

Green Hydrogen Production: Electrolyzer Markets 2023-2033

Alkaline electrolyzer (AWE), polymer membrane electrolyzer (PEM) and solid oxide electrolyzer (SOEC), techno-economic analysis, players, applications, forecasts.

Alex Holland

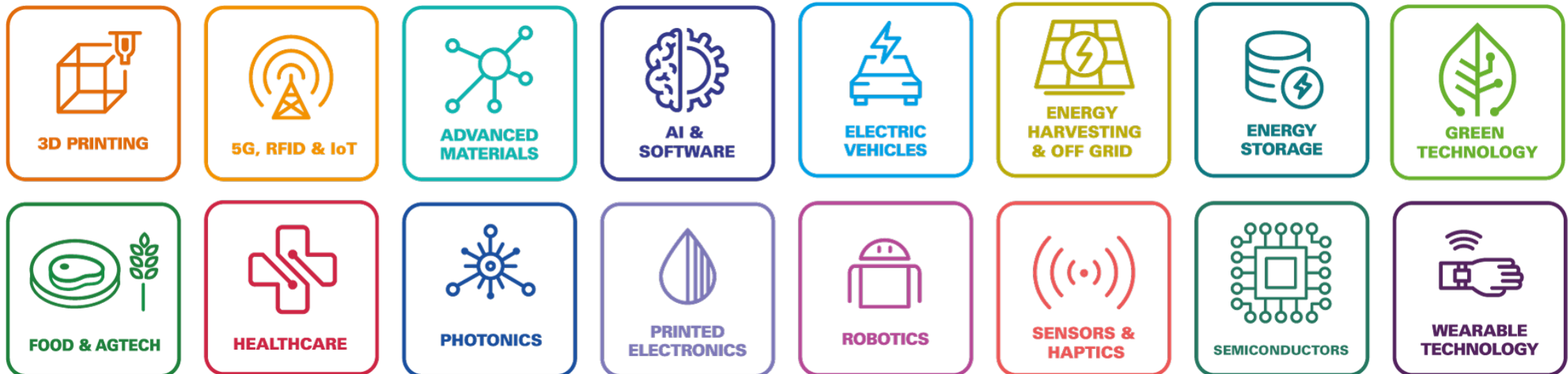


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IDTechEx forecasts the water electrolyzer market to reach over US\$120B by 2033

Green Hydrogen Production: Electrolyzer Markets 2023-2033

IDTechEx forecasts the water electrolyzer market to grow to over US\$120B by 2033. While previous periods of hype for green hydrogen and the hydrogen economy have waned, significant capital, both public and private, is now being spent on developing water electrolysis systems for the production of green hydrogen. Hydrogen demand is expected to grow globally from both incumbent markets, including refining and ammonia production, as well as from new markets such as in methanol, green steel, and transport applications. This increase in hydrogen production and use is being driven by a growing desire to improve energy security and by decarbonisation efforts. However, to play a role in decarbonisation, the hydrogen produced must itself be low carbon.

[IDTechEx.com/electrolyzer](https://www.IDTechEx.com/electrolyzer)

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Forecasts to:	2033
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<u>Introduction</u>	15 slides
<u>Policy and regulation</u>	21 slides
<u>Electrolyzer technology</u> • Alkaline (AEL, AWE) • Proton-exchange-membrane (PEM) • Solid-oxide (SOEL) • Cost analysis	82 slides
<u>Electrolyzer market landscape</u> • Key players • Production capacities • Regional targets • Regulation and policy impact	32 slides
<u>Company Profiles</u>	15 companies profiled
<u>Forecasts</u>	9 slides

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Drivers	Restraints
Environmental targets and goals	Cost competitive green H ₂ production heavily reliant on electricity costs/prices.
Government and public funding	Uncertain capability and impact on flexible and dynamic electrolyzer operation, especially for alkaline and solid-oxide electrolyzers.
ESG targets from private companies and industries	Demand for platinum group metals problematic for PEM electrolyzers
Reduction in renewable power capex	Competition from potentially cheaper blue H ₂ and business as usual grey H ₂
Reduction in electrolyzer capex from electrolyzer manufacturing scale	Large water demand and requirement including potential need for desalination
Diversification from fossil sources and greater energy security	Increase in electrolyzer manufacturing capacity required.

The vast majority of hydrogen produced today is grey hydrogen, produced from coal or natural gas. Estimates put hydrogen production at ~3% of global GHG emissions. While small compared to energy, power and transport, it is not insignificant and hydrogen consumption is expected to increase steadily over the next few decades.

Green hydrogen is produced through the electrolysis of water with associated emissions primarily stemming from the carbon intensity of the electricity used to operate the water electrolyzer. However, green hydrogen is estimated to account for a very small percentage of the global hydrogen market, and is estimated to contribute <1% to the total hydrogen market.

Hydrogen has the potential to be an important tool in the decarbonisation of a number of sectors, but especially hard-to-abate sectors. In addition to enabling a low carbon source of hydrogen for refining and ammonia, growth sectors include steel, transport, methanol and power/heat generation.

However, difficult challenges remain regarding the economics of green hydrogen production, scale of electrolyzer manufacturing required, and the necessary investment into the storage, transport and distribution infrastructure, not to mention the eventual use of hydrogen in its intended end-use application.

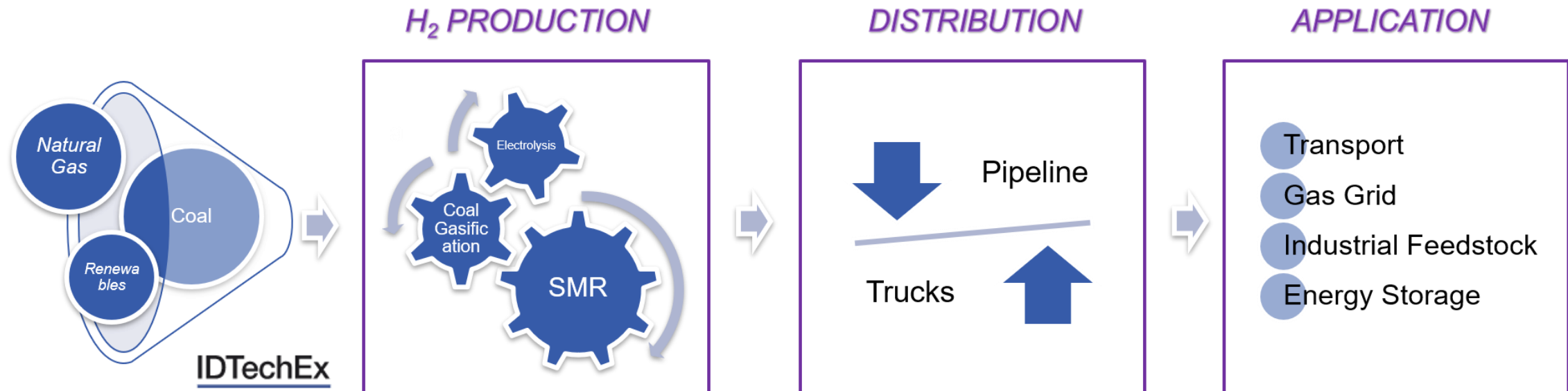


What is the Hydrogen Economy?

Hydrogen can be used in different ways: as fuel for vehicles, as an energy storage medium, as feedstock material in different industries (i.e. steel industry, ammonia production, etc). Because of the multiple applications, the term hydrogen economy is used to describe the combination of different sectors to producing, trading and consuming hydrogen.

Moreover, hydrogen can be produced from different sources (e.g. natural gas, ammonia, coal, renewable energies, and others), and at the same time it can be stored in different ways.

Because of the wide use of hydrogen in many sectors, and the possibility of producing it without emissions using electrolyzers, the hydrogen economy has broadly two important aims: decarbonisation of various sectors and the diversification in reliance from fossil fuel producing countries.



The **vast majority of hydrogen currently used is grey hydrogen**, produced via steam methane reformation for use in refineries or the production of ammonia. As such, there is **large room for growth in green hydrogen**.

Electrolyzers use electricity to split water into hydrogen and oxygen. In recent years, colours have also been assigned to electrolytic hydrogen produced from specified electricity sources. For example, yellow can refer to hydrogen produced from a mixed electricity grid (though it has also been referred to electrolysis powered by solar PV), while pink/purple hydrogen has been used to describe electrolytic hydrogen using nuclear power as the electricity source.

A Kaleidoscope of Hydrogen Colors



Canada. Aim to establish large-scale blue hydrogen for domestic use and transatlantic export. \$1.1 billion funding over five years

UK. 10 GW of H₂ by 2030, with at least 5 GW of electrolyzer and the rest from blue H₂.

EU. 10MMT clean H₂ produced and imported each by 2030. \$2.5B funding. Some countries, e.g. Netherlands, have plans for blue hydrogen.

China. 0.1-0.2MMT green H₂ produced by 2025.

Japan. 3MMT H₂ consumed by 2030. \$3.4B funding for green H₂.

Korea. 2MMT H₂ consumed by 2030. \$2B funding for green H₂.

Australia. Aims to be top 3 exporter of H₂ to Asia by 2030.

USA. 10MMT clean H₂ produced by 2030. \$3/kg tax credit for clean H₂. \$7B funding.

Chile. 5 GW of electrolyzer by 2025, 25 GW by 2030.

South Africa. 11.7 GW of electrolyzer by 2030.

Saudi Arabia. 2.9MMT of green H₂ a year by 2030.

India. 5MMT of green H₂ a year by 2030.

Putting a price on carbon emissions is an established method of encouraging polluters to reduce the amount of greenhouse gases they emit into the atmosphere.

Economists generally agree that introducing a carbon price is an effective way for a country to reduce its emissions.

There are multiple ways governments can price carbon, all of which lead to the same result. They help to capture the “external” costs of carbon emissions – costs the public pays for in other ways, such as damage to crops, healthcare costs from heat waves and droughts, or to property from flooding and sea level rise – and tie them to their source through a price on carbon.

The Two Main Types of Carbon Pricing

Emissions trading systems (ETS)

Sometimes called a cap-and-trade system, an ETS caps the total level of greenhouse gas emissions and lets industries with low emissions to sell their extra allowances to larger emitters.

This creates supply and demand for emissions allowances, creating a market price for greenhouse gas emissions. The cap helps ensure that the required emissions reductions will take place to keep the emitters (in aggregate) within their pre-allocated carbon budget.

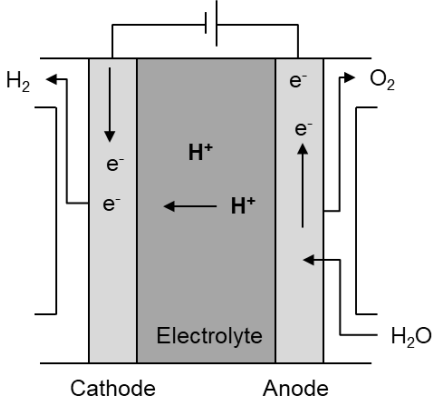
Carbon tax

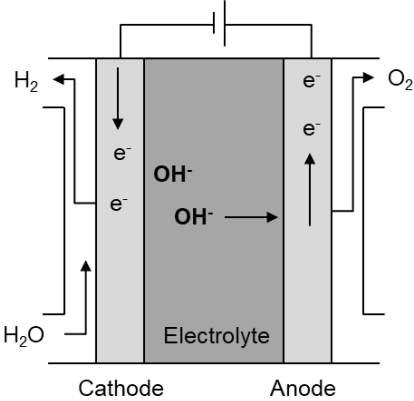
A carbon tax directly sets a price on carbon by defining a tax rate on greenhouse gas emissions or, more commonly, and the carbon content of fossil fuels.

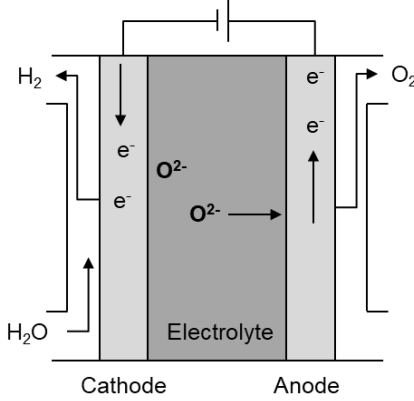
It differs from an ETS in that the emission reduction outcome of a carbon tax is not pre-defined, but the carbon price is.

Three general types of electrolyzers have been developed: alkaline water electrolyzer (AWE), proton exchange membrane electrolyzer (PEMEL), and solid oxide electrolyzers (SOEL). The three types of systems employ water and electricity to split water into hydrogen and oxygen. The three systems are characterised by different ions exchanged between the two electrodes, OH^- , H^+ , and O^{2-} for AWE, PEMEL, and SOEL respectively, the electrolyte and electrode materials used, stack designs, and system designs.

AWE systems are the oldest and most adopted at industrial scale, with the first installations starting in the 1920s. The first installations of PEMEL systems were recorded in the 2000s. The electrolyzer market is currently split between these two technologies: alkaline and PEMEL with SOEL starting to enter the market.

	PEM electrolyser  Cathode Anode
Electrolyte	Polymer e.g. Nafion
Cathode	Pt, Pt-Pd
Anode	RuO_2 , IrO_2

	Alkaline electrolyser  Cathode Anode
Electrolyte	KOH solution
Cathode	Ni, Ni-Mo alloys
Anode	Ni, Ni-Mo alloys

	Solid oxide electrolyser  Cathode Anode
Electrolyte	YSZ (yttrium stabilized zirconia)
Cathode	LSM/YSZ (lanthanum strontium manganite)
Anode	Ni/YSZ

Source: IDTechEx



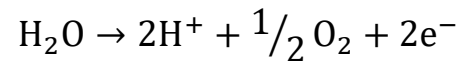
Company	Type	Model	H ₂ production rate (Nm ₃ /h)	Size (MW)	Minimum flow/load	Hydrogen purity	DC efficiency (kWh/Nm ³)	Output H ₂ pressure (barg)	Ramp (idle) - start-up time
Cummins	PEM	HyLyzer 200-30	200	1	Not specified	Not specified	4.87	30	Not specified
Cummins	PEM	HyLyzer 4000-30	4000	20	Not specified	Not specified	4.51	30	Not specified
Johnson Matthey	PEM	HyLynx 1000	1000	10	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 2000	2000	20	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 4000	4000	40	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 8000	8000	80	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 16000	16000	160	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 32000	32000	320	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 64000	64000	640	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 128000	128000	1280	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 256000	256000	2560	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 512000	512000	5120	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 1024000	1024000	10240	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 2048000	2048000	20480	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 4096000	4096000	40960	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 8192000	8192000	81920	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 16384000	16384000	163840	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 32768000	32768000	327680	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 65536000	65536000	655360	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 131072000	131072000	1310720	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 262144000	262144000	2621440	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 524288000	524288000	5242880	Not specified	Not specified	4.5	30	Not specified
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Johnson Matthey	PEM	HyLynx 2097152000	2097152000	20971520	Not specified	Not specified	4.5	30	Not specified
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Johnson Matthey	PEM	HyLynx 8388608000	8388608000	83886080	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 16777216000	16777216000	167772160	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 33554432000	33554432000	335544320	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 67108864000	67108864000	671088640	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 134217728000	134217728000	1342177280	Not specified	Not specified	4.5	30	Not specified
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Johnson Matthey	PEM	HyLynx 536870912000	536870912000	5368709120	Not specified	Not specified	4.5	30	Not specified
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Johnson Matthey	PEM	HyLynx 4503599627370496000	4503599627370496000	45035996273704960	Not specified	Not specified	4.5	30	Not specified
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Johnson Matthey	PEM	HyLynx 302231454903657293676544000	302231454903657293676544000	3022314549036572936765440	Not specified	Not specified	4.5	30	Not specified
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Johnson Matthey	PEM	HyLynx 4835703278458516698824704000	4835703278458516698824704000	48357032784585166988247040	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 9671406556917033397649408000	9671406556917033397649408000	96714065569170333976494080	Not specified	Not specified	4.5	30	Not specified
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Johnson Matthey	PEM	HyLynx 309485009821345068724781056000	309485009821345068724781056000	3094850098213450687247810560	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 618970019642690137449562112000	618970019642690137449562112000	6189700196426901374495621120	Not specified	Not specified	4.5	30	Not specified
Johnson Matthey	PEM	HyLynx 1237940039285380274899124224000	1237940039285380274899124224000	12379400392853802748991242240	Not specified	Not specified	4.5	30	Not specified
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Johnson Matthey	PEM	HyLynx 4951760157141521099596496896000	4951760157141521099596496896000	49517601571415210995964968960	Not specified	Not specified	4.5	30	Not specified
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Johnson Matthey	PEM	HyLynx 3961408							

Proton Exchange Membrane or Polymer Electrolyte Membrane Electrolyzers (PEMEL), also called Proton Exchange Membrane Water Electrolyzers (PEMWE) are electrochemical devices employed for the production of hydrogen and oxygen, employing water as feedstock and electricity as an energy source to split the water molecule.

Structurally similar to the PEM Fuel Cell, the PEMWE is technically different from it due to the catalyst, materials, and operation condition.

ANODE:

Oxygen Evolution Reaction (OER) – $V_{\text{applied}}: 1.5\text{V} - 2\text{V}$

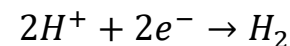


CATALYST: $\text{RuO}_2/\text{IrO}_2$ - loading: $0.8\text{-}2\text{ mg/cm}^2$

SUPPORT: TiO_2 , SnO_2 , Ta_2O_5 , Nb_2O_5 , Sb_2O_5 , TaC, TiC

CATHODE:

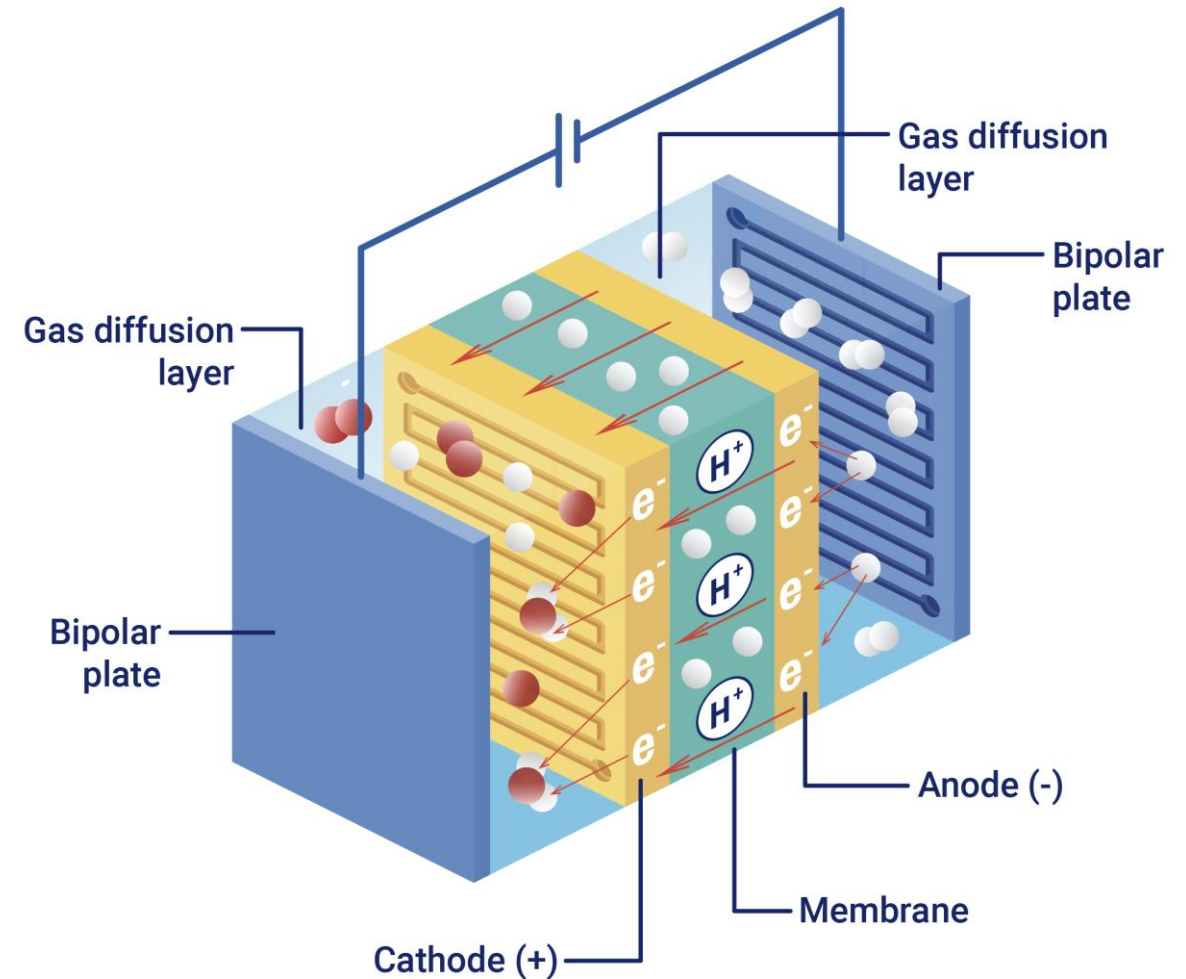
Hydrogen Evolution Reaction (HER) – $V_{\text{Applied}}: 0.5\text{V} - 1\text{V}$



CATALYST: Pt - loading: $0.2\text{-}1\text{ mg/cm}^2$

SUPPORT: Carbon black/ CNT

Schematic Representation of a PEM Electrolyzer

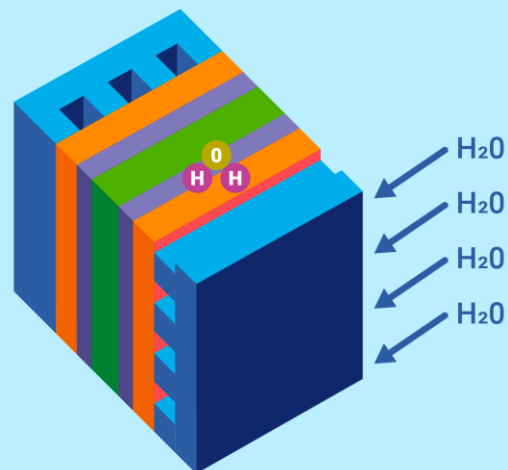


1



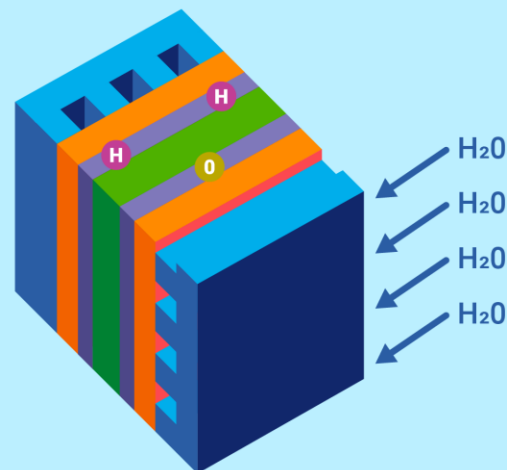
PEM electrolyte
Electroactive material
Current collector
Bipolar plates

2



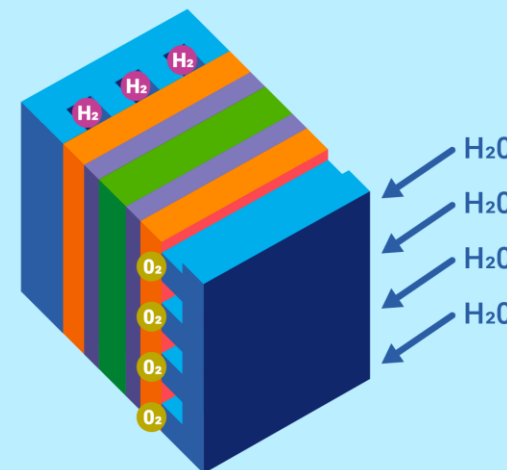
Water enters from the anode side (oxygen), and flows through the current collector getting in contact with the anode electrode (TiO₂-IrO₂ electroactive material).

3



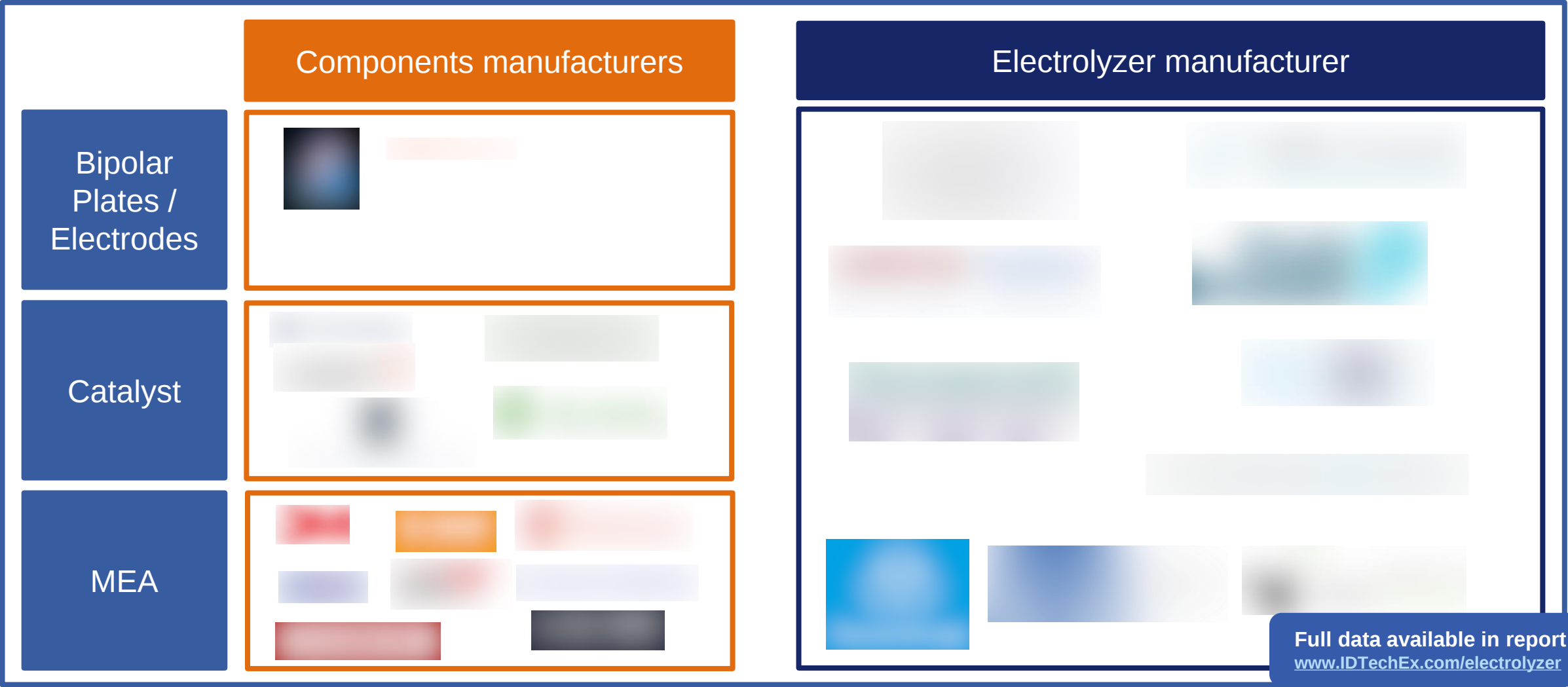
Water is then split into protons which flow through the PTFE membrane and react on the cathode surface. Molecular oxygen is formed on the anode surface.

4



Molecular oxygen diffuses back across the current collector (against the water flows), and diffuses out of the cell.

Molecular hydrogen, after being formed on the cathode surface, diffuses across the current collector into the separator plates, and out of the cell.

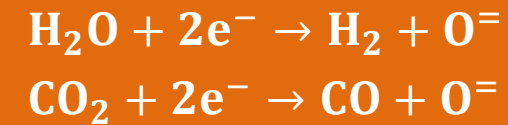


The solid oxide electrolyzers (in short SOEL or SOEC) operate at high temperatures (600-850°C) to split water vapor into hydrogen and oxygen. The high operating temperatures also allow them to employ CO₂ as fuel, which leads to formation of CO, and O₂. Water vapor and CO₂ can therefore be used together to produce H₂/CO also called Syngas. Syngas is the feedstock of the chemical process called Fischer-Tropsch, which is the core reaction for production of synthetic fuels.

Anode – Oxygen electrode



Cathode – Hydrogen electrode



The SOEC high operating working temperatures are required to:

- Allow the solid electrolyte to conduct O²⁻ ions
- Increase the reaction kinetic (hence larger current density), and decrease the applied thermoneutral voltage (V_{TN})

The reduced V_{TN} is translated in both lower operational costs (since lower applied

potentials are required) and lower capital costs (since a reduced number of electrolyzers are required).

SOECs can be thermally integrated with a range of chemical syntheses, enabling recycling of captured CO₂ and H₂O into synthetic natural gas or gasoline, methanol, or ammonia, resulting in further efficiency improvements compared with low temperature electrolysis technologies.



Anode (Oxygen electrode):

The most common material is **Sr-doped LaMnO₃ (LSM) perovskite oxide**, because of its good catalytic activity at high temperatures, high electrical conductivity, and good thermal and chemical compatibility with YSZ electrolytes. Addition of oxides and nanoparticles (NPs) are also included in the base LSM material to enhance its properties.

For higher-performing applications, there are electrodes based on mixed conductors, such as lanthanum-strontium-ferritecobaltite (**LSCF**) or lanthanum-strontiumcobaltite (**LSC**).

YSZ oxide forms a composite electrode YSZ-LSM, together with NPs of gadolinium-doped ceria (GDC), and Pd into LSM are employed to improve the three-phase boundary (TPB), and electrode activity.

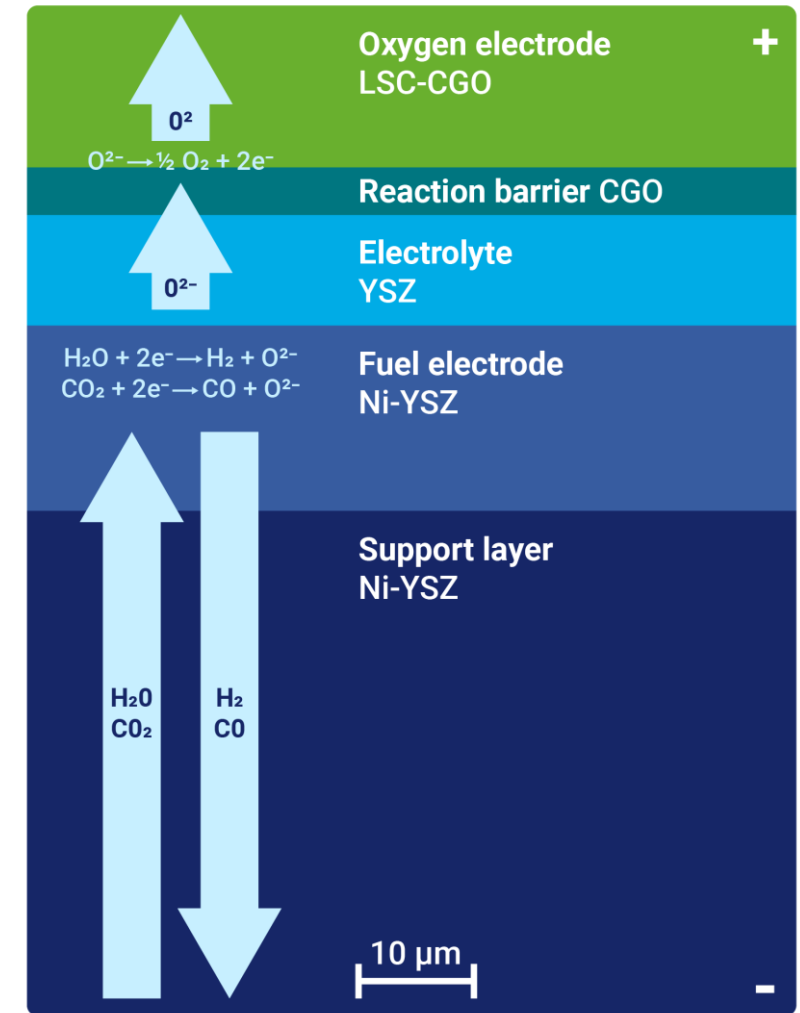
Moreover, thin layers (0.1- to 5- μm) of gadolinia-doped ceria (**GGO**) are commonly used to prevent reaction between oxygen electrode materials and YSZ.

Cathode (Hydrogen electrode):

Ni-based cermet (cermet: ceramic-metals composite material) is the most commonly used anode material, due to its high electrical and catalytic activity, and low cost. Moreover, the Ni-YSZ enlarge the TPB at the anode side.

Improvement of catalytic and electrical conductivity of the hydrogen electrode is obtained by addition of ceria nanoparticles in Ni-YSZ, and Ni infiltrated ceria electrodes.

SOEC Single Cell Representation



AEL systems are characterised by a lower efficiency than PEMEL systems.

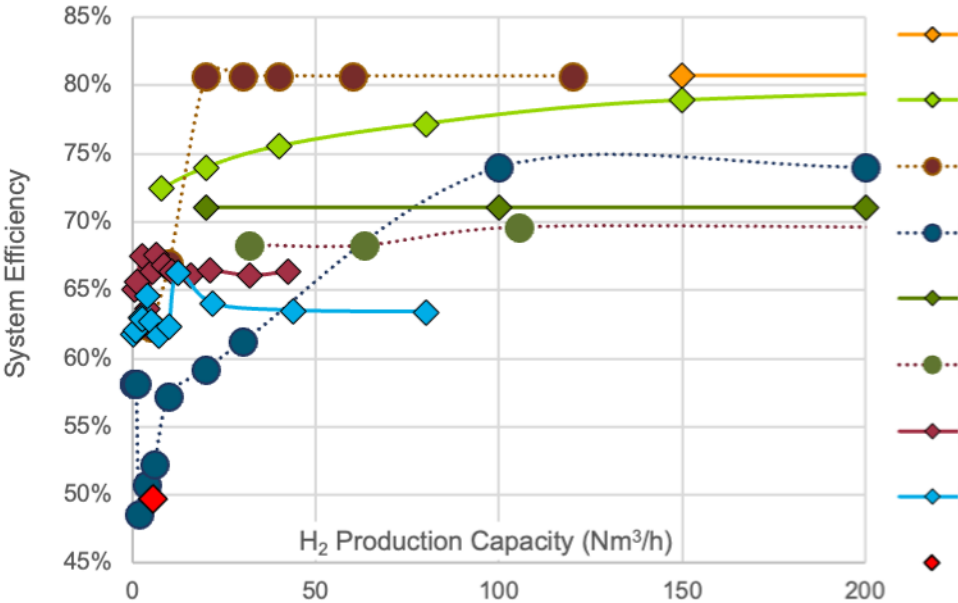
Although this is true, at first sight the AEL systems present a comparable efficiency to PEMEL. The key parameter which shows the higher efficiency of the PEMEL systems is actually the hydrogen purity.

In fact, by comparing the efficiency of Teledyne AEL system, which presents a high hydrogen purity of 99.9998% comparable with PEMEL purity, Teledyne

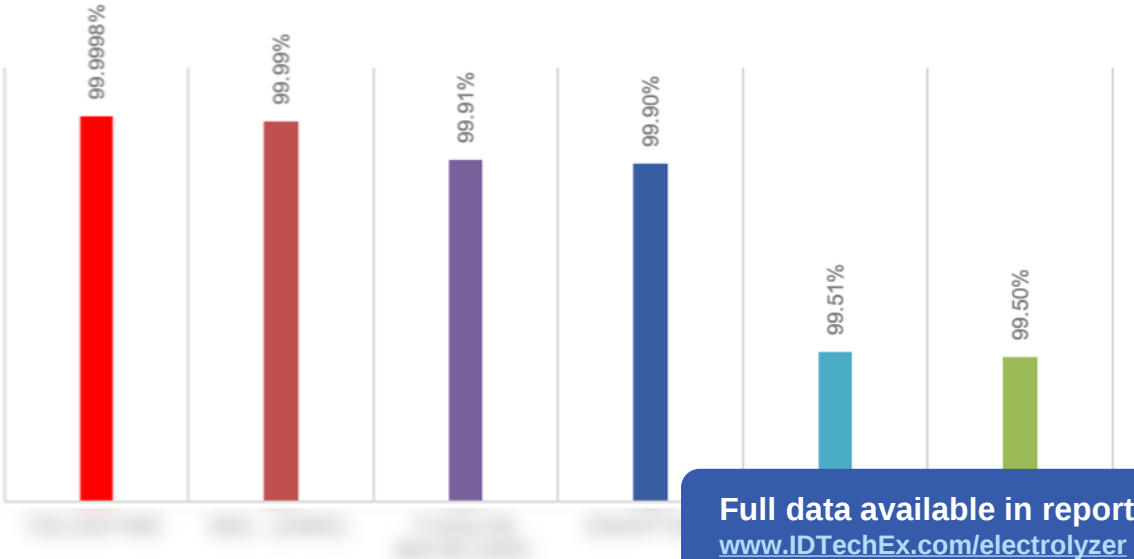
systems present a lower efficiency in comparison with most of the commercialised PEMEL device with the same hydrogen production capacity.

Therefore, the advantage of PEMEL systems comes from the hydrogen purity these devices can provide, and their future application will mostly be driven by the necessity of high hydrogen purity.

PEMEL - AEL Efficiency Comparison

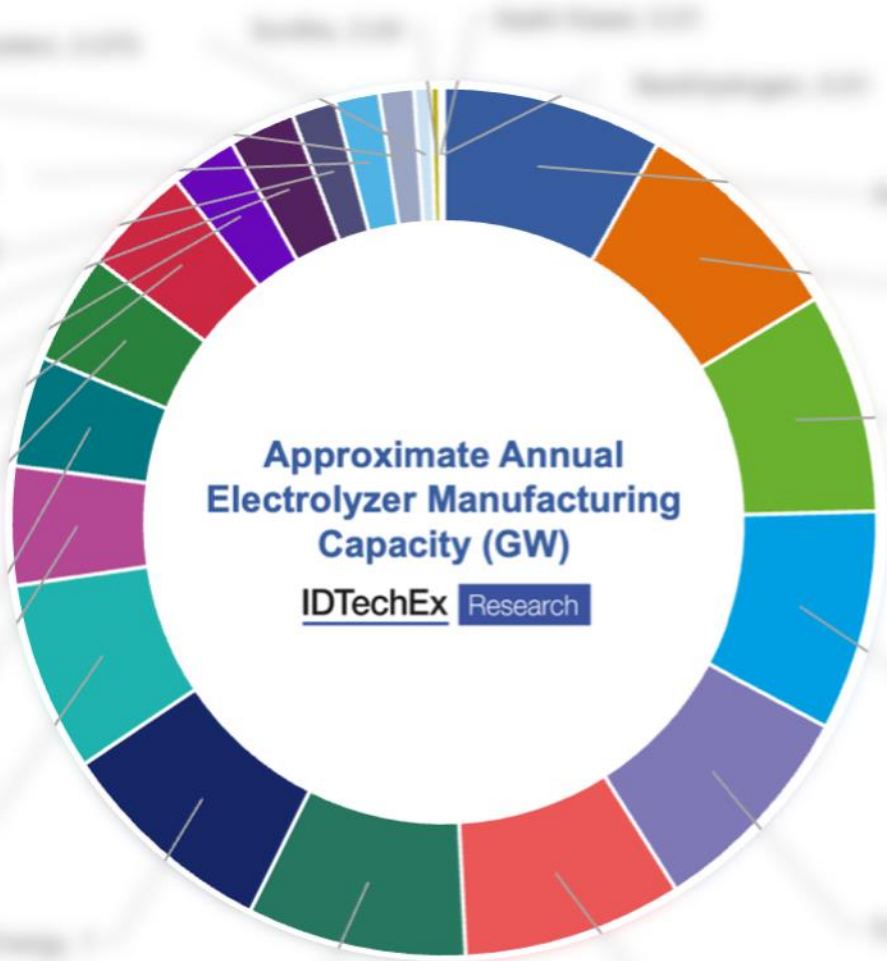


COMMERCIAL AEL - H₂ PURITY



Full data available in report
www.IDTechEx.com/electrolyzer



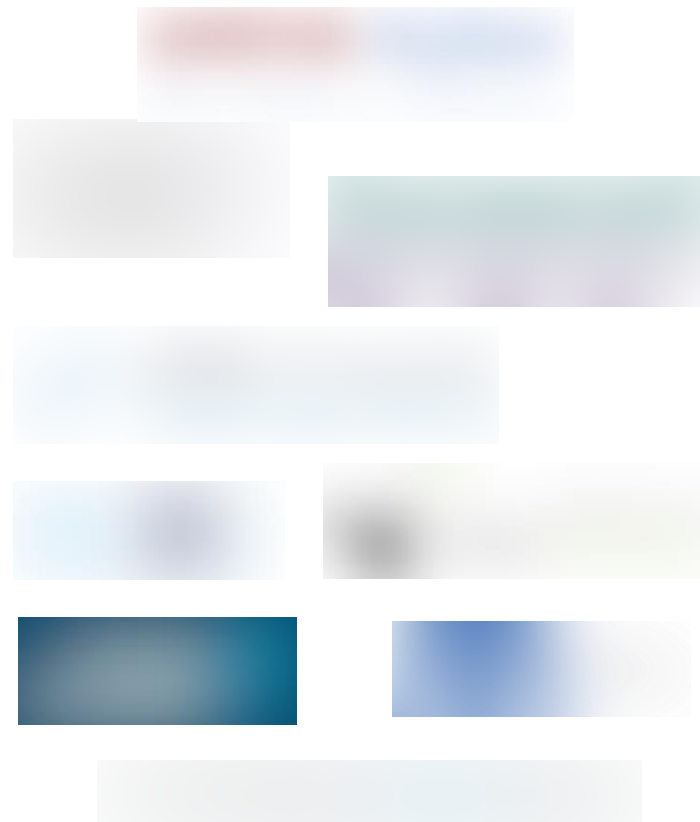


Electrolyzer manufacturing capacity is expected to grow significantly in the coming years, driven by the increasing demand for hydrogen fuel cells in various applications. The market is expected to reach a value of \$1.2 billion by 2025, up from \$0.5 billion in 2020. The market is expected to be dominated by North America and Europe, which together account for over 60% of the total capacity.

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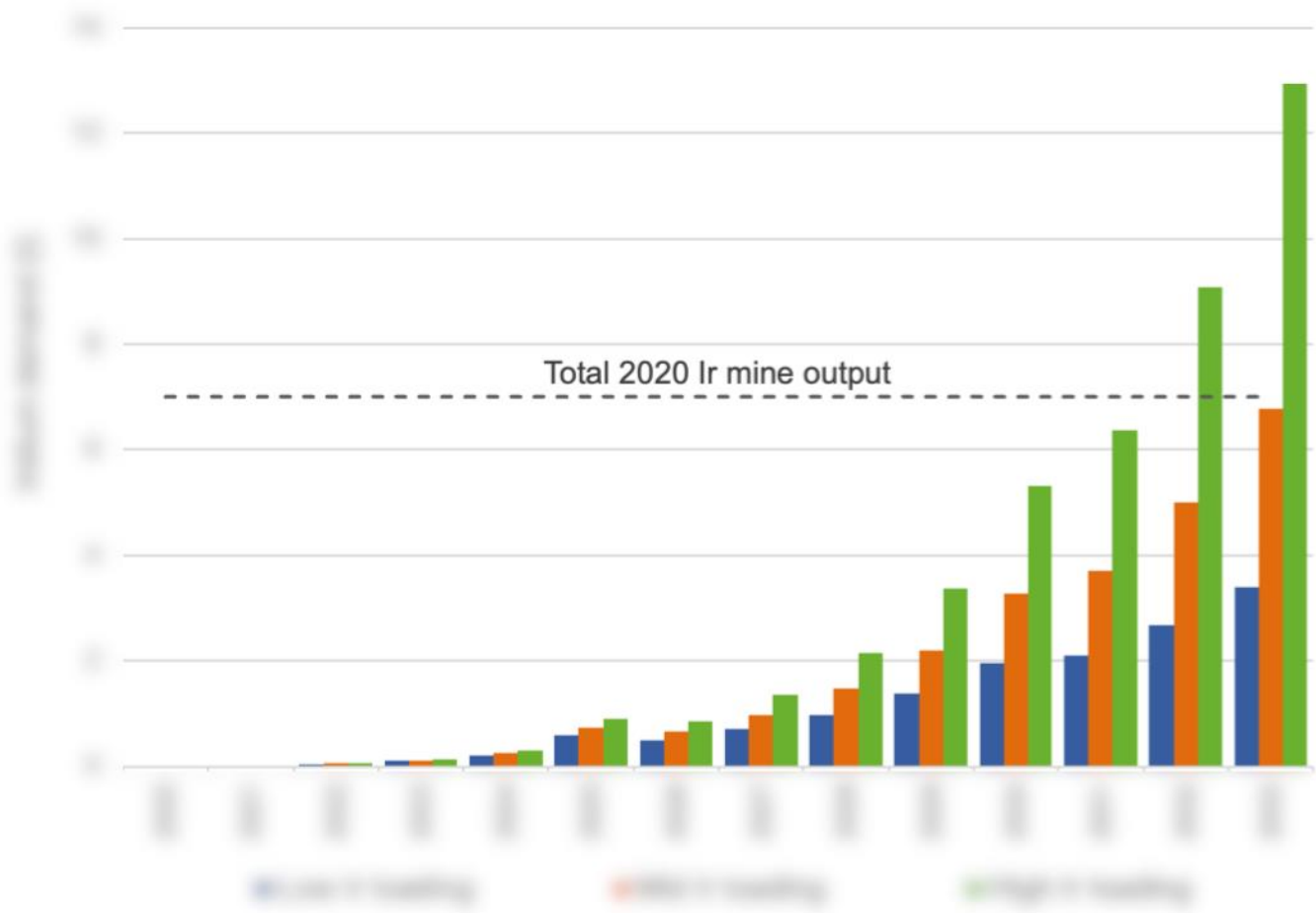
Full data available in report
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AEL	PEMEL	SOEL
		

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PEMEL Ir Demand Outlooks



One of the key disadvantages of PEMELs are their use of PGM metals. This contributes to high capital costs compared to AWE. Furthermore, the use of iridium in particular could put a limit to the growth of the PEMEL market due to the fact that iridium is one of the rarest metals on Earth.

The catalyst demand outlook presented in this report is based on the current state of the market and is subject to change. The catalyst demand outlook is based on the current state of the market and is subject to change.

High demand is expected to be reached by 2027, with demand reaching approximately 10,000 kg.

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