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Large-scale Electrolysis

Technology of the Past to Shape the Future

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April 2021

Intelligence Report

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1. INTRODUCTION

Electrolysis is a process in which electricity, including from renewable sources, is used to split water (H2O) into its component molecules -- hydrogen (H2) and oxygen (O2) -- in systems known as **electrolysers.** Direct current electrolysis was discovered by English scientists William Nicholson and Anthony Carlisle in 1800, thus establishing the scientific field of electrochemistry. Initially, and for a long time, this process dominated the field of industrial hydrogen production, before being displaced by the more cost-effective steam reforming thanks to the increasing adoption of natural gas.

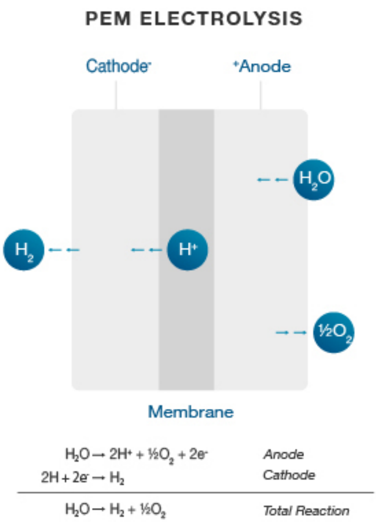
Nowadays, electrolysis is resurfacing as the world focuses on a greener future. Companies increasingly rely on electrolysis to produce hydrogen with zero greenhouse gas emissions, depending on the source of electricity used.

Electrolysers contain an anode and a cathode that are separated by an electrolyte. There are three main types of electrolysers based on the electrolyte material involved -- polymer electrolyte membrane (PEM), alkaline and solid-oxide electrolysers. In addition, there is the much less mature (lab-scale) technology called anion exchange membrane (AEM).

Types of electrolysers

PEM

The electrolyte in a polymer electrolyte membrane (PEM) electrolyser is a solid speciality plastic material. In this type of systems, on the anode side water reacts to form oxygen and positively charged hydrogen ions, or protons, which then move across the PEM to the cathode side and combine with electrons from the external circuit to form hydrogen gas.



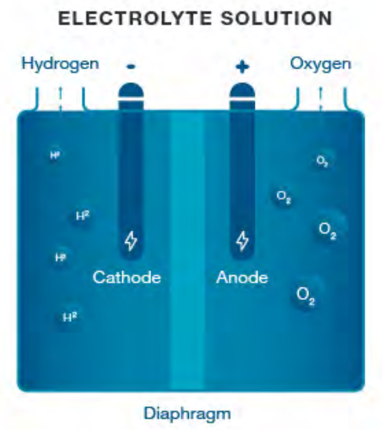
The half-reactions are as follows:

Anode Reaction: 2H2O → O2 + 4H+ + 4e

Cathode Reaction: 4H+ + 4e- → 2H2

Some examples of companies manufacturing PEM electrolysers (in alphabetical order) are: Cummins, Hitachi Zosen, Honda, ITM Power, Nel Hydrogen, Plug Power and Siemens Energy.

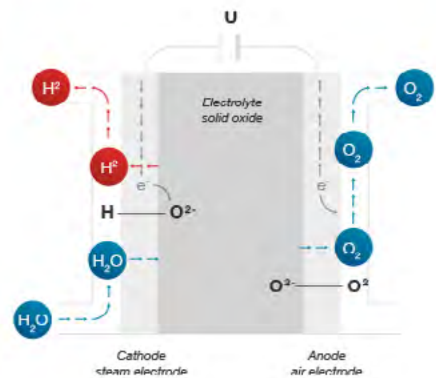
ALKALINE



Alkaline electrolysers include "cells" that consist of an anode, cathode and membrane, and are typically assembled in stacks. The system uses a liquid electrolyte solution such as potassium hydroxide (KOH) or sodium hydroxide (NAOH), and water. By applying current on the cell stack, the hydroxide ions (OH-) move from the cathode to the anode of each cell. This leads to the production of hydrogen gas bubbles at the cathode and oxygen gas on the anode side.

Some examples of companies manufacturing alkaline electrolysers (in alphabetical order) include: Cummins, Green Hydrogen Systems, Hitachi Zosen, McPhy, Nel Hydrogen and ThyssenKrupp Uhde Chlorine Engineers.

SOLID OXIDE (SOEC)



Solid oxide electrolysers are a less mature technology that uses a solid ceramic material as the electrolyte. In these systems, water on the cathode side combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions. Then, these oxygen ions pass through the solid ceramic membrane and react on the anode side to form oxygen gas and generate electrons for the external circuit.

Some examples of companies manufacturing solid oxide electrolysers (in alphabetical order) are: Haldor Topsoe, SOLIDpower, Sunfire and Toshiba.

AEM

On paper, AEM combines the simplicity and efficiency of a PEM electrolyser with the less harsh environment in which alkaline electrolysers operate, but enables the use of non-noble catalysts and titanium-free components. It is the latest of the main technologies to be developed and as such is still dealing with unstable lifetime profiles caused by chemical and mechanical stability issues.

Enapter is among the few companies exclusively focused on the AEM electrolyser manufacturing.

Key performance indicators and differences of the four technologies

In addition to the electrolyte used, another distinguishing factor between the four technologies is the temperature of operation, which ranges from as low as 40°C to as high as 850°C. The already commercialised technologies are in the mid- to low-range, with PEM operating at 50°C to 80°C and alkaline electrolysers operating at 70°C to 90°C. Solid oxide electrolysers are at the upper end of the range, operating at 700-850°C, while AEM does so at 40-60°C. The operating pressure also varies from 1 bar for solid oxide electrolysers, to 1-30 bar for alkaline, up to 35 bar for AEM and up to 70 bar for PEM.

Alkaline electrolysis is a mature technology for large systems. It has the lowest installed cost, but also the highest footprint with 10 ha-17 ha per 1 GW, whereas PEM electrolysers are more flexible and can also be used in small decentralised solutions. Their reduced stack footprint also translates into a 20%-24% reduction in the facility footprint, compared to alkaline, at about of 8 ha-13 ha for a 1 GW facility.
Though still at an early development phase, solid oxide has the highest electrical efficiency and "holds the best promise for a wider adoption thanks to unrivaled energy conversion efficiencies," according to a recent article in Science magazine.

	2020				2020			
	Alkaline	PEM	AEM	SOEC	Alkaline	PEM	AEM	SOEC
Cell pressure [bara]	<30	<70	<35	<10	>70	>70	>70	>20
Efficiency (system) [kWh/Kg H2]	50-78	50-83	57-69	45-55	<45	<45	<45	<40
Lifetime [thousand hours]	60	50-80	>5	<20	100	100-120	100	80
Capital costs estimate for large stacks (stack-only/ >1 MW) [USD/kW]	270	400	-	>2,000	<100	<100	<100	<200
Capital cost range for the entire system, >10 MW	500-1,000	700-1,400	-	-	<200	<200	<200	<300

Table 1: Key performance indicators for the four technologies today and in 2050.

Applications

The different types of electrolysers can be commercialised in power-to-mobility, power-to-fuel, power-to-industry and power-to-gas applications. For instance, they can: produce hydrogen for stations to refuel fuel-cell electric vehicles (EVs); be used in refineries to eliminate sulfur from fossil fuels; provide hydrogen for direct use as an industrial gas in various industries such as the steel and semiconductor sectors; and be used in the production of green chemicals like methanol, ammonia and any other liquid fuel.

Renewable energy producers can turn to electrolysis to address the intermittent nature of these power sources. For instance, electrolysers can be installed at the site of renewable energy plants such as wind and solar parks to produce hydrogen from surplus electricity generation, storing this as compressed gas or liquefied. The hydrogen can then be used in various applications, including in transportation through fuel cells.

In addition to hydrogen, the electrolysis process can also be used for the production of carbon monoxide (CO) as is the case with Danish firm Haldor Topsoe's eCOs solution. It reduces carbon dioxide (CO2) to CO by electrolysis.

Cost

According to estimates included in a report for the US Department of Energy (DOE), presently hydrogen can feasibly be produced from PEM electrolysers at a cost of between USD 4 and USD 6 per kg, from renewable and grid feedstocks.

The table below shows hydrogen production costs from various external analysis and associated assumptions.

Low	High	Year	Electricity cost	Capacity factor	System CapEx	System efficiency	Reference
(USD/kg- H2)	(USD/kg-H2)		(USD/kWh)	(%)	(USD/ kWHyd)	(% LHV)	
4.00	6.00	2020	0.04 - 0.10	20 - 30	750	65	H2Council
3.75	5.10	2018	ATB	ATB	1,124	63	E3/UCI
2.70	6.80	2018	0.023 - 0.085	26 - 48	840	65	IRENA
2.50	6.80	2019	0.035 - 0.045		1,400		BNEF

Table 2: Green hydrogen production costs estimates .

2. KEY SECTOR PLAYERS

This section of the report presents the more notable electrolyser manufacturers around the world, most of which are based in Europe. First come those with the larger (reported) production capacities. Please note that such information is not publicly available for all parties.

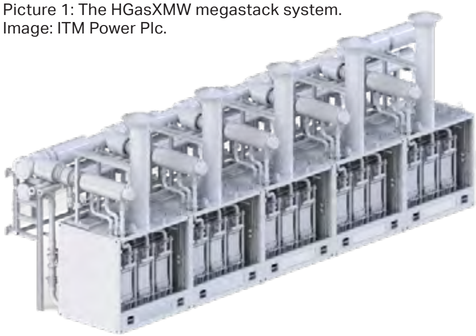
ITM Power

UK-based company ITM Power is a 20-year-old manufacturer of integrated hydrogen energy solutions utilising PEM electrolysers. Its offerings include the HGas1SP, HGas2SP, HGas3SP and HGasXMW systems.

- The HGas1SP, rated at 0.65 MW, is the company's smallest containerised PEM electrolyser system and it includes a single PEM electrolyser stack, capable of producing around 11 kg of hydrogen per hour.
- The HGas2SP, rated at about 1.26 MW, is the company's medium sized containerised PEM electrolyser system that contains two PEM electrolyser stacks capable of producing some 22 kg of hydrogen per hour.
- The HGas3SP, rated at about 2 MW, is the company's largest containerised system, comprising three stacks that can produce around 36 kg of hydrogen per hour.

All three of these products are packaged in two separate ISO containers – one that includes the electrolyser stacks, process equipment, hydrogen purification and a PLC control system, and one that includes power distribution within the equipment and rectifiers for the electrolyser stacks.

Picture 1: The HGasXMW megastack system. Image: ITM Power Plc.



Last but not least is ITM Power's modular system for large-scale hydrogen production – the HGasXMW. It is based on modules of three stacks. Each three-stack module, rated at about 2 MW, is built on a skid frame suitable to be housed indoors. Based on the requirements of the customer, an HGasXMW system installation could include a number of 2-MW modules. ITM Power notes that this product is suitable for: various hydrogen fuel stations; refineries; facilities for methanation, renewable ammonia and renewable methanol; decarbonising heat; and grid balancing.

The following table includes specifics for each of the four products.

Table 3: ITM Power product range.

	HGas1SP	HGas2SP	HGas3SP	HGasXMW
Number of stacks	1	2	3	15
Power supply	400 V AC, 3 Phase, 50 Hz	11 kV AC, 3 Phase, 50 Hz	11 kV AC, 3 Phase, 50 Hz	11 kV AC, 3 Phase, 50 Hz
Control	PLC	PLC	PLC	PLC or DCS
Hydrogen generation pressure (bar)	20	20	20 now / 30 from 2022	20
Hydrogen purity	Up to 99.999% (ISO standard)	Up to 99.999% (ISO standard)	Up to 99.999% (ISO standard)	Up to 99.999% (ISO standard)
Maximum hydrogen production appx (kg/h)*	11	22	36	4,050
Input power at maximum appx (kW)	700	1,390	2,350	10,070

*In the case of HGasXMW, the maximum is for 24 hours.

Speaking to the authors of this report, James Collins, head of investor relations at ITM Power, disclosed that the company is working on an even larger electrolyser system.

"The largest electrolyser that we will make is a 5-MW electrolyser. That will come out within the next 18 months to two years, if not sooner. We're pretty far down that road in terms of the R&D side of things. That would be the largest building block that we can use. The reason why we won't build anything over a 5-MW unit is surely because they don't fit in a shipping container. They are too big to fit in a shipping container. So you lose some of the flexibility of having a PEM system. If it's too big and unwieldy you might as well just have alkaline," Collins said.

In January 2021, ITM Power initiated production at its first Gigafactory at Bessemer Park in Sheffield, the UK. The complex has an annual production capacity of 1,000 MW and is considered to be the largest in the world. According to Collins, the company is fully funded to build a new facility, which will be even bigger than the current one, with a higher degree of automation and larger test capacity. It will proceed with this plan once the existing facility gets up to 60% capacity.

"It takes us about 18 months from when we take the decision to build the factory to actually producing at that new factory," Collins added.

The company, which counts Linde Plc and Snam SpA as shareholders, has supplied electrolyser systems for some notable projects such as REFHYNE and HyDeploy.

ThyssenKrupp AG

Germany-based industrial group ThyssenKrupp is best known as a steel manufacturing major, but is also an engineering company with interest in energy storage systems. In this particular field, ThyssenKrupp is developing two technologies: redox flow batteries and hydrogen electrolysis.

Through ThyssenKrupp Uhde Chlorine Engineers, the group is developing its own advanced alkaline water electrolysis technology and it claims it is the world's number one supplier for electrolytic production equipment, with hundreds of electrochemical plants globally. ThyssenKrupp offers modular, skid-mounted water electrolysers for multi-megawatt installations.

More details on its offerings are available in the following table.

Table 3: ThyssenKrupp electrolysers offering.

	10 MW module	20 MW module
Design capacity H2	2000 Nm³/h	4000 Nm³/h
Efficiency electrolyser (DC)	> 82%HHV*	> 82%HHV*
Power consumption (DC)	max. 4.3 kWh/Nm³ H2	max. 4.3 kWh/Nm³ H2
Water consumption	<1l/ Nm³ H2	<1l/ Nm³ H2
Standard operation window	10% - 100%	10% - 100%
H2 product quality at electrolyser outlet	> 99.95% purity (dry basis)	> 99.95% purity (dry basis)
H2 product quality after treatment (optional)	as required by customer, up to 99.999%	as required by customer, up to 99.999%
H2 product pressure at module outlet	~300 mbar	~300 mbar
Operating temperature	up to 90°C	up to 90°C

* HHV = calculated with reference to higher heating value of hydrogen.

ThyssenKrupp notes that its standartised modules of 10 MW to 20 MW are easy to transport and setup and can be used to realise projects of up to several hundred megawatts.

In June 2020, the company announced it had expanded its annual manufacturing capacity for electrolysis cells up to 1 GW, together with its strategic supplier and joint venture partner De Nora, which has developed the anodic and cathodic coatings featured in the cells. ThyssenKrupp pointed out that its production capacities will be extended continuously in the future.

Nel ASA

Norway-based Nel describes itself as a dedicated hydrogen company that delivers solutions covering the entire value chain from hydrogen production technologies to hydrogen fueling stations.

In 2017, Nel said it became the world's largest hydrogen electrolyser company with a global footprint by acquiring Connecticut-based sector player Proton Energy Systems Inc, also known as Proton OnSite, for an enterprise value of USD 70 million. That is when Nel added PEM electrolysers to its product offering. When it comes to hydrogen production, the company now offers a number of different systems with either alkaline or PEM electrolysers. Nel's A Series electrolysers use an atmospheric alkaline method for splitting water, while its M, C, H and S Series utilize the PEM technology. Units from both the A and M Series can be containerised to facilitate deployment and setup.

The table below includes information about the largest of Nel's electrolysers within its A and M Series.

Table 4: Nel's A and M electrolysers series

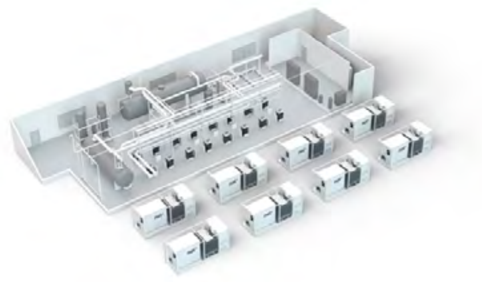
	A3880	M5000
Net Production Rate	2,400-3,880 Nm^3/h	5,000 Nm^3/h
Production Capacity Dynamic Range	15-100% of flow range	10-100% (Input Mode); 10-100% (H_2 Demand Mode)
Power Consumption at Stack1	3.8-4.4 kWh/ Nm^3	4.53 kWh/ Nm^3
H_2 Purity (with Optional Purification)	99.99-99.999 %	99.9995%
O_2-Content in H_2	< 2 ppm v	< 1 ppm v
H_2O-Content in H_2	< 2 ppm v	< 5 ppm v
Delivery Pressure	1-200 barg	30 barg (435 psig)
Ambient Temperature	5-35º C	10-40º C
Electrolyte	25% KOH aqueous solution	Proton Exchange Membrane

In 2019, Nel secured a location in Herøya Industrial Park for a new manufacturing plant. Initially, the company aimed at starting with an annual production capacity of 360 MW there, but that target has now been increased to 500 MW. That is more than 12 times the firm's total current capacity of 40 MW, Nel says in its 2020 annual report, released in late March 2021.

The new factory is scheduled to have its test phase during the second quarter of 2021 and ramp up phase in the third quarter of the year. It will be possible for the capacity at the site to be further expanded to beyond 2,000 MW.

At the end of 2020, Nel registered a record-high order backlog of about USD 114 million, up by 91% on the year. Just last year, it received a number of notable electrolyser orders in the double-digit megawatt range, including an 85-MW purchase by Nikola Corporation related to the deployment of the world's first 8 ton/day hydrogen fueling stations.

Picture 2: The M4000 electrolyser system. Image: Nel ASA.



Also in 2020, Nel signed a pact with energy major Iberdrola to develop and deploy large-scale electrolysers and promote the technology's supply chain in Spain. Nel's CEO Jon Andre Lokke stated that the collaboration relates to electrolyser projects in the 100-MW scale and beyond.

The company has set itself a target of producing green hydrogen at USD 1.5 per kg by 2025, based on electricity of USD 20 per MWh, over 8% cost of capital, cost of land, civil works, installation, commissioning, building, water etc., and a lifetime of 20 years.

Plug Power

Plug Power Inc is a US-based provider of clean hydrogen and fuel cell systems that made the news in January, when it agreed a USD-1.5-billion investment from South Korean industrial conglomerate SK Group. The latter eventually completed a capital investment of USD 1.6 billion in February to secure a 9.6% stake in the US company.

While Plug Power is a supplier of hydrogen and various fuel cell solutions, it has PEM electrolyser offerings as well. This includes the Allagash, Merrimack and GenFuel stacks, the latter of which comes in two versions of 1 MW and 5 MW per unit. The larger system provides on-site hydrogen for markets such as heavy industry, e-mobility, renewable energy and energy storage.

Below you can see the product specifications for the two GenFuel versions.

Table 5: Plug Power's GenFuel electrolysers.

	GenFuel 1 MW	GenFuel 5 MW
Electrical input	480VAC, 60Hz (USA) / 400VAC, 50Hz (EU)	--
AC power requirements	--	5.2kWh/Nm³ @ full capacity / 200kWh standby (0% flow, system on)
Water	Feed: Maximum 411 kg/hr @ 2barg, potable water	Feed: 1,400L/hr @ 4barg, potable water
Ambient temperature	-20°C to +40°C	-20°C to +40°C
Hydrogen production (flow rate)	200 Nm³/hr / 18 kg/hr	100 to 1,000 Nm³ /hr / 9 to 90 kg/hr, 10% to 100% range
Hydrogen purity	99.999% with H2 dryer*	99.9% to 99.999%
Hydrogen pressure	40 barg	Up to 40 barg
Startup time	30 seconds (warm start) / 5 minutes (cold start)	30 seconds (warm start) / 5 minutes (cold start)
Efficiency	Up to 84%	Up to 58 kWh/kg of H2 @ 100% flow
Life expectancy	Stack: 80,000 hours	Stack: 80,000 hours

In January, Plug Power announced it has chosen to build a PEM stack and electrolyser innovation centre in New York's Rochester area by mid-2021. The complex will have a capacity of more than 1 GW of electrical output and will manufacture an estimated 7 million membrane electrode assemblies (MEAs)/plates, some 60,000 stacks and 500 MW of electrolysers per year. It will also house a research and development (R&D) facility for MEAs and fuel cell stacks.

The so-called Plug Gigafactory project will lead to USD 125 million being invested in the local economy and the creation of 375 jobs. Green hydrogen produced on-site will supply local commercial fleets.

Cummins Inc

While starting the development of its fuel cell capabilities over 20 years ago, diesel and alternative fuel engines manufacturer Cummins entered the hydrogen economy in September 2019 by taking control of hydrogen fuel cells and electrolyser technology maker Hydrogenics Corporation at an enterprise value of about USD 290 million. Cummins now holds an 81% stake in that company, while Air Liquide SA of France owns the remainder.

Following the acquisition, Cummins has both fuel cell and hydrogen generation from electrolysis capabilities. Hydrogenics is being run under the company's Electrified Power business segment, which designs and manufactures fully electric and hybrid powertrain systems.

Picture 3: Cummins' HyLYZER system. Photo: Cummins Inc

Cummins currently offers two different types of electrolysers: the HyLYZER PEM electrolyser, which is better suited for large-scale hydrogen production; and the HySTAT alkaline electrolyser, which is well-suited for small- to medium-scale hydrogen production.
The HyLYZER technology is featured in what Cummins says is the world's largest operational PEM electrolyser, installed at a hydrogen production facility in Becancour, Canada's Quebec province.

Siemens Energy

Siemens Energy is another large company that manufactures and provides electrolysers as it continues to drive the development of a hydrogen economy. In February 2021, Siemens Energy announced an electrolysis and hydrogen technology partnership with a familiar sector player – Air Liquide. The two signed a memorandum of understanding (MoU) that outlines a plan to combine their expertise in PEM electrolysis, focusing on the co-creation of large industrial-scale hydrogen projects, preparing for the mass fabrication of electrolysers in Europe, and on research and development (R&D) activities to co-develop next generation electrolysers.

The German company and its French partner have already identified cooperation opportunities for large-scale sustainable hydrogen projects both in both countries and elsewhere in Europe. This includes the Air Liquide-H2V Normandy project in France with a capacity of 200 MW.

Siemens has created the Silyzer product family, a fully-CO2-free PEM electrolysis system that runs on wind and solar power to produce hydrogen. The Silyzer 300 is what Siemens says is the most powerful product line in the double-digit megawatt range of its PEM electrolysis portfolio.

Picture 4: Render of a 12-MW Silyzer system. Source: Siemens Energy

Silyzer 300 has a modular design and the capability to produce between 100 and 2,000 kg of hydrogen per hour. According to Siemens, it has a plant efficiency of more than 75.5% and a startup time of less than a minute. The system consumes about 10 litres of demineralised water per kg of hydrogen.

McPhy Energy SA

France's McPhy is another notable company in the field of hydrogen production and distribution equipment, with a specialty in the design, production and integration of high-pressure alkaline electrolysers and hydrogen stations.

The company's McLyzer range includes both small and large lines of electrolysers. The high-capacity electrolysers in that offering can generate hydrogen in large volumes for heavy industries and/or continuous applications. McPhy says that the McLyzer range is especially adapted for Power-to-Gas and industrial hydrogen applications.

Picture 5: A small electrolyser from the Piel-McLyzer line. Photo: McPhy.

So far, McLyzer electrolysers have been used in a number of mobility projects in combination with McFilling hydrogen stations, projects in the refining, steel-work and chemistry industries, as well as in the field of Power-to-Gas, including the Jupiter 1000 demo in France. The latter project utilises one 0.5-MW alkaline electrolyser and one PEM electrolyser of 0.5 MW to form a 1-MW configuration.

The table below contains more information about the larger models in the McLyzer range.

Models	Pressure (barg)	Rated output of H2 (Nm^3/h)	Power Class	Specific DC consumption at rated output (kWh/Nm^3)
McLyzer 100-30	30	100	0.5 MW	4.5
McLyzer 200-30	30	200	1 MW	4.5
McLyzer 400-30	30	400	2 MW	4.5
McLyzer 800-30 (core-module Augmented McLyzer)	30	800	4 MW	4.5

Table 6: McLyzer larger electrolysers range.

Green Hydrogen Systems

Danish firm Green Hydrogen Systems (GHS) aims to eventually build one of the largest alkaline electrolysis factories in Europe. Its HyProvide line of alkaline electrolysers are available in 30, 60 or 90 Nm^3/h versions and are fully upgradable. The units can operate standalone or in clusters up to multi-megawatt scale. GHS says that its A-Series enables the clustering of units to scale from 15 Nm^3/1.4 kg to more than 3,330 Nm^3/300 kg of hydrogen per hour.

The table below includes the HyProvide A-Series specifications.

Table 7: HyProvide A-Series specifications.

	A30	A60	A90
Hydrogen production rate (Nm^3/hour | kg/hour)	30 | 2.7	60 | 5.4	90 | 8.1
Hydrogen pressure (bar)	35	35	35
Hydrogen purity (%)	>99.998	>99.998	>99.998
Hydrogen dew point (°C)	-70	-70	-70
Oxygen purity (%)	>99	>99	>99
Maximum stack power consumption (kW) BOL-EOL*	125 - 150	250 - 300	390 - 450
Maximum stack voltage max. (DC)	120	250	250
Stack current at 100% load (A)	1200	1200	1800

* BOL - Beginning of life; EOL - End of life

GHS says its electrolysers are suitable for refueling stations, industrial sites, Power-to-X applications and some special projects, including grid stabilisation. Just last year, the company's solutions were chosen by big names in the renewable energy industry such as Ørsted A/S and Siemens Gamesa Renewable Energy SA.

At the end of 2020, GHS received investments for a total of EUR 28 million from both new and existing backers. According to Troels Oberg, Partner at GHS' major shareholder Nordic Alpha Partners, an initial public offering (IPO) "could be the next step on the funding journey."

In early March 2021, GHS announced the completion of its new 150-MW production facility near Kolding, in Denmark. It represents the first phase of the combined manufacturing, R&D and office facility that can be expanded to an annual capacity of 1,000 MW in the future to meet the growing demand for electrolysers.

Haldor Topsoe

Picture 6: A solid oxide electrolyser. Photo: Haldor Topsoe.

Another Danish company, Haldor Topsoe, is the latest to unveil ambitious electrolyser production capacity plans, but unlike its competitors described above, it focuses on the solid oxide technology. The firm is a provider of energy-efficient technologies, catalysts, services and hardware used in the production of chemicals and fuels. It already offers technologies for traditional natural-gas-based hydrogen production with the option of carbon capture, as well as solid oxide electrolyser cells, which, it claims, deliver up to 30% more green hydrogen from the same amount of renewable electricity when compared to PEM and alkaline electrolysers.

In early March 2021, Haldor Topsoe announced its intention to build a 500-MW production plant for industrial-scale solid oxide electrolysers, with the potential to expand its annual capacity to 5,000 MW in the future. The company noted that this facility will be the largest of its kind.

The project is currently under development. Construction work is seen to start in 2022 and be completed by 2023.

"With Topsoe's SOEC electrolyser, more than 90% of the renewable electricity that enters the electrolyser is preserved in the green hydrogen it produces. This is significantly more efficient than the other available technologies in the market," CEO Roeland Baan commented when announcing the plan.

Topsoe's technology will be used in a number of projects including the supply of the aforementioned eCOs system for DeLille Oxygen Co in the US state of Ohio, a few projects at home and the Helios project in the NEOM economic zone in Saudi Arabia. As part of the latter development, Topsoe will deliver ammonia technology for a green hydrogen facility that will produce 650 tonnes of CO2-free hydrogen per day to power trucks and busses.

Enapter

Enapter is the only company in this list that manufactures AEM electrolysers. Its plug-and-play solution is modular and can produce hydrogen at any scale by stacking units to achieve the required production rate, from kilowatts to megawatts range. The company says that up to 70 electrolysers can be stacked in a 20-foot container to create the AEM Cluster that is suitable for larger refueling stations and industrial use.

Below you can see more information about Enapter's Electrolyser EL 2.1.

Production rate	500 NL/hr
Hydrogen output purity	35 bar: ~ 99.9% (Impurities: ~ 1000 ppm H_2O)
8 bar: > 1500 ppm H_2O	35
Output pressure	Up to 35 barg
Nominal power consumption per Nm³ of H_2 produced (beginning of life)	4.8 kWh/Nm³
Operative power consumption	2400 W
Stand-by power consumption	15 W
Power supply	200-240 V, 50/60 Hz
Ambient operative temperature range	5°C to 45°C
Ambient operative humidity range	Up to 95% humidity, non-condensing
Water consumption	~400 ml/hr
Maximum water input conductivity	20 μS/cm at 25°C
Water input pressure range	1 - 4 barg

Enapter says that its electrolyser can be deployed in a variety of applications including: electricity storage, power-to-heat, power-to-gas, industrial solutions, mobility solutions and research. It refers to its AEM offering as "a PEM 2.0 technology."

Picture 7: Enapter's EL 2.1 solution. Source: Enapter.

The company, which is listed on the Frankfurt Stock Exchange, has offices in Italy, Thailand, Germany and Russia. At present, it is carrying out serial production in Italy, but in October 2020 it unveiled plans to build its first mass-production facility in North Rhine-Westphalia, Germany. The "Enapter Campus" will feature both a production centre and R&D facilities. The company will be able to manufacture more than 100,000 AEM electrolyser modules per year there, relying on renewable energy generated by on-site solar arrays and hydrogen storage systems, as well as on Saerbeck municipality's existing solar, wind and biomass power output.

According to a news release from February 2021, construction work on the campus should start in September and it is seen to begin operations in 2022.

3. CASE STUDIES

In operation

Becancour

Picture 8: The Becancour facility in Quebec. Photo: Air Liquide.

While significantly larger projects are currently in the works, the largest one already in operation is the 20-MW PEM electrolyser system at Air Liquide's hydrogen production site in Becancour, the Canadian province of Quebec.

The particular project was inaugurated at the end of January 2021. It produces over 8.2 tonnes of low-carbon hydrogen per day, or more than 3,000 tonnes annually. The system runs on 99% renewable electricity from hydropower plants operated by Hydro-Quebec, avoiding some 27,000 tonnes of CO2 emissions a year compared to the traditional hydrogen production process.

In this case, the technology supplier was Cummins, which provided its modular HyLYZER solution for the project. The installation includes four compact pressurised electrolyser skids that were fitted inside an existing building.

The factory in Becancour was opened in 1987 to serve Air Liquide's industrial customers in the US and Canada. The installation of the additional system has increased the site's hydrogen production capacity by 50%. The output of the new electrolysers is enough to fuel more than 2,000 cars, 16,000 forklifts, 275 buses, or 230 large trucks.

Fukushima (FH2R)

The Fukushima Hydrogen Energy Research Field (FH2R), said to be the world´s largest-class hydrogen production project at the time, entered the construction phase in July 2018 and was completed at the end of February 2020. This demonstration project was developed by Toshiba Energy Systems & Solutions Corporation (Toshiba ESS), Tohoku Electric Power Co Inc and Iwatani

Corporation in cooperation with the New Energy and Industrial Technology Development Organization (NEDO).

Picture 9: The FH2R facility in Fukushima. Photo: Toshiba ESS.

Located in Namie town, Fukushima Prefecture, the facility is equipped with a 10-MW hydrogen production unit that runs on electricity generated by a 20-MW solar park, built on a 180,000-sq-m site, plus power from the grid. The installed electrolysis system can produce up to 1,200 Nm³ of hydrogen per hour.

The project is designed to adjust to supply and demand in the power grid in order to maximise the use of renewable energy. Toshiba ESS noted at the time of the inauguration that using the hydrogen energy management system to achieve the optimal combination of production and storage of hydrogen and power grid supply-demand balancing adjustments, without the use of storage batteries, was the most important challenge in the first stage of testing. The immediate goal was to identify the optimal operation control technology that combines power grid demand response with hydrogen supply and demand response, using units of equipment with different operating cycles.

Hydrogen produced at the FH2R site is transported in tube trailers and hydrogen bundles for supply to users in Fukushima prefecture, the Tokyo Metropolitan Area and other regions. It is also being used to power stationary fuel cell batteries and to support the mobility of fuel cell cars and buses, and more.

Toshiba ESS was responsible for the supervision of the overall project and the overall hydrogen energy management system, while Tohoku Electric was in charge of EMS, SCADA and grid-related matters. Meanwhile, Iwatani's tasks include: hydrogen demand, supply forecast system, transportation and storage of hydrogen.

Under development

SeaH2Land

While existing electrolyser plants in operation around the world do not impress when it comes to size, projects currently under development tackle the gigawatt scale. One such scheme is being developed by Ørsted A/S.

The Danish energy major announced at the end of March 2021 that it will develop a 1-GW green hydrogen production project in two phases by the end of the decade as part of the SeaH2Land vision. The facility will run on renewable power generated by a new 2-GW offshore wind farm in the Dutch North Sea. The goal of the overall project is to cater to the large industrial demand in the Dutch-Flemish North Sea Port cluster.

Aside from Ørsted, the participants in this initiative include major industrial companies ArcelorMittal, Yara, Dow Benelux and Zeeland Refinery. They will support the development of the required regional infrastructure to make it possible to produce steel, ammonia, ethylene and fuels sustainably in the future.

The plan is to link this gigawatt-scale electrolyser to a new (yet-to-be-developed) regional open-access pipeline network of about 45 km that stretches from Vlissingen-Oost in the Netherlands to Gent in Belgium. The local industrial players will be discussing this matter with transmission system operators (TSOs). The partners also need to engage in dialogue with the regulatory authorities on the framework and policies needed to support the project. A full feasibility study of the project is yet to be undertaken as well.

Ørsted estimates that an electrolyser of this size will be able to convert some 20% of the current hydrogen consumption in the region to green hydrogen. It notes that the North Sea Port cluster is currently among the largest fossil hydrogen production and demand centres in Europe, with 580,000 tonnes annually. It is possible that industrial demand in the cluster jumps to 1 million tonnes by 2050, which equals 10 GW of electrolysis, according to the company.

If the project progresses to realisation, Ørsted will be in charge of developing both the electrolyser facility and the offshore wind farm. It has identified a number of locations north and south of the river Scheldt for gigawatt-scale electrolysis. Some of the partners already have their own electrolysis projects like the 150-MW electrolyser planned by Zeeland Refinery. These would also be hooked to the network, Ørsted said.

When announcing the large-scale project, Ørsted did not mention where it intends to source electrolysers from, but a couple of months earlier compatriot Green Hydrogen Systems said that the offshore wind power company had chosen its offerings for a 2-MW plant as part of a wind-to-hydrogen demonstration known as H2RES. That facility will produce some 1,000 kg of green hydrogen per day to fuel road transport in Greater Copenhagen and on Zealand.

NEOM

Two of the manufacturers showcased in this report, namely ThyssenKrupp and Haldor Topsoe, are suppliers to what Air Products Inc said in July 2020 would be "the world's largest green hydrogen project." At the time, the US-based industrial gases company announced a partnership with Riyadh-headquartered ACWA Power and the planned city state of Neom to develop and co-own a USD-5-billion green hydrogen-based ammonia production facility in the northwest corner of Saudi Arabia.

Picture 10: ThyssenKrupp electrolysis technology. Source: Air Products Inc.

ThyssenKrupp Uhde Chlorine Engineers, which last year entered into a strategic cooperation agreement with Air Products in relation to water electrolysis plants, will provide its technology for the project so it can produce 650 tonnes of green hydrogen per day. The multi-billion-dollar scheme also calls for the integration of more than 4 GW of renewable power from solar, wind and energy storage.

According to a ThyssenKrupp presentation from December 2021, the NEOM project will start with a 20-MW electrolysis facility in its first phase and then pursue the development of a 2-GW plant in the second phase.

In addition to hydrogen, the new complex will produce nitrogen by air separation using Air Products technology, along with 1.2 million tonnes per year of green ammonia through technology supplied by Haldor Topsoe. Completion is planned for 2025.

Air Products said it will be the exclusive off-taker of the green ammonia, with plans to transport it around the world to be dissociated to produce green hydrogen for the transportation market.

4. CHALLENGES & OPPORTUNITIES

Underpinned by a global shift of regulators, investors, and consumers toward decarbonisation, hydrogen (H2) is receiving unprecedented interest and investments.

At the beginning of 2021, over 30 countries have released hydrogen-specific strategies, governments have committed more than USD 70 billion in public funding, and the industry has announced more than 200 hydrogen projects and ambitious investment plans.

If all projects come to fruition, total investments will exceed USD 300 billion in hydrogen spending through 2030 – the equivalent of 1.4% of global energy funding. However, only USD 80 billion of this investment can currently be considered "mature," meaning that the investment is either in a planning stage, has passed a final investment decision (FID), or is associated with a project under construction, already commissioned or operational. (Hydrogen Council, McKinsey & Company January 2021).

In other words, the current green hydrogen market is still nascent, costs remain high and transportation is complex. For the industry to grow sustainably, these key challenges need to be solved and like the two sides of a coin, each challenge is also an opportunity, if the right market solution is found.

The affordability and scale challenge

A critical challenge that the renewable hydrogen industry faces today is how fast it can close the price gap with unabated fossil-fuel produced hydrogen. While estimates of green hydrogen production costs by different organisations vary (See Table 1: Green hydrogen production costs estimates), the reality today is that to customers green hydrogen remains two to three times more expensive than blue hydrogen (produced from fossil fuels with carbon capture and storage) and 3-6 times more expensive than grey hydrogen (produced from fossil fuels without carbon capture).
The industry consensus is that for green hydrogen to become competitive, it must be produced at costs of around USD 2 per kilogram, and most jurisdictions with green hydrogen ambitions have established target production prices around that figure.

The opportunities for cost improvement start with the largest single cost component for production of green hydrogen – the cost of the renewable electricity needed to power the electrolyser unit. The rapid decline in the cost of renewable energy over the past decade is actually what brought green hydrogen to the table of viable options for decarbonising the economy. Now, the continued decline in clean power prices is also key to scaling green hydrogen.

According to IEA, electrolysis requires electricity prices of USD 10-40/MWh and full load hours in the 3,000-6,000 range to become cost-competitive with blue hydrogen. Prices under USD 40/MWh are now the norm for utility scale solar and wind power in resource abundant locations and the trend is likely to continue, further improving the competitiveness of green hydrogen. Solar projects in countries such as Brazil, Portugal, the UAE and the US have been deployed with costs of electricity as low as USD 13.5-20/MWh due to supportive policy instruments, such as auctions, to guarantee a stable payment and reduce the investment risk. (IRENA 2020).

Still, low electricity cost is not enough by itself for competitive green hydrogen production, the cost of electrolysis facilities will need to follow suit, as this is the second largest cost component of green hydrogen production.

So far, the signs are encouraging: the cost of electrolysers produced in North America and Europe fell by 40% between 2014 and 2019, according to a recent report on the hydrogen economy by BloombergNEF (BNEF).

BNEF also predicted that if costs continue to fall, green hydrogen could be produced for USD 0.7 to USD 1.60 per kilogram in most parts of the world by 2050. At this price, it would be competitive with natural gas on an energy-equivalent basis and would be cheaper than blue hydrogen.

More recent industry associations' market forecasts are a great deal bolder, projecting cost parity with blue hydrogen and even grey hydrogen within the current decade or so.

Several studies show that potential learning rates for fuel cells and electrolysers are similar to solar PV and can reach values between 16% and 21%. With such learning rates and a deployment pathway in line with a 1.5°C climate target, a reduction in the cost of electrolysers of over 40% may be achievable by 2030, IRENA notes in a 2020 report on hydrogen costs.

According to estimates of the Hydrogen Council, a fast-growing association of the largest industrial names promoting hydrogen, roughly 65 GW of electrolysis production capacity are required to bring costs down to a break-even with gray hydrogen under ideal conditions. Deployment of renewable hydrogen at this scale will require the development of giga-scale hydrogen production projects that will most likely boost utilisation by using energy from multiple renewable sources, such as a combined supply from onshore wind and solar photovoltaics (PV), and by overbuilding renewables supply versus electrolyser capacity.

For hydrogen production facilities collocated with renewable energy generation assets, projections show that renewable hydrogen production costs could decline to USD 1.4-2.3/kg by 2030 (the range results from differences between optimal and average regions).1 This means new renewable and gray hydrogen supply could hit cost parity in the best regions by 2028, and between 2032 and 2034 in average regions.

Procurement of materials and balance of plant supply chains

Scarce materials can represent a barrier to electrolyser cost and scale-up, mostly to PEM electrolysers where two of the scarcest, most energy-intensive and emission-intensive metals on Earth - platinum and iridium, are used. Current production of iridium and platinum for PEM electrolysers will only support an estimated 3 GW-7.5 GW annual manufacturing capacity, compared to an estimated annual manufacturing requirement of around 100 GW by 2030. (IRENA, 2020).

The supply chain for these materials also presents a limitation. South Africa supplies over 70% of global platinum and over 85% of global iridium which potentially leaves the whole PEM electrolyser sector with very limited options to diversify supply and potentially subject to high price volatility.

Solid oxide electrolysers would also suffer from a similar risk, since almost 95% of the supply for all their critical materials currently come almost exclusively from China.

Alkaline electrolysers do use some platinum and cobalt, but there are already commercial designs that do not include these materials and the supply of nickel is more diversified when compared to the other metals.

In general, strategies to improve the performance of the electrolysers are mostly linked to innovation in materials and manufacturing, most probably leading to a set of specific system designs tailored to different applications in the future.

Immense opportunities lie in potential breakthroughs in technology development which can be disruptive in terms of accelerating cost reductions for the stack. For the balance of plant, on the other hand, it is more about economies of scale, standardisation of design and supply chains, as well as learning by doing.

Two years ago, the electrolyser market was just 135 MW/year, with the largest manufacturers in the order of 10-20 MW/year. Several industrial players (Thyssenkrupp, Nel, ITM) have now reached 1 GW/year level or are working towards expansion in the immediate future. The 1 GW mark is where the largest benefits for economies of scale for electrolyser manufacturing are projected to be reached.

As that level is achieved, economies of scale will bring hydrogen supplies in line with demand and allow prices to drop as the industry observed with wind and solar.

The storage & transportation challenge

Hydrogen is touted as the Swiss army knife of low-carbon energy solutions as it can be used to store surplus renewable power generation, transport it from the point of production to the point of use as well as use it directly to fuel cars and larger vehicles, and even to replace fossil fuels in heat and power generation. However, the issues and costs associated with storage and transportation of hydrogen are another challenge (and opportunity) for the industry to solve.

Unless combined with other chemicals, it must be compressed to 700 times atmospheric pressure or refrigerated to minus 253°C. Hydrogen is also highly flammable and due to its low density, it takes up significant amounts of space and this can further complicate transport and storage. If no pipeline infrastructure can be used, hydrogen is likely to require liquefaction or conversion into a carrier such as ammonia in order for transportation to be economically feasible and safe.

At present, there are three means of hydrogen transportation: pipelines, trucks and ships. Pipelines can achieve low-cost hydrogen transport, especially where retrofits of existing infrastructure are possible, but large-scale exports of hydrogen are likely to require maritime freight. The optimal choice of a carrier for shipping would ultimately depend on the targeted end-use, further overland transportation, and the projected storage time. The biggest challenge and breakthrough opportunity is finding a way to safely store hydrogen (or hydrogen-derived fuels) on board at an affordable cost.

5. TRENDS AND FUTURE EXPECTATIONS FOR THE GREEN HYDROGEN INDUSTRY

Green hydrogen is arguably the hottest topic in the energy sector right now. The industry has seen a significant acceleration of activity with a flurry of new projects, pilot studies and commercial partnerships. The ongoing pandemic and current political push for infrastructure spending to spur economic recovery also seem poised to channel government funds to hydrogen development.
While cost-competitiveness is unlikely to be achieved by 2025, policy targets and pilot projects will likely produce enough volume to drive substantial capex declines beyond 2025.
However, the future path of the green hydrogen market development is not yet clear. In theory, green hydrogen could be used to decarbonise industrial processes, transport, power and heating. In practice, some applications may prove more worthy to pursue than others.

It is worth remembering that despite the overwhelming versatility of hydrogen, for each specific use case it will compete not only against the incumbent fossil-fuel based solution but also against other zero-carbon options.

As outlined by BNEF founder Michael Liebreich in October 2020: "As a chemical feedstock, of course, hydrogen is irreplaceable. However, as an energy storage medium, it has only a 50% round-trip efficiency – far worse than batteries. As a source of work, fuel cells, turbines and engines are only 60% efficient – far worse than electric motors – and far more complex. As a source of heat, hydrogen costs four times as much as natural gas. As a way of transporting energy, hydrogen pipelines cost three times as much as power lines, and ships and trucks are even worse.

What this means is that hydrogen's role in the final energy mix of a future net-zero emissions world will be to do things that cannot be done more simply, cheaply and efficiently by the direct use of clean electricity and batteries ."

According to Liebreich, if green hydrogen can close the price gap with grey hydrogen, it will easily take up the existing market for hydrogen in the chemical industry. The production of steel is less straightforward but still a very promising market for hydrogen, while swapping natural gas for hydrogen in the industrial heat market is more challenging and would require significant cost reductions. The same applies to an even greater extent to the commercial and residential water and space heating market where heat pumps and green electricity may prove more effective and cheaper solution than hydrogen.

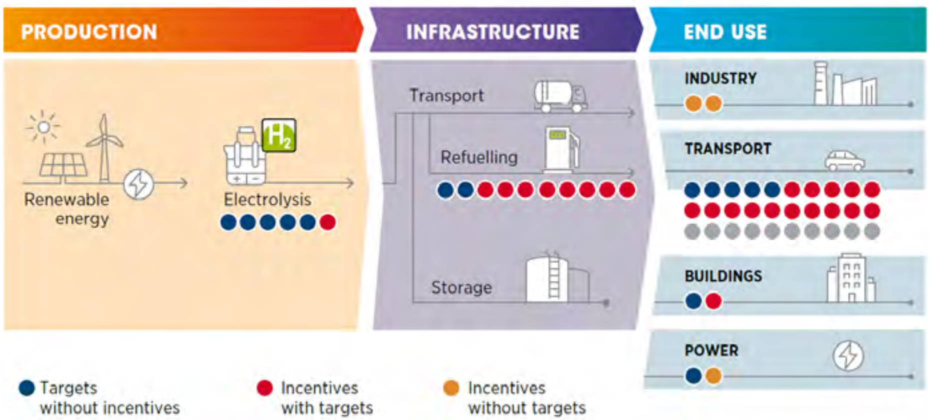
When it comes to transport, the picture is even more complex. Fuel-cell powered vehicles have captured the imagination of many over the past 50 years but so far little progress has been made to perfect the technology beyond pilot projects. At present, hydrogen-powered vehicles have no clear advantage over battery-powered vehicles and it is difficult to project a technological breakthrough that could turn the trend in hydrogen's favour.

Prospects look better for hydrogen in aviation and shipping. The most likely zero-carbon replacement for kerosene will be synfuels (power-to-liquid) where electricity is used to first produce hydrogen and to capture carbon, combining the two into a kerosene-like fuel. The same, more or less, applies to the shipping industry.

Outside technological advances, the industry expectations mainly lie with policy developments around the world as overcoming the barriers and transitioning green hydrogen from a niche player to a widespread energy carrier will require dedicated policy in each of the stages of technology readiness, market penetration and market growth.

In this respect, the past two years represented a game-changing moment for green hydrogen policies, with interest rising around the world. Many countries (including Austria, Australia, Canada, Chile, France, Germany, Italy, Morocco, the Netherlands, Norway, Portugal and Spain, along with the European Union) announced, drafted or published national hydrogen strategies and post-COVID-19 recovery packages that included support measures for clean hydrogen. (IRENA, 2020).

See the figure below.



Source: IRENA analysis based on IEA (2019)

According to IRENA, the change is not just quantitative (with pledges in the order of the billions of USD/EUR), but also qualitative: the emphasis of these new strategies has shifted to industry and product differentiation and future competitiveness, away from the previous focus on hydrogen use in transport. It is important to prioritise the sectors where its use can add the most value to avoid diluting efforts or putting hydrogen in competition with more immediate decarbonisation solutions, such as battery electric vehicles, the association notes.

The EU's policy push is a prime example of how policies can spur private-sector response.

The EU hydrogen strategy, released in July 2020, aims for an integrated view of the hydrogen value chain, and establishes a supporting governance system and policy framework to promote hydrogen deployment. The EU plans to have 6 GW of renewable hydrogen electrolyser capacity by 2024, enough to produce up to 1 million tonnes/year of green hydrogen, compared to just 5,000 tonnes/year in 2018. This capacity will expand to 40 GW by 2030, respectively 10 million tonnes/year of green hydrogen output by 2030.

The staged approach of the strategy sets a number of enabling actions, supporting not only regulatory changes, but also investment schemes designed to kick-start deployment and then scale up supply, transport infrastructure and demand. Reaching the 2030 goals is estimated to require investment of EUR 24 billion-42 billion for electrolyser capacity, in addition to EUR 220 billion-340 billion for 80-120 GW of additional renewable power generation capacity, EUR 65 billion for infrastructure and EUR 11 billion for retrofitting existing natural gas plants.

This bold strategy is already bearing fruit. In February 2021, a group of 30 European energy-focused companies announced they were working on a project to produce and deliver 100% green hydrogen across the Old Continent at a price of fossil fuels before 2030. The group behind the HyDeal Ambition project said that the alliance can achieve the cost of solar-made hydrogen at the price of EUR 1.5 (USD 1.82) per kg, including transmission and storage.

Picture 11: McPhy is one of the electrolysis OEMs that are part of the HyDeal Ambition. Source: McPhy Energy SA.

To reach the goal, the companies plan to install 93 GW of solar power and 67 GW of electrolysis capacity by 2030 to deliver 3.6 million tonnes of green hydrogen per year via the gas transmission and storage network. Production will begin in the Iberian Peninsula in 2022. The first step is seen within a year in Spain, based on a portfolio of solar sites with a combined capacity of close to 10 GW. Deliveries will be made in phases, with the first starting in Spain and the southwest of France, later moving towards the east of France and then Germany.

Up to April 2021, 75 countries, representing over half the world's GDP, have net zero carbon ambitions and more than 30 have hydrogen-specific strategies. The investments sparked by these policies over the course of the next decade, will to a large extent determine how the hydrogen market will develop.

Long story short, there is no denying green hydrogen has a material role to play in decarbonising hard-to-abate areas of industry, power, heating, storage and transport, and experts are forecasting hydrogen could easily reach 10-20% of the global energy mix once rolled out in all viable sectors. But it will face fierce competition in some areas, so anyone planning on investing in the hydrogen industry will have to keep a close eye on research, pilot projects and business alliances to catch early breakthroughs and trends that might change the industry landscape in a fairly short period of time.

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