RES4Africa Knowledge Platform

Green Hydrogen technologies: state of the art and what’s next

RINA

RES4AFRICA FOUNDATION

Electrolyzers have become a key component in the technological landscape of a decarbonized energy system

The Platform covers the following thematic areas:

- **Technologies**
- Policies and regulations
- Access to market
- Permitting
- Financing
- Operation
- Sustainability

Recent evolutions of electrolyzer technology

What is the context: in the challenge to achieve decarbonized energy system, hydrogen plays a crucial role, and in particular green hydrogen produced by electrolysis, as no green house gases are released in atmosphere during production. Great progress has been made in electrolyzers technology, but there is still much work to be done.

Why is this relevant: Hydrogen is the enabler of large-scale renewables roll-out, by overcoming the issues of intermittence to electrify some industrial sectors. Its versatility as a clean fuel and feedstock makes it the link between low-carbon energy solutions.

What are the key questions:

– How does an electrolyzer work?

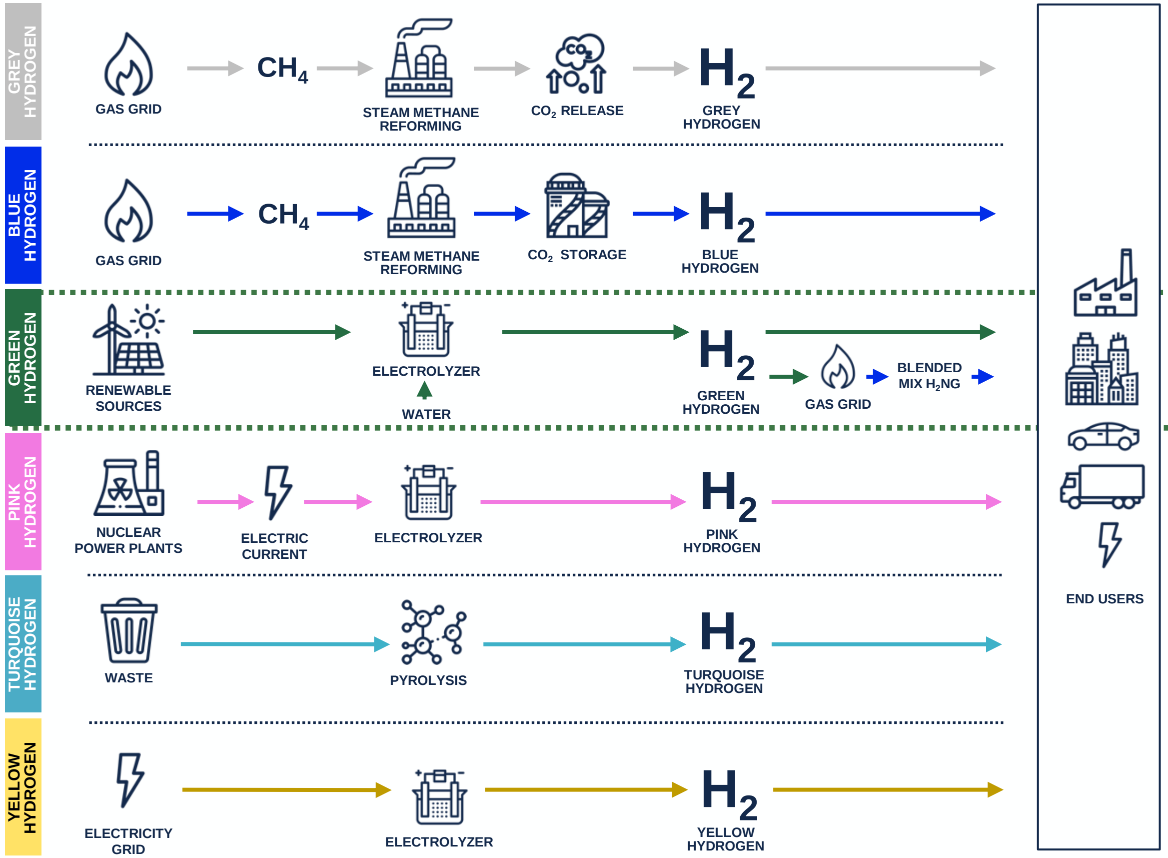
– What is the state of the art of electrolyzers?

– How much does it cost to produce green hydrogen?

– What developments and improvements can we expect from the future?

What is Green Hydrogen

Hydrogen can be produced using several processes and feedstock, with varying efficiencies, environmental impacts and costs.
Some colors are often attributed to hydrogen to provide information about how it is produced, the energy sources used and the climate neutrality. Green hydrogen is the one produced with no harmful greenhouse gas emissions.



Grey hydrogen is extracted from fossil sources such as methane or coal resulting in the massive production of CO_2 which is then released into the environment without any other use

Blue hydrogen is Grey Hydrogen with the usage of Carbon Capture and Storage (CCS) techniques

Green hydrogen is produced by electrolysis of water, using only electricity from renewable energies. Since production is based on renewable energy, hydrogen is produced without any CO_2 emission

Pink hydrogen is extracted by electrolysis through electric current produced by nuclear power plants (dependence on local regulations)

Turquoise hydrogen is achieved with pyrolysis, sometimes using catalysts or membrane, which in high-temperature (800-900°C) reactors produces the splitting of carbon and hydrogen from the natural gas molecule or from other sources. This process leads to hydrogen gas and carbon dust without emitting CO_2 into the atmosphere

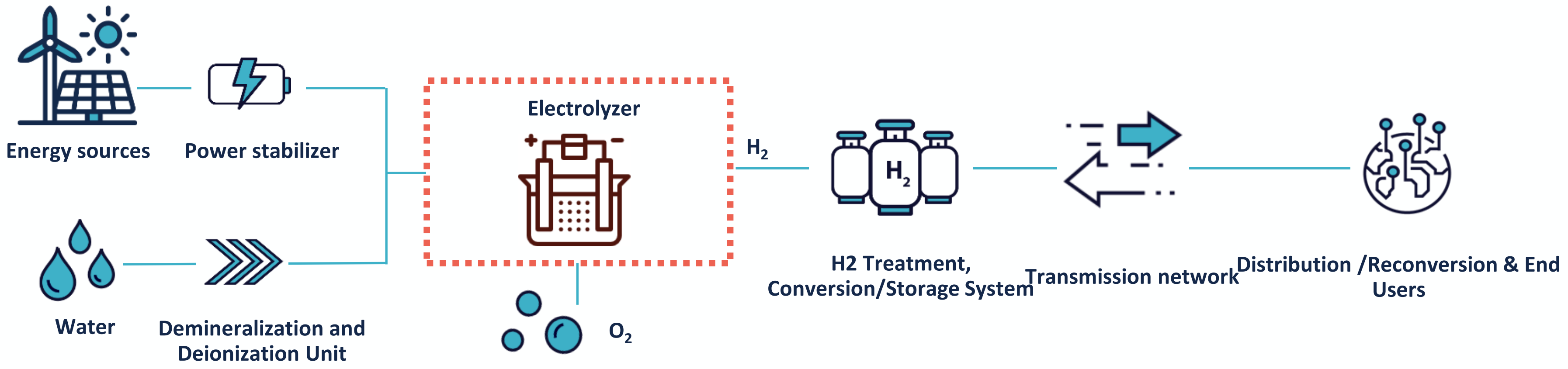
Yellow hydrogen is produced by electrolysis using grid electricity from various sources (i.e. renewables and fossil fuels)

What is Green Hydrogen

	Inspired by Global Energy Infrastructure (GEI) 2021 DIRECT: emissions for H2 production process INDIRECT: emissions by feedstock and energy supply chains	Hydrogen Council (2021) and Energy Transition Commission (2021)
GREY HYDROGEN	9,5 – 15 Kg CO_2/Kg H_2 DIRECT: 9 – 11 INDIRECT: 0,5 – 4	2020: 0,7 - 2,1 USD/kg 2030: 0,8 – 2,1 USD/kg
BLUE HYDROGEN	1 – 11 kg CO_2/Kg H_2 DIRECT: 0,5 - 4 INDIRECT: 0,5 - 7	2020: 1,6 – 2,6 USD/kg 2030: 1 – 2,1USD/kg
GREEN HYDROGEN	> 0 kg CO_2/Kg H_2 DIRECT: 0 INDIRECT: >0	2020: 3,2 – 5,3 USD/kg 2030: 1,8 – 2,7 USD/kg
PINK HYDROGEN	> 0 kg CO_2/Kg H_2 DIRECT: 0 INDIRECT: >0	NA
TURQUOISE HYDROGEN	NA	NA
YELLOW HYDROGEN	< 1 – 30 kg CO_2/Kg H_2 DIRECT: 0 INDIRECT: <1 – 30 depending on the grid mix	NA

The Green Hydrogen value chain

The machine that uses the electrolysis process to obtain hydrogen is the *electrolyzer*.
It converts electrical energy into chemical energy, making it possible to store it, convert it into further energy vectors, transporting it according to the most effective manner and use it, as a feedstock, as a fuel or transformed back into electricity.



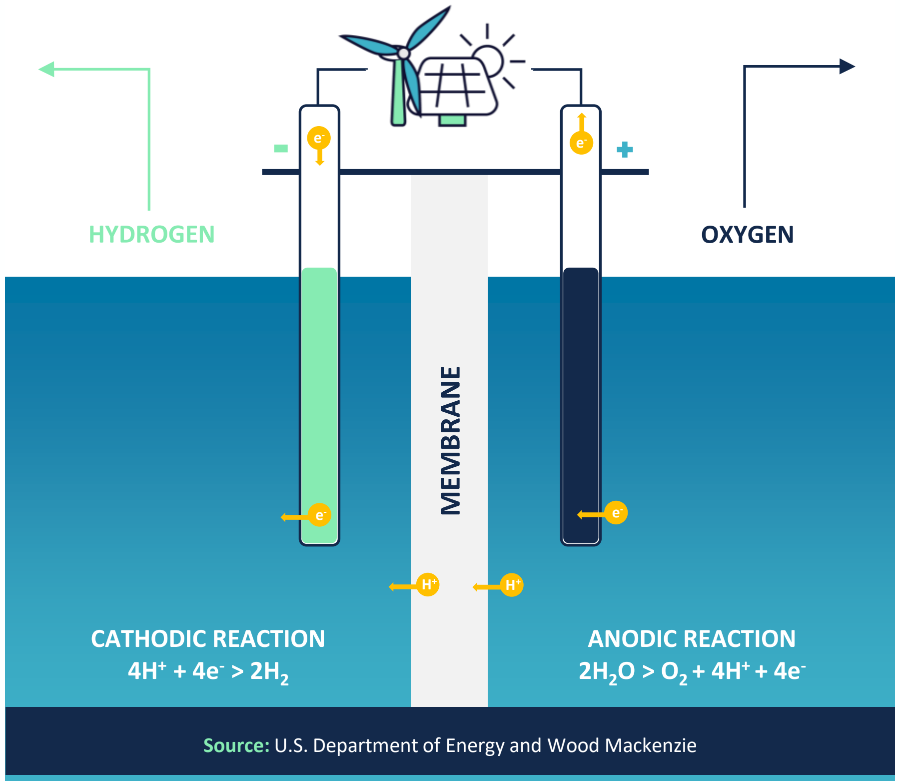
Green hydrogen production is a fundamental building block of the value chain. However, to ensure large scale deployment a holistic approach needs to be applied, covering all the building blocks.
Design, manufacturing and operation of electrolyzers have to be done in parallel with renewables projects, infrastructure development and the demand (including the adoption of new technologies by industry and end users). Also, standardization, a clear regulatory framework, personnel education, and thus investments, are essential aspects of the picture.

Electrolyzers: the working principle

Water electrolysers are electrochemical devices used to split water molecules into hydrogen and oxygen by passage of an electrical current.

The core of an electrolyzer is the *electrolytic cell*, where electrochemical reactions take place. According to basic principles of *electrochemistry*, the electrolysis of water occurs when a *direct current* is passed between two *electrodes immersed in an electrolyte* giving rise to *reactions* at the electrodes where the product gases are released: hydrogen and oxygen.

Once the products are released a physical separation is needed to avoid the mixture.

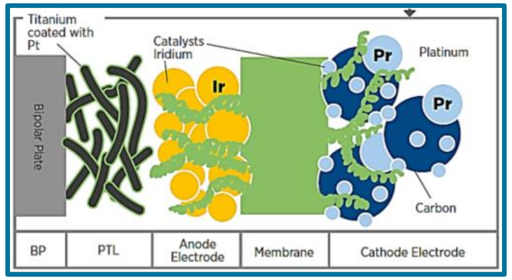


An electrolytic CELL

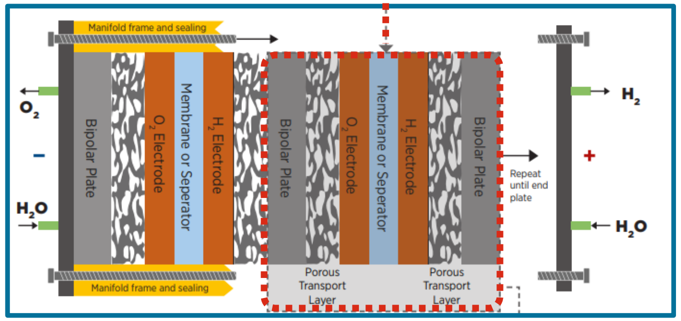
Electrolyzers: how they are made

From the cell to the stack to the system

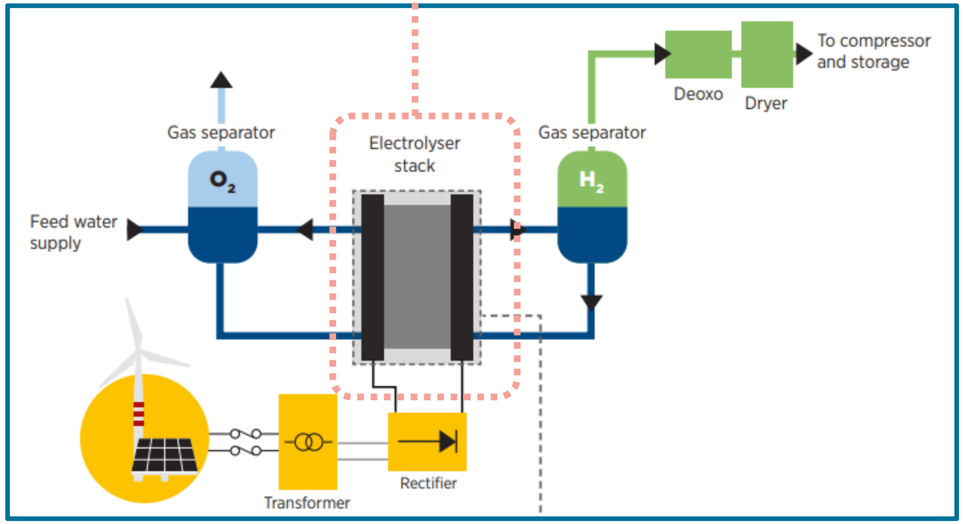
The single *cell* is where the electrochemical process takes place. It is composed of two electrodes immersed in a liquid electrolyte or adjacent to a solid electrolyte membrane, two porous transport layers (to facilitate the transport of reactants and removal of products) and the bipolar plates for mechanical support and flow distribution. The *stack* includes multiple cells connected in series, spacers made by insulating material seals, frames and end plates (to avoid leaks and collect fluids). The *system* level (or balance of plant) goes beyond the stack to include equipment for converting the electricity input (e.g., transformer and rectifier), treating the water (e.g., deionization) cooling and processing the hydrogen.



CELL LEVEL



STACK LEVEL



SYSTEM LEVEL: the ELECTROLYZER

Source: IRENA, Green hydrogen cost reduction - Scaling up electrolysers to meet the 1.5°c h climate goal

Available electrolyzers today: some figures

$2\ H_2O \rightarrow 2H_2 + O_2$

Water required to produce 1 kg of hydrogen* (high water purity required: 99.8% to 99.9998%)	9 l/kg of hydrogen: stechiometric value 10 - 11 l/kg of hydrogen: de-ionized water 20 - 25 l/kg of hydrogen: tap water
Energy required to produce 1 kg of hydrogen *	about **50 kWh/kg** of hydrogen
Hydrogen energy density: • Lower heating value • Higher heating value	 **33.33 kWh/kg** of hydrogen (3.00 kWh/Nm³ - 120,1 MJ/kg) 39.39 kWh/kg (3.54 kWh/Nm³ - 141,9 MJ/kg)
Electrolyzer system efficiency (BoP included)*	55% - 75%
Hydrogen density	0,089 kg/m3 @ 0°C, 1 bar: a volume of ab. **11 m³** to store **1 kg** of H_2 0,081 kg/m3 @ 25°C, 1 bar

* Data refer to the most mature electrolyzers in the market, Alkaline and Proton Exchange Membrane electrolyzers. They are closely dependent on the electrolysis type and system design

Available electrolyzers today

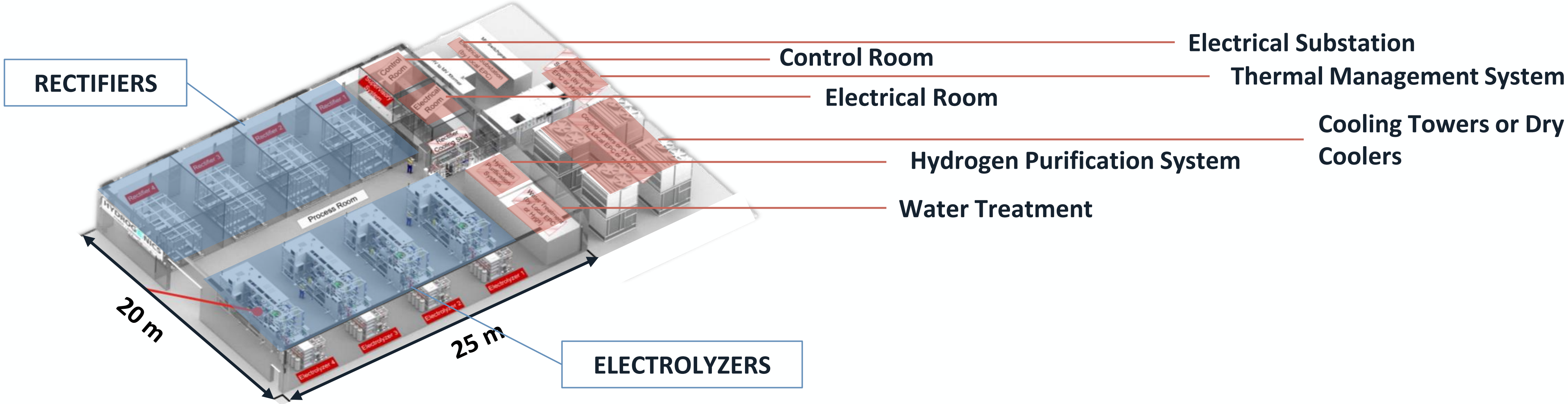
There is no single electrolyzer technology that performs better across all dimensions

	ALKALINE (AEL)	PROTON EXCHANGE MEMBRANE (PEM)	ANION EXCHANGE MEMBRANE (AEM)	SOLID OXIDE (SOEC)
	 **Cargo van** Reliable, proven, low CAPEX	 **Race car** Flexible, compact but higH CAPEX	 **New concept** New and promising but still immature	 **Off-road car** High performer in the right environment
Strength	▪ Long established tech. ▪ Cheap (CAPEX) ▪ Made with abundant materials on the Earth ▪ Long lifetime	▪ High flexibility to load changes ▪ Compact footprint ▪ High H2 output pressure ▪ High H2 purity	▪ High flexibility ▪ Compact footprint ▪ No need for Critical Raw Materials	▪ Highest efficiency, IF waste heat is available ▪ Resilient to impurities ▪ High H2 purity
Weakness	▪ Low flexibility ▪ Limited output pressure	▪ Expensive (noble materials) ▪ Need for Critical Raw Materials (CRMs)	▪ Low maturity ▪ Short lifetime ▪ Low performances	▪ Long cold start ▪ Short lifetime ▪ Lower scale & maturity than AEL and PEM

Available electrolyzers today some figures

	2020				2050			
	Alkaline	PEM	AEM	SOEC	Alkaline	PEM	AEM	SOEC
Cell pressure [bara]	< 30	< 70	< 35	< 10	> 70	> 70	> 70	> 20
System efficiency [kWh/kg H_2]	50 - 78	50 - 83	57 - 69	45 - 55	< 45	< 45	< 45	< 40
Lifetime [thousands hours]	60	50 - 80	> 5	< 20	100	100 - 120	100	80
System capital cost [USD/kWel]	500 - 1000	700 – 1400	-	-	< 200	< 200	< 200	< 300

Example of a 20 MW electrolyzer system by Cummins (4 x 2,5 MW)



IRENA: 1 GW plant coud occupy about 0,17 km² of land, an area equivalent to Manhattan (New York)

How to select the best electrolyzer

ALKALINE (AEL)

The ideal project environment is **large-scale industrial installations** requiring a **steady H2-output** at **low pressure levels**.
In this scenario, the electrolyzer is typically **grid-connected**, operated at **high utilization and steady load**.
H_2-production is often located **close to the demand center** with no need for high compression.

PROTON EXCHANGE MEMBRANE (PEM)

Well suited for **off-grid installations** powered by **highly variable renewable energy sources** (e.g., wind turbines, PV plants). The co-location, close to the renewable power plant and dynamic operation mode, often entails a **need for compression** to transport and store hydrogen. The high load variability combined with the demand for elevated output pressure, the **small footprint** and **low maintenance needs**, make the PEM the ideal candidate for the **offshore environment**.

SOLID OXIDE (SOEC)

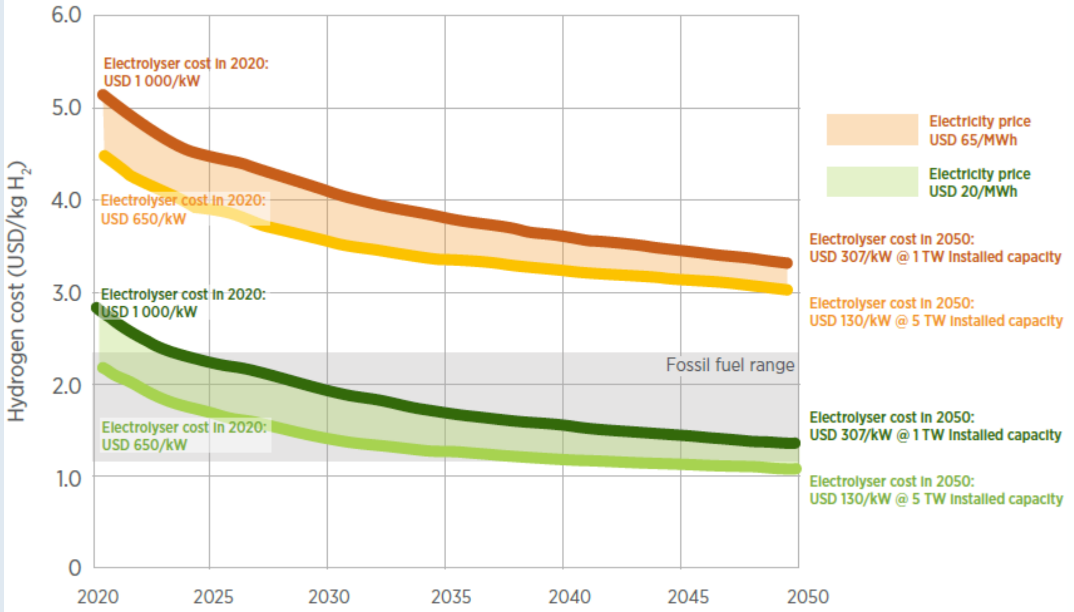
They work very well when coupled with exothermal reactions, in locations where waste heat is available: for example, in the methanation processes of Power to Hydrogen to Gas, ammonia plants, refineries, etc

How much will it cost to produce green hydrogen?

The most important components influencing the cost of green hydrogen production are the cost of the **renewable electricity** needed to power the electrolyzer unit and the **electrolyzer** itself.

VARIABLES and ASSUMPTIONS:

- Time interval: 2020 to 2050 - cost reductions in 2050 include efficiency improvement and the electrolyzer cost guaranteed by scale effect for the capacity deployment increase
- Renewable electricity price: 20 USD/MWh (low-cost) and 65 USD/MWh (average cost)
- Electrolyzer cost:
  •in 2020: 650 USD/kW and 1000 USD/kW
  •in 2050: 130 USD/kW and 307 USD/kW
- Electrolysis deployment: 1 TW and 5 TW
- Only bare technical production costs are considered: conversion/transport cost to demand centres are not included



*Source: **IRENA 2022** Green hydrogen cost reduction - Scaling up electrolyzers to meet the 1,5 °C climate goal*

- Low costs of electricity are a necessary condition for producing competitive green hydrogen (green area).
- Cost reductions in electrolysers cannot compensate for high electricity prices.
- Combined with low electricity cost, an aggressive electrolyser deployment pathway (5TW) can make green hydrogen cheaper than any low-carbon alternative (i.e., < USD 1/kg), before 2040. If rapid scale-up takes place in the next decade, green hydrogen is expected to start becoming competitive with blue hydrogen by 2030 in a wide range of countries, where the electricity prices is ab. 30 USD/MWh

These are only bare technical production costs,16
and transport transport cost to demand centres needs to be considered on top

Electrolyzers: what's next

R&D on technologies:

- Goals: cost reduction and performance improvement
- Both on novel concepts (e.g. salty water electrolyzers) and improvements to existing technologies
- Reduction of use of critical raw material

Upscaling of electrolyzers production capacity:

- Cost reduction by economies of scale
- Maunfacturing capacity incease at the gigawatt scale supported by national fianancing
- Automation of the production process
- Standardization of the systems

Personnel:

- Training experienced and qualified personnel

Growth of the value chain

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