figure 1-10. Hydrogen on renewable energy storage (Hinicio, 2020)



An electrolyser is an electrochemical device where water molecule is split into hydrogen and oxygen. Oxygen is vented and hydrogen stored on tanks or vessels. A fuel cell in a device with the opposite function, it is fed with hydrogen from tanks, takes oxygen from air and delivers electrical power and water. Alternatively and depending on the volume of hydrogen available, turbines can be used to convert hydrogen into electricity (see section 1.6).

Figure 1-11. Electrolyser and fuel cell operation (Hinicio, 2020)



Fuel cells provide electricity to hydrogen vehicles (Fuel Cell Electric Vehicles). In stationary applications, they are used on power applications and low energy consuming systems from kilowatts to few megawatts (houses, telecom antennas, etc.). In high demandant energy applications and centralized power generation, hydrogen is used as a fuel for turbines of 20-400 MW.

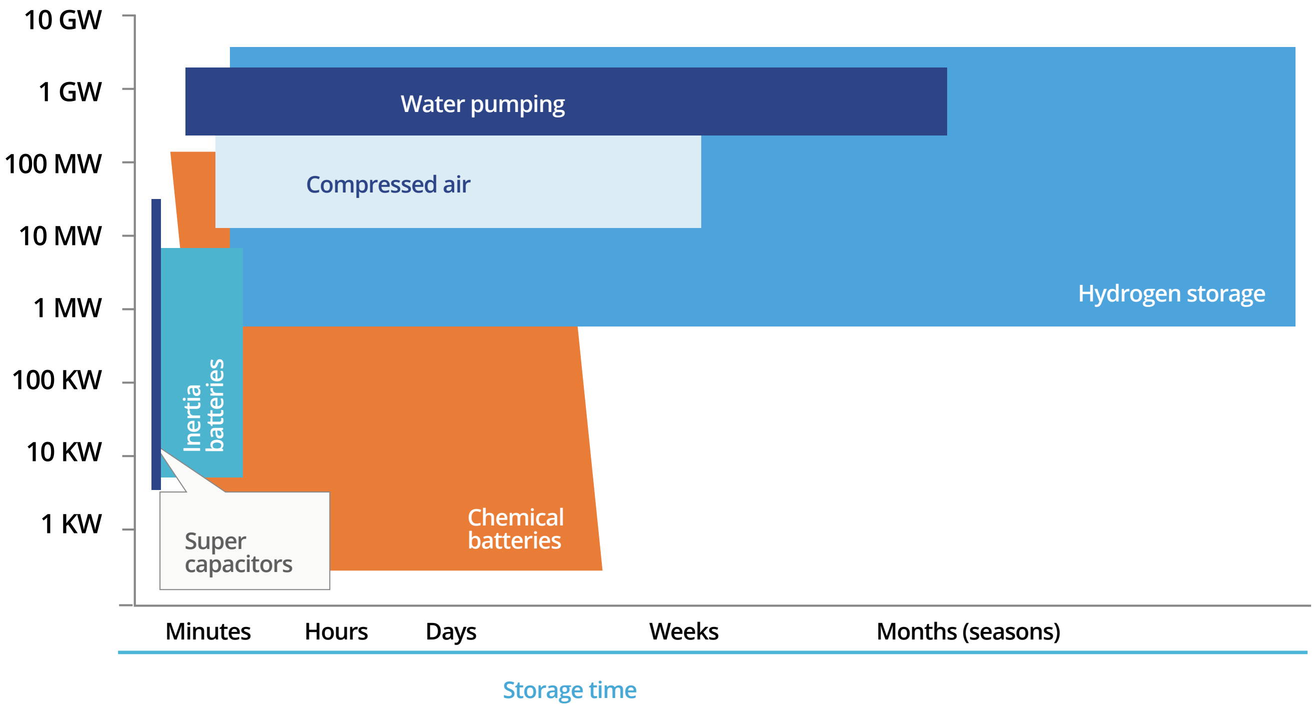
1.2. Renewable energy storage (and re-electrification)

There are a number of technologies available in the market to store renewable energy such as pumped hydropower, compressed air, capacitors, batteries, and hydrogen.

Figure 1-12 shows a technological map to choose between energy storage options according to the volume of energy, storage time, and technical capabilities.

Hydrogen is a viable option when the energy volume to store is high, and energy must be stored over long periods.

Figure 1-12. Energy storage technologies (IEA, 2013)



Hydrogen is a chemical gas that can be compressed or liquefied and stored on different sizes and types of vessels.

With capacities from some grams to millions of kilograms, there is a complete offer of hydrogen vessels. The size of the hydrogen container determines the capacity to store renewable energy. Some hydrogen containers involve complex processes (like the Liquid Organic Hydrogen Carriers, which need a catalytic reactor to absorb and desorb hydrogen from an organic molecule)while other are simply closed vessels, like steel tanks.

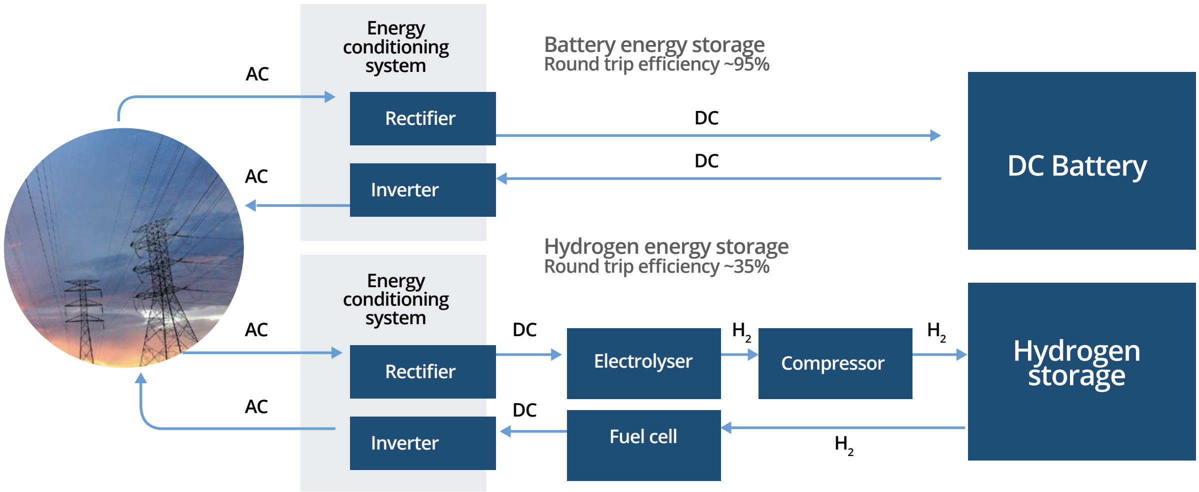
Depleted oil and gas fields and saline geological reservoirs are compatible with hydrogen storage, being the most extensive available vessels with capacities from 300,000 kg to 6,000,000 kg of compressed hydrogen. For this technology, just geological exploration is needed. Injecting hydrogen into underground reservoirs is a simple technological process of compression. Reservoirs do not require maintenance, resulting in a low storage cost by kilogram of hydrogen.

Figure 1-13. Hydrogen storers and their capacity (Hinicio, 2020)

Batteries and hydrogen are commonly compared because both are electrochemical processes. In battery energy storage the electrons are directly stored on a chemical substance, while hydrogen is transformed from electrical to chemical energy.

Hydrogen must be produced, compressed, stored, and converted back to electricity, and despite the high efficiencies of electrolizers (≈60%) and fuel cells (50-60%), the cumulative energy loses result in a round-trip, or cycle efficiency of 35% for hydrogen-fuel cell systems, while batteries are 95% efficient.

Figure 1-14. Hydrogen and battery comparison in energy storage (Hinicio, 2020)



Despite their low round trip efficiency, hydrogen technologies have life cycle advantages such as a higher Energy Stored on Invested ratio (ESOI) compared with batteries. ESOI is given by the following equation (Pellow, 2015):

Equation 1 - Energy Stored on Invested

$$\text{ESOI}= \frac{[\textit{Energy dispatched to grid over life time}]}{[\textit{Energy required to manufacture}]}$$

According to Pellow, a hydrogen energy storage system has a ESOI of 59, while a battery system has 35. This means electrolysers and fuel cell are less energy-intensive and they have longer lifespans.

Another advantage of hydrogen systems is their low self-discharge rate and high energy density. More energy can be stored in less system mass, which provides an opportunity for high energy demand mobile applications, such as mining trucks.

It is important to remember that there will not be an absolute "storage winner". We are likely to see a menu of technologies depending on the application, volume of energy to store, and storage time.

Table 2 shows a comparison between charge, storage, and discharge costs for Battery Energy Storage Systems (BESS), hydrogen stored in tanks, and hydrogen stored in underground reservoirs.

Even when charge and discharge of hydrogen systems is up to 9 times more expensive, the storage costs of underground reservoirs is 0.036% of the battery storage cost. Because of that, **hydrogen is the best technical and economical option for high volumes of stored energy.**

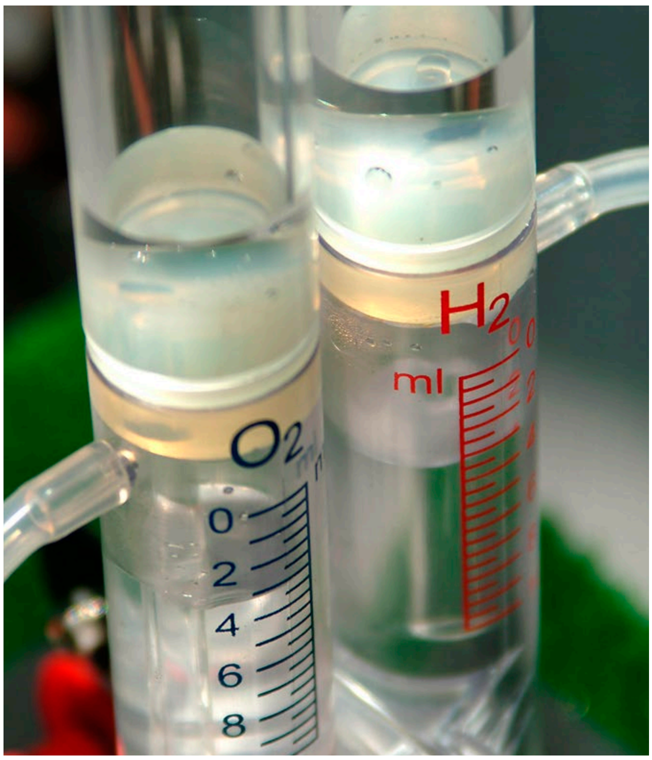


Table 2. Battery and hydrogen cost comparison for energy storage (NREL, 2019)

Technology		Charge (USD/kW)	Storage (USD/kWh)	Discharge (USD/kW)
BESS	Current	196	218	60
	Future	183	80	60
Hydrogen on tanks	Current	942	35	574
	Future	432	18	300
Hydrogen underground	Current	942	0.08	574
	Future	432	0.08	300

Hydrogen energy storage has:

- Lower cost per kWh stored
- Higher costs for charge and discharge
- Lower round-trip efficiency

Charging equipment

- BESS: rectifier
- Hydrogen: Electrolyser, compressor

Storage equipment

- BESS: batteries
- Hydrogen: tanks, underground reservoirs

Discharge equipment

- BESS: invertor
- Hydrogen: Fuel cell

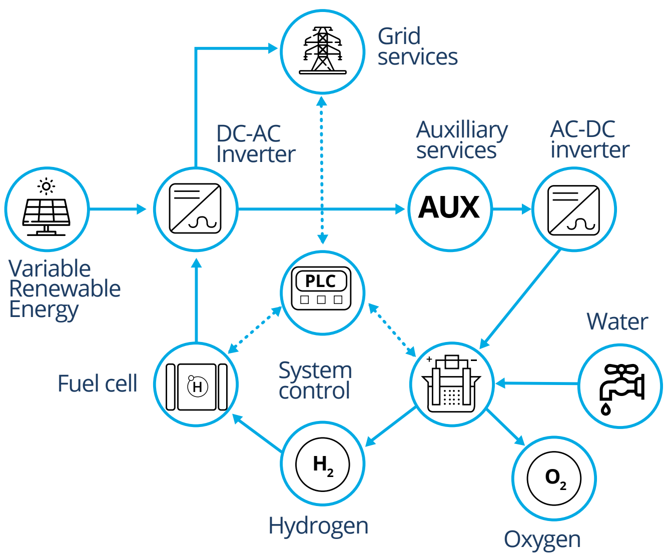
- **Lower round-trip efficiency means higher operating costs for hydrogen.**
- **Lower CAPEX for underground hydrogen storage reduces the total cost of energy storage, but requires higher volumes**
- **Hydrogen is more competitive when higher energy storage capacities are required.**

In addition to the energy storage applications of hydrogen, electrolysis could be used to provide grid services on variable renewable energy grids. A good example is the Secondary Frequency Control. The Secundary Frequency control matches the total system generation with full system load, or demand (transmission, losses, and consumption). It corrects variations in power system frequency by correcting short-term changes in electricity use that might affect the power system's stability. Production deficiencies can be compensated by the electrical production of a fuel cell while excess production of variable renewable sources can be absorbed by a PEM electrolyser.

A PEM electrolyser is a fast-responding dynamic load whose power consumption can be changed every 2 seconds over its entire operating range in response to a grid operator signal. It can be “set” at the full or minimum load of its complete operating range if it is required.

It is possible (and recommended) to dynamically allocate a portion of an electrolyser plant's operating capacity for frequency regulation and other grid services.

Figure 1-15. Secondary Frequency Control with hydrogen technologies (Hydrogenics, 2018)



1.3. Electric Mobility

Hydrogen can propel electric transport when used in Fuel Cell Electric Vehicles (FCEV). FCEV don't burn hydrogen into an internal combustion engine, but they convert hydrogen into electricity inside a fuel cell to drive an electric powertrain.

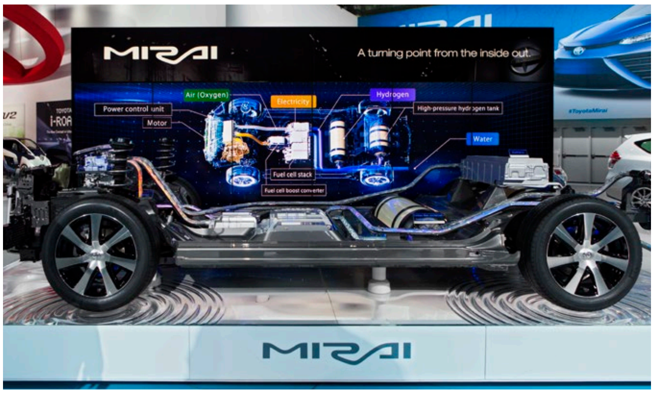
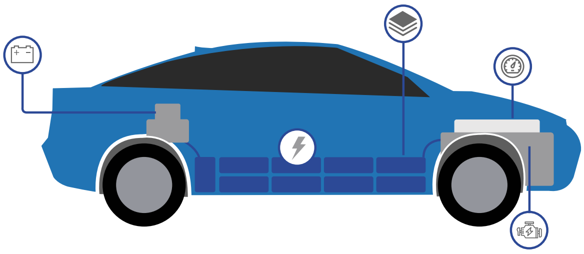


Figure 1-16. Battery electric and fuel cell electric vehicles comparison (Hinicio, 2020)

Battery electric vehicles (BEV)

- ✗ Refuelling 40 m - 8 h for 200 - 300km
- ✓ Lower cost, higher efficiency

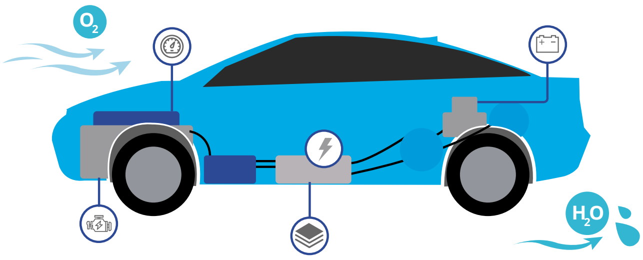
Better for:
- Light vehicles
- Short to medium distances
- Private use



Fuel cell vehicles (FCEV)

- ✓ Refuelling 4 - 6 minutes for 550 - 750km
- ✗ Higher cost, lower efficiency

Better for:
- Freight and buses
- Long distances
- Intensive use (commercial)



Fuel Cell Electric Vehicles have been developed since the 2000s by European and Japanese car manufacturers like Mercedes Benz, Toyota and Honda. During the spring of 2015, Toyota started the operation of the first production line worldwide for a FCEV vehicle, the Mirai, a sedan passenger vehicle (Mirai means "future" in Japanese language).

FCEV are positioning themselves as a competitor of batteries for electric mobility in the segments where long range and fast refueling is critical, such as buses and freight trucks. As mentioned in section 1.2, hydrogen has a very high energy density, storing more energy per kilogram of storage system than other technologies such as batteries. This is a critical advantage for the commercial transport segment, because FCEV allow carrying more passengers, or more payload, for the same total weight of a vehicle, when compared to batteries. Higher energy density also translates in higher ranges; FCEV in all transportation segments have the same range as Internal Combustion Engine Vehicles (ICEV), while battery electric vehicles (BEV) typically have autonomies below 70% that of ICEV.

Hydrogen refueling takes as much time as gasoline or diesel refueling, while batteries typically need to be plugged for a few hours to fully recharge, compromising vehicle availability.

Figura 1-17. Range comparison between BEV and FCEV (Hinicio, 2020)

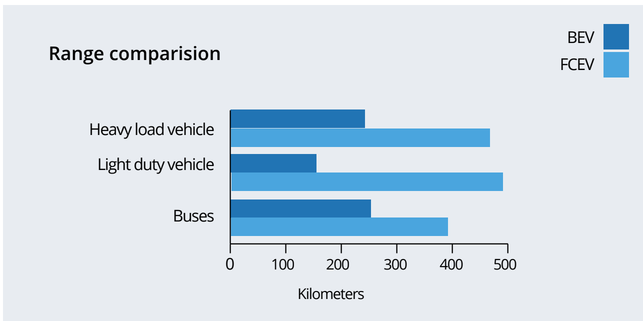
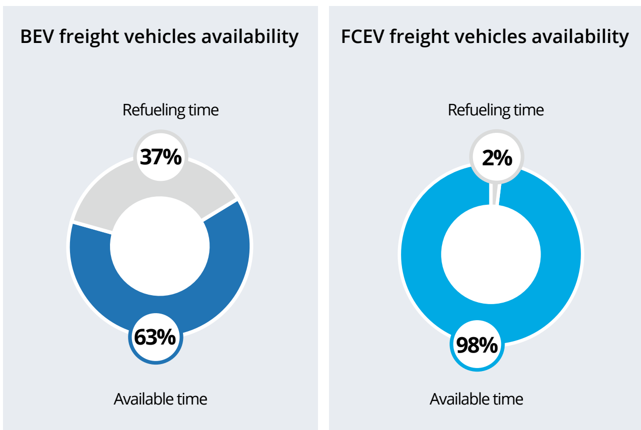


Figure 1-18. Vehicle availability comparison between BEV and FCEV (Hinicio, 2020)

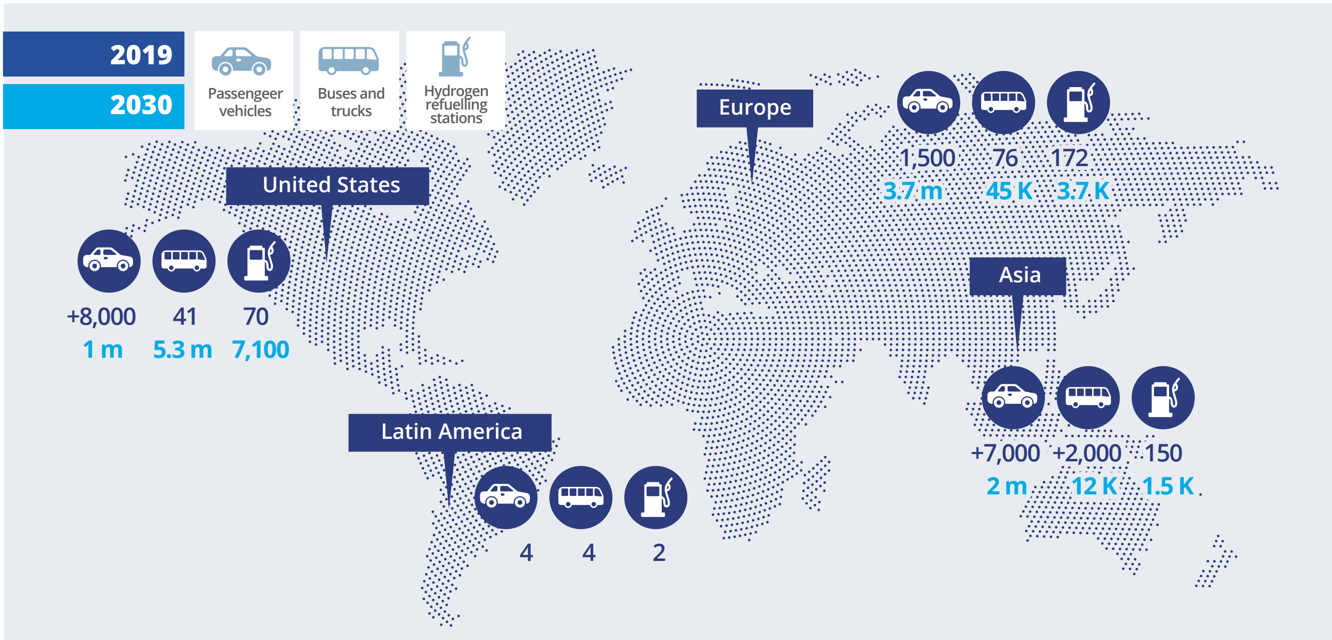


In the United States, the most active state in hydrogen adoption for transportation is California, positioning as an international leader on FCEV adoption. California has the highest share of passenger FCEV in the world with more than 8000 hydrogen cars in September 2020. California is also leading the deployment of fuel cell trucks to decarbonize freight transportation, with already a pilot project running in 2020 in the Long Beach Port.

China has the largest fleet of fuel cell buses, while Switzerland recently received the first order for 50 medium-duty trucks from Hyundai, the first batch of an order of 1600 units to be deployed by 2025.

In Latin America, the first 4 hydrogen passenger cars are operating in Costa Rica as taxis for the high-end tourism sector. This project also includes a fuel cell bus running since 2018. Costa Rican effort for hydrogen adoption is led by the "Alianza por el Hidrógeno" an association of private companies promoting hydrogen.

Figure 1-19. World overview of hydrogen mobility deployment and targets 2030



1.4 Green chemicals and industrial feedstock

According to the Hydrogen Council, the industrial sector demands 90% of the hydrogen produced today in the world. However, 95% of this hydrogen is produced from fossil sources such as coal, natural gas or crude oil.

Thus, switching from gray to green hydrogen represents a huge opportunity for decarbonization of this industry.
Electrolizers coupled to renewable energy assets can help decarbonize many industries, as shown below.

Refineries: Used to remove sulphur from diesel and gasolines.	**Production:** On site	**Volume of H_2:** >10.000 Nm³/h	**Green H_2 status:** still under needed capacities
Green ammonia Used as feedstock for the ammonia production.	**Production:** On site	**Volume of H_2:** >5.000 Nm³/h	**Green H_2 status:** firsts projects under development
Steel and metal industry Mining mobility, steel purification and thermal applications.	**Production:** On site, semi-centralized	**Volume of H_2:** >5.000 Nm³/h	**Green H_2 status:** firsts projects under development
Chemical synthesis: Feedstock for acids, synthetic resins and other chemical synthesis.	**Production:** On site, semi-centralized	**Volume of H_2:** <5.000 Nm³/h	**Green H_2 status:** ready to play
Glass Heating applications and atmospheres for shaping and conditioning	**Production:** On site, semi or centralized	**Volume of H_2:** <2.000 Nm³/h	**Green H_2 status:** ready to play
Oil and food fats: Feedstock for oil and fats hydrogenation	**Production:** On site, semi or centralized	**Volume of H_2:** >100 Nm³/h	**Green H_2 status:** ready to play

Several pilot projects are running or in planning stages to prove the use of green hydrogen for chemical process around the world. In Latin America one of the most important is the ENAEX-Engie project in Chile to produce green mining explosives with a Power-to-Ammonia plant that would reduce the emissions of CO_2 in more than 600.000 tons/year.

Figure 1-20. Worldwide green hydrogen projects for green chemicals

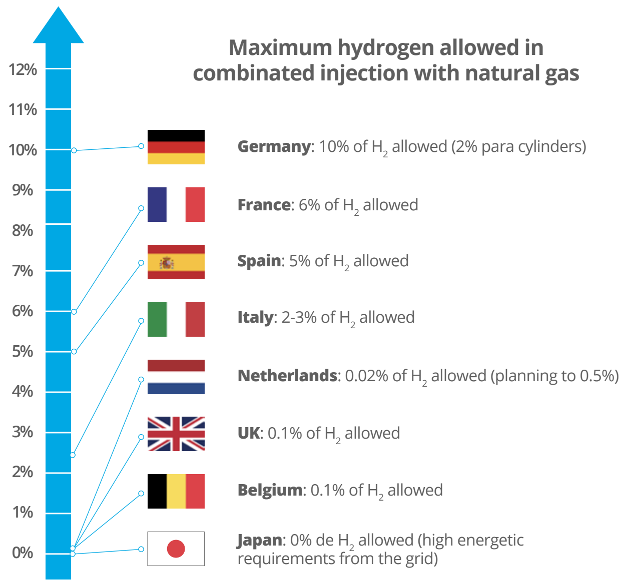
1.5 Natural gas decarbonization

Hydrogen can reduce carbon emissions when mixed with other fuels such as natural gas. It can be transported as a mix with natural gas in the gas pipeline networks, and burnt as a fuel mix in several end-use equipment such as boilers or turbines.

Technically there is a limit for the hydrogen - natural gas mixture, which varies depending on the characteristics of the equipment that uses the mixture (ovens, burners, boilers, etc.). It is estimated that the maximum percentage of H_2-NG mixture possible without making modifications to the gas consumption systems is 20%. Current regulations in European countries accept a maximum of 10% of H_2 mixed with natural gas. Some pilot projects are running nowadays with higher percentages of hydrogen in the mix. HyDeploy, a UK project, has proven feasible the mix of up to 20% of hydrogen on a volume basis when injected into natural gas pipelines. Nonetheless, it is important to note that these trials are developed under controlled conditions and in small and delimited gas networks.

Hydrogen has 1/3 of energy density by volume concerning natural gas density. This is the reason why reduction in emissions is not proportional to injected H_2 percentages. A 20% mixture of hydrogen in natural gas reduces emissions by around 10%.

Figure 1-21. Limits for hydrogen – natural gas mixtures in pipelines (Dolci, 2019)

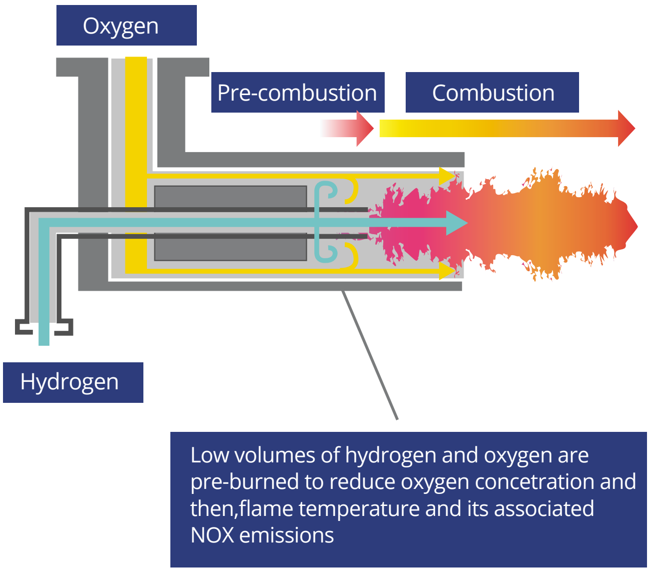


1.6 Industrial heat and power

One of the advantages of hydrogen as an energy vector is transforming (renewable) electrical energy into chemical energy. As hydrogen has a high energy density per unit of mass, it can be used as a heat source for industrial applications. Hydrogen combustion can reach temperatures above 1000º C, so depending on the burner configuration, H_2 can be used to produce high (>400°C), medium (150-400°C), and low temperatures (<150°C).

Hydrogen combustion is not widely extended today because the gas is not available in abundance, and it is still more expensive than fossil fuels.

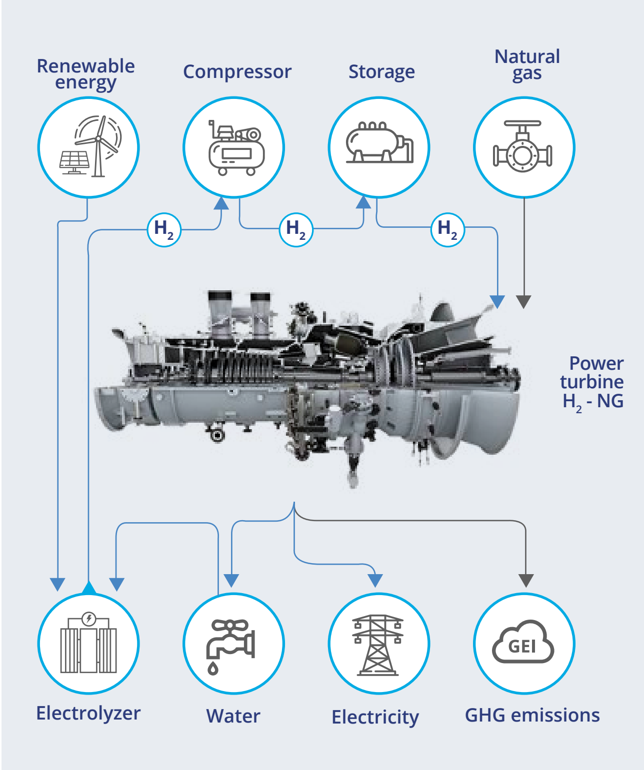
Figure 1-22. Hydrogen burner developed by Toyota and Chugai (Toyota, 2018)



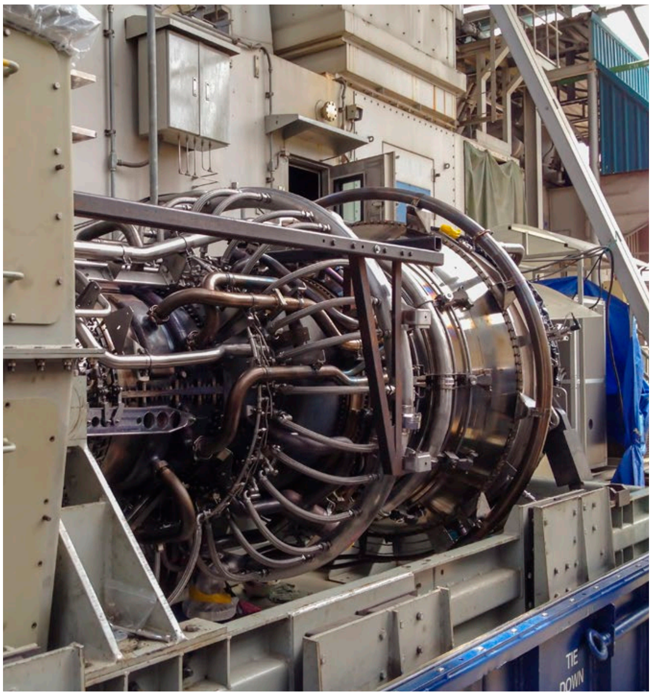
Hydrogen is a by-product of many industrial processes, like oil reforming and chlorine production. Companies producing residual hydrogen have used hydrogen to produce electricity using turbines since the 1990s. Mexichem is an example in Mexico. The company obtains hydrogen as a by-product of chlorine production and burns H_2 mixed with diesel in their boilers.

Companies like General Electric and Siemens have at least 25 years of designing gas turbines that allow hydrogen mixes in proportions of 10-50%. Such mix helps reducing CO_2 emissions. For example, a 265MW turbine burning 5% of hydrogen would avoid 19,000 tons of CO_2 annually. Turbine manufacturers, like Siemens, are planning to increase hydrogen – natural gas acceptable blends and produce turbines running on pure hydrogen by 2030.

Figure 1-23. Mixed Natural gas – hydrogen turbines (Hinicio, 2020)



Hydrogen combustion is a very exothermic process that produces nitrogen oxides (NOx). To avoid emissions of this pollutant gas, turbine manufacturers are developing specialized burners that reduce the flame temperature. These burners are named Dry Low Emission or Dry Low NOx.



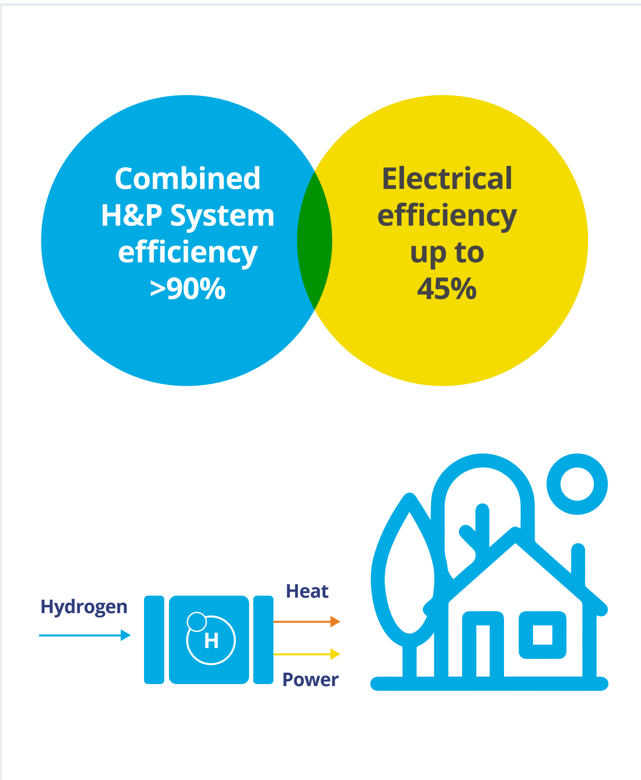
1.7 Buildings

The modularity of hydrogen allows for its use not only in high demand activities such as heat and power generation for industry, but also for less energy intensive applications like the use in residential and commercial buildings. Fuel cells produce electricity and heat. Depending on the fuel cell technology, they can produce temperatures above 900º C (Solid Oxide Fuel Cells), or between 70 and 80º C (PEM).

PEM fuel cells can be used in buildings to produce electricity and heating with electrical efficiencies of 45% and global efficiencies up to 90%.

Japan is a leader in the development and adoption of Combined Heat and Power Systems for residential applications. Since 1999 Japan has developed these systems and, during the 2000s, promoted their adoption through demonstration programs funded by METI (Ministry of Economy, Trade, and Industry). There are about 300,000 CHP units installed in Japan, reducing emissions by 35 and 40% (even using gray hydrogen. Emission reduction associated to the reduction in the use of primary energy (LP gas) and the high efficiency of the process) when compared to traditional fossil-based systems (EU-JP Centre for Industrial Cooperation, 2019).

Figure 1-24. Residential Combined Heat and Power systems



1.8 100% renewable methane

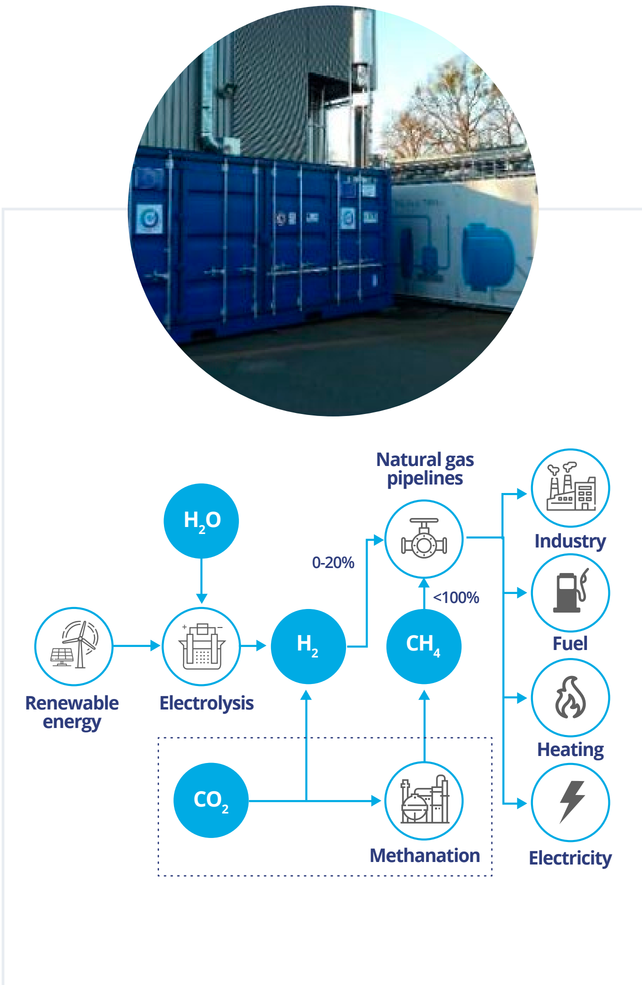
Another alternative offered by hydrogen to keep using the existing infrastructure for natural gas is synthetic methane production, a process known as methanation.

Synthetic methane is produced from electrolytic hydrogen and captured CO_2 (from industry or air).

Methanation represents an opportunity to produce a 100% carbon-neutral gas, while keeping the use of conventional infrastructure such as gas pipeline networks and other end-use equipment. Disadvantages of methanation include 25 to 40% energy losses associated with the synthesis process's efficiency.

The European Union has developed some pilot projects to test this concept, for example, the HELMETH project. HELMETH was developed between 2014 and 2017. This project achieved a process efficiency of 76% and reduced carbon emissions by 150 grams of CO_2/kWh equivalent of produced gas.

Figure 1-25. Methanation process – HELMETH Project (Helmeth, 2017)



1.9 Liquid synthetic fuels

In addition to the production of gaseous fuels like methane, hydrogen offers the possibility of synthesizing liquid fuels. Although this process has a round-trip efficiency of only 41%, it provides the opportunity of using critical infrastructure without modifications while decarbonizing some industrial sectors. An example of the above is aviation, which, due to the planes' pressure changes at different heights, would face difficulties transporting gaseous fuels. Jet fuel synthesis from captured CO_2 and green hydrogen would allow for the decarbonization of the aviation sector, which contributed with 915 million tons of CO_2 globally in 2019.

1.10 Hydrogen technologies TRL and CRI

All the hydrogen technologies that have been mentioned so far have different levels of technological maturity. The NASA developed a methodology for evaluating technical maturity of new technologies with a 9-point scale.

Hinicio developed a 5-level scale to evaluate commercial maturity, assigning 5 to technologies that have been used for more than 10 years and 1 to technology that has just come out of the laboratory and is starting to be tested in pilot projects.

The graph below shows an schematic of hydrogen TRL and CRI for different applications.

Figure 1-26. Power to Liquids process (Karlsruhe Institute, 2019)

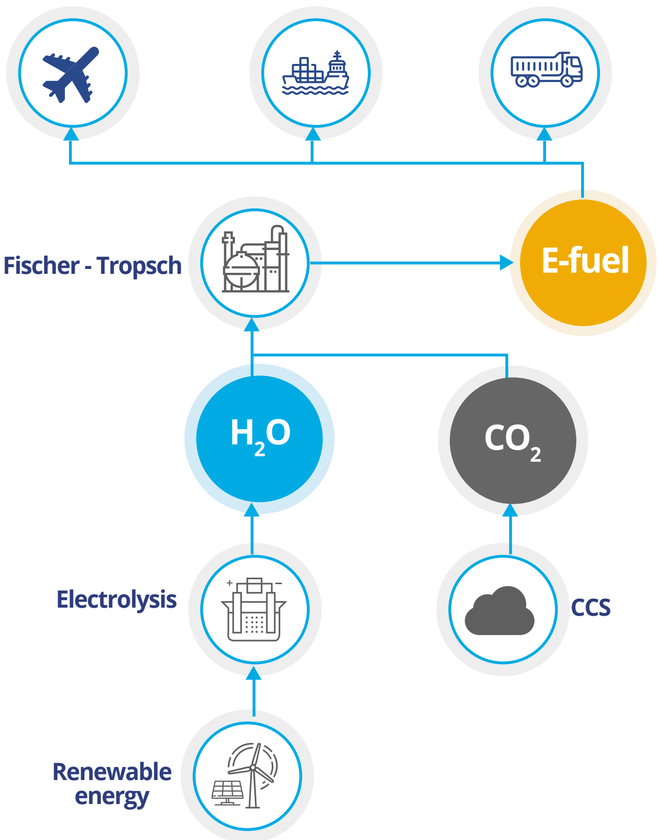
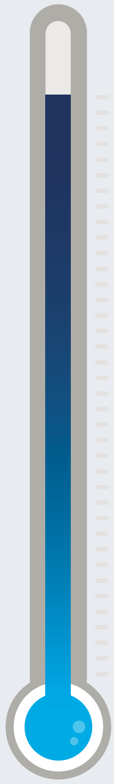


Figure 1-27. Technological and commercial readiness of new hydrogen applications (HInicio, 2020)

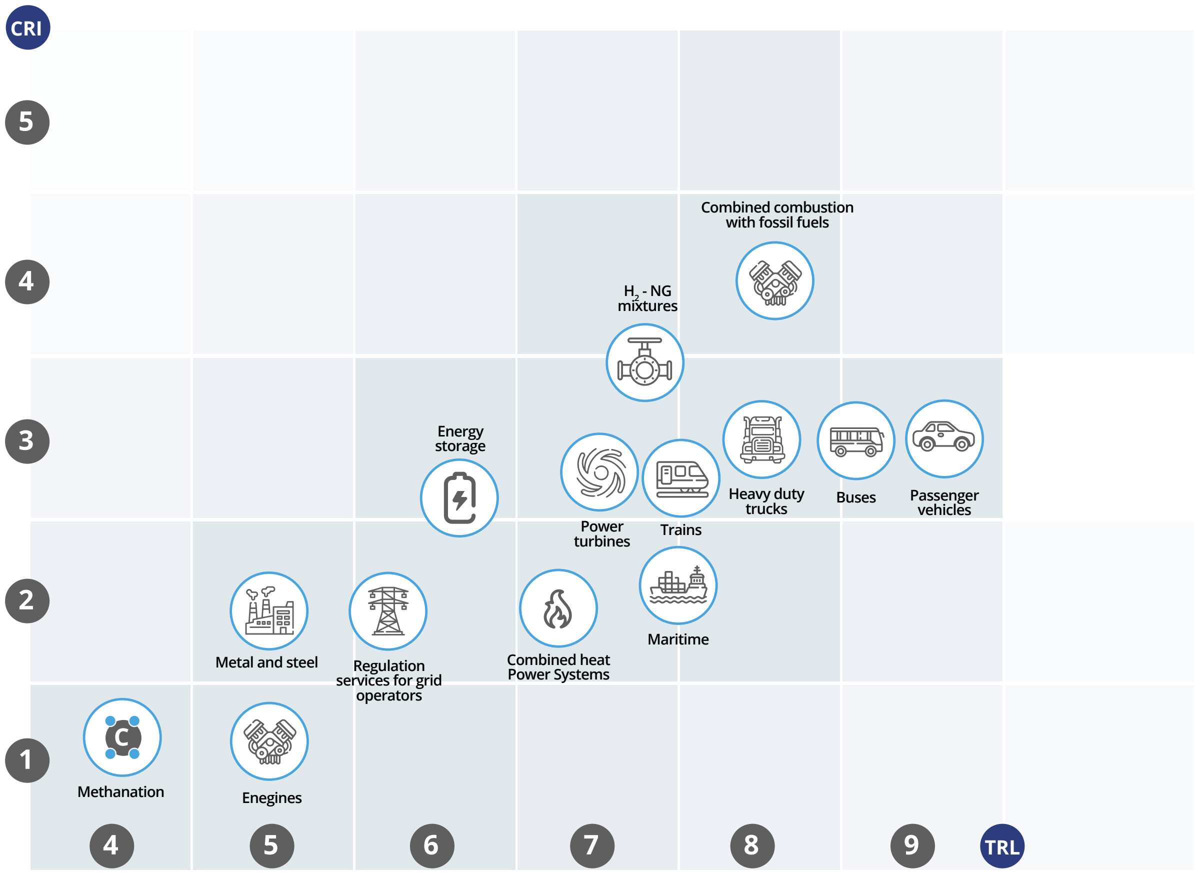
Technology readiness level (TRL)

9	Actual system "flight proven" trough successful mission operations.
8	Actual system completed and "flight qualified" throgh test and demonstration.
7	System prototype demonstration in an operational environment.
6	System / sub-system model or prototype demonstration in an operational environment.
5	Component and / or breadboard validation in relevant environment.
4	Component and / or breadboard validation in laboratory environment.
3	Analytical and experimental critical function and / or characteristic proof of concept.
2	Technology concept and / or application formulated.
1	Basic principles observed and reported.

Commercial Readiness Level (CRI)



5	Used extensively for more than 10 years
4	Used extensively for less than 10 years
3	Early adoption. With projection for its expansion soon.
2	Used in demonstration projects at a medium to large scale.
1	Used in pilot projects at low or medium scale. Just after the R&D stage.




H2
H2 HYDROGEN POWER
CLEAN ENERGY OF THE FUTURE

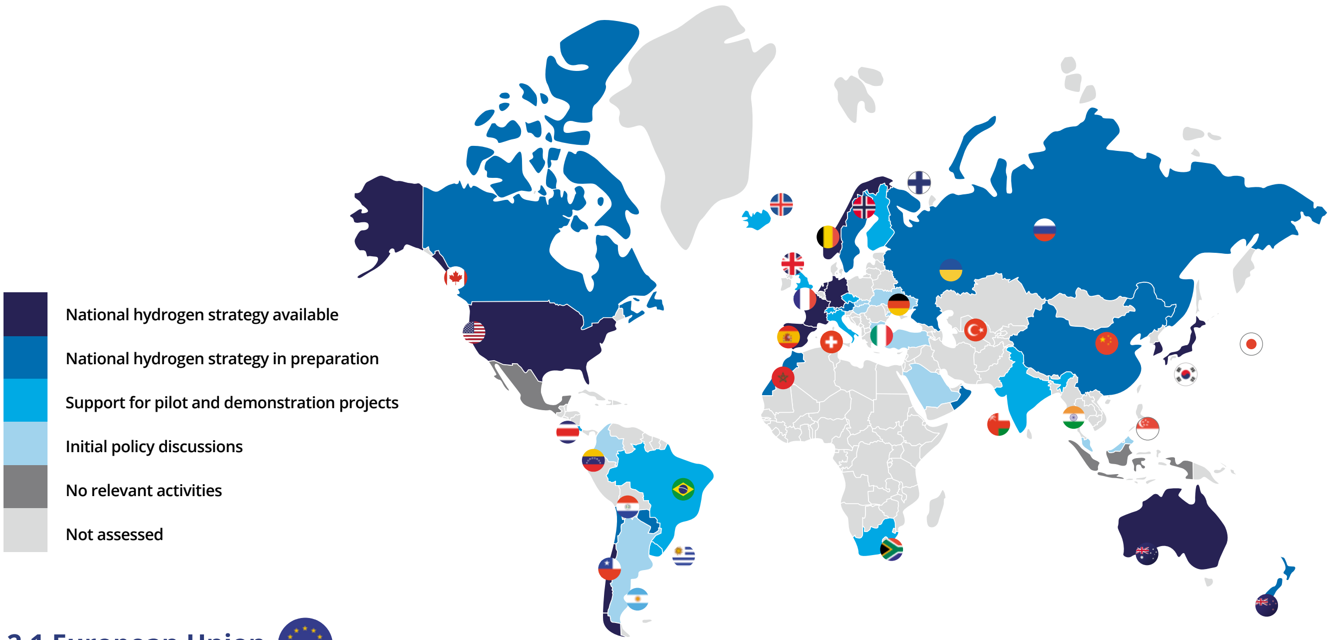
2. International background of hydrogen as a decarbonization vehicle

During the last 5 years, the interest in hydrogen technologies has grown exponentially. In September 2020, 19 countries in the World already had a roadmap or strategy for developing green hydrogen. Some of them include international cooperation plans for the future creation of global hydrogen markets.

Other countries are preparing roadmaps while promoting pilot projects to generate technical capacity and establish the market.

Until a few years ago, only the European Union, Japan, and the United States had plans for hydrogen; however, Latin America is now taking a significant role today. Chile is the leading country in the region with pilot projects in development, and a strategy under development (to be published in late 2020). Other states like Costa Rica, Colombia, Uruguay, and Argentina are also taking action and preparing green hydrogen developments.

Figure 2-1. Countries developing hydrogen policies or pilot projects. Adapted from (WEC, 2020)



2.1 European Union

The European Union has been the undisputed world leader in the promotion and development of Hydrogen technologies.

In 2008, the European Commission founded the Fuel Cell and Hydrogen Joint Undertaking (FCH-JU), a public-private partnership for the development of hydrogen in the EU. Since then, the FCH-JU has invested more than 2 billion euros in multiple projects.

Over the past 12 years, multiple policies have been issued from the European Commission and country's governments. The two most relevant so far are the European Green Deal (2019) and the European Hydrogen Strategy (2020).

The European Gren Deal is a framework document that provides an action plan to promote sustainable development and adopt a circular economy in Europe to mitigate climate change. Within this document, hydrogen is identified as an essential vector of transition and integration of multiple sectors. The European Hydrogen Strategy provides an action plan for H_2 in all the applications described in section 1 of this document.

An important example of the EU's commitment to adopting green hydrogen is the creation of CertifHy, the first guarantee of origin scheme for green and low-carbon hydrogen in the world.

The objectives of CertifHy are to:

Comply with decarbonization goals	Create a market pull for "Premium Hydrogen"
Improve the business cases of green hydrogen production	Empower the customers and allow them to make information -based decisions

Figure 2-2. CertifHy, the first guarantee of origin scheme for green hydrogen (Hinicio, 2018)

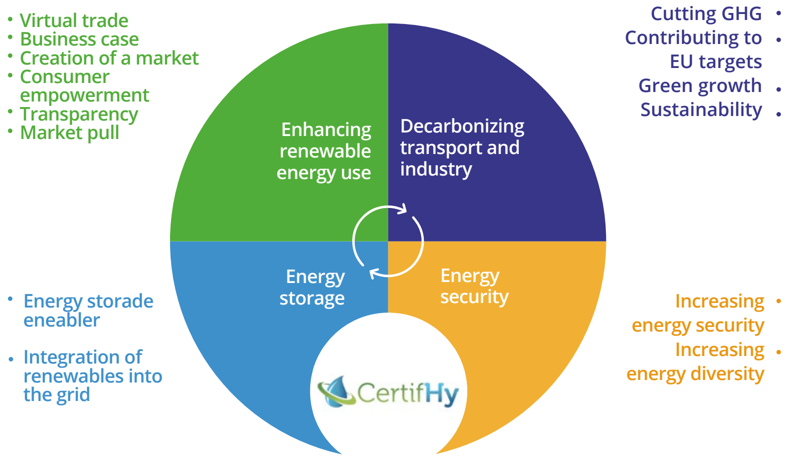


Table 3. Summary of incentives for hydrogen in the European Union

Sector	Policy Type	Policy name and details	Details
Transport	Credits	Directive (EU) 2015/652 (2016)	Establish the methods for calculating GHG intensity of fuels and efficiency factor of FC power trains
Transport	Mandate	Directive (EU)2015/1513 (2015)	Definition and guidelines of hydrogen as renewable gaseous transport fuel of non-biological origin
Power Generation	Regulation	Commission Regulation (EU)2017/2195 (2017)	Establish a guideline on electricity balancing, including hydrogen technologies as an option for grid integration
Cross-sectorial	Strategy	European Green Deal (2019)	The European Green Deal provides an action plan to boost the efficient use of resources by moving to a circular economy, restore biodiversity and cut pollution. Hydrogen is described as a key instrument for meeting climate neutral and secure energy objectives.
Cross-sectorial	Strategy	European Hydrogen Strategy (2020)	The EU Hydrogen Strategy gives a boost to clean hydrogen production in Europe and promote the use as a feedstock, a fuel or an energy carrier and storage as well as many possible applications which would reduce greenhouse gas emissions across industry, transport, power and buildings sectors. The Commission's economic recovery plan 'Next Generation EU' highlights hydrogen as an investment priority

According to the roadmap for hydrogen deployment in Europe, hydrogen could provide up to 24% of total energy demand, or up to 2,250 TWH of energy in the EU by 2050. This projected deployment of hydrogen would create an estimated € 130 billion industry for hydrogen and its associated equipment for EU companies in 2030, reaching € 820 billion by 2050.

The European Commission has created an informal group of experts, made up of representatives of the ministries in charge of energy policy in the EU Member States. This group of experts, called the Hydrogen Energy Network (HyENet), aims to support national authorities in charge of energy policy to develop the opportunities that hydrogen offers as an energy carrier.

In Europe, another important actor is Hydrogen Europe, an association that promotes hydrogen as the enabler of a zero-emission society and has over 120 industry members, comprised of companies of various sizes.

Figure 2-3. European hydrogen participation by 2050 (FCH-JU, 2019)

2.2 Germany

Germany has shown remarkable leadership as an individual nation developing and financing H_2 projects within its borders. It has also carried out many collaborative projects with other countries.

- Residential sector: development of Combined-Heat-Power (CHP) pilot projects. More than 5,000 installed with capacities from 50 to 60 kW.
- Transportation sector: with> 6 00 FCEV circulating,> 15 passenger buses, and> 75 hydrogen supply stations. Germany ranks 4th in the World for H_2 refuelling infrastructure.
- Industrial sector: with a consumption of 15 billion Nm3 / year of hydrogen: Germany has plans to decarbonize its industrial sector with the help of hydrogen.

Germany has plans for hydrogen adoption focused on: mobility, industry, residential, power generation and power-to-x projects. Some highlight for these sectors includes:

- Electricity generation: German companies like Siemens develop turbines that can use H_2 to produce electricity. Current developments make it possible to feed turbines with up to 60% hydrogen.
- Backup power generation sector: Germany has more than 700 fuel cell systems such as UPS or its digital radio network's back-up.
- Power-to-X: During 2019, more than 50 power-to-gas plants with 55 MW capacity were planned. The first project with a 10 MW capacity will start operation by the end of 2020. The first 100 MW system was announced by the operator Tennet. It will harness the electrical potential of northern Germany to produce hydrogen, mainly from wind power.

Table 4. Summary of incentives for hydrogen in Germany

Sector	Policy Type	Policy name and details	Details
Cross-sectorial	Strategy	Growth, structural change and employ-ment	Green hydrogen and power-to-gas is mentioned in one of the key recommendations in the context of creating new values chains for innovative technologies for regions affected by the phase-out of coal. The report also lists concrete measures and projects in the different regions, several linked to hydrogen.

Sector	Policy Type	Policy name and details	Details
Transport	Financial incentive	Electric cars financial support	Provides a grant of 4,000 EUR. For hybrid cars, it amounts to 3,000 EUR. Rewards are only for cars with a list price of maximum 60,000 EUR (base model). The promotion lasts for a maximum total of 400,000 cars. This promotion ends in 2020.
Transport	Financial incentive & targets	NIP II call 2018	H_2 refueling stations targets: 100 by 2020, 400 by 2025. Subsidy for construction/installation for publicly accessible stations for road transport.
Transport	Financial incentive & targets	The National Innova-tion Programme	By 2021, there will be 14 trains operating in Lower-Sax-ony. The NIP provided funding support for the development and deployment of the Alstom trains.
Cross-sectorial	Strategy	Germany's National Hydrogen Strategy	It is a document that expresses the interest of Germany to be a leader in hydrogen technologies. Identify actors and shape a strategy to achieve the vision of the country through 38 measures in 8 development sectors.

During the 2010s a development ecosystem for hydrogen was created in Germany. In 2020, it reached a significant milestone with the issue of Germany's National Hydrogen Strategy. This document was published together with an investment announcement of 9 billion Euro. 7 billion runs for hydrogen develop-ment in Germany, and 2 billion for international cooperation to help other nations develop capacities.

Germany's national hydrogen strategy was created by the country's Energy Ministry and establishes Germa-ny's vision as a leading country in hydrogen technolo-gy. The Strategy recognizes the need for the country to import hydrogen, and proposes actions for cooper-ation with other nations that could help meet German hydrogen needs.

Figure 2-4. Hydrogen mobility in Germany

The strategy on a nutshell

Generalities

- Published by the Bundesministerium für Wirtschaft und Energie (BMWi) on 10 june 2020.
- Germany expects to become a global leader in hydrogen technologies (and secure the market for internationally reputed industry).
- Green hydrogen is considered the only sustainable solution in the long term. Low carbon hydrogen is only to be used on a "Transitional basis".
- Plants to ramp up hydrogene production capacity to 5 GW by 2030 and 10 GW by 2040.

Aims and ambitious

- Assume global responsability.
- Make hydrogen competitive.
- Develop a "home market" for hydrogen technologies in Germany and pave the way for imports.
- Make hydrogen as a raw material for industry sustainable.
- Enhance the transport and distribution infrastructure
- Support research and train qualified personnel
- Establish international hydrogen markets and cooperation

Funds for hydrogen

- The coalition Committee´s future package of 3 june 2020 approved:
  - 7 billion euros to be made available for the market tramp-up of hydrogen technologies in Germany
  - 2 Billion euros for international partnerships

2.3 Japan

Japan is possibly the most enthusiastic country in the adoption of hydrogen and its applications. Like Germany, Japan recognizes that its production capacities will be limited, so they are dedicating a great deal of effort to become a leading technology producer and generate an action plan to import H_2 from different countries of the world to feed their equipment.

Since 2017, Japan has a hydrogen strategy, which is one of the most ambitious in the world, and establishes the greatest amount of quantitative goals for the demand for hydrogen and for the adoption of vehicles, CHP systems, and other technologies.

Towards 2030, Japan plans to develop a commercial hydrogen supply chain for 300 thousand tons of hydrogen, at 3 USD / Kg H_2 or less. With regard to mobility, its goal is the installation of 900 hydrogen recharging stations to supply 800,000 vehicles, 1,200 buses and more than 10,000 forklifts. Towards 2050 the goals become even more ambitious, seeking 2 USD / kg H_2 or less and a total replacement of conventional internal combustion mobility by electric mobility with high participation rates of FCEVs.

Table 5. Summary of incentives for hydrogen in Japan

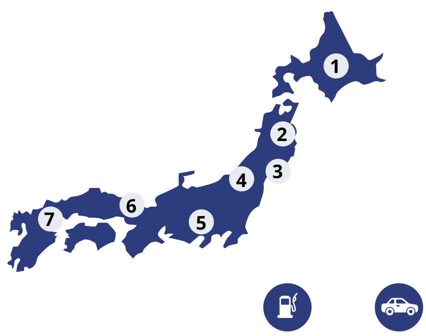
Sector	Policy Type	Policy name and details	Details
Production	Targets + Financial incentive	Basic Hydrogen Strategy (2017)	Procure 300,000 tons of hydrogen/year by 2030. Reduce the cost of hydrogen to JPY30/Nm³(by 2030), JPY 20/Nm³ (in future). Subsidy for R&D, demonstration
Transport	Targets + Financial incentive	Basic Hydrogen Strategy (2017)	Target of 40,000 FCEVs by 2020, to 200,000 units by 2025, and to 800,000 units by 2030. Subsidy for purchase.
Buildings	Targets + Financial incentive	Basic Hydrogen Strategy (2017)	Residential Fuel Cell (micro-CHP: Ene Farm) 5.3 million units (in stock) by 2030.
Power generation	Financial incentive	(national government initiative)	Japan aims to commercialize hydrogen power generation as well as international hydrogen supply chains and cut the unit hydrogen power generation cost to 17 yen/kWh (0.15 USD/kWh) around 2030. Subsidy for R&D, demonstration.

Japan aims to have a CO2-free hydrogen supply system by 2040. This CO2-free hydrogen is planned to come primarily from lignite combined with carbon capture storage (CCS) and renewable energy.

There are government incentives given not only to final consumers (FCEV, residential FC), but also to technology developers. This has resulted in a rapid reduction in costs associated with the hydrogen supply chain in Japan, for example, the world's most successful fuel cell marketing program. ENE-FARM has supported the deployment of more than 120,000 residential fuel cell units (2015).

Some of the largest companies offering products and services for the hydrogen economy are Toyota, Honda, Toshiba, Panasonic, Denso, Fuji, Hitachi and Mitsubishi.

Figure 2-5. Japan hydrogen mobility status (Hinicio, 2020)



1. Hokkaido	1	16
2. Tohoku	3	44
3. Kanto	40	1.033
4. Chubu	25	1.021
5. Kansai	12	243
6. Chugoku / Shikoku	8	92
7. Kyushu	11	131

2.4 United States (California)

California has distinguished itself as a state of technological development and a deep concern for the environment. No surprisingly it is the United States' hydrogen development pole.

California has more than 480 stationary fuel cell systems installed with more than 210 MW of generation capacity. However, it has focused its efforts on the mobility sector more than for any other hydrogen application. California is the region of the world with the highest amount of fuel cell vehicles per million people. There are already 42 Hydrogen Refuelling Stations (HRS) installed in 2020 and more than 8,600 FCEV on California's roads. An average demand of approximately 9 tons of hydrogen per day was expected in 2020, for the transport sector alone.

Californian commitment to green hydrogen established that all HRS must use at least 33% renewable hydrogen by 2020. The state has provided several incentives for green hydrogen to achieve such ambitious plans.

Table 6. Summary of incentives for hydrogen in the United States

FCEV	H_2 Projects
California Clean Vehicle Rebate Project Buyers or lesseers of FCEV, BEV, PHEV y ZEM ■ Refunds of up to 5,000 USD for purchase or rental	**Low Carbon Fuel Standard (California Air Resources Board)** California Fuel Suppliers ■ Compliance credits for suppliers, based on their fuel efficiency. Credits are monetized by buying and selling in an active Market.
CAV (Clean Air Vehicle) Decal ZEV users, including FCEVs ■ Authorizes the use of lanes for high occupancy vehicles to single occupant vehicles.	**Renewable Hydrogen Refinery Credit (pilot program)** Refineries using green hydrogen instead of gray hydrogen ■ Compliance credits for suppliers, based on the amount of carbon in the hydrogen they consume. Monetizable credits through purchase and sale.
Free Parking at participating hotels ZEVs users ■ Participating hotels in CA offer free parking and / or free charge (EV and PHEV) at their facilities	**Renewable Fuel Standard** Fuel suppliers nationwide (biofuels and renewable fuels) ■ Credit incomes for the supply and sale of renewable fuels.
Free Parking at participating hotels Buyers or lessees (individual or companies) of clean vehicles in San Joaquin Valley, CA ■ Refunds of up to 3,000 USD for the purchase or rental of FCEV	
Senate Bill 1505 Mandatory use of green hydrogen in HRS, regardless of support or subsidies. ■ 33.3% of hydrogen must come from renewable sources	

California has the goal of reaching 200 hydrogen stations by 2025; and a thousand stations and a million FCEV by 2030. Current projections for the state, provided by FCEV manufacturers predict 26,900 FCEV in 2022 and 48,000 FCEV in 2025.

California's hydrogen supply network is expected to continue to meet the 33% minimum renewable requirement, with potential for further renewable implementation in the future. The Low Carbon Fuel Standard for Hydrogen Refueling Infrastructure credit program requires the implementation of 40% renewable hydrogen.

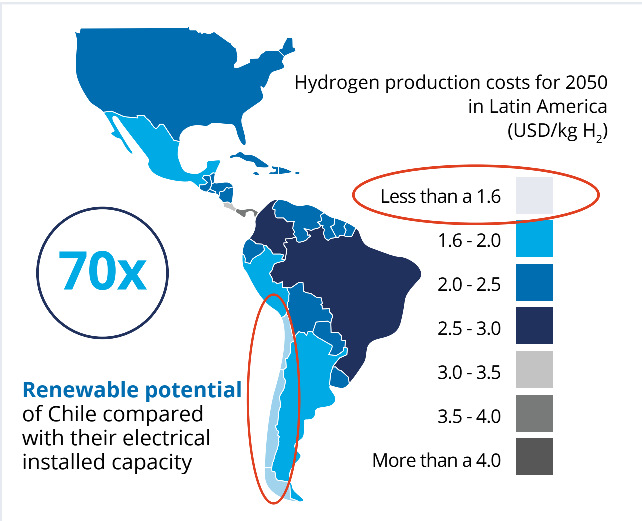
Figure 2-6. Hydrogen mobility status in California (CaFCP, 2020)

2.5 Chile

Chile is the Latin American leader in hydrogen policy and project development. Since 2018, the Ministry of Energy has been very active in the organization of events for knowledge transfer, boosting the development of regulation and legislation, carrying out studies, and promoting the development of pilot projects.

Driven by its renewable energy potential, Chile has developed multiple studies to quantify its potential, finding that by 2050 its green hydrogen production costs could be among the lowest in the World with less than 1.6 USD / kg.

Figure 2-7. Chilean green hydrogen potential (Ministry of Energy, Chile, 2020)



Chile has an energy policy since 2015 with ambitious decarbonization goals, including a goal for 70% renewable production by 2050. It has published a roadmap to achieve its goals, which support the generation of the Chilean Hydrogen Strategy, published in November 2020.

One of Chile's most notable goals is to be an exporter of hydrogen to the United States, Asia, and Europe. Some of its most emblematic green hydrogen projects include the green hydrogen plant for mining explosives leaded by Engie and Enaex, or the Hydra project, led by Engie and MINAE3 for the development of fuel cell mining trucks.

Chile, a country with an important mining industry, sees hydrogen as the opportunity to decarbonize one of the most energy-demanding industries.

Figure 2-8. Chilean context for the Hydrogen Strategy Development

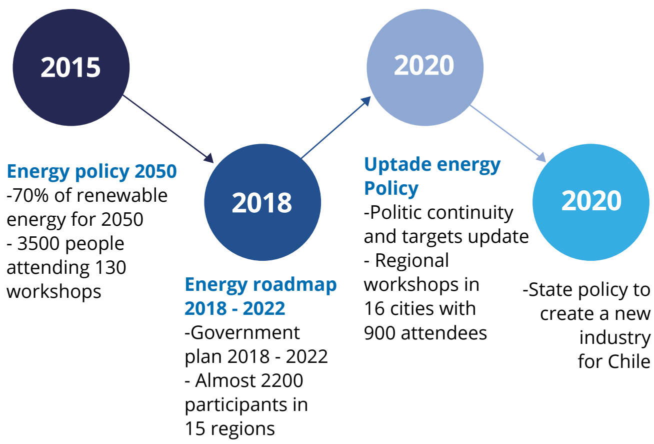


Table 7. Green hydrogen projects under development in Chile

	Engie and Enaex signed an agreement in 2019 to evaluate feasibility of a Power to Ammonia plant in Mejillones. 1000 MW photovoltaic plant,hydrogen pan (800MW electrolyser, 62,000 ton H_2 / year), 350,000 M ton / year NH_3 ammonia plant. First phase of the project is expected to start operations before 2025.	Enaex, ENGIE
	Synthetic fuel production pilot project in Magallanes. Official launch on October 2 (www.hif.cl) Involves ENAP, ENEL, Siemens and Andes Mining and Energy (AME)	HIF
	Pilot project for a dual-combustion mining truck under a consortium led by ALSET, with a budget of a CLP 12,000 MM (4,000 MM financed by Corfo). The prototype truck is expected operations on site by 2021.	Anglo American, CORFO, ALSET
	Hydra project (2020): Project to design and manufacture a powertrain prototype for mining truck (CAEX) FC to be tested in laboratory conditions that mimic real vehicle operation.	mining3, ENGIE, CORFO, CSIRO
	Walmart is implementing fleets of hydrogen forklifts in 3 of their logistics centers in Chile. The first fleet is expected to go into operation in 2021 with 180-200 vehicles. Project developed by Plug Power ang ENGIE.	Walmart Chile
	Green hydrogen pilot (PV plant), with a production capacity of 2 kg/day to operate a forklift crane. Developed by Tratebel and Engie.	Anglo American

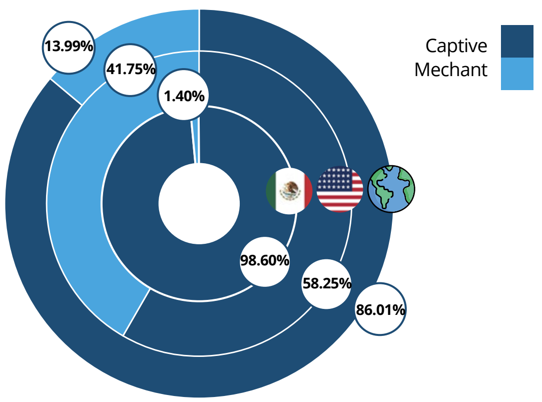
3. Current hydrogen situation in Mexico

3.1 Hydrogen market in Mexico

In Mexico, there is already a hydrogen market driven by refining and petrochemical activity. Globally 86% of hydrogen is captive, and 14% is merchant. In Mexico 98. 6% of hydrogen is captive, and just 1.4% is merchant.

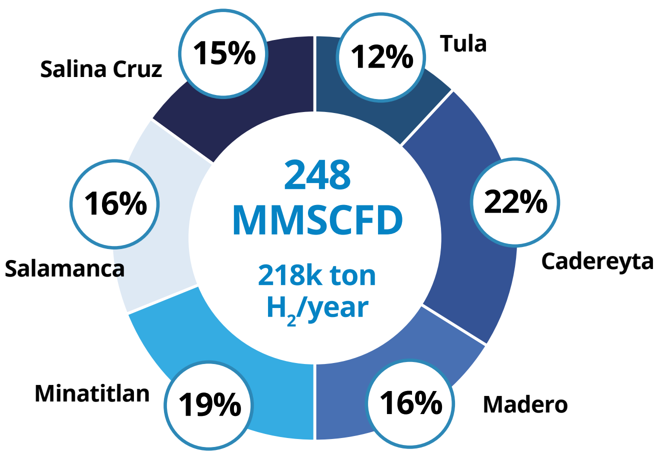
The captive hydrogen in Mexico is being produced by PEMEX's, with approximately 218 kilo tons of H_2 for its refining and ammonia production processes. PEMEX hydrogen production is distributed through its 6 refineries. 42% is obtained from steam reforming plants and 58% from naphtha reforming (intermediate product of crude oil refining). Less than 10% of Pemex's hydrogen is destined for ammonia production. During 2019 Pemex's ammonia production plants did not operate.

Figure 3-1. Comparison of Merchant - Captive Hydrogen distribution



The production of merchant hydrogen in Mexico is approximately 2,650 tons per year, virtually all in the hands of 3 companies: Air Liquide, Linde, and Cryo-Infra.

Figure 3-2. Pemex hydrogen production capacity



There is a small international hydrogen trade balance in Mexico, driven by private gas companies. Out of the 734 tons of hydrogen per year in the international Mexican market, 40% represent exports mainly to Central America and the Caribbean, and 60% are imports from the United States. Mexican imports of hydrogen have to do with down times in gas plants or unforeseen requests by customers.

Figure 3-3. International hydrogen market in Mexico (Ministry of Economy, 2019)

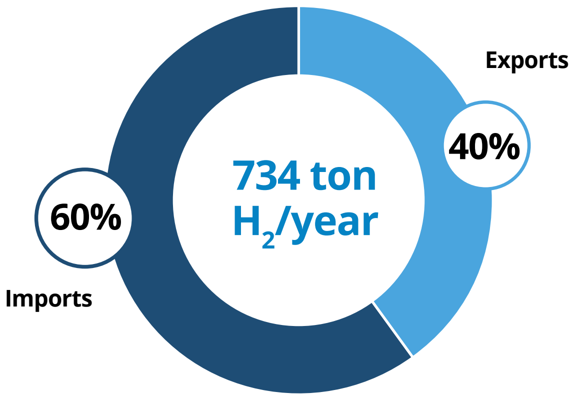
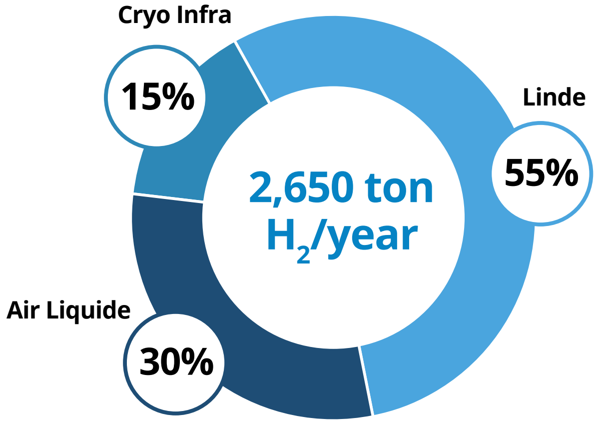
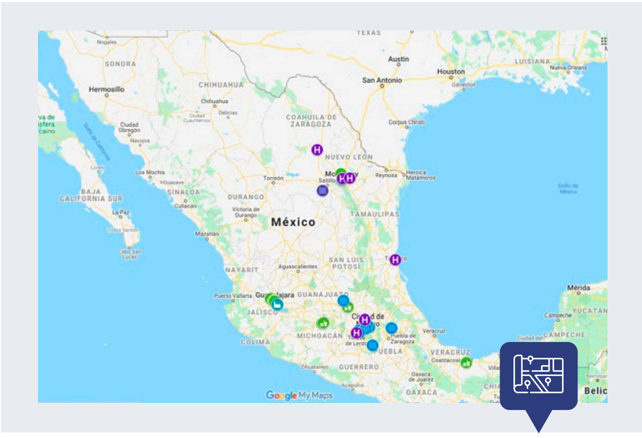


Figure 3-4. Industrial gas companies production in Mexico (Fortuna, 2020)



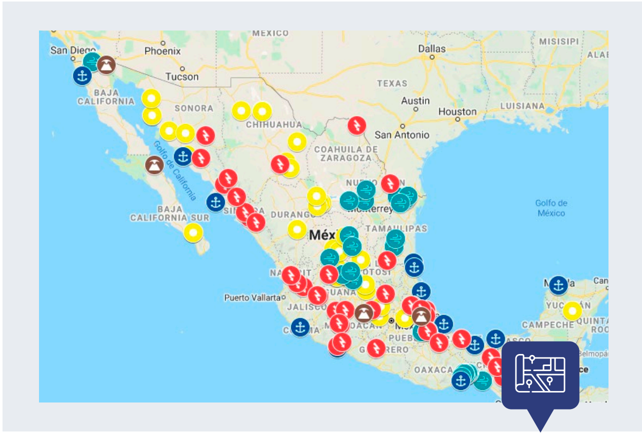
Currently, both captive and merchant hydrogen production are located in the country's central area, nearby industrial sites (companies producing steel, glass, food fats, etc.).

Figure 3-5. Main hydrogen producers and consumers in Mexico



Click for watch / Interactive map

Figure 3-7. Renewable Energy infrastructure in Mexico



Click for watch / Interactive map

3.2 Potential hydrogen consumers and renewable energy infrastructure

Renewable energy infrastructure in Mexico matches the location of potential future hydrogen consumers, which is homogeneously distributed throughout the country. Some of the potential hydrogen consumers identified are steel production companies, extraction mines with the highest production at the national level, and the electrical networks of the Baja California peninsula and Yucatán. An example of such match between supply and demand can be seen in the municipality of Mulegé, which has an isolated electrical system, copper mines, significant renewable potential, and a nearby geothermal generation region.

Figure 3-6. Potential hydrogen consumers in Mexico

Click for watch / Interactive map

3.3 Academic production

In Mexico, there are many researchers in different universities and research centres developing hydrogen technologies. There were developments and prototypes identified for most of the hydrogen value chain from production to consumer applications. Through the Mexican Hydrogen Society (SMH), more than 10 research groups were identified.

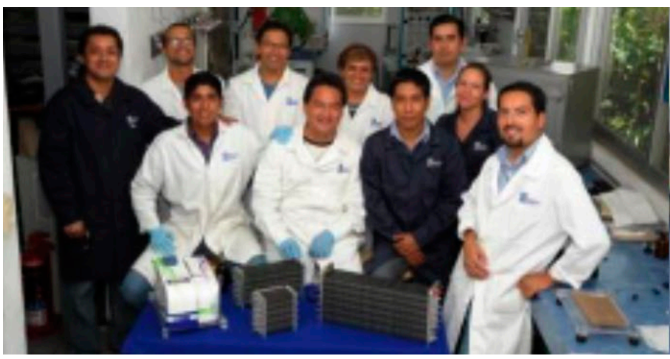
Each year between 100 and 130 academic papers on the subject are presented at the SMH's international congress. Some of the leading groups in hydrogen research belong to the Polytechnic National Institute (IPN), the Research and advances Studies Centre (CINVESTAV), the National Institute of Electricity and Clean Energy (INEEL), the Autonomous National University of Mexico (UNAM), the Electrochemistry Research and Development Centre (CIDETEQ), and the Scientific Research Centre of Yucatan (CICY).

Below we present a summary of these research groups' work around hydrogen.

Table 8. Academic production on hydrogen in the INEEL

Production	Conditioning	Storage	Transport	Re-conditioning	Consumption systems
X	X			X	X

Department	Renewable Energy	**People on the team**	Ulises Cano-Castillo, Félix Loyola-Morales, J. Roberto Flores-Hernández, Lorena Albarrán-Sánchez, Tatiana Romero-Castañón, Manuel López-Pérez
Research description	RD&T group working on H_2 technologies since the year 2000. Developed its own PEMFC technology (MEA's, stacks and Systems) and PE Electrolysis (MEA's and small stacks). We have evolved as to develop projects for E-Mobility using H_2 technologies and other Electrochemical Storage Systems for all-electric traction transport. The institution integrated one of the first Green H_2 (solar) systems already back in 2003.		
Years on the research line	20 years	**Financing sources**	Government and private industry projects
Featured projects	3-4 representative projects and their description (See next page)		
Featured scientific or technological productions	**Green Solar-hydrogen production.** In 2003 INEEL designed a Photovoltaics system to take advantage of surplus Energyto power an electrolyser of 1m3/hr capacity, under specifically peak power PV conditions. The PV System was directly connected to the electrolyser avoiding expensive power electronics **Hydrogen Fuel Cell hybrid all-electric Utility Vehicle** This Project gathered 4 Universities plus INEEL to develop from scratch, a hybrid alle electric utility vehicle. The power plant was integrated by a 3kW hydrogen PEM fuel cell developed by INEEL, a vehicle designed and manufactured by CIMAITESM and power electronics from CENIDET. The Project developed a utility vehicle with an electric traction system based on our PEMFC system, lithium-ion batteries and Supercapacitors. The focus was on Energy efficiency taking advantage of hybrid configurations and using regenerative breaking. The vehicle, its control, some power electronics and the PEMFC power plant (INEEL's) were developed in Mexico by participants **PEMFC-based Range Extender for a GRT vehicle.** The Project explored and proposed a range extender based on a fuel cell for a Group Rapid Transport electric vehicle developed by a Mexican Company. The proposed configuration added the possibility of delivering power from the PEMFC as well as from the batteries, extending the functionality of the PEMFC power plant from range extender to a hybrid electric configuration giving flexibility to the vehicle's operation.		
Number of professionals formed on the research group	The INEEL receives many students to fulfill their experimental work on technologies that we are experts on. Most of our projects do not require to perform thesis work as we are open for all levels of education, from high school to postgrads. Approximately we have received more than 100 students since the founding of our group. Some of our students are now part of international organizations working on hydrogen related technologies in Canada, USA, UK, Switzerland and Germany		



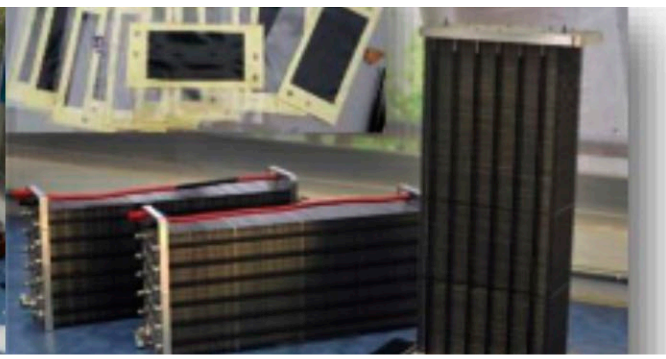


Table 9. Academic production on hydrogen in the IPN

Production	Conditioning	Storage	Transport	Re-conditioning	Consumption systems
X	X				

Department	Instituto Politécnico Nacional-ESIQIE	**People on the team**	10 Permanent researchers
Research description	Development of hydrogen technologies, management of renewable energy (solar, wind, ocean) and storage systems. Synthesis and characterization of electrocatalysts and preparation of electrode membrane assemblies (MEA) for fuel cell and electrolyser PEM. Development of alkaline reactors for dual combustion hydrogen-fossil fuels .		
Years on the research line	15 years to consolidated group	**Financing sources**	IPN Internal projects, Government institutions (CONACYT, SECTEI)
Featured projects	Development of sustainable house solar-hydrogen with energy management. Hybrid Hydrogen Integral Systems. Design of Alkaline Electrolyser for Integration in Diesel or gasoline Engines to Reduce Pollutants Emission. Innovation and manufacture of burners for hydrogen combustion and save natural gas in furnaces. Kinetic study of oxygen reduction reaction and PEM fuel cell performance.		
Featured scientific or technological productions	**Paper JCR:** 50. **Copyrights:** 2 patents assigned; 2 registered trademarks and 3 industrial designs assigned. **Books:** 3 on hydrogen technologies. Editor of 2 books on hydrogen technologies.		
Number of professionals formed on the research group	**Human Resources:** 37 undergraduate, 20 master and 4 doctoral theses completed, 2 prizes to better thesis of degree and 5 of master. One post doctorate has worked in the group. **In process** (2020): 8 doctorates, 8 master and 6 undergraduate students.		

Table 10. Academic production on hydrogen in the CINVESTAV

Production	Conditioning	Storage	Transport	Re-conditioning	Consumption systems
X	X				

Department	**Chemistry Department**	**People on the team**	18 permanent researchers
Research description	Electrocatalysis and fuel cells: Synthesis and characterization of catalysts with low Pt content for H_2-PEMFCs applications. Design and manufactute of hibrid transport vith H_2-PEMFCs and rechargeable batteries		
Years on the research line	**25 years**	**Financing sources**	CONACyT (national budget)
Featured projects	Naya- first hybrid H_2-PEMFCs prototype with a 350W PEMFC and H_2 content in PET bottles. Sicarú in first and second version prototype with 50kg H_2, 500W PEMFCs and autonomy of H_2.		
Featured scientific or technological productions	i) Mexican contributions for the improvement of electrocatalytic properties for the oxygen reduction reaction in PEM fuel cells. Int. J. Hydrogen Energy, 44(2019) 12477-12491. ii). Chapter 6 Development and applications of portable systems base on conventional PEM fuel cells, in Portrable hydrogen energy systems: Fuel cell and storage fundamentals and applications. Paloma Ferreira-Aparicio and Antonio M. Chaparro Eds. Academic Press. Pp 91-106, 2018. ISBN 978-0-12-813128-2. More than 170 scientific articles		
Number of professionals formed on the research group	19 PhD in H_2- energy applications: Electrocatalysis and fuel cells		

Tabla 11. Academic production on hydrogen in the Materials Institute – UNAM

Production	Conditioning	Storage	Transport	Re-conditioning	Consumption systems
		X			

Department	**Materials Research Institute-Morelia Unit**	**People on the team**	2
Research description	Development of materials for hydrogen storage, Development of hydrogen storage systems.		
Years on the research line	**2 Years**	**Financing sources**	CONACyT, SENER
Featured projects	-NaAlH4 from recycled Al cans/NaH (~250g material tank) -Development of apparatus for hydrogen storage characterization -Development of hydrogen storage tanks filled with metal hydrides and Na-alanate		
Featured scientific or technological productions	-Alanates, a Comprehensive Review. Materials 2019, 12, 2724; doi:10.3390/ma12172724 -From the can to the tank: $NaAlH_4$ from recycled aluminum. Int. J. Hydrogen Energy, 2019, 44, 20183-20190. DOI: /10.1016/j.ijhydene.2019.06.033. -Low-cost Sieverts-type apparatus for the study of hydriding/dehydriding reactions. HardwareX, 2018, 4, e00036-14. DOI: 10.1016/j.ohx.2018.e00036. -Solicitud de patente: Producción de Na3AlH6 y $NaAlH_4$ como materiales almacenadores de hidrógeno a partir de NaH, Al reciclado proveniente de latas de bebidas. En trámite, MX/a/2019/002891, 13-Mar-19.		
Number of professionals formed on the research group	Bachelors: 7; Master: 1; , Doctorate: 2 (in progress)		

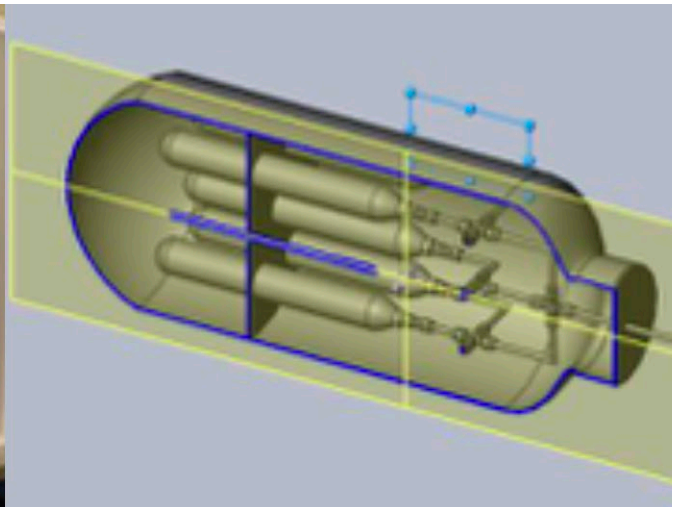


Table 12. Academic production on hydrogen in the Engineering Institute UNAM

Production	Conditioning	Storage	Transport	Re-conditioning	Consumption systems
X					

Department	**Academic Unit, Juriquilla Queretaro**	**People on the team**	12 permanent researchers
Research description	Focused on biological processes for wastewater and organic fraction of solid waste treatment. Gaseous biofuel generation (hydrogen, methane) and value added products.		
Years on the research line	**25 years**	**Financing sources**	CONACYT, European Union, UNAM, SENER, Private companies
Featured projects	Gaseous biofuel cluster. Project financed by Fondo de Sustentabilidad Energética Biohydrogen production through dark fermentation and photofermentation Biohydrogen production through bioelectrochemical systems		
Featured scientific or technological productions	About 250 international papers in high ranked scientific journals (ISI-JCR), 5 patents and more than 500 diverse publications		
Number of professionals formed on the research group	About 50 bachelors, 100 master, 25 doctorate and 15 post doctorate have gotten their grade within the group		

Table 13. Academic production on hydrogen in the Centre of Scientific Research of Yucatan (CICY)

Production	Conditioning	Storage	Transport	Re-conditioning	Consumption systems
X					X

Department	**Renewable Energy Department, Yucatan Center For Scientific Research (CICY)**	**People on the team**	10 permanent researchers
Research description	Bionenergy, hybrid systems of energy, electrochemical technologies for energy		
Years on the research line	**10 years**	**Financing sources**	Government calls, industry
Featured projects	Fuel cells with novel architectures for the supply of air and fuel without the need for auxiliary services. Hydrogen production with ion exchange membrane electrolysis systems Numerical Simulation to Determine the Effect of Topological Entropy on the Effective Transport Coefficient of Unidirectional Composites Seaweed derived KOH activated biocarbon for electrocatalytic oxygen reduction and supercapacitor applications		
Featured scientific or technological productions	209 scientific papers (JCR), 6 patents		
Number of professionals formed on the research group	71 master in science, 20 PhD		

3.4 Mexican Regulatory Framework for Hydrogen

The Mexican legal framework is composed by the Political Constitution of the Mexican United States, thirteen federal laws, 7 regulations, 7 guidelines, an electrical market bases, 4 provisions and additional criteria for the listed documents.

Within this regulatory framework, hydrogen is mentioned explicitly in a few documents, as follows:

Electrical Industry Law

Last update:	Hydrogen is mentioned in:	Mention says:
03-Mar-2021	- Article 3 - Numeral XXII – Clean Energy - Option (g)	(Is considered as a clean energy): The energy generated by the use of hydrogen through its combustion or its use in fuel cells, as long as the minimum efficiency established by the CRE and the emission criteria established by the Ministry of Environment and Natural Resources in its lifecycle is met

Transition Strategy to Promote the Use of Cleaner Technologies and Fuels

Last update:	Hydrogen is mentioned in:	Mention says:
07-Feb-2020	- Bioenergy - 6.1.2 Clean Energy - 6.1 Strategy Action Paths - 6. Clean energy generation goals	(Table 19): Main efficient technologies for the use of bioenergy: Biomass gasification (Low TRL and null adoption in Mexico)

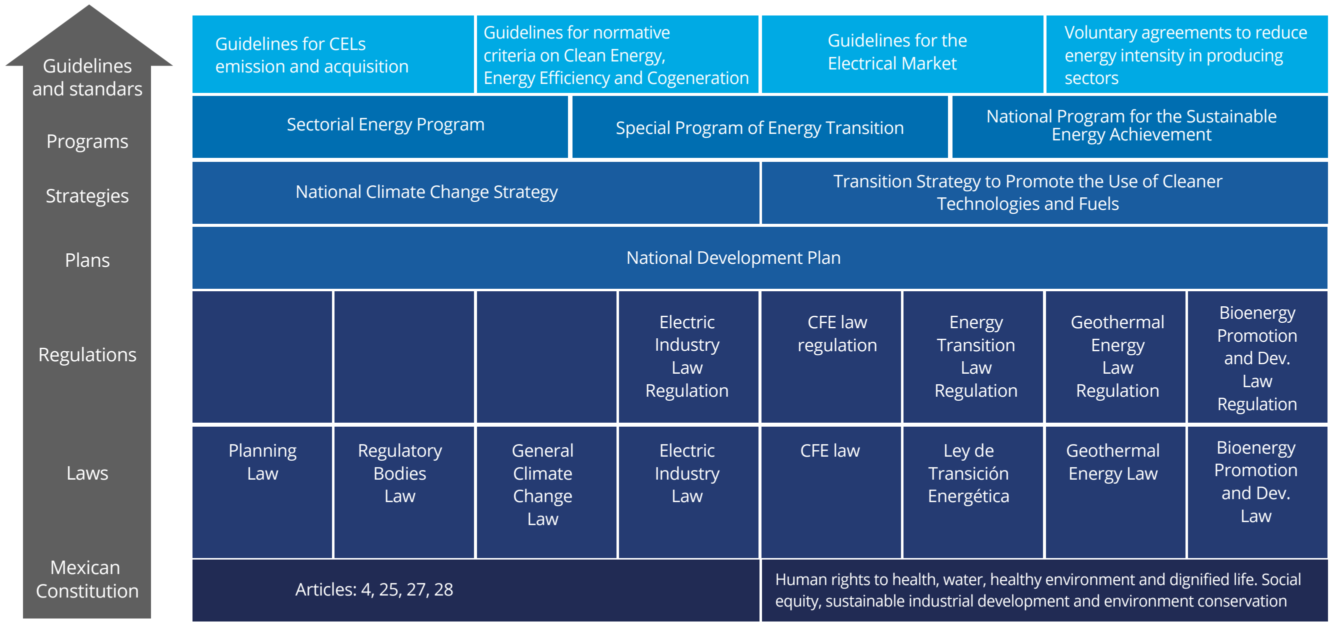
Sectorial Energy Program

Last update:	Hydrogen is mentioned in:	Mention says:
08-Jul-2020	- 6. Strengthen the national energy sector to promote the development - 6.6 Relevance of the priority objective 6	Take advantage, in a sustainable way, of all the energy resources of the Nation ...Also, explore the use of other energy sources like hydrogen.

Guidelines for CELs emission and acquisition

Last update:	Hydrogen is mentioned in:	La mención dice:
21-Ene-2019	- Agreement point 14 - Title 6th - Case IV	Mention says: energy produced by the use of hydrogen through its combustion or its use in fuel cells, as long as the minimum efficiency established by the CRE and the emission criteria established by SEMARNAT in its life cycle are met.

Figure 3-8. Mexican Energy Regulatory Framework (Source: CONUEE with information on Laws and Regulations of Federal Legislation.)



All the mentions to hydrogen in the Mexican regulatory framework identify hydrogen as a possibility for valorising biogas or as an independent energy carrier when hydrogen is obtained as a by-product. Hydrogen can even access the issuance of Clean Energy Certificates; however, there is no formal definition of this gas as an energy molecule. There are not adoption plans or incentives for hydrogen technologies.

Beyond the explicit references to hydrogen within laws and regulations, the Mexican regulatory framework offers possibilities for the production and use of hydrogen in the country. The reference standards and laws for the main stages of the hydrogen value chain are identified below.

- Production: If the production of hydrogen involves the consumption of natural gas (reforming plants), permits must be obtained for its processing, transportation, storage or handling (as applicable) by the Energy Regulatory Commission, whose granting criteria are stipulated. in the Hydrocarbons Law.

  If the hydrogen is to be produced from electrolysis, the necessary permits are those that apply for a regular chemical plant, for example: Environmental Impact Manifestations (General Law of Ecological Balance and Environmental Protection - SEMARNAT), operating permits and registration of activities (Ministry of Economy) and compliance with Official Mexican Standards of the activity, for example, NOM-001-SEDE-2012, Electrical Installations, NOM-002-STPS-2010 Prevention and protection against fires, NOM-005- STPS-1998 Handling, transport and storage of dangerous substances, NOM-020-STPS-2011 Pressure vessels and boilers.

- Conditioning and handling: The conditioning and handling of hydrogen is something that gas companies carry out nowadays in accordance with the occupational safety regulations of Mexico (STPS) and some technical standards of the United States such as ASME B31.12 Standard on Hydrogen Piping and Pipelines or the NFPA 2, Hydrogen Technologies Code. No special permits are required from Mexico's energy regulatory entities for these activities.

- Transport: The land transport of hydrogen is regulated by the “Regulation for the land transportation of hazardous materials and hazardous waste” (SCT), which does not make a specific mention of hydrogen but this is included in the "Class 2, which includes compressed, refrigerated gases, liquefied or dissolved under pressure", division 2.1 " Flammable gases: Substances which at 20 ° C and a normal pressure of 101.3 kPa burn when in a mixture of 13% or less by volume of air "

  Hydrogen transportation by pipelines in Mexico is not currently practiced, but it could depend on permits from the Energy Regulatory Commission and the Ministry of the Environment and Natural Resources (environmental impact analysis and passage permits).

- Use in power generation: The generation of electricity through combustion (turbines) or fuel cells (electrochemical process) is considered by the Electricity Industry Law and its Regulations, as long as the process complies with the technical requirements of the CRE (minimum efficiency shall not be less than 70% of the calorific value of the fuels used in the production of such hydrogen), which is an application of the Guide for the Evaluation of New Technologies and its Application Form (SENER).

  For a power generator, in order to be connected to an electrical grid, the power system should comply with the guidelines of the "Manual for the Interconnection of Power Stations and Connection of Load Centers". In the event that the regulatory authority (CENACE) considers that the equipment has not been sufficiently tested in the field in its country of origin or in Mexico, it could demand performance tests, carried out by authorized laboratories, such as LAPEM, from CFE.

- Use as a chemical: The use of hydrogen as a feedstock is a common practice in Mexico today. Margarine, glass, steel and synthetic resin plants handle and consume hydrogen for their processes. The regulation that must be complied with in this case has already been described in the production, storage and handling and transportation sections. They are technical regulations. There are no specific regulations that control the hydrogen market in Mexico; Until now it has been considered a chemical substance within a free competition market.

- Use in mobility applications: Hydrogen mobility is actually a category of electric mobility. The FCEV is moved by electric motors that are powered by a hydrogen fuel cell, rather than a battery. Considering this, its legal basis is found in the Transition Strategy to Promote the Use of Cleaner Technologies and Fuels, in terms of the Energy Transition Law. This strategy identifies the need to promote the use of hybrid and electric vehicles with efficient technologies, among which FCEVs could be included.

Vehicles in Mexico must be registered with the Public Vehicle Registry (REPUVE). To get the registration it is necessary to comply with some regulations regarding:

- Emissions (NOM-044-SEMARNAT-2017, NOM-167-SEMARNAT-2017, among others, depending on the fuel and type of vehicle) that would not apply in the case of an electric vehicle.
- Safety features: NOM-194-SCFI-2015, Essential safety devices in new vehicles - Safety specifications.
- Homologation: carried out by national or international laboratories certified for this purpose in different directives such as the CE framework for different types of vehicles (cars, buses, trucks, trailers, motorcycles, etc.)

Some actions are necessary for the consideration of green hydrogen energy (without including any incentive) into the Mexican regulatory framework:

- Explicit definition of hydrogen as an energy molecule, and identification of its possible sources and applications. The definition could be included in laws or regulations.
- Define, within the laws or regulations, the capabilities of the State and private companies for the production, transport, storage and consumption of hydrogen as an energy carrier.
- Differentiate responsibilities and compliance requirements for users of green hydrogen for energy purposes or as an industrial raw material
- Include the green hydrogen value chain (and not just some isolated applications) in the Clean Energy Certificates mechanisms, National Electricity Market rules and other technical-legal guidelines
- Define the legal requirements (permits, allowed participants, energy volumes, conditions for the connection, etc) for the coupling of hydrogen production plants to renewable generation plants or to the electricity grid.
- Define the legal requirements (permits, allowed participants, energy volumes, conditions for the connection, etc) for the coupling of Power to Power systems to the National Electric System
- Create technical and safety regulations for plants, systems and equipment across the green hydrogen value chain (electrolysers, fuel cells, plant balance equipment, pipelines, trucks, etc.)

3.5 Commercial efforts

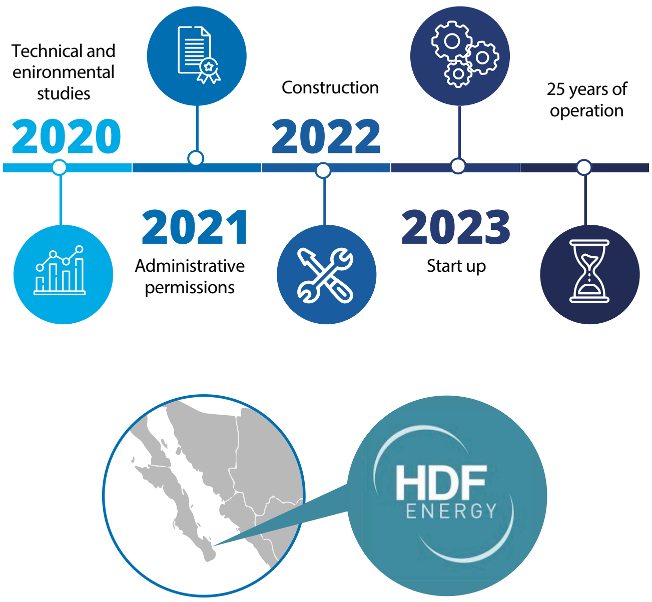
Mexico has offices of many international companies developing green hydrogen projects in Europe, the United States, and other latitudes; nevertheless, practically no efforts have been identified to promote these technologies in Mexico.

We identified two companies with plans for developing H_2 projects in Mexico (both of them are still in the conceptualization stage). Below is a summary of these projects

HDF, Energía los Cabos

- Photovoltaic generation plant coupled to a Power to Power system.
- Power to Power system includes an electrolyser, hydrogen storage tanks and fuel cell to re-electrify stored hydrogen. Lithium batteries are also included to manage and buffer the energy fluctuations.
- Energía Los Cabos will produce 22MW during the day and 6MW during night.
- Annual energy production will be 115 GWh, equivalent to 60,000 people energy consumption.

Figure 3-9. HDF – Energía Los Cabos, Power to Power project



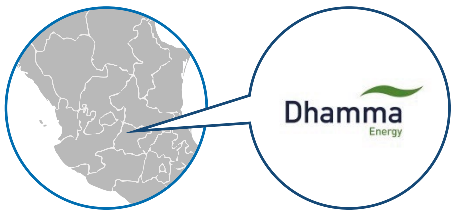
Dhamma Energy

- Development, construction, and operation of a hydrogen production plant using water electrolysis and photovoltaic energy (PV).
- A solar PV plant powers an electrolyser that splits water molecules into hydrogen and oxygen gases.
- Hydrogen off-takers: Electric mobility (Passenger vehicles, buses, ships, trains, etc) and industry (cement, refineries, Steel makers, etc)

Figura 3-10. Dhamma Energy - H_2 Guanajuato - Power to Hydrogen project

Solar PV + H_2 Plant

- Area: **220 ha**
- Solar PV capacity: **120 MWac**
- Electrolysis capacity: **100 MWac**
- Annual hydrogen production: **12.6 k ton H_2**
- GHG emissions reduction: **110,000 tCO_2/year**
- Location: **Guanajuato**
- Off-takers: **mobility and industry**
- Ready to build: **Q2-2022**
- Construction: **2023**




H2


H2
350bar
BUS
VATTENFALL

4. Conclusions and recommendations

4.1 Conclusions on the global context for hydrogen

Hydrogen technologies have been developed since the 1960s when NASA tested hydrogen propulsion. Since then, many H_2 technologies have evolved, reaching the technical maturity necessary to be commercially available today, for example, FCEV.

Hydrogen is not a source of energy; it is a sector integrator and a renewable energy intermittency buffer that provides reliable energy for critical and continuing processes.

As of July 20210, more than 20 countries (which accumulate more than 50% of global GDP*) have published a Roadmap or a Strategy to promote and integrate hydrogen into their energy systems. At the Latin American level, Chile will present its strategy by the end of 2020.

Countries pushing up hydrogen technologies have in common one or more of the following characteristics:

- Ambitious decarbonization plans (political agreement)
- Need for energy independence (applicable to Mexico)
- Need for energy supply diversification (applicable to Mexico)
- Need for grid flexibility while introducing renewables (applicable to Mexico)
- Plans for developing new value chains in the energy sector
- Plans for green economy recovery

Countries with high renewable energy potential, like Chile, Morocco, and Australia, are planning to be huge hydrogen exporters to supply H_2 adopters like Japan, South Korea, or the European Union.

Some hydrogen technologies, like turbines, burners, and cogeneration systems, are still under development. Other technologies like FCEV and electrolysers need to be produced on a mass scale to achieve cost reductions.

Hydrogen value chains are diverse, with multiple production and delivery pathways. The magnitude of hydrogen volumes also varies according to each application, so there is need for case-by-case analysis of use-cases and business models.

Each hydrogen application competes against different conventional technologies, so its economic competitiveness depends on local factors such as location, resource availability, regulations, etc.

The most advanced states in the global hydrogen race are Japan, the EU, Germany, California, and South Korea. They all have in common a deep interest in decarbonize their energy matrix and mitigate climate change effects, a need for energy security, and the interest to create new value chains in the energy sector.

Only green hydrogen would allow a complete decarbonization of the global energy system. However, many countries are also considering a transition based on blue hydrogen to drive down the costs and kick-start the new hydrogen value chains.

Since the decade of 1990s, many strong economies like the European Union, Japan or the United States have financed programs for the development of technologies and demonstration projects. They have paid for a good proportion of the learning curve. Latin American countries entering the business today won't have a learning curve as steep. However, if Latin American countries keep on lagging behind, they will miss the opportunity to develop capabilities, resulting in smaller market share in the future global energy markets.

The Hydrogen Strategy or Roadmap of each country responds to their specific context and national development plans. Nonetheless, common ideas are expressed in most of them:

- Hydrogen is clearly recognized as an essential element of a decarbonized energy system.
- Renewable energy potential guides the decision: being hydrogen exporter, importer or self-sufficient.
- Large industrial partnerships will be essential for production, export and import of hydrogen.
- Current measures are insufficient to catalyze envisaged strong growth.
- Policies should focus on commercialization.
- Public acceptance is key.

4.2 Conclusions on the Mexican context for hydrogen

Mexico already has a market for hydrogen which represents 0.3% of the global market (70 MM ton in 2019). This is all gray hydrogen for now. This hydrogen is provided mainly to/by refineries, but also to chemical and steel production plants.

There is no evidence of green hydrogen production in Mexico yet. For this market to develop, the right policies need to be in place.

Mexico has a well-developed energy infrastructure that could effectively enable green hydrogen developments. Mexico has a number of international seaports, robust power and gas transmission networks, hydropower, PV, wind and other renewable energy plants.

The Mexican Regulatory Framework already considers some energy uses of hydrogen; however, a formal inclusion, definition, and regulation is needed. There is need for a clear differentiation between energy and feedstock uses, as well as for incentives that help drive green hydrogen developments.

There at least a couple of international companies that have seen the potential for green hydrogen developments in Mexico, and that are already conceptualizing their first pilot projects in the country.

The regions with the highest renewable energy potential in Mexico match the location of potential hydrogen consumers. For example, Mulegé Municipality has an important irradiation ratio, copper mines, and an isolated energy grid.

The most significant share of the hydrogen market is captive in the hands of PEMEX. This has some implications:

- There are just a few stakeholders in the hydrogen business, leaving the decision to transition from gray to green hydrogen in the hands of a reduced number of entities.
- The green hydrogen market in Mexico is still to emerge, which could potentially bring opportunities for new entrants.

The leading merchant (gray) hydrogen producers in Mexico (Air Liquide, Linde, and Cryo-Infra/Air Products) are involved in green hydrogen projects worldwide. These companies will naturally enter the green hydrogen in Mexico, once in place.

Mexican universities and research centers have been working on hydrogen technologies since the 1990s. It means Mexico has the technical capacity to leverage for the development of industrial green hydrogen projects. The main activities identified by academia are in the field of scientific research: technology transfer and project development capabilities have to be developed.

4.3 Perception of Mexican Stakeholders

In general, most of the interviewed actors still observe how hydrogen develops in other latitudes and maintain an interest in the subject, but without active participation yet.

Having a national policy to promote green hydrogen is useful for companies that are already developing projects in other countries. Due to policies of prioritization of resources, these companies are allocating their R&D funds in African countries such as Morocco or South Africa where there is already government interest in the subject, or in Latin American countries such as Costa Rica and Chile where the regulatory frameworks for hydrogen development are favorable.

Without exception, the interviewed actors agree that Mexico has a high renewable potential and a wide territorial extension that could enable the development of green hydrogen in the country.

Other drivers identified are the size of some industrial sectors in Mexico, the proximity to the US and NAFTA as possible enablers of hydrogen exports and even the country's experience with the adoption of new energy technologies, its electrical manufacturing capacity, and human resources availability.

Regarding the barriers, the actors identify as the main barrier for green hydrogen, the current energy policy of the country and therefore, the adverse ecosystem of investment in renewable projects in Mexico.

The second most important barrier for hydrogen in Mexico is the lack of regulations aimed at meeting the goals of the Paris Agreement. This lack of regulation in terms of emissions has not made it necessary to issue technical regulations for new technologies, such as hydrogen production and use.

The generalized view of the interviewed actors is that hydrogen will arrive in Mexico, it is only a matter of time: the faster the policy framework is in place, the sooner it will arrive.

Some actions are considered necessary in the short term, such as developing a hydrogen roadmap or national strategy, developing pilot projects and identifying low hanging fruits for the adoption of green hydrogen, possibly forklifts, mining trucks or energy islands and peninsulas. The export of hydrogen from Mexico is a possibility that is also in sight.

Annex A: Recommendations for future works to be carried out in depth

From the experience of the effort in other countries in the development of the hydrogen economy, it would be desirable for Mexico to carry out some further studies in greater depth. The objective of the recommended studies is to broaden the understanding of the potential benefit that hydrogen could bring to Mexico in the social, economic, and environmental fields. Some studies include:

- **Ex ante analysis of public policy for the adoption of hydrogen in Mexico:** preliminary evaluation of the impact and possible consequences of the application of different policies for the adoption of hydrogen in Mexico. It should analyze the impact of these possible policies in the economic, fiscal, environmental (by environmental matrix), social and domestic and foreign policy spheres.

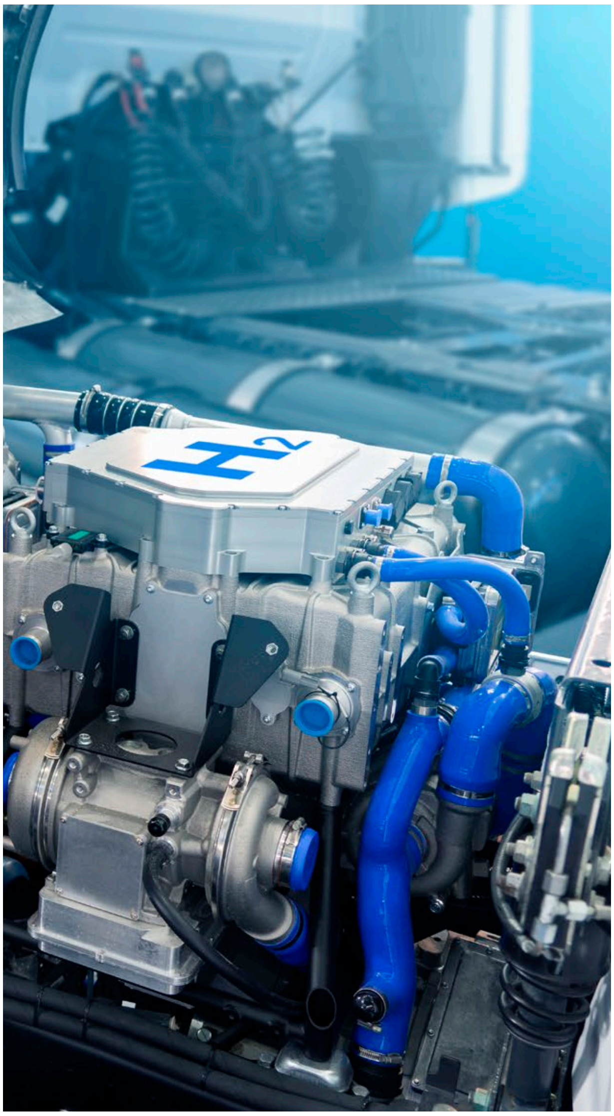
- **Quantification of social impacts:** analysis of the creation of companies and jobs due to the new productive chains of green hydrogen, analysis of displaced jobs in other industries as well as reduction of energy poverty, reduction of inequality and other social co-benefits of renewable energies

- **Analysis of environmental impacts of the adoption of green hydrogen:** detailed analysis of the environmental impact of different applications of green hydrogen. Life cycle assessments are recommended to better understand the global impact of hydrogen technologies on atmospheric emissions, consumption of water, energy, and other non-renewable resources.

- **Study of the macro-economic impacts of hydrogen in Mexico:** identification and quantification of impacts of the adoption of green hydrogen to different indicators in Mexico such as GDP or the energy trade balance. This study may include an identification of the new routes in the purchase and sale of hydrogen between sectors and their impact on the input - product matrix of the Mexican economy.

- **Higher resolution studies for specific applications of hydrogen with high potential in Mexico:** sectors such as mobility, electricity generation or hydrogen as feedstock can be analyzed in greater depth, analyzing more applications of hydrogen, making deeper mapping on the possible producers and off takers of hydrogen and expanding the number of drivers that could lead to the replacement of fossil fuels by green hydrogen in the operations of each sector.

- **Analysis of regional opportunities for H_2 in Mexico:** there is currently a trend in the world for the adoption of green hydrogen: the creation of regional hubs. Regions with high renewable potential, good levels of industrialization and development and access to energy infrastructure can develop industrial clusters to produce hydrogen in high volumes (taking advantage of economies of scale) and consume it in different applications, such as mobility, industrial heat, feedstock, etc. This study could identify the real potential to develop hydrogen hubs in some regions that intuitively seem interesting in Mexico, such as the Northeast, Northwest and the Bajío region.



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