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Green Hydrogen

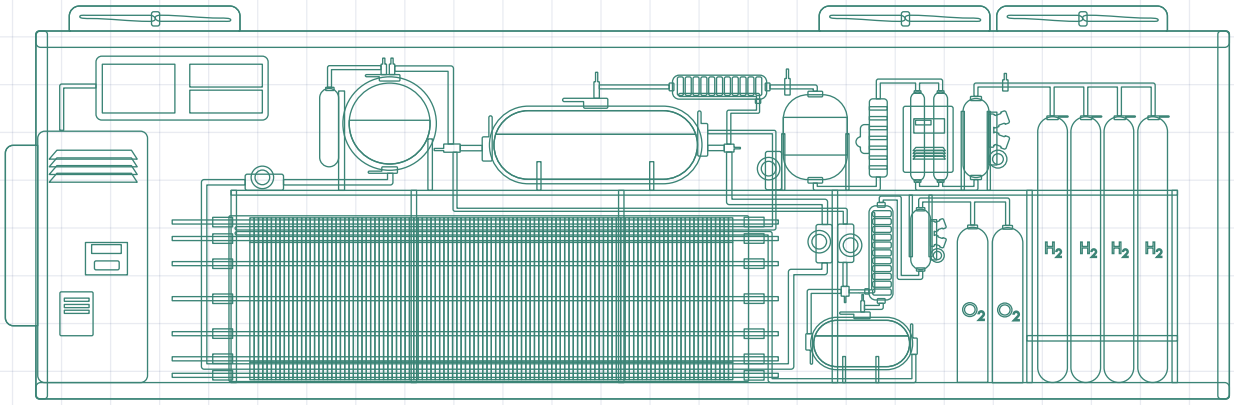
In the last few years there has been an increasing conversation around green hydrogen, and its potential to change the current world's energy matrix. Until recently my knowledge in the subject was limited, and that led me into inaccurate ideas about the capabilities and the maturity of the technology.

I do recognize now, its true potential as I have now learned about multiple new applications and the many advantages of Green Hydrogen, and believe than in a near future, it will become a key role player in the world energy matrix, maybe not exactly as I originally thought.

I believe that similar to my case, there is a great number of people that has a limited understanding of the technology or its applications, I also believe that the widespread and understanding of any new technology is a key enabler for its own deployment.

The purpose of this paper is to explain to an extensive and multidisciplinary audience, how the technology functions and what are its capabilities, emphasizing the functionality of the technology over how the technology actually works. Substituting technical explanations for illustrative information, gives the audience the advantage of a fast comprehension rather than a deep understanding.

Ideally, the reader will then have a comprehensive knowledge over the main functions of the technology in our current economy, as well as what is needed for its widespread deployment, and what can be achieved by implementing it. The readers that desire to obtain more knowledge about the technology should be inspired to investigate and learn further into the technology.



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Hydrogen as an energy carrier

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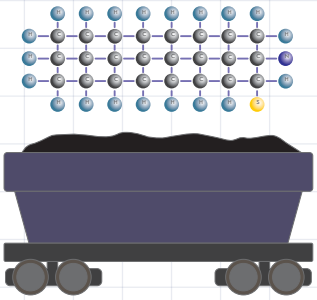
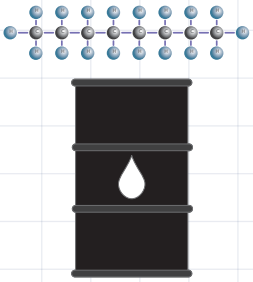
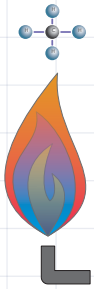
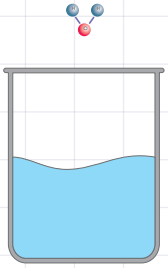
Hydrogen is the simplest and most abundant element on earth, consisting of only one proton and one electron. Hydrogen is an energy carrier, not a source of energy, meaning that it can be stored and later used to deliver energy. Hydrogen in nature is mostly combined with other elements, so first it must be separated from compounds that contain it.


Coal

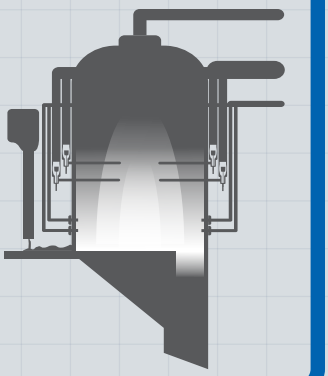

Hydrocarbons

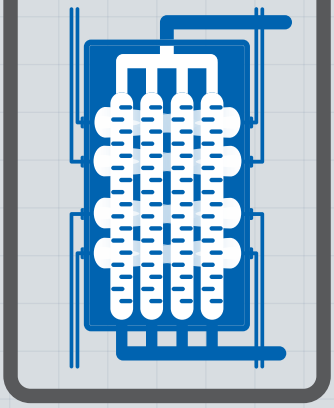

Methane

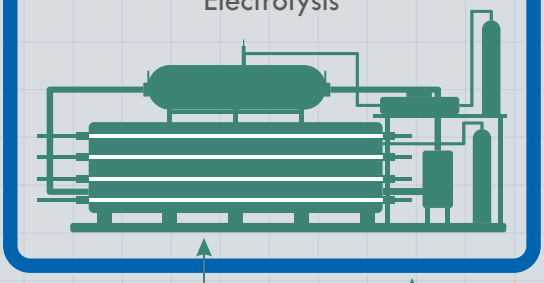

Biomass


Water

Industrialized methods


Gasification


Steam Reforming


Electrolysis

Any method can have different emissions depending on the process or sources, its possible that their resulting H2 doesn't fully fit in a certain category.

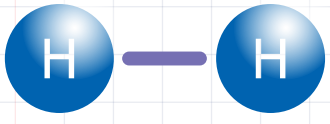
Commonly H2 is branded by color depending on its emissions, or carbon neutrality.

Green hydrogen

Carbon neutral produced form renewable energy

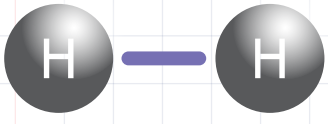
Turquoise hydrogen

Most carbon is sequestrated and stored in the process.



Blue hydrogen

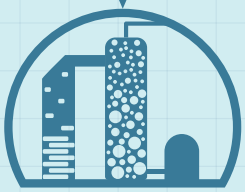
CCS is implemented eliminating around 85% of emissions

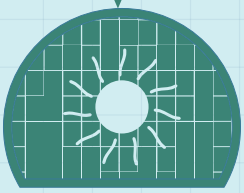


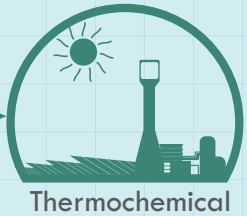
Grey hydrogen

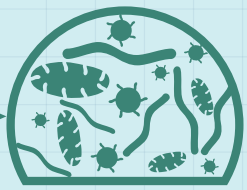
Multiple gases are emitted during the production process

Experimental methods


Methane pyrolysis


Photoelectrochemical splitting


Thermochemical splitting


Microbial conversion

Energy density

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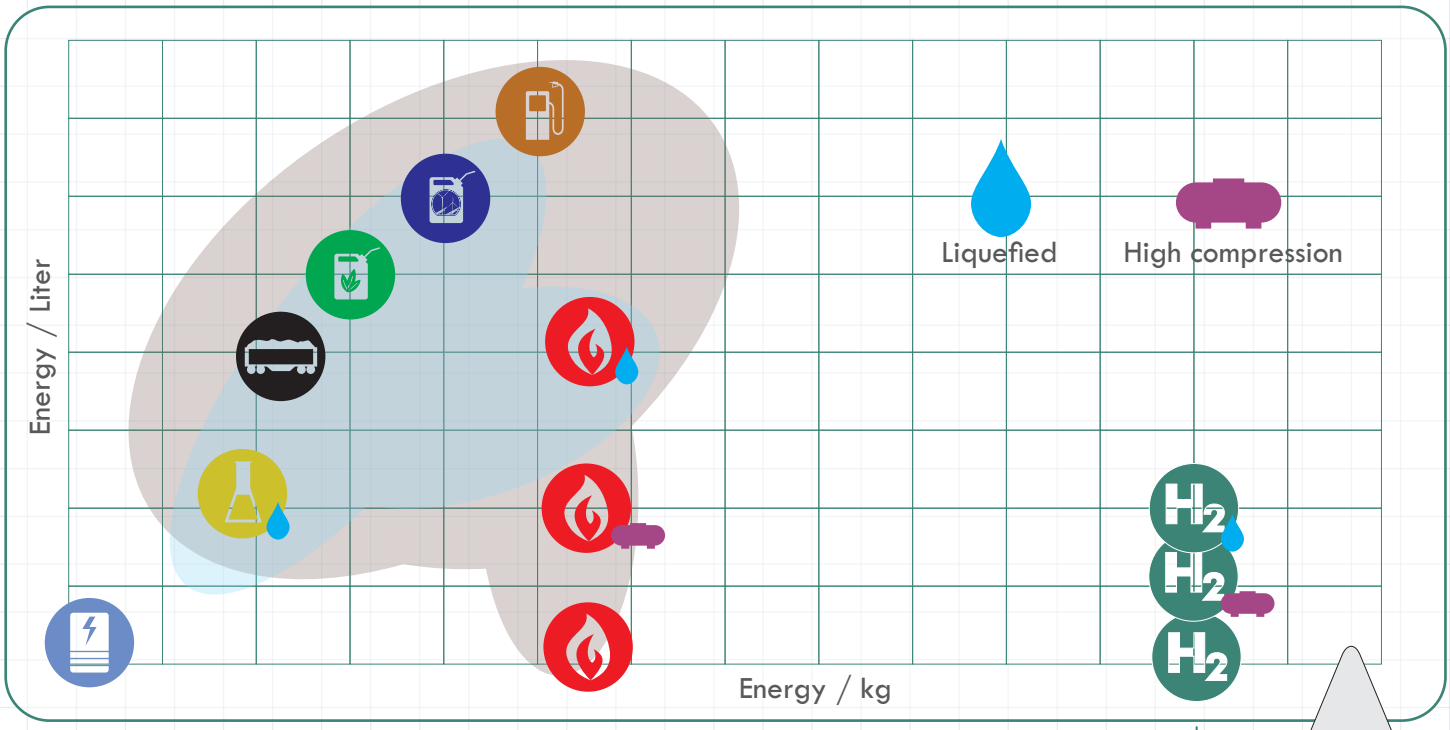
Energy density can be measured by volume or weight, the energy density of different fuels or storage systems, help determine their functionality for mobile applications. Hydrogen is densely packed in terms of weight but not in terms of volume, it is necessary to compress it or even liquify it in other to make it useful for most applications, any of these process consume energy, diminishing the overall efficiency of hydrogen as an energy carrier.



H_2 Pure hydrogen

Hydrogen is the lightest energy carrier, but it requires a large amount of volume, its low weight makes it a great rocket fuel where volume is not as a big constrain as weight.

Synfuels

e.g. Liquid ammonia

E-fuels
e.g. Butanol

Bio-fuels
e.g. Ethanol

Fossil fuels

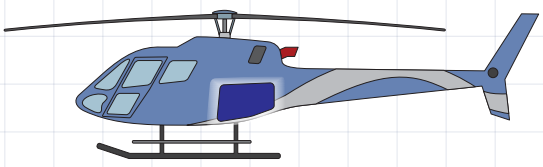
Bituminous coal

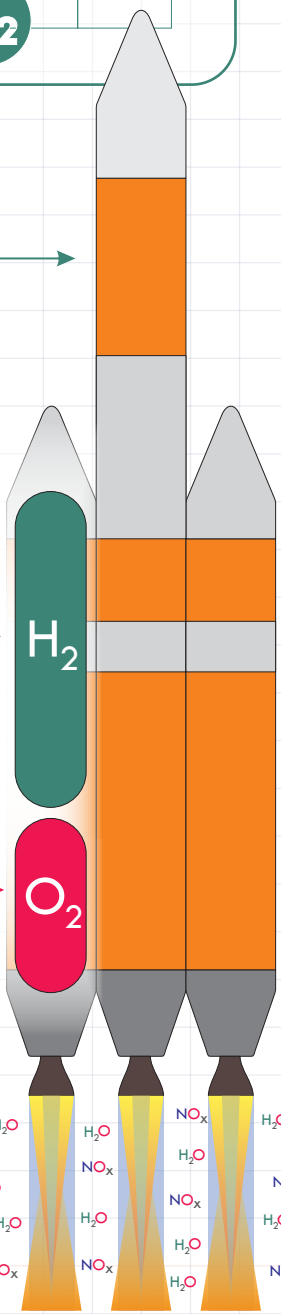
Fuel gas
e.g. Methane
(Natural gas)

Liquid fuel
e.g. Diesel

Batteries
e.g. Lithium Ion

Smaller vehicles like planes and helicopters, require to store energy as densely as possible in a tight volume, e-fuels can be a carbon neutral option in a near future.





Pure hydrogen combustion with oxygen will result only in water vapor, making it one of the cleanest fuels, however, due to high combustion temperatures atmospheric nitrogen also reacts emitting nitrogen oxides.

Green Hydrogen life cycle

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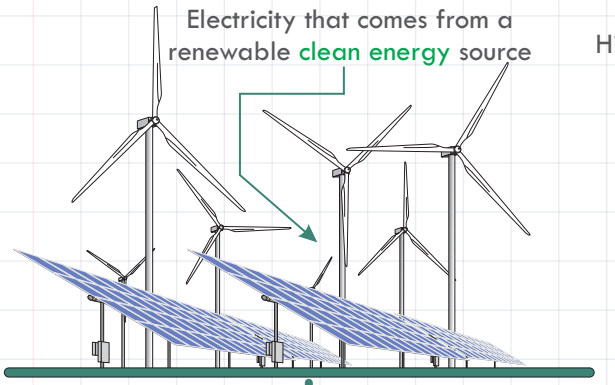
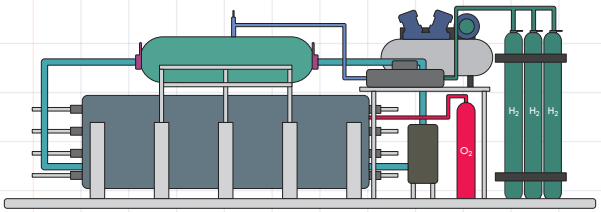
Being such a versatile element, hydrogen can be produced from multiple sources and used in a vast range of applications, multiple industries rely on hydrogen as a feedstock chemical, as multiple compounds created by it, such as synfuels, and the energy it carries can be applied in several industries. The transportation industry also benefits directly from hydrogen as a clean fuel alternative, the range of applications for hydrogen is creating an expanding circular economy around the production, storage, transportation, and consumption of hydrogen and its related compounds.



Electricity that comes from a renewable clean energy source

Electricity is transmitted to the production site

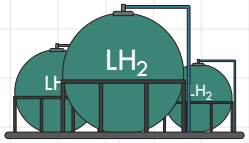
Production



Electrolysis

High energy density for storage and transportation H2

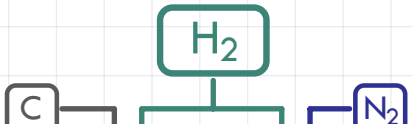
Cryo-compressed liquid hydrogen [300 bar] [-235°C]



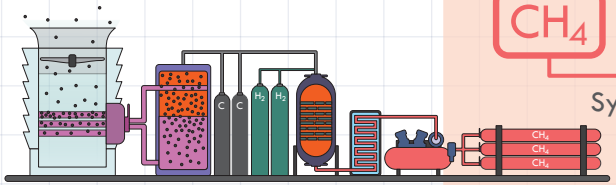
Storage

High pressure [700 bar] gaseous storage

Power to X



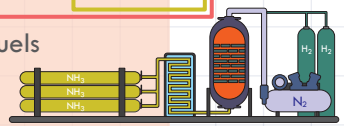
Synfuels



Carbon capture

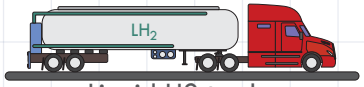
Carbon + Hydrogen synthesis

e.g. Methane

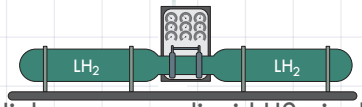


e.g. Liquid ammonia

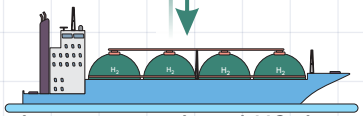
Nitrogen + Hydrogen synthesis



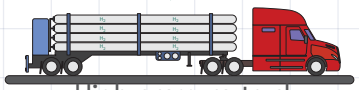
Liquid H2 truck



High pressure or liquid H2 pipeline



High pressure or liquid H2 shipping



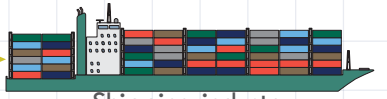
High pressure truck

Transportation

Synfuels for aviation

Public transportation

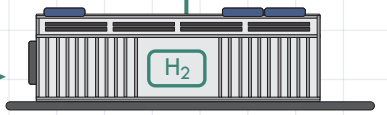
Road vehicles



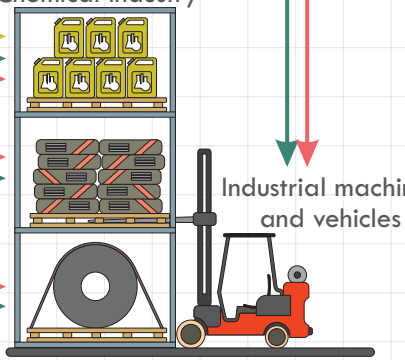
Shipping industry

$ Application

Power production

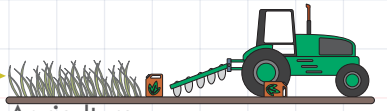


Chemical industry



Industrial machines and vehicles

Cement & Steel industry



Agriculture

Hydrogen today

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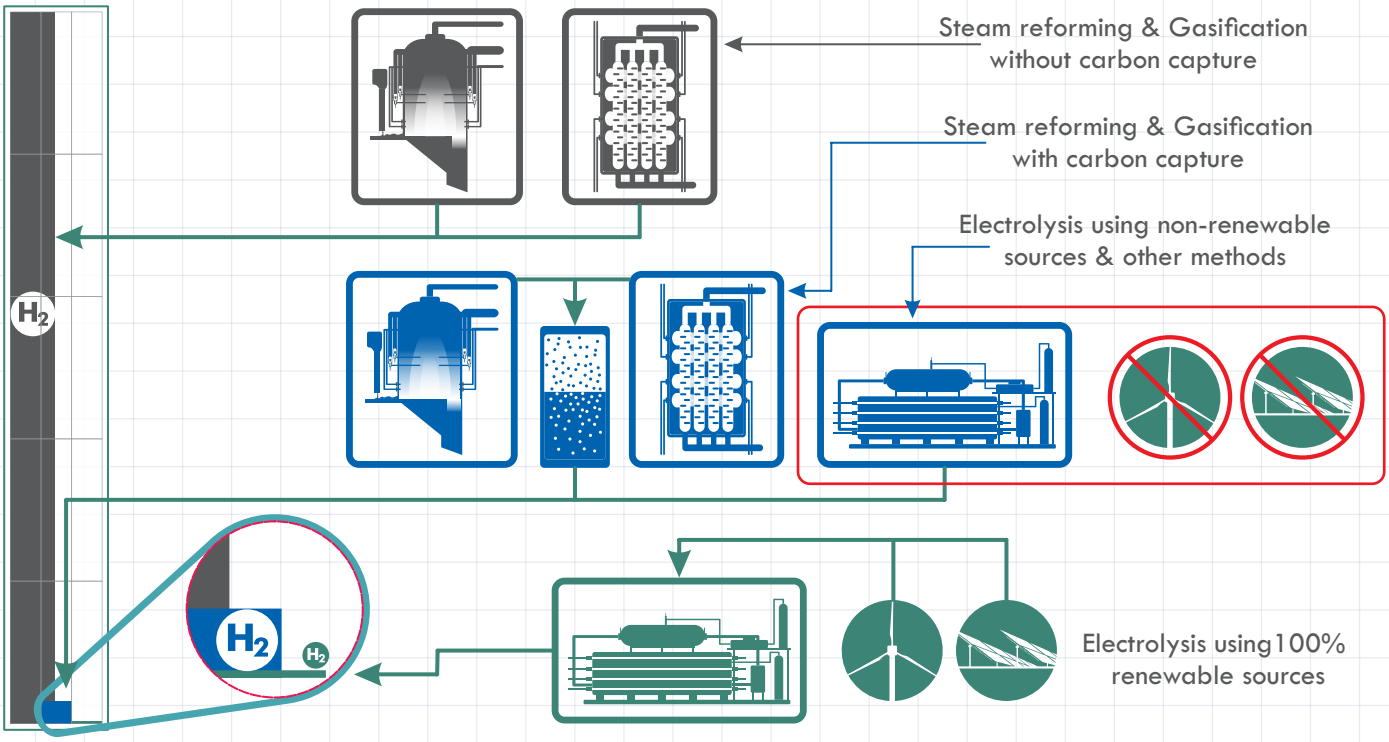
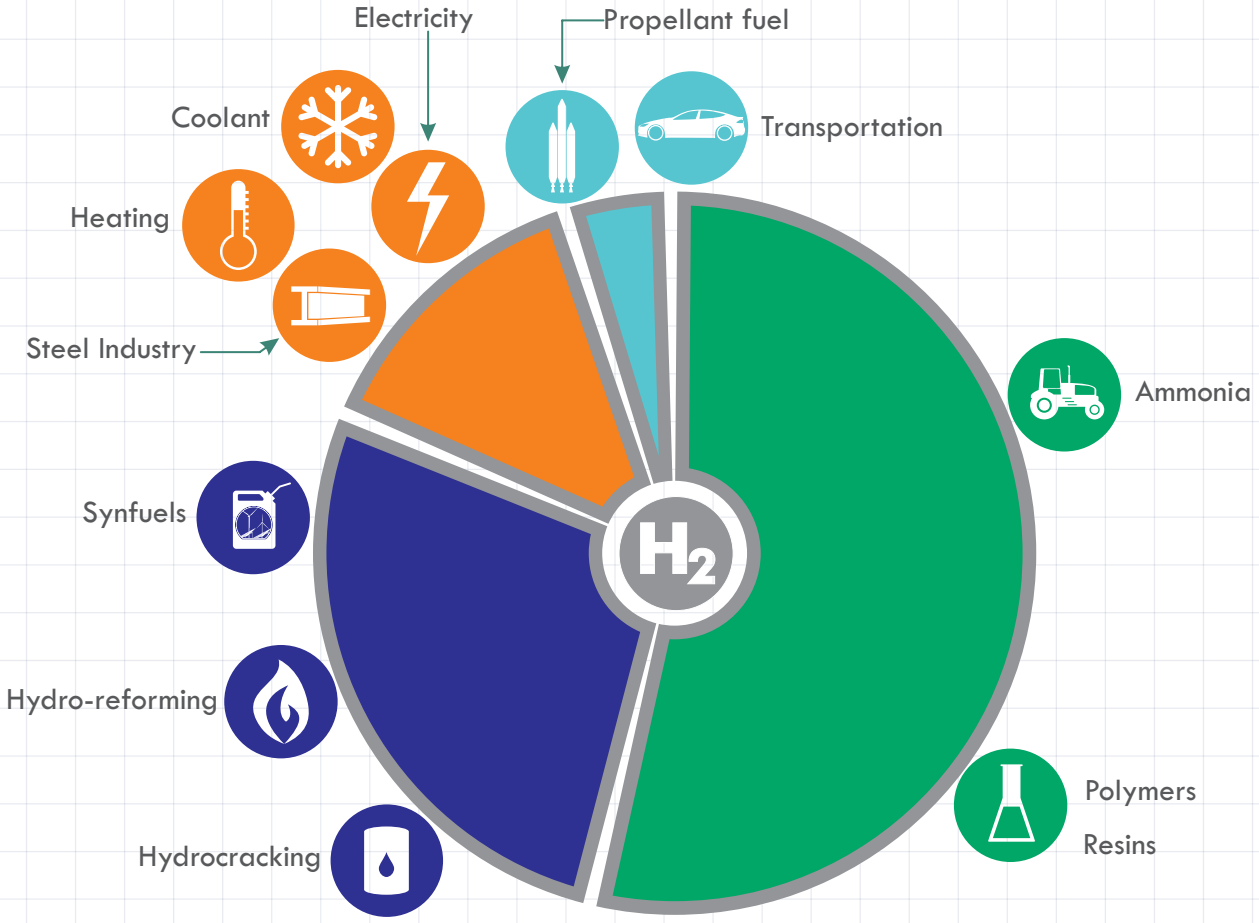
Currently most hydrogen production is done using steam reforming of natural gas, coal is also widely used for the production H2 through gasification, since only near 0.7% of this production uses carbon capture, around 97% of all produced hydrogen is considered grey hydrogen. Currently only about 0.4% total H2 production is Green Hydrogen, meaning it was produced via electrolysis using only renewable energy sources.



For a long time, multiple industries have relied on hydrogen as a feedstock material, mostly to produce ammonia, a common fertilizer, but also for the production of many other chemicals. Oil industry widely uses hydrogen for different fuel processing methods, more than three quarters of Hydrogen production are used by these two industries. Many other industries could benefit more from Hydrogen if the prices reduce even more, in addition, as a method of reducing overall production emissions.



Electrolysis

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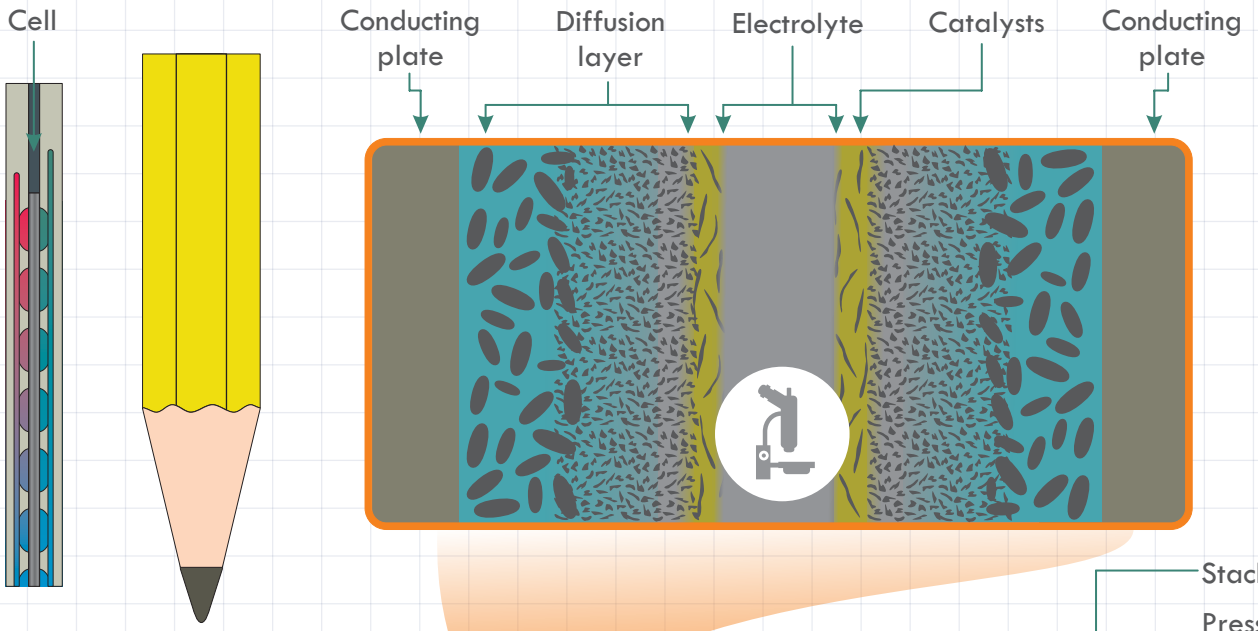
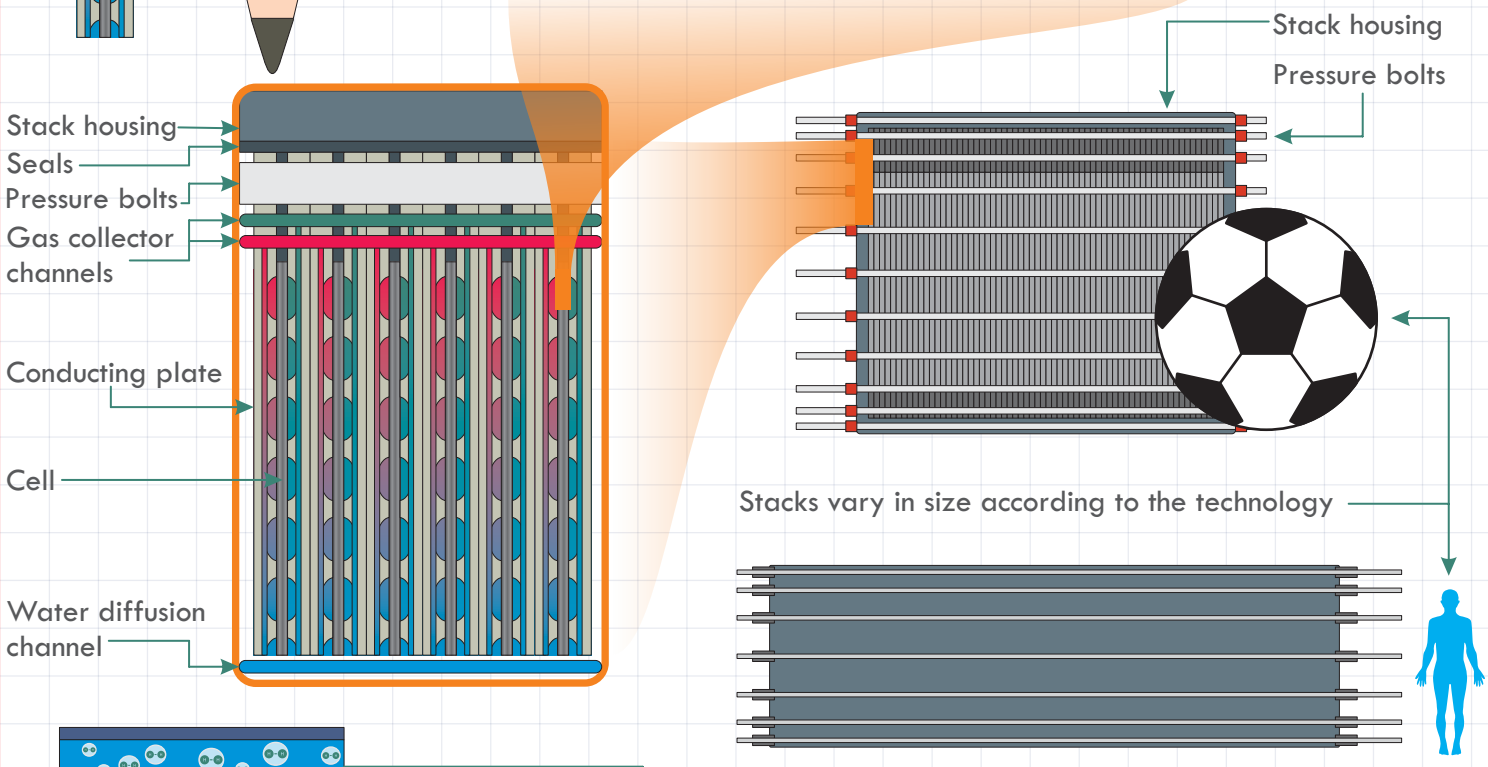
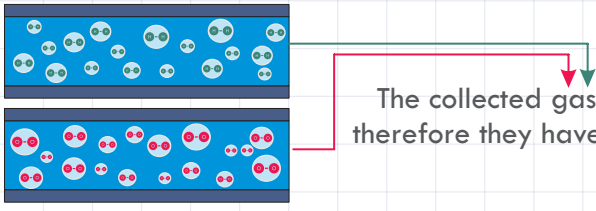
In Green hydrogen production, electrolysis is the method of using a direct energy current as a way of splitting a water molecule through a simple chemical reaction. The electrolyzer is the system that produces the Hydrogen from water, its main component is the electrolyzing cell, where the chemical reactions occur simultaneously, as long as the cell is fueled by water and a DC current. An electrolyzer has multiple cells stacked next to each other, to increase conductivity and efficiency the cells are as thin as possible.

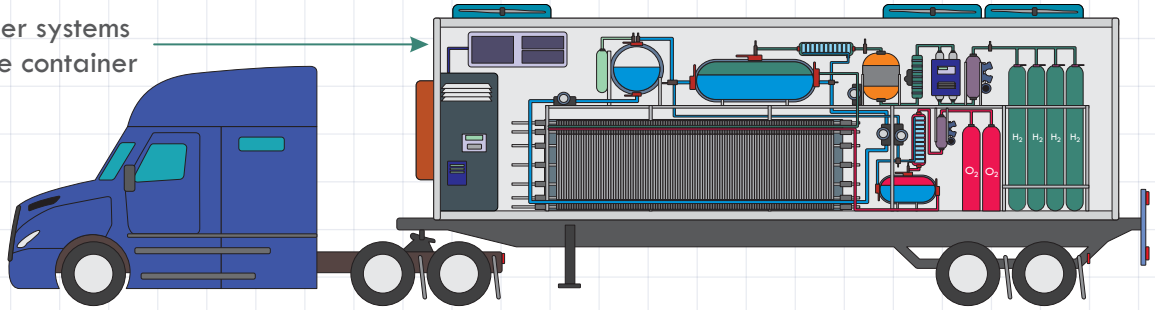






The collected gases are still mixed with water, therefore they have to be treated first before use

Some modern electolyzer systems are able to fit in a single container



Electolyzer technologies

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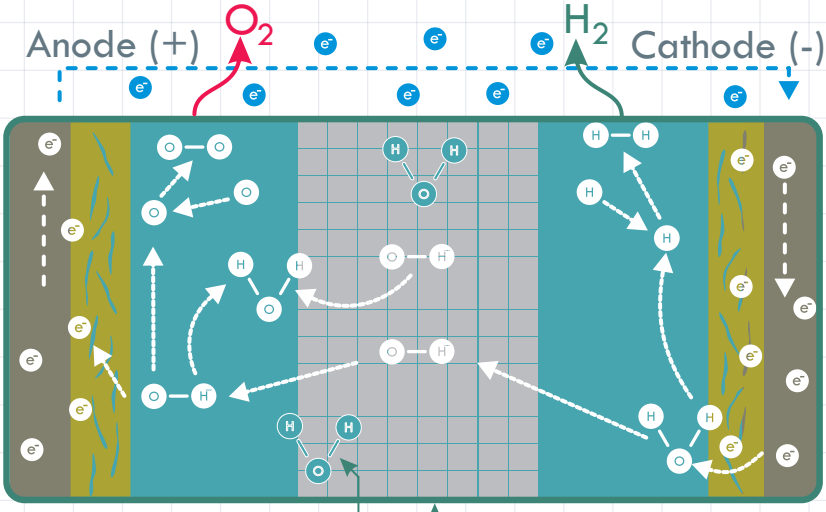
The most common or promising technologies are Alkaline, PEM (Polymer Electrolyte Membrane) and SOEC (Solid Oxide Electrolysis Cell). The Alkaline is the most widely used and most proven technology, PEM electrolyzers are increasingly popular even after their elevated costs, although their production is limited by the availability of scarce materials used as catalysts. SOFC are a promising technology, but with plenty of challenges to overcome before it can be fully scalable and commercially deployed.

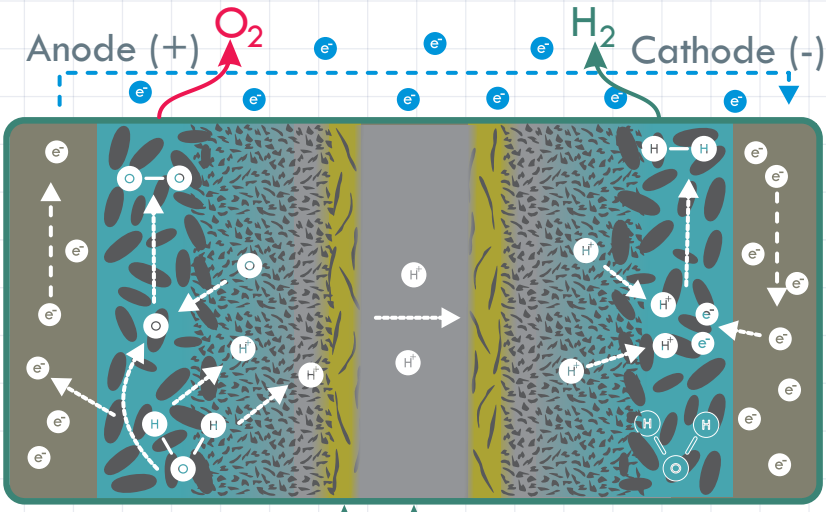


The entire cell is submerged in an electrolyte solution

Non-conductive diaphragm allows the OH ions to pass

Alkaline

Cost*	270 USD / $kW_{elec.}$
Efficiency*	50% - 70% kWh/kgH_2
Durability*	60,000 hr
Technology	Mature
Availability	Commercial
Op. temperature	70-90 °C
Op. pressure	30 bar
Size	Large

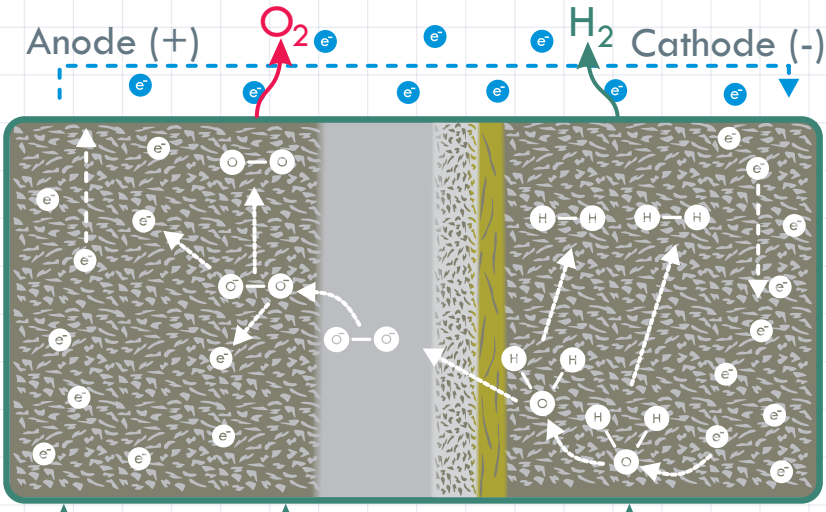


Catalysts speed up the reaction

Non-conductive membrane reduces the space between the plates improving conductivity

PEM

Cost*	400 USD / $kW_{elec.}$
Efficiency*	50% - 83% kWh/kgH_2
Durability*	50,000 -70,000 hr
Technology	Developing
Availability	Scarce components
Op. temperature	50-80 °C
Op. pressure	70 bar
Size	Compact



Gas diffusion layers increase the reaction area

High temperatures augment the reaction efficiency

Solid Oxide

Cost*	+2000 USD / $kW_{elec.}$
Efficiency*	45% - 55% kWh/kgH_2
Durability*	20,000 hr
Technology	Experimental
Availability	Under development
Op. temperature	700-850 °C
Op. pressure	1 bar

*Costs are capital costs estimates for only stacks > 1 MW [USD/kW]
*Cost, efficiency and Durability are based on the IRENA analysis on Key performance indicators for four electrolyser technologies today and in 2050. IRENA (2020), Green Hydrogen Cost Reduction.

Balance of plant

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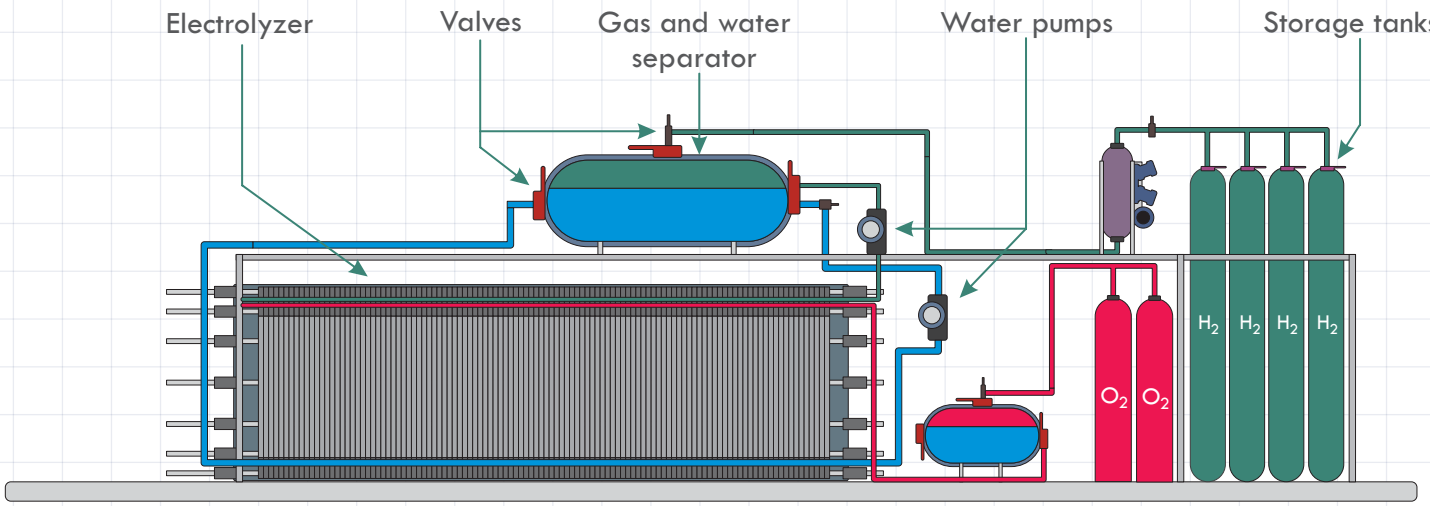
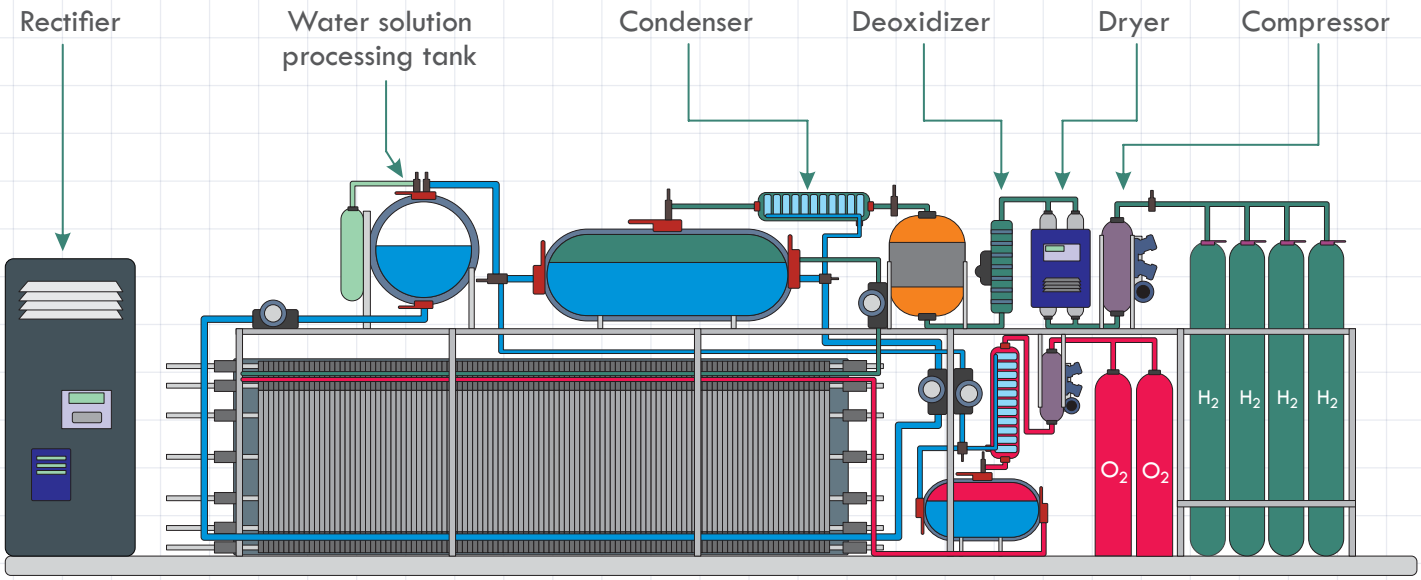
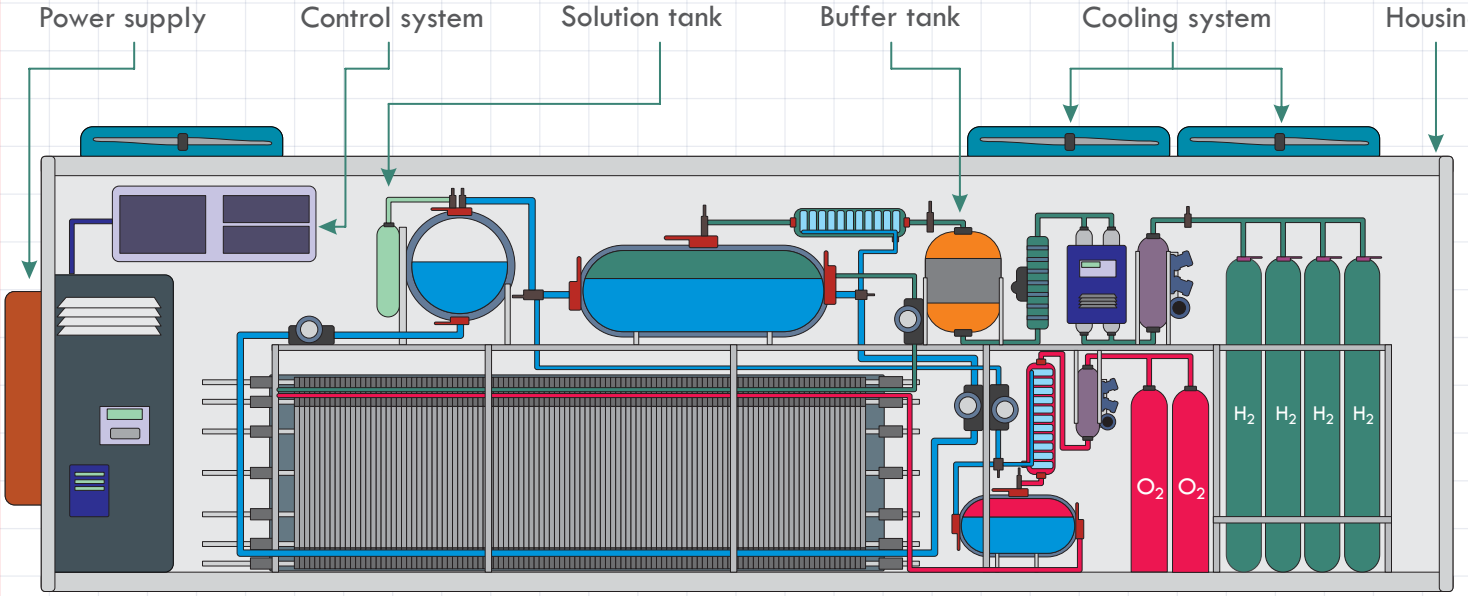
Electrolyzers alone are not enough to produce industrial amounts of pure hydrogen, a group of complementary systems aid in the creation of the pure hydrogen, free of any contaminants, as well as supporting the electroylzer functionalities. The (BoP) Balance of Plant often varies depending on the electrolyzer technology and characteristics, still multiple elements are common in most systems, where the end product is pure and compressed gaseous hydrogen.







Production & Distribution

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The final efficiency of hydrogen is heavily dependent on the implemented production and distribution method, a balance between improving efficiency by scaling up production meets the inefficiencies of complex distributions systems. As the technology matures larger production facilities are proposed, nevertheless this doesn't mean that small scale and distributed facilities are inefficient, its most likely that technology will adapt to different niches in the sector.

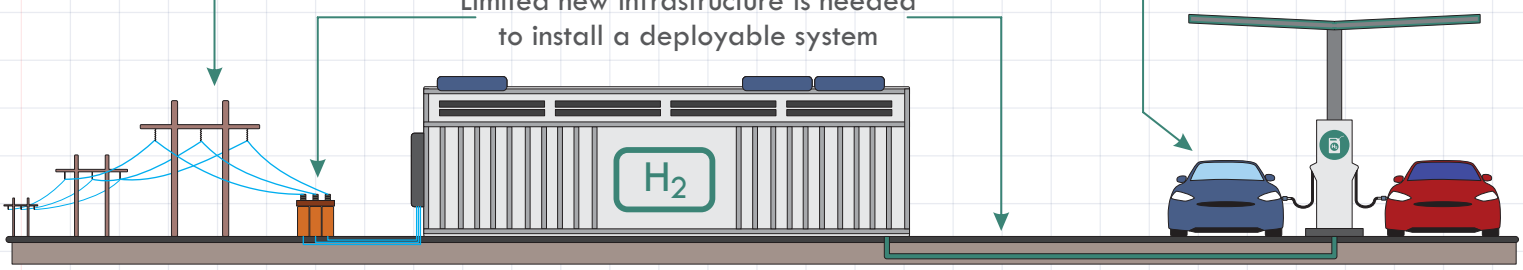
On-site

Automatized systems require minimum supervision

Ideally the facility produces only when a surplus of renewable energy in the grid drives down prices

Locating the production near the end user drives down costs

Limited new infrastructure is needed to install a deployable system

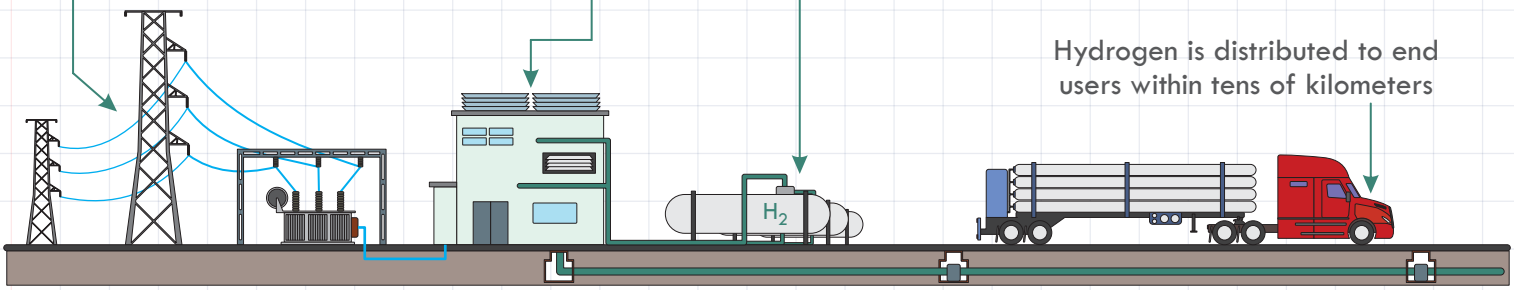


Regional

The facility can hold a PPA's with renewable energy producers, assuring the production of pure green hydrogen

Hydrogen does not need to be liquified since the end users are nearby

Hydrogen is distributed to end users within tens of kilometers



Centralized

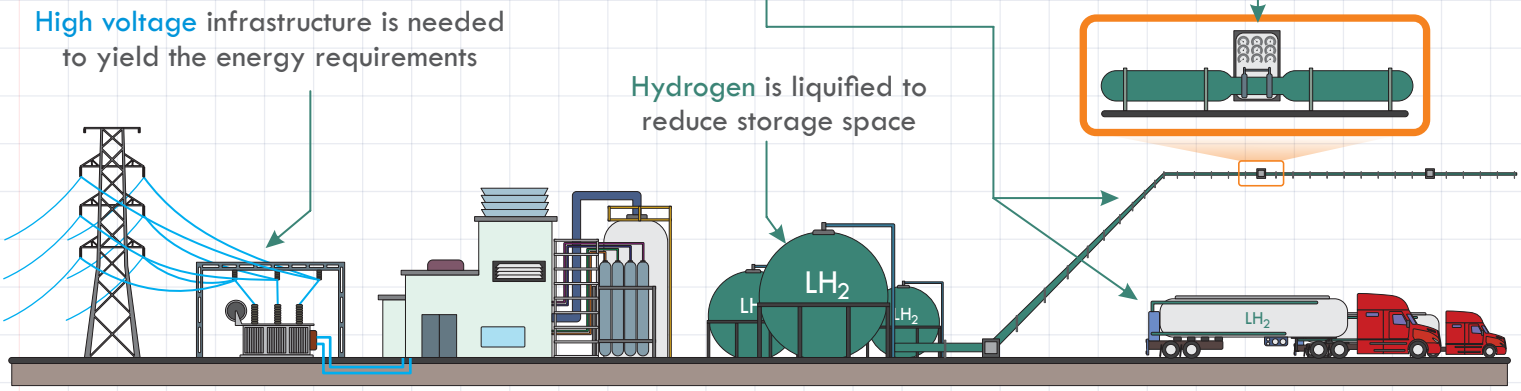
Upscaling the production offsets the additional costs and inefficiencies of long distance transportation

Complex systems require constant professional supervision

Multiple transportation systems, allow distribution within hundreds of kilometers

High voltage infrastructure is needed to yield the energy requirements

Hydrogen is liquified to reduce storage space



Macro production of Green Hydrogen

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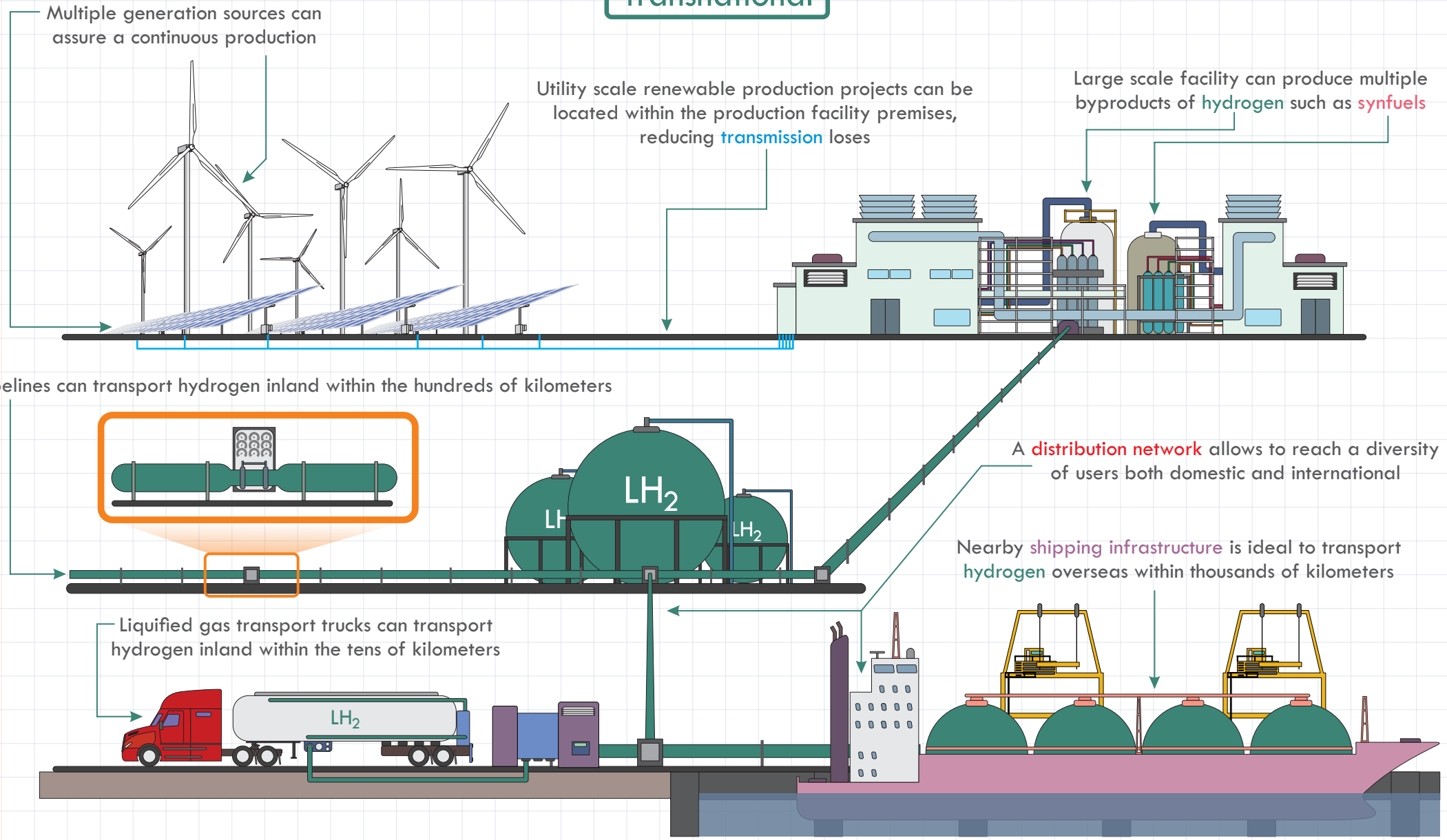
There are plenty of regions around the globe with a high potential for renewable energy and without consuming demand nearby, these regions are ideal for mega hydrogen production facilities, where the sole intention is to produce and distribute H2, at the lowest possible costs and as far as possible. These regions even can be isolated or offshore where land prices and social impact is low, connected by high volume transportation infrastructure that allows the facility to reach international markets.

Transnational



The fuel Cell

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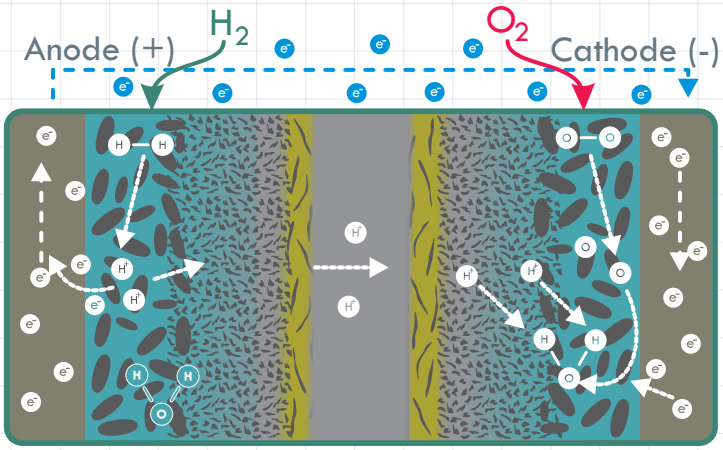
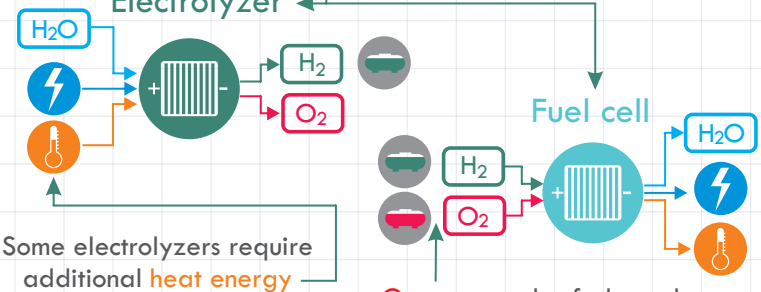
The fuel cell is the main component that carries the chemical reaction of Hydrogen and Oxygen, generating an electric current from it and emitting water as a byproduct of the reaction, a fuel cell works in the opposite way of an electolyzer, therefore the components and design of both stacks are quite similar. Fuel cells can generate electricity out of a variety of fuels as well as hydrogen, the components as much as their efficiency depends on the specific fuel they are fed. Likewise pure or mixed hydrogen can be burnt in different types of engines, many gas turbines can run on hydrogen with some modifications on their fuel injection systems.

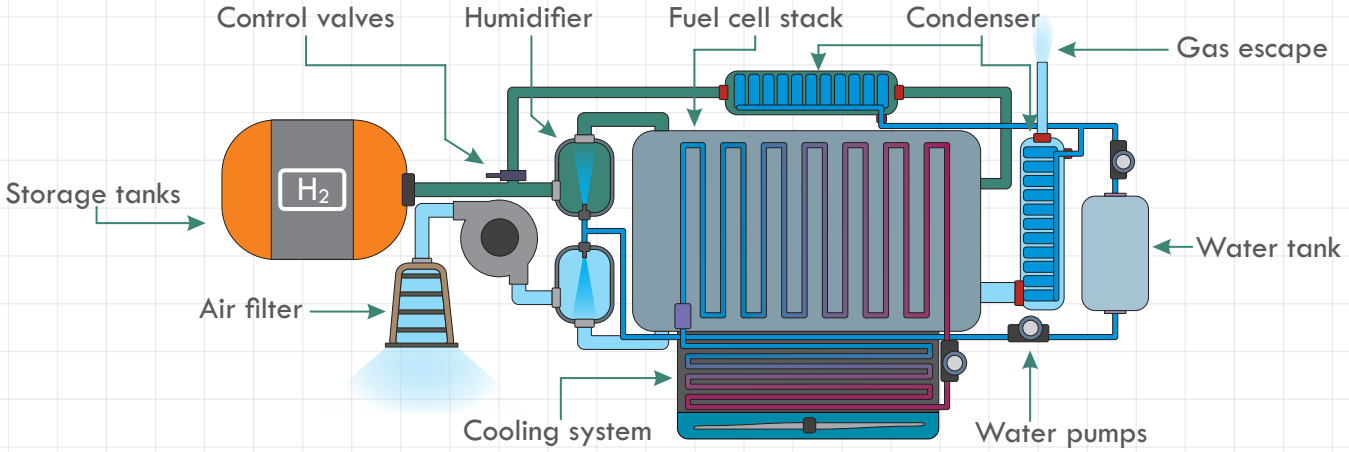


Most fuel cell technologies such as Alkaline, PEM, or Solid oxide are symmetrically opposed to their electolyzer counterparts



Some electrolyzers require additional heat energy to improve reactiveness

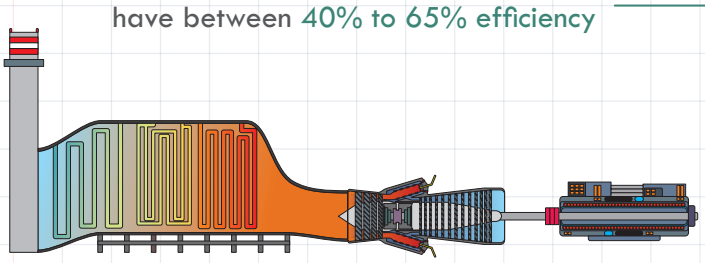
Oxygen can be fed purely or mixed in atmospheric air

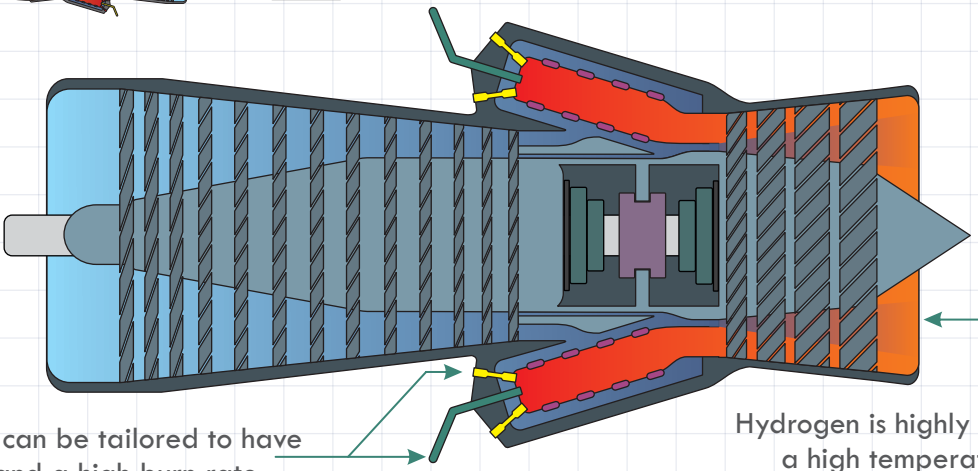


Current commercial fuel cell stack systems have between 40% to 65% efficiency

Fuel cells or Hydrogen combustion?

Multiple manufacturers are developing pure hydrogen and fuel flexible turbines that are expected to produce electricity with a 60% thermal efficiency in combined cycle





Hydrogen combustion can be tailored to have minimal emissions and a high burn rate

Hydrogen is highly reactive and has a high temperature burn rate

Competing technologies

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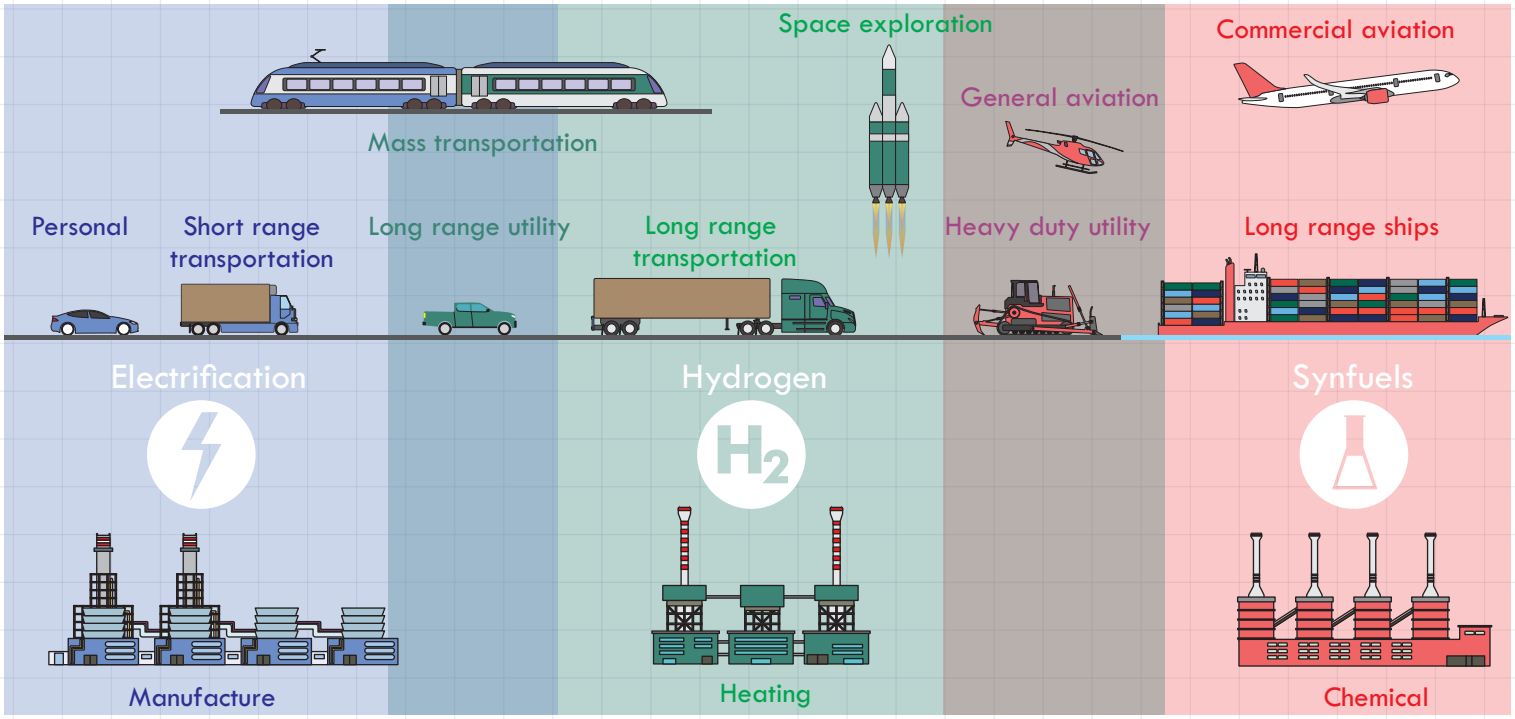
Who is going to win the race?

Each technology will find their own segments, markets, and regions, where each specific technology will have more economical sense than the others. With this in mind, its important to state that any energy conversion process will always have inefficiencies, the more conversions needed for the final end use, the more energy will be lost due to inefficiencies.

For transportation it is quite complex, since each different method has different power, weight and volume requirements, in addition to multiple economical, geographical and market drivers, it is most likely than in a near future vehicles will adapt to the energy sources that better fit their characteristics.

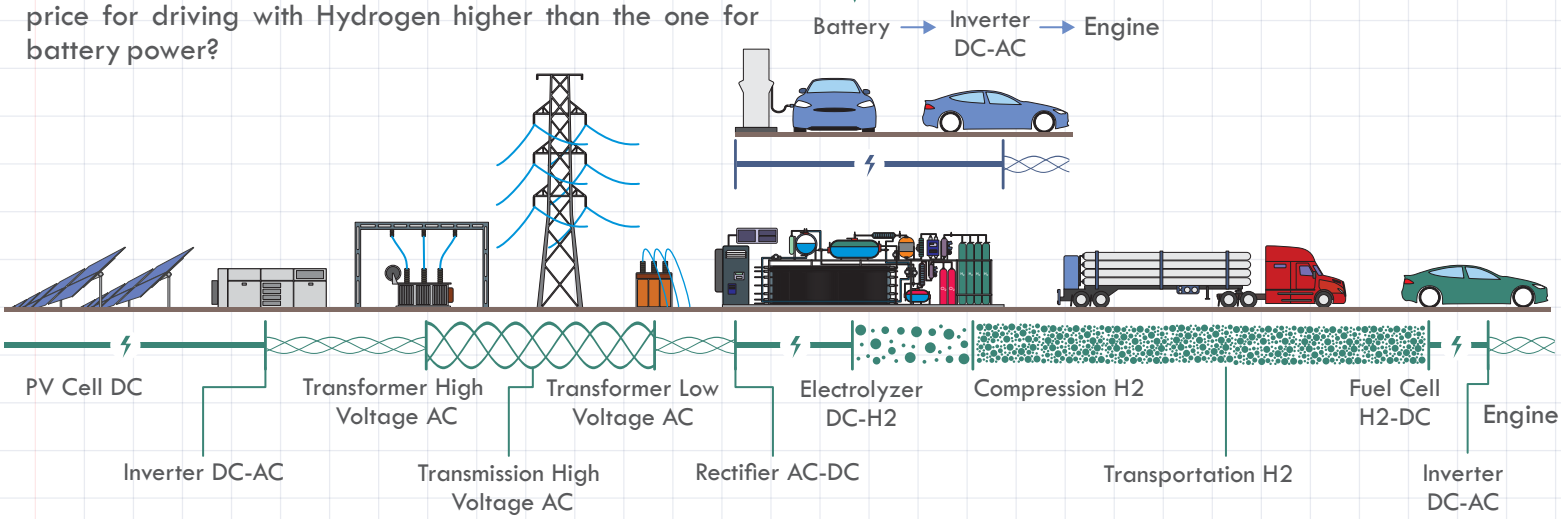


For general Industry direct electrification is already taking over, as it is the most efficient way to power most machines. However multiple industries can't rely only on electrification, and will have to depend on products such as Hydrogen or synfuels if necessary, this will require more energy and thus, a higher price on their energy source, but their final emissions can still be substantially reduced by switching to greener energy sources.

Why electric are vehicles winning over?

The short range personal green vehicle market is leaning towards electric vehicles over hydrogen, mainly because of the energy source, price, and the availability of both the product and the necessary infrastructure. But why is the price for driving with Hydrogen higher than the one for battery power?

Battery power vehicles require less energy conversions and/or fuel transportation, reducing the final price of the driven kilometer



The hydrogen economy enablers

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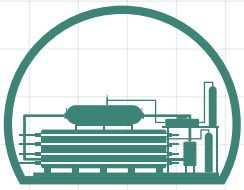
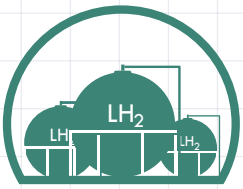
Policy making

A hydrogen economy is only worth it, if a low emissions hydrogen is used, policy must be implemented in order to achieve this, otherwise emissions could double if the current production status is maintained in order to satisfy the increasing demand for hydrogen.



Infrastructure

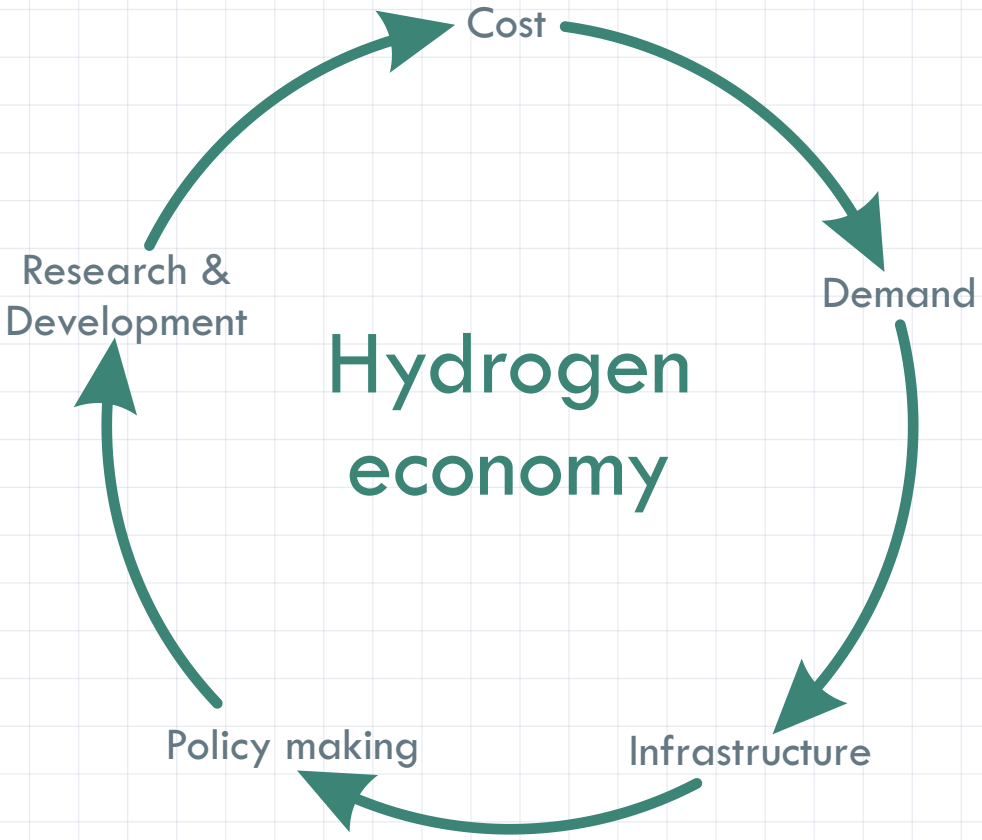
A considerable investment is needed to prepare our existing infrastructure, otherwise Hydrogen won't be as efficient as competing technologies, even more dependent on infrastructure are the users, that won't adopt Hydrogen if associated inconveniences are too many.



Research & Development

Hydrogen related technologies are still "GREEN" and still have a long way to be fully matured, this however presents a huge range of improvement, development still has to tackle the complications related to the scale up of the technology, which is quite dependent on the available demand and available infrastructure

If Costs keep dropping it is most likely that a chain reaction will start once a certain tipping point is reached, the massification of the technology depends heavily on the associated costs



Abbreviations

H2 - Pure hydrogen

O2 – Pure Oxygen

PEC – Photoelectrochemical

CH4 – methane

NG – Natural Gas

LNG – Liquified Natural Gas

LH2 -Liquified Hydrogen

CCS – Carbon Capture and sequestration

PPA – Power Purchase Agreement

Synfuels – Synthetic fuels

e-fuels – (Electronic fuels), Fuels that are synthesized using an electric current

bio-fuels – Fuels that produced from organic matter

DC – Direct current

FC – Fuel Cell

EC – Electrolyzer Cell

PEM – Polymer Electrolyte Membrane

SO – Solid Oxide

BoP – Balance of plant

Op. – Operational

e.g. – Example

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