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SUPPORTING THE ENERGY TRANSITION BY ADDRESSING THE TECHNOLOGY GAPS OF ELECTROLYZERS

WRI INDIA

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AUTHORS

Dr. Guncha Munjal
Mr. Anuraag Nallapaneni
Mr. Pawan Mulukutla
Dr. Garima Dwivedi
Mr. Shubham Mishra

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PREFACE

The need for an energy transition is now universally acknowledged, and the attention is now on finding ways to do it as quickly as possible. There is a growing worldwide commitment towards combating climate change and moving toward a more sustainable future. Central to this transformation, is the increasing emphasis on renewable energy sources and the adoption of clean technologies. Among the various sustainable solutions, green hydrogen has emerged as a promising alternative energy vector for decarbonization.

To meet the net-zero targets, most of the electricity would need to come from renewables. Green hydrogen, which is produced by electrolyzing water using renewable energy, offers a versatile and carbon-neutral energy carrier. It has the potential to revolutionize multiple sectors, including transportation, industry, and power generation. Electrolyzers are the centerpiece of future green hydrogen supply chains. Their manufacturing is closely intertwined with the broader energy transition goals requiring collaboration between academia, industry leaders, policymakers, and investors to create an ecosystem conducive to innovation and regulatory support. Governments across the globe are increasingly recognizing the significance of green hydrogen and are implementing policies and incentives to promote its production, storage, and utilization.

We can strive toward a sustainable and climate-resilient future by increasing electrolyzer output and tackling the difficulties involved in large-scale manufacturing and operation. Green Hydrogen has the potential to play a vital role in supplying energy to the global economy in the 21st century provided the right investments and legislative measures are put in place by the international community.

Mr. Madhav Pai,
CEO, WRI India

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

AE	Alkaline electrolysis
AEM	Anion exchange membrane
CAGR	Compound annual growth rate
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CRI	Commercial readiness index
EPDM	Ethylene propylene diene monomer
ETFE	Ethylene tetrafluoroethylene
EU	European union
GDL	Gas diffusion layer
GHG	Greenhouse gas
GO	Guarantee of origin
GW	Gigawatt
H_2	Hydrogen
HER	Hydrogen evolution reaction
HR	Hour
IR	Iridium
KOH	Potassium hydroxide
KWH	Kilowatt-hour
LSCF	Lanthanum strontium cobalt ferrite
LSM	Lanthanum strontium manganite
MEA	Membrane electrode assembly
MT	Megatonne
MTPA	Megatonnes per annum
O_2	Oxygen
°C	Degree celsius
OEM	Original equipment manufacturers
OER	Oxygen evolution reaction
OH-	Hydroxyl ion
PEM	Proton exchange membrane
PFSA	Perfluorosulfonic acid
PLI	Production-linked incentives
PPS	Polyphenylene sulfide
PSF	Poly(bisphenol-a sulfone)
PSU	Polysulfone
PT	Platinum
PTFE	Polytetrafluoroethylene
PTL	Porous transport layer
RE	Renewable energy
SMR	Steam methane reformation
SOEC	Solid oxide electrolysis cell
SS	Stainless steel
T/GW	Tonnes per gigawatt
TRL	Technology readiness level
TWH	Terawatt-hour
UN	United nations
US	United states
YSZ	Yttria-stabilized zirconia

Image credit: ACME group (www.acme.in)

EXECUTIVE SUMMARY

HIGHLIGHTS

- Green hydrogen is recognized to play a crucial role in the energy transition along with renewables-based electrification.
- Mass manufacturing of electrolyzers is required to make green hydrogen accessible, affordable, and scalable, and to meet the global market demands.
- Rapid upscaling of, and improvements in, electrolyzer performance would leverage the novel possibilities in product design and enhance the opportunities. for collaboration among the G20 nations.

Rising global concern over climate change has accelerated the shift toward clean energy. The energy sector is undergoing a dynamic transition to improve access to energy, which could limit climate change through the adoption of renewables and related technologies in different sectors. Renewables-based systems have been rapidly moving from the niche to the mainstream in recent times. Electricity generation from renewables such as solar and wind are becoming technically reliable enough to potentially displace fossil energy.

Green hydrogen produced through electrolysis using renewable electricity can link renewable electricity generation with hard-to-abate sectors of the economy, such as steel, ammonia, and long-haul mobility. The versatile nature of hydrogen makes it suitable for long-duration energy storage, and it can be transported as required. Fifty-one countries have already established or are developing strategies and roadmaps for the hydrogen economy to accelerate the clean energy transition.

More than 1,000 large-scale clean hydrogen projects have been announced by industry, representing US$320 billion of investment to develop these projects through 2030 (Hydrogen Council 2023).

In 2021, the global hydrogen demand was about 94 megatonnes, which was mostly produced from fossil fuels such as natural gas. This demand was equivalent to about 2.5 percent of the global final energy consumption (IEA 2022). The policies arising out of net-zero commitments, technology development, and international cooperation could help hydrogen meet up to 12 percent of the global energy use by 2050 (IRENA 2021).

Electrolyzers are critical for producing green hydrogen through electrolysis. The role of electrolyzers is widely acknowledged by many countries because it is a crucial technology for rolling out the hydrogen value chain. Many projects are proliferating in new applications such as green ammonia, green steel, and transport. Every country wants to lead the electrolyzer manufacturing industry owing to its expanding prospects. The global electrolyzer manufacturing capacity was 8 gigawatts/year (GW/year) in 2021, and based on industry announcements, it could reach 65 GW/year, with a cumulative capacity of around 270 GW by 2030, according to projections by IEA (2022).

Large-scale deployment of the electrolyzer will open up vast opportunities for the development of different electrolyzer technologies. The different types of electrolyzer technologies are alkaline, proton exchange membrane, solid oxide electrolysis cell, and anion exchange membrane. In this ongoing global race to produce green hydrogen, technology for manufacturing electrolyzers can become a bottleneck, especially because of the supply chain of critical raw materials (especially platinum group metals), design challenges, and the intermittent supply of renewable energy for producing green hydrogen. These emerging challenges could be solved by diversifying the supply chain, supporting the manufacturing of electrolyzer-related components, and funding research and development on the intermittent nature of renewable energy.

A combination of addressing technology challenges, exploring collaboration opportunities among G20 countries, and synchronizing policy action with end-use applications is suggested to promote electrolyzer manufacturing.
Recommendations for facilitating the growth of green hydrogen include demand creation, financial support, technology and scale of manufacturing, international trade, global standards and certification harmonization, and the development of a common platform for collaborative analysis. These suggestions can be further tailored to the priorities and constraints of a country depending on resource availability, infrastructure requirements, and the expected investment
and growth.

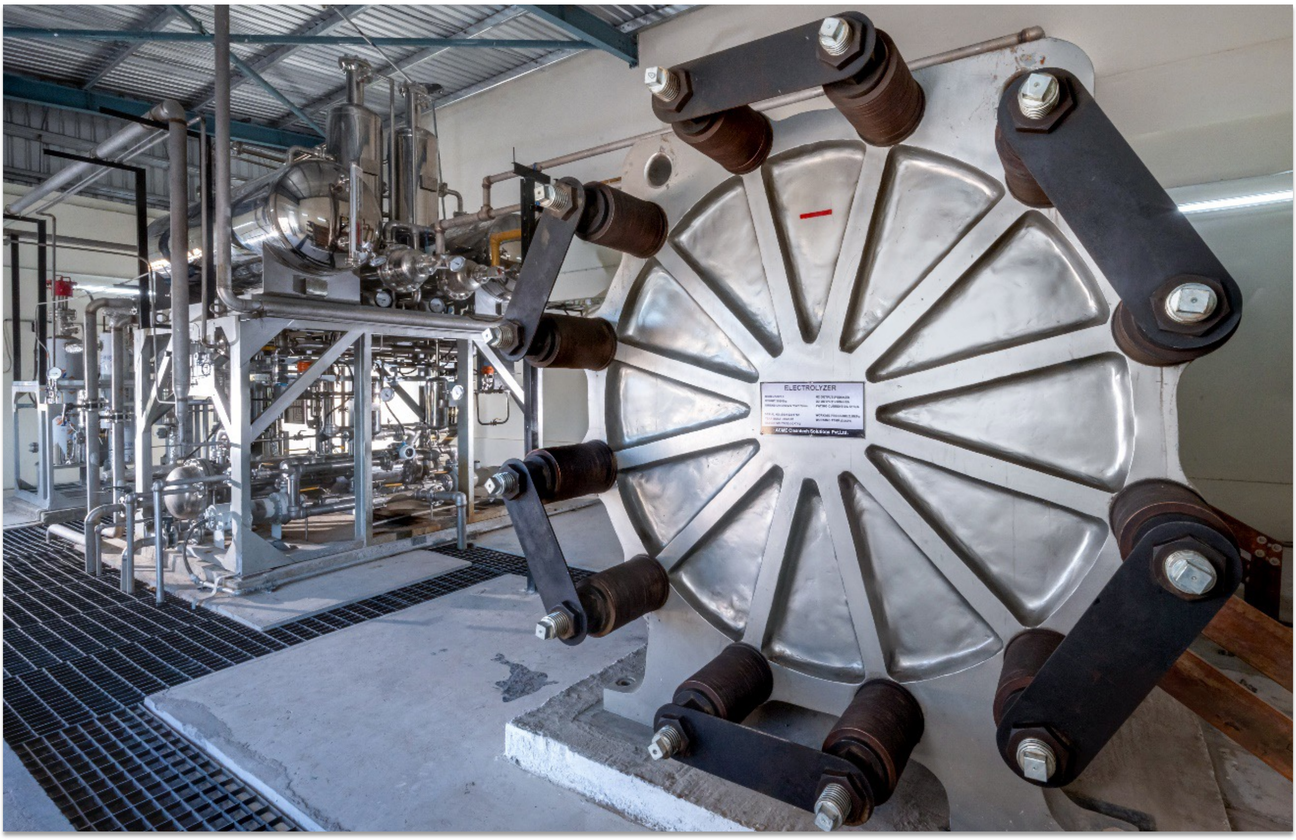


Photo Credit: ACME Group (www.acme.in).

1. INTRODUCTION

Deep and rapid reduction in CO_2 emissions is required to keep global warming to no more than 1.5°C, as called for in the Paris Agreement (United Nations n.d.-a). Global greenhouse gas (GHG) emissions need to be reduced by 45 percent by 2030 and reach net zero by 2050 (United Nations n.d.-b). The G20 brings together the 20 leading economies of the world, which account for over 80 percent of the world's GDP and 75 percent of the global GHG emissions (UNEP 2022). It is evident that their participation is required to address the issues of climate change and that their joint actions—or inaction—will shape the global energy future. Achieving deep or full decarbonization of economies will require concerted and wide-ranging action across all economic sectors. A major shift in electricity generation to renewable sources such as solar and wind from fossil fuels is required for the energy transformation and is important for the widespread electrification of many end uses.

Hydrogen is a versatile clean fuel that can play several end-use roles. Not all sectors or industries can easily transit from fossil fuels to electricity. Steel, cement, chemicals, long-distance road transport, maritime shipping, and aviation are examples of hard-to-abate industries. Hydrogen produced through electrolysis can be converted into fuel, chemicals, and power, enabling it to connect with and fundamentally reshape current hard-to-abate sectors to facilitate the net-zero emission scenarios. Hydrogen can enable the clean energy transition because of its ability to be stored in large volumes and transported over long distances through pipelines and shipping. In addition to green hydrogen's importance in decarbonization, it is also gaining traction among countries for energy independence and energy security. Industrial consumers, allied stakeholders from government bodies, industries, and consumers have started recognizing the potential of green hydrogen in achieving net-zero targets.

Electrolyzers are the leading technology for producing green hydrogen by using renewable electricity. Here, the term "green" signifies that emissions from the production of hydrogen using renewables-powered electrolysis are negligible. The rise in green hydrogen production is linked with the rapid deployment of renewable energy and growth in electrolyzer capacities. The manufacturing capacity of electrolyzers should be ramped up to achieve economies of scale. Generally, there are four types of electrolyzer technologies: alkaline electrolysis (AE), proton exchange membrane (PEM), solid oxide electrolysis cell (SOEC), and the emerging anion exchange membrane (AEM). Each electrolyzer functions differently depending on the operating conditions, electrolyte, and material used. Parameters such as high product purity, high efficiency, feasibility at large scale, cost, and lifespan are evaluated before finalizing a suitable technology for commercial application.

This report describes the types and requirements of electrolyzer technologies, the policies needed to grow the hydrogen production sector, and the technical challenges involved in rapidly upscaling and improving electrolyzer technology. The initial assessments, which include hydrogen demand, production, electrolyzer capacity, and electrolyzer manufacturing, have the global landscape as the backdrop. The methodology for determining the present and projected demands for green hydrogen and in turn these demands for electrolyzers is based on projections published in reports by the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), Det Norske Veritas (DNV), and National Institution for Transforming India (NITI Aayog). These projections are categorized into the base case and aggressive development scenarios. In the base case scenario, the average of all the announcements made by nations across the world for promoting the hydrogen economy as well as the initiatives that are currently in the works is considered. For the aggressive development scenario, the global net-zero ambitions for 2050 are considered, along with favorable policies to advance the low-carbon or green hydrogen economy.

The next part of this report builds on the projected demand scenarios for electrolyzers to discusses the technical aspects of electrolyzers. It addresses the major bottlenecks in electrolyzer manufacturing such as the availability of critical raw materials, design constraints, the use of seawater, and the intermittent supply of renewable energy to power electrolyzers. It highlights the supporting policies for regulating demand uncertainties, and research, innovation, and development measures for expanding electrolyzer manufacturing worldwide.

1.1 GREEN HYDROGEN FOR DECARBONIZATION AND ENERGY SECURITY

Current hydrogen production mainly depends on the process of steam methane reforming (SMR) using natural gas as feed. Hydrogen is a fundamental raw material in the production of ammonia (NH_3), which is an important manufacturing input for fertilizers used in agriculture. It is also commonly used in hydrocracking to manufacture petroleum products such as gasoline and diesel. In 2021, the total global hydrogen production was 94 megatonnes (Mt), with associated emissions of about 900 Mt of CO_2 (IEA 2022).

Hydrogen is labeled in different color shades—brown, black, gray, blue, and green—based on the hydrogen production technology, energy source, and environmental impact, as shown in Table 1

Table 1 | **Hydrogen color shades, source, technology, carbon dioxide emissions, and cost**

HYDROGEN COLOUR	SOURCE	TECHNOLOGY	PRODUCTS	CO_2 EMISSIONS (kg CO_2/kg H_2)	COST ($ kg/H_2)
BROWN H_2	Brown Coal	Gasification	$H_2 + CO_2$	18-20	1.2-2.1
BLACK H_2	Black Coal	Gasification	$H_2 + CO_2$	18-20	1.2-2.1
GREY H_2	Natural Gas	Reforming	$H_2 + CO_2$ (Released)	11-13	1-2.1
BLUE H_2	Natural Gas	Reforming + Carbon capture	$H_2 + CO_2$ (Captured)	6-9 (56% Capture) 2-5 (90% Capture)	1.5-2.9
GREEN H_2	Water	Electrolysis	$H_2 + CO_2$	0.3-1	3.6-5.8

Note: CO_2 = carbon dioxide; H_2 = hydrogen; O_2 = oxygen.

Sources: Authors' compilation with data from Hydrogen Council (2021), Moberg and Bartlett (2022), Rosa and Mazotti (2022), and Arcos et al. (2023).

(Hydrogen Council 2021; Moberg and Bartlett 2022; Rosa and Mazotti 2022; Arcos et al. 2023). The evolution of low-carbon and green hydrogen production technologies has gained traction for decarbonizing existing hydrogen production and ensure energy security. The emissions are 10 times lower than those of the conventional process, which uses fossil methane with SMR.

Hydrogen is a versatile clean molecule that plays multiple roles across end uses and combines well with other potential decarbonization levers such as direct electrification and carbon capture and storage (CCS). Strong growth in hydrogen demand along with the adoption of green hydrogen production technologies can contribute to avoiding up to 60 gigatonnes (Gt) of CO_2 emissions in 2021–50 (IEA 2021). However, the cost of green hydrogen is currently significantly higher than that of other production options.

1.2 GLOBAL HYDROGEN MARKETS

Globally, hydrogen markets are mainly captive. There are almost no open commodity markets specifically for hydrogen. However, markets for derivatives of hydrogen, such as ammonia and methanol, do exist. The captive global hydrogen generation market was valued at $155.35 billion in 2022 and is expected to expand at a compound annual growth rate (CAGR) of 9.3 percent from 2023 to 2030. The global green hydrogen market size was valued at $0.68 billion in 2022 and is projected to reach $7.31 billion by 2027, growing at a CAGR of 61 percent during the forecast period of 2022 to 2030 (MarketsandMarket 2022).

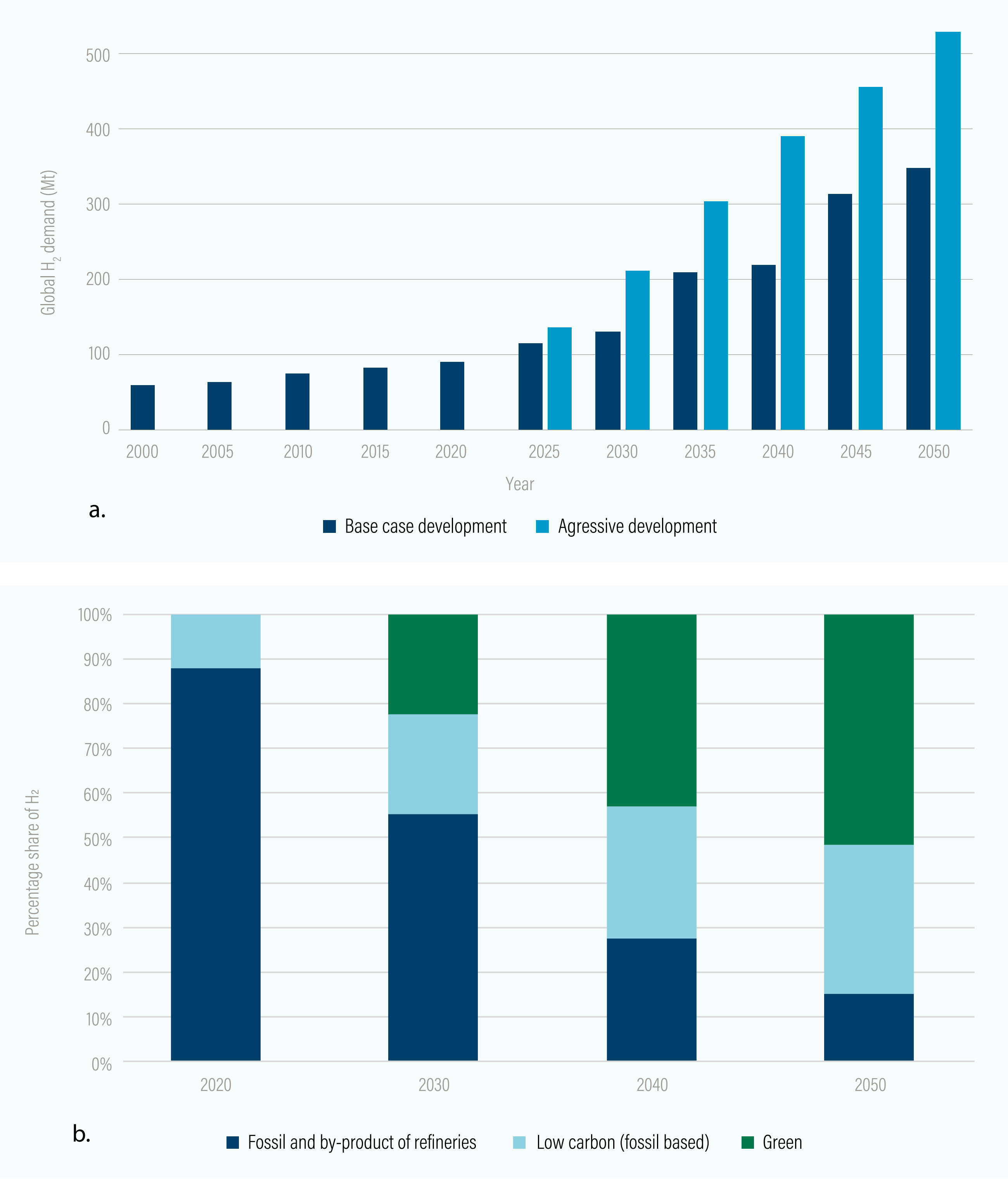
The global hydrogen demand in 2020 stood at about 90 Mt, and under the base case scenario, it is expected to grow to about 348 Mt H_2 by 2050, which is almost four times that of 2020. Under aggressive development, this forecast will grow considerably to about 527 Mt H_2 by 2050, nearly six times that of 2020. This development in demand can be tracked in Figure 1a (Lovegrove 2022 IEA 2022).

The contribution of green hydrogen to the total global hydrogen production is expected to reach significantly high levels with time. From little to no green hydrogen production in 2020, it can rise to 52 percent of the total global H_2 production by 2050 (Lovegrove 2022; IEA 2022). Figure 1b compares the growth in electrolysis-produced hydrogen, carbon capture and utilization (CCU)- or CCS-produced fossil-based low-carbon hydrogen, and fossil-produced hydrogen (IEA 2021). The traditional sources of hydrogen production, such as fossil fuels or by-products of refineries, are projected to be surpassed by rapid scaling in green hydrogen or low-carbon hydrogen production pathways.

To boost the expansion of the hydrogen market, the international value chain must be developed, existing hydrogen production must be replaced with low-carbon or green hydrogen, which must be adopted in new sectors.

The pace of deployment of hydrogen in different applications is influenced not only by market adoption and regulations but also by other factors also such as geopolitics, commodity prices, the state of the global economy, and the state of global supply chains. This necessitates strong policy initiatives to ensure that energy security evolves in the context of the clean energy transition. Decisive policy support can help overcome the barriers to transitioning green hydrogen from the niche market and reaching the minimum threshold for market penetration.

Figure 1 | **Global hydrogen demand: a. Present and projected scenarios for hydrogen b. Present and projected share of different hydrogen production routes**



Note: H_2 *= hydrogen; Mt = megatonne.*

Sources: Figure created by WRI based on data from IEA (2022), IRENA (2021), Lovegrove (2022), and Raj et al. (2022).

1.3 POLICY AND INITIATIVES FOR GREEN HYDROGEN

The policy developments and investment focus within the hydrogen ecosystem are currently facing a major “chicken-and-egg” dilemma. Green hydrogen is more expensive than gray hydrogen, which inhibits its demand. However, without demand and infrastructure, investment in massive green hydrogen production that could compress the cost remains risky. This problem must be tackled, and policymakers along with industries should work together to overcome this dilemma. To address this quandary, it is critical that the issue be addressed through the lens of both supply and demand of hydrogen through a working public-private partnership arrangement.

To enable the clean energy transition, countries are looking forward to implementing an array of policy levers (see Table 2). A well-known example in the renewable energy sector is India's solar parks program, which addressed the chicken-and-egg challenge head on. In the late 2000s to early 2010, the government effectively acted as both a market maker and price taker, leading the development of “shovel-ready” solar projects through state-level transmission companies (state-owned companies).

This approach eliminated almost all the development risk and successfully crowded in the private sector to build the solar power plants. This approach could work for developing hydrogen hubs or clusters, but governments need to be proactive in taking the lead. This should be a relatively easy approach in certain places, where existing solar and wind parks could be retrofitted with electrolyzers, or the transmission networks modified (if necessary) to send renewable electricity to existing H_2 production sites, where electrolyzers can be installed to replace gray H_2.

Other measures are applied to the hydrogen market through the learnings acquired from the renewable energy sector, such as contracts for differences, renewable obligations, and feed-in tariffs. Novel mechanisms such as the Guarantee of Origin (GO) Scheme, Carbon Border Adjustment Mechanism, blending targets in natural gas, and carbon pricing for fossil-based hydrogen sources are innovative measures for boosting the consumption of green/low-carbon hydrogen around the globe. The United States, meanwhile, is supporting clean hydrogen with a 10-year tax credit of up to $3/kg that was launched as part of the federal government’s wide-ranging Inflation Reduction Act, which was passed in August 2022. This incentive is credited with making clean hydrogen competitive with fossil

Table 2 | **Policies and initiatives to support the development of the hydrogen ecosystem and electrolyzer manufacturing**

SUPPLY	DEMAND	SUPPLY AND DEMAND
▪ Production-linked incentives ▪ Capacity targets ▪ Export agenda ▪ Feed-in-tariffss (gas and electricity) ▪ Cost reduction targets ▪ Feedstock subsidies and relaxations ▪ Guarantees of origin ▪ Renewable energy banking ▪ Long-term land lease agreements	▪ Fuel cell vehicle subsidies ▪ Hydrogen production subsidies ▪ Renewable gas obligations ▪ Co-located hubs ▪ Blending targets	▪ Value chain standardization ▪ Trade partnerships ▪ Carbon tax/pricing

Sources: Authors’ compilation.

fuel-based versions of the gas, which dominate the market today (Esposito and Tallackson 2022).

Another unique policy measure is the issuance of GO certifications in the European Union (EU), for example, CertifHY; Australia; and a few G20 member states, whereby the "greenness" of hydrogen can be verified and incentivized, further pushing the transition from fossil-based hydrogen to low-carbon hydrogen supply sources. Such certification schemes also enable standardization and international trade of green hydrogen and its derivatives. It is critical that such certification schemes have a standardized universal definition of green hydrogen, which is currently not the case. The development and global adoption of these common definitions can facilitate cross-border trade and support value chain development on both the supply and demand sides.

1.4 COMMERCIALIZED AND EMERGING ELECTROLYZER TECHNOLOGY

Electrolyzers play an important role in producing green hydrogen using renewable electricity. Emissions from the production of hydrogen through electrolysis using solar or wind energy are minimal compared to those from the conventional process, which uses fossil fuels such as methane or coal (Rosa and Mazotti 2022).

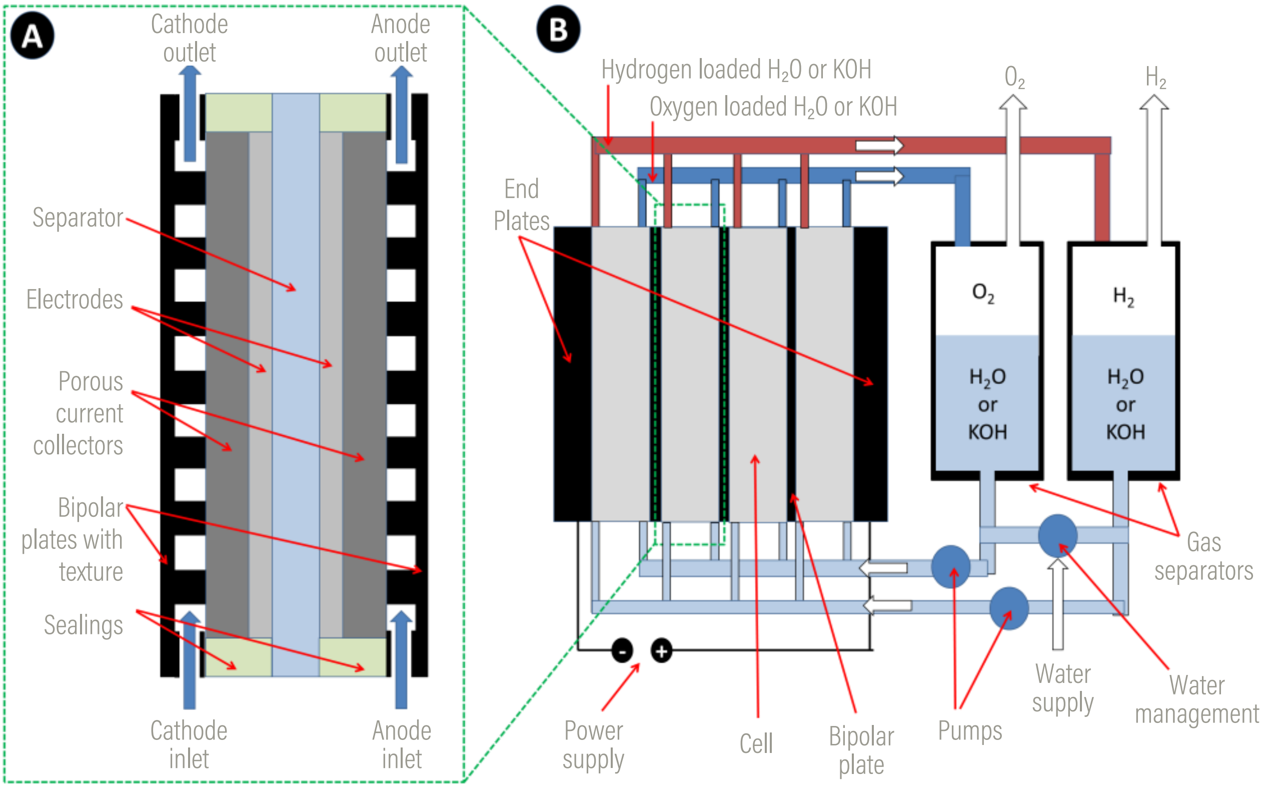
The electrolytic hydrogen production system is made up of an electrolyzer stack (which is its core electrochemical component; it is the site of water splitting) and the balance of plant (BOP) comprising the water supply, power supply, purification, and hydrogen processing. The hydrogen gas produced on the cathode in these stacks is purified through separation and drying processes by the auxiliary components present in the electrolytic hydrogen system. The oxygen produced on the anode is either released into the atmosphere or captured and stored for applications in other industrial processes.

The main electrochemical reaction occurs at the core of the electrolyzer, at the first level, the cell. It includes two electrodes: an anode and a cathode separated by a membrane/diaphragm. In the PEM-type electrolyzer, the catalyst layers are directly coated on the membrane (CCM) or coated on the substrate (CCS). The cell also has two porous transport layers that facilitate the transport of reactants and removal of products. The bipolar plate provides mechanical support and distributes the flow. The second level, the stack, is a combination of many cells, porous transport layers, bipolar plates, and other small parts such as bolts, seals spacers, and frames. This level usually accounts for about 40–50 percent or higher of the total cost of the electrolyzer. The third level, the system, involves the BOP and other peripherals responsible for operating the electrolyzer. It includes water supply treatment (e.g., deionization), electricity input conversion (e.g., using transformers and rectifiers), gas output (e.g., of oxygen), and equipment for cooling and processing the hydrogen (e.g., for purity and compression). Figure 2 shows the detailed layout of the electrolyzer system at the stack level (Schalenbach et al. 2018).

The material-level analysis for the four types of electrolyzers, namely, AE, PEM, SOEC, and AEM, is listed in Table 3 (IRENA 2020). Certain components in less mature technologies such as AEM and SOEC may vary with different manufacturers or R&D institutes. Table 4 gives insights into the relative performance of only three commercial electrolyzer technologies, because AEM electrolysis technology is promising but at a nascent stage of development.

AE Electrolyzers are the most mature and well-developed electrolyzers with a simple system and stack design. They have lower capital costs than

Figure 2 | **Illustration of (A) a bipolar water electrolysis cell and (B) a water electrolysis system**



Sources: Schalenbach 2018.

other electrolyzer technologies because they do not use precious materials. They are sturdy, reliable, and use highly concentrated liquid electrolyte (KOH solution) for their operations. The electrodes (anodes and cathodes) are separated through a porous structure known as the "diaphragm," which allows only hydroxyl ions (OH-) to permeate through it and inhibits the passage of electrons. However, the use of diaphragms allows the intermixing of produced gas dissolved in the electrolyte, limiting the operability of electrolyzers at high pressures. To counteract this, diaphragms with thicker diameter are used, which results in higher resistance and lower overall electrolyzer efficiencies. The operating range of these electrolyzers varies from a minimum load of 10 percent to full design capacity (IEA 2019).

PEM Electrolyzers are simple and have compact designs, with a faster response to abrupt load changes and an almost 100 percent turndown capability to meet the variable hydrogen demand. This attribute makes PEM electrolyzers ideal for intermittent renewable energy applications. Typically, a perfluorosulfonic acid (PFSA) polymer is used as the solid membrane electrolyte owing to its chemically and mechanically robust nature along with lower resistance levels. This achieves higher efficiencies and allows operation at high differential pressure. PFSA, which is highly acidic in nature, paired with a high range of voltages and the evolution of oxygen at the anode creates an exacting corrosive environment in the electrolyzer. This warrants the use of noble metals such as platinum (Pt) and iridium (Ir), which can withstand harsh conditions, for long-term stability and high electrical conductivity, thereby increasing the cost of the electrolyzer stack and subsequently the system.

SOEC Electrolyzers operate at high temperatures

Table 3 | **Material details of different components involved in the electrolyzer stack**

S.NO.	PARAMETERS	ALKALINE	PEM	SOEC	AEM
1	Electrolyte	Alkaline Solution	Solid Polymer Membrane	ZrO_2 ceramic doped with Y_2O_3	Divinylbenzene polymer support with KOH/ $NaHCO_3$
2	Electrode/Catalyst (H_2 side)	Ni coated perforated SS/ NiMo alloys	Pt nanoparticles on carbon black,	Ni/YSZ*	High surface Ni/ Transition metals based materials
3	Electrode/Catalyst (O_2 side)	Ni coated perforated SS/NiCo based alloys	Iridium Oxide	Perovskite-type (e.g. LSCF, LSM)*	NiFeCo alloys/ Transition metals based materials
4	(Anode)Porous Transport Layer	Ni mesh (not always present).	Pt coated sintered porous titanium.	Coarse Nickel-mesh or foam.	Ni foam
5	(Cathode)Porous Transport Layer	Ni mesh	Sintered porous titanium or carbon cloth.	None	Ni foam/ carbon cloth
6	(Anode)Bipolar Plate	Ni-coated SS	Platinum-coated titanium	None	Ni-coated SS
7	(Cathode) Bipolar Plate	Ni-coated SS	Gold-coated titanium	Cobalt-coated SS	Ni-coated SS
8	Frames and Sealing	PSU, EPDM, PTFE,	PTFE, PSU, ETFE	PTFE, Silicon	Ceramic glass

Note: AE = alkaline electrolysis; AEM = anion exchange membrane; EPDM = ethylene propylene diene monomer; ETFE = ethylene tetrafluoroethylene; IrO_2 = iridium oxide; LSCF = lanthanum strontium cobalt ferrite; LSM = lanthanum strontium manganate; PEM = proton exchange membrane; PFSA = perfluorosulfonic acid; PPS = polyphenylene sulfide; PSF = poly (bisphenol-A sulfone); PSU = polysulfone; Pt = platinum; PTFE = polytetrafluoroethylene; SOEC = solid oxide electrolysis cell; SS = stainless steel; YSZ = yttria-stabilized zirconia.

Sources: IRENA 2020; Patonia and Poudineh 2022.

(700–850˚C) to produce hydrogen from steam. The electrolyzer stacks are composed of a mixture of ceramics (generally perovskite oxides) and metals/ materials that can withstand operation in this extremely high temperature range. The usage of high temperature lowers electricity consumption and enables faster kinetics for the hydrogen evolution reaction. Waste heat from other industries (such as nuclear) could be used to achieve high system efficiencies. However, the high temperatures inhibit quick ramp-up and shutdown, which makes them better suited for base load applications. Further, the constant thermo-chemical cycling accelerates stack degradation and shortens operation lifetimes. Other challenges, such as efficient sealing at high differential pressure due to contamination of electrodes by silica sealants, also arise at high temperatures.

AEM Electrolyzers are the least mature technology in the market today and are currently being developed at a laboratory scale. These electrolyzers generally employ anion exchange membranes (such as divinyl benzene polymers) as solid-state electrolytes, which are a less corrosive environment for the stacks. This enables them to use non-noble catalysts and titanium-free components, bringing down the cost of the electrolyzer while retaining the simplicity and efficiency of PEM electrolyzers. However, the AEM membrane has low conductivity, and slower kinetics together with chemical and mechanical stability issues shorten operational lifetimes. Further, the hydroxyl ion (OH–) is inherently slower than protons (H+), because of which they have thinner membranes or very high charge densities.

Table 4 | **Relative performance of AE, PEM, and SOEC electrolyzers**

S.NO.	PARAMETERS	1ST	2ND	3RD
1	Technology Maturity	AE	PEM	SOEC
2	Efficiency	SOEC	AE	PEM
3	Life Span	AE	PEM	SOEC
4	Response Time (Fast & Slow)	PEM	AE	SOEC
5	Safety	PEM/AE		SOEC
6	Physical 'footprint' (from small to large)	PEM	AE	SOEC
7	Cost of capital (from low to high)	AE	PEM	SOEC

Note: AE = alkaline electrolysis; PEM = proton exchange membrane; SOEC = solid oxide electrolysis cell.

Source: Authors' compilation.

Low-temperature water electrolyzers: AE and PEM are the main commercially available technologies today. These technologies offer adequate energy storage and grid-balancing utility in power-to-gas operations (Olivier et al. 2017). The SOECs are high-temperature water electrolyzers that exhibit a high conversion efficiency because some energy is derived from thermal energy (F. Wang et al. 2021). Countries such as the United Kingdom, France, and Chile have recognized electrolyzer technology for producing green hydrogen and have set very high electrolyzer capacity targets of 10 GW, 6.5 GW, and 25 GW, respectively, by 2030 (Raj et al. 2022).

Image credit: ACME group (www.acme.in)

2. ELECTROLYZER DEMAND AND MARKET DEVELOPMENT

In 2021, only 0.1 percent of the global dedicated hydrogen production came from electrolysis. However, the installed electrolyzer capacity has been growing at a very fast pace. By the end of 2021, the globally installed capacity of electrolyzers reached 510 MW, which was 70 percent higher than that of 2020. In the coming years, this rapid growth in electrolyzer capacity is anticipated to accelerate. Around 460 major electrolyzer projects are under construction globally, and nearly 680 new proposals for large-scale clean hydrogen projects were made in 2022 (Hydrogen Council 2022; IEA 2022). Some of these gigawatt-scale projects are listed in Table 5 in order of electrolyzer capacity (FuelCellsWorks 2022).

2.1 CURRENT AND PROJECTED GLOBAL DEMAND FOR ELECTROLYZERS

In 2020, the global installed capacity for electrolyzers was only about 300 MW, of which 61 percent was dominated by AE technology and 31 percent by PEM technology. This installed capacity grew to 510 MW by the end of 2021. By 2022, this capacity could reach nearly 1.4 GW, rising three times from the 2021 level (IEA 2021; IRENA 2021).

Table 5 | **Largest green hydrogen projects, 2022**

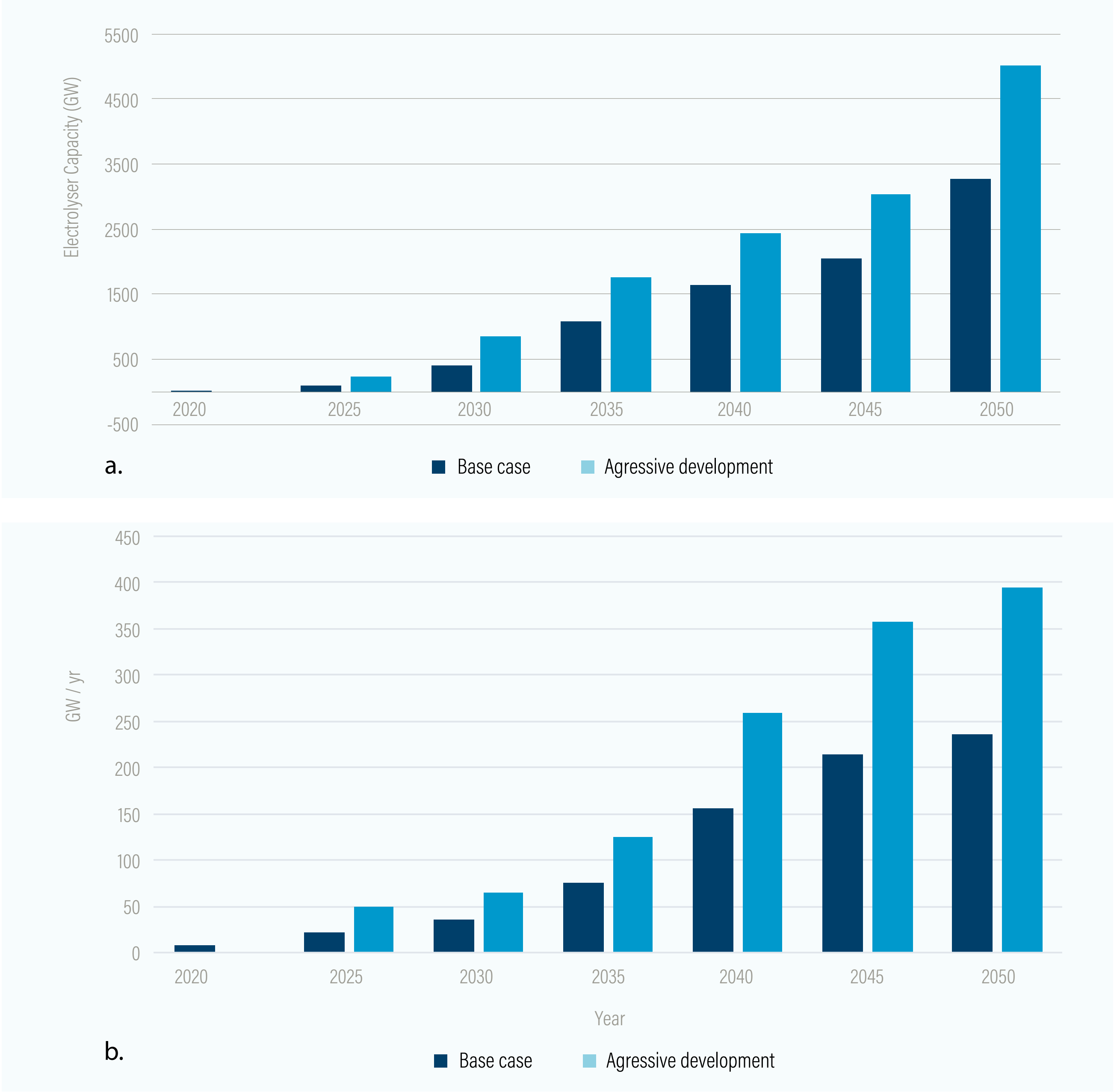
PROJECT NAME	LOCATION	CAPACITY OF RENEWABLE ENERGY	H_2 YIELD (MTPA)	EXPECTED COMPLETION DATE
HyDeal Ambition (67GW)	Western Europe – from Spain, eastern France to Germany	95GW of solar power	3.6	2030
Reckaz (30GW)	Western and central Kazakhstan	45GW of wind and solar power	3	2028
Western Green Energy Hub (28GW)	The South east and western Australia	50GW of wind and sun energy	3.6	2028
Aman (16-20GW)	Mauritania	30GW of wind and solar will power Electrolyzers	1.7	Not Started Yet
Green Energy Oman (14GW)	Oman	25GW of wind, solar and hydro energy	1.8	2038
Asian Renewable Energy Hub (14GW)	Pilbara, Western Australia	26GW of upstream wind and solar power	1.6	2027-28
NorthH2 (4 GW)	Northern Netherlands	10GW offshore-wind energy	1	2030

Note: GW = gigawatt; Mtpa = megatonnes per annum.

Sources: FuelCellsWorks 2022.

By 2030, under the base case scenario, the global installed electrolyzer capacity can reach 405 GW. This projection considers the pipeline projects that are under construction and the hydrogen production capacity targets announced by different countries worldwide. Under the aggressive development scenario, these projections could double to 848 GW by 2030. This depends, however, on whether the capacity targets are met aggressively and whether favorable policies and norms are implemented. For both the base case and aggressive development scenarios, in 2050, the installed electrolyzer capacity is expected to increase eight times from their respective projections for 2030. Figure 3a depicts the outlook for the forecast electrolyzer capacity deployment for 2020–2050 (Lovegrove 2022; IEA 2022).

Figure 3 | **Electrolyzer present and projected capacity, 2020-2050: a. installation capacity b. Manufacturing capacity**



Note: GW = gigawatt; yr = year.

Sources: Figure created by WRI based on data from IEA (2022), IRENA (2021), Lovegrove (2022), and Raj et al. (2022).

2.2 ELECTROLYZER MANUFACTURING CAPACITIES

An increase in electrolyzer manufacturing capacities can make it possible to achieve the electrolyzer and green hydrogen targets set out in the different national hydrogen strategies and roadmaps. In 2021, the global electrolyzer manufacturing capacity was about 8 GW/yr. From the announcements of electrolyzer capacity targets, this can be further raised to about 50 and 65 GW/yr by 2025 and 2030, respectively, in the case of the aggressive scenario, which considers the average of all the projections in recent reports by organizations such as IEA and IRENA. The reason for this boost is the positive outlook for the growth in electrolyzer demand. By 2050, electrolyzer manufacturing capacities around the globe are expected to reach 235 GW/yr and 395 GW/yr under the base case and aggressive development scenarios, respectively, as show in Figure 3b.

Some of the major companies involved in electrolyzer manufacturing are Plug Power, Nel Hydrogen, and ITM Power. Table 6 lists the leading companies involved in manufacturing AE, PEM, SOEC, and AEM technologies.

Table 6 | **Technology-wise list of leading electrolyzer manufacturers across the globe**

AE	PEM	SOEC
▪ Cummins-Hydrogenics: Columbus, Indiana (U.S.) ▪ Thyssenkrupp: Essen, Germany ▪ Enapter: Berlin, Germany ▪ John Cockerill: Seraing, Belgium ▪ Hydro: Oslo, Norway ▪ Nel Hydrogen, Oslo, Norway ▪ Cockeril Jingli Hydrogen, Suzhao, China ▪ Hydrogen Pro: Porsgrunn, Norway. ▪ McPhy: France ▪ Teledyne Energy Systems, Maryland, United States ▪ Wasserelektrolyse Hydrotechnik, :Karlsruhe. Germany ▪ PERICHydrogen Technologies: Handan City, China ▪ Sagim S.A : Saint-Étienn, France ▪ G-Philos: Gyeonggi-do, Republic of Korea	▪ Cummins-Hydrogenics, ▪ Plug Power: Latham, New York, United States ▪ H2B2: Seville, Spain ▪ Ohmium: Incline Village, USA ▪ H-Tec System: Augsburg, Germany ▪ Nel Hydrogen, ▪ Cockeril Jingli Hydrogen, ▪ Proton OnSite: Connecticut, USA ▪ Areva H2Gen: Les Ulis, Île-De-France, ▪ ITM Power: Sheffield, United Kingdom, ▪ Siemens: Munich, Germany, ▪ Green Hydrogen Systems: Denmark ▪ Rhizome: UK ▪ Enphos: Italy	▪ Bloom Energy: San Jose, California, United States, ▪ SunFire: Dresden Germany ▪ Haldor Topsoe: Lyngby Denmark ▪ OxEon: Salt Lake Valley, UT, US. ▪ FuelCell Energy: Danbury, US ▪ H2E Power: Pune, India

Note: AE = alkaline electrolysis; PEM = proton exchange membrane; SOEC = solid oxide electrolysis cell.

Sources: Authors' compilation.

2.3 INITIATIVES IN ELECTROLYZER TECHNOLOGY

The momentum for green hydrogen alongside electrolyzer technology is building up and is expected to continue and spur future innovation. It is expected that the cost of the electrolyzer could fall by 70 percent compared to the current price if all the electrolyzer projects in the pipeline are implemented and the scale-up for electrolyzer manufacturing is achieved by 2030 (IEA 2022).

On the technology side, countries are focusing on dedicated R&D for electrolyzers with the involvement of industries, academia, and research centers. These efforts could bring down the cost of the electrolyzer and increase its efficiency, scale manufacturing capabilities, and reduce the dependence on noble material. Five sub-technology areas were identified for patenting trends in recent years (IRENA and EPO 2022):

- Operation conditions and structure of cells
- Electrocatalyst material (the use of non-noble materials)
- Separators (thinner organic membranes)
- Stackability of Electrolyzers (stacks)
- Photoelectrolysis

Countries such as the United States, Japan, China, Germany, and France are leading the research on electrolyzer technology at the global level, supported by ongoing R&D activities in many organizations. Table 7 lists some of the major global initiatives on electrolyzer technology (Esposito and Tallackson 2022; Radowitz 2022; Scottish Government 2022).

Table 7 | **Global initiatives to support electrolyzer technology**

PROJECT NAME	LOCATION	CAPACITY OF RENEWABLE ENERGY	H_2 YIELD (MTPA)
Germany	SOEC and AE	Funding: $67.8 million	Sunfire gets grant to build gigawatt-scale manufacturing of SOEC and AE.
	X	Funding: ~$828 million	Support for electrolyzer manufacturing, hydrogen transport, and offshore hydrogen production.
Green Hydrogen Catapult (UN's High-Level Climate Action Champions and Rocky Mountain Institute)	X	X	Aims to bring down the cost of green hydrogen below $2/kg by scaling up manufacturing of electrolyzers to 45 GW by 2026. The overall electrolyzer target is increased to 80 GW.
Japan	X	Funding 70 billion yen (~$7.2 million)	Develop a large-scale, cost-efficient electrolyzer-based hydrogen production system.
United States	X	Inflation Reduction Act (clean hydrogen production incentive)	Provides incentives up to $3/kg of clean hydrogen produced, depending on the carbon intensity linked with its production.
European Union	X	Joint declaration	The Commissioner for Internal Market (EU) signed a joint declaration with European electrolyzer manufacturers to achieve 17.5 GW/year of electrolyzer manufacturing capacity by 2025.
United Kingdom	X	£100 million ($108 million)	Provide support for 250 MW of electrolyzer-based hydrogen production in 2023 for the hydrogen business model.

Note: AE = alkaline electrolysis; SOEC = solid oxide electrolysis cell; MW = megawatt; X = not available.

Sources: Authors' compilation from Esposito and Tallackson (2022), Radowitz (2022), and Scottish Government (2022).

3. ELECTROLYZER TECHNOLOGY: CHALLENGES AND OPPORTUNITIES

Electrolyzers are widely used in the chlor-alkali industry to produce chlorine and sodium hydroxide. Alkaline systems deployed in the fertilizer and chlor-alkali industries were optimized for high efficiency under continuous operations. However, the electrolysis capacity to produce green hydrogen from renewable energy is growing from a very low base and requires a significant acceleration to align with net-zero emission scenarios.

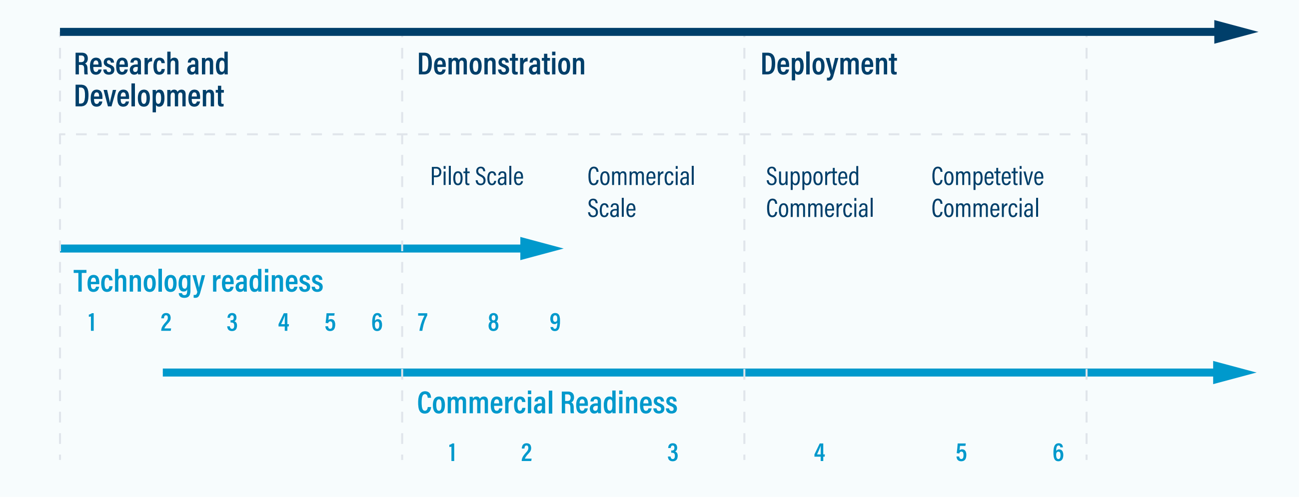
As the market share of different types electrolyzers increases, their cost will be crucial. The investment costs are difficult to compare across systems, because information about key system parameters such as temperature, voltage, current density, and pressure is often lacking. In the present scenario, the approximate capital expenditure (CAPEX) requirements are currently in the range of $500–1,400 per kilowatt-electric (kWe) for AE electrolyzers and $1,100–1,800/kWe for PEM electrolyzers, whereas estimates for SOEC electrolyzers range across $2,800–5,600/kWe. Over recent decades, PEM technology has shown significant cost reductions, approaching the cost of AE systems. AEM is at an earlier stage of development, but it could become cost-effective when manufacturing at scale begins.

Electrolyzers for hydrogen production in energy applications (power-to-gas, power-to-liquid, power-to-fuel) are on a spectrum ranging from mature to nascent. Megawatt-scale AE and PEM electrolyzers are already commercialized; however, SOEC and AEM electrolyzers are not yet widely available. SOEC electrolyzers are closer to commercialization because they seem suitable for coupling with intermittent renewables, but they are expensive and have a low production capacity. AEM electrolyzers have a long way to go before large-scale deployment can commence. The commercialization process of these different electrolyzer technologies can be assessed by mapping their future market through two major frameworks: Technology Readiness Level (TRL) and the Commercial Readiness Index (CRI) (Patonia and Poudineh 2022).

The TRL level assesses technological maturity based on the level of research, development, and deployment, and the CRI index considers factors that affect commercial and market conditions beyond technology maturity. Both the TRL level and the CRI index are mapped on the technology development chain. The CRI index extends to when the technology is commercially deployed and has become a bankable asset. The index helps address the key barriers to the commercialization of electrolyzer technology. A pictorial representation of TRL and CRI is shown in Figure 4 (ARENA 2014).

Table 8 indicates the operational parameters, key performance indicators, and the TRL levels and CRI indexes for the four major electrolyzer technologies. It shows that out of all the currently available electrolyzer technologies, the conventional one, AE, has progressed to the upper stages of commercialization, followed by PEM systems, which have recently started being deployed at large scale. The table also identifies areas where significant improvements are required in

Figure 4 | TRL and CRI mapping on the technology development chain



Note: CRI = Commercial Readiness Index; TRL = Technology Readiness Level.

Sources: ARENA 2014.

Table 8 | Operational parameters, key performance indicators, TRL, and CRI for AE, PEM, SOEC, and AEM electrolyzers

S.NO.	PARAMETERS	AE	PEM	SOEC	AEM
1	Nominal current density (a/cm^2)	0.2–0.8	1–2	0.3–1	0.2–2
2	Electrode area (cm^2)	10,000–30,000	1,500	200	<300
3	Cell voltage (v)	1.8–2.4	1.8–2.2	0.7–1.5	1.6–2.0
4	Cell pressure (bar)	<30	70	<10	<30
5	Temperature (°c)	70–90	50–80	700–850	40–60
6	Load range (%)	15–100	5–120	30–125	5–100
7	Cold start (to nominal load in minutes)	<20	<50	>600	<20
8	Stack electrical efficiency (kWh/kg H_2)	47–66	47–66	35–50	51–66
9	Electrical efficiency of system (kWh/kg H_2)	50–78	50–83	45–55	57–69
10	Stack degradation (%/1000 hours)	0.13	0.25	2.80	Unknown
11	Lifetime of stack (thousand hrs.)	<120	<100	<23	>5
12	Technology readiness level (TRL)	9	9	5–6	4–5
13	Applicability	Mature	Commercialization	Demonstration	Laboratory-scale
14	Commercial Readiness Index (CRI)	5–6	3–4	1–2	1

Note: AE = alkaline electrolysis; AEM = anion exchange membrane; CRI = Commercial Readiness Index; kWh = kilowatt-hour; PEM = proton exchange membrane; SOEC = solid oxide electrolysis cell; TRL = Technology Readiness Level.

Sources: Based on raw data from IRENA (2020), modified by the authors.

electrolyzers to address challenges related to high cost, performance, and durability.

The subsequent section will cover some of the major technology gaps in electrolyzer manufacturing and green hydrogen production.

3.1 RAW MATERIAL AVAILABILITY AND SUPPLY CHAIN OF MINERALS

A unique combination of minerals and subcomponents is needed to manufacture electrolyzers because of the diversity in the technologies and materials used. Given the scale of the prospective market for green hydrogen production, electrolyzers need to be scaled up from the megawatt to the gigawatt range. This implies that the upstream supply chain of electrolyzers will have to grow rapidly as well. Large-scale deployment of electrolyzers is in a nascent stage of development and is largely shaped by the priority usage of green hydrogen in different sectors.

AE technology is advantageous in terms of its design and does not require precious and costly minerals from the platinum-group metals (PGMs). It mainly requires nickel, small amounts of zirconium, and (nickel-plated) stainless steel for its manufacture. The supply chain of unrefined nickel is reliable because its reserves, extraction, and refining are not concentrated heavily in one region. The largest source of nickel extraction is in Indonesia, which enjoys a global share of over 30 percent. In refining strategic minerals, China is the dominant player. Globally, 68 percent of nickel is refined in China, and it has a clear downstream competitive advantage (Castillo and Purdy 2022).

In the case of PEM electrolyzers, the supply chain issue is critical because they use noble metals such as Pt and Ir, which are heavily concentrated in South Africa. These metals are expensive and scarce, and alternatives to using Ir in PEM units are not known. The current mining rates are limited for both the metals and will allow only an increase of 3–7.5 GW capacity annually. Substantial growth in mining activity is required for the upcoming colossal demand for PEM electrolyzers. Major players in AE and PEM electrolyzers are shown in Figure 5 (Ansari et al. 2022).

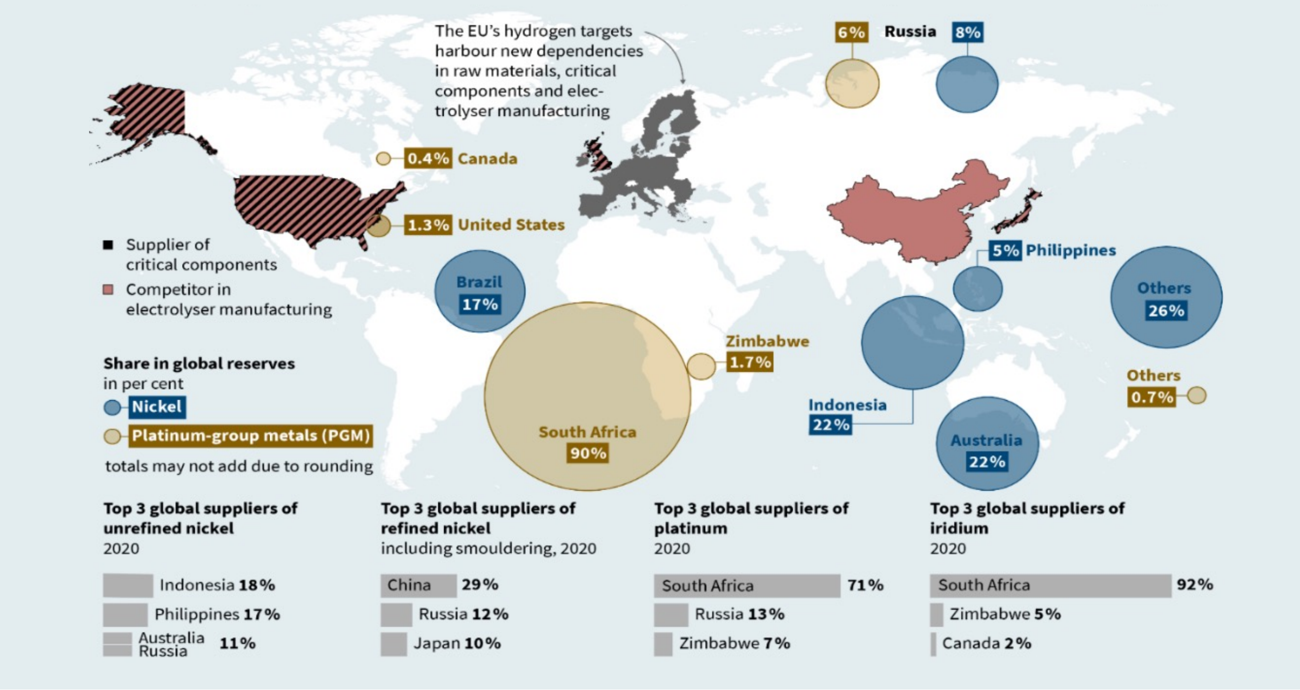
Rare-earth-related composite oxides play an irreplaceable role in SOEC components because they exhibit mixed ionic and electronic conductivity. This electrolytic cell uses ceramics such as yttria-stabilized-zirconia (YSZ) for ion transport at high temperatures and cermet (ceramic-metal composites) as electrodes materials. Most of the reserves and refining sites of rare earth elements that are commonly used in SOEC such as lanthanum, zirconium, and yttrium are present in China (Minary-Jolandan 2022). Table 9 shows the mineral requirements for different electrolyzer technologies (IEA 2021).

To achieve the envisioned production scaling of electrolyzers by different countries, problems related to the availability and processing of minerals used in stack manufacturing should be resolved. Some suggestions to ease the risk in the supply chain are the following:

- **Diversify the supply chain of PGM and rare earth metals:** Establishing refining, catalyst manufacturing, and recycling facilities around the globe can diversify the supply chain of minerals, which are currently highly concentrated in a few countries. Establishing consistent and reliable trade flows among countries will also be necessary.

- **Support domestic manufacturing of electrolyzer-related components:** Policies and incentives that catalyze the domestic manufacturing of electrocatalysts, cells, stacks, and system should be instituted.

Figure 5 | Players for minerals used in AE and PEM technologies



Note: AE = alkaline electrolysis; PEM = proton exchange membrane.

Sources: Ansari et al. 2022.

Table 9 | Minerals required by different electrolyzer technologies

TECHNOLOGY	TRADITIONAL MATERIAL	NOBLE METALS	RARE EARTH	QUANTITY (T/GW)
Alkaline	Nickel			800
	Zirconium			100
	Aluminum			500
	Steel			10000
PEM		Iridium		0.7
		Platinum		0.3
SOEC	Nickel			150-200
	Zirconium			40
			Lanthanum	20
			Yttrium	<5

Note: AE = alkaline electrolysis; GW = gigawatt; PEM = proton exchange membrane; SOEC = solid oxide electrolysis cell; t = tonne.

Sources: IEA 2021.

- **Expand R&D initiatives:** Expanding research to reduce the vulnerabilities arising from dependence on minerals, especially Ir loading in electrolyzer manufacturing, is necessary. Recycling technologies to recover PGMs and rare earth metals from electrolyzers and fuel cells should be developed and commercialized; this will make secondary production of minerals from these technologies a reliable source. Mandates concerning recycling in this space will maximize end-of-life (EoL) metal recovery. EoL recycling of electrolyzers can further reduce the primary demand for these minerals.

3.2 OPERATIONAL, DESIGN, AND MATERIAL CHALLENGES

AE, PEM, SOEC, and AEM electrolyzers differ in their construction material, half-cell reactions, operational parameters, and investment cost. The operational temperature range of AE and PEM electrolyzers lies between 20°C and 120oC, and these electrolyzers are categorized as low-temperature electrolyzers (LTEs) with an efficiency of 60–80 percent. SOEC electrolyzers, which are known as high-temperature electrolyzers (HTEs), operate between 600°C and 1,200oC to perform steam electrolysis. Thermodynamically, the electrical energy demand to electrolyze water decreases as the operating temperature increases. An electrolytic cell reaches its maximum threshold efficiency at the thermoneutral voltage (at which no heat is exchanged between the cell and its surroundings), which is 1.48 V and 1.27 V for LTEs and HTEs, respectively, at atmospheric pressure. The HTE achieves a 25–30 percent reduction in electricity consumption and can reach higher efficiencies of about 95 percent if integrated with external waste heat (Chandrasekar et al. 2021).

Improving the performance of the electrolyzer stack in one dimension usually implies reduced performance in other parameters such as efficiency, lifespan, mechanical strength, and manufacturing cost. The size of the electrolyzer module and innovation in materials and manufacturing methods depend upon the specific application of hydrogen produced through electrolysis of water. AE electrolyzers have a significant economic appeal due to the abundance and low cost of nickel and iron, which are used as material for the electrode and other components during stack manufacturing. A reliable list of benchmark materials has not yet been established in AE because a great deal of research is required to identify new electrocatalyst materials that are highly active in water splitting and remain stable for a long time. Another problem is that the use of thick diaphragms increases the resistance and could lead to high gas cross-overs (Karacan et al. 2022). These systems also face challenges in stabilizing the production rate of hydrogen under transient start-up/shutdown operations, which affects the stability of the electrodes and limits the lifetime of these electrolyzers (Kim et al. 2022).

PEM technology is suitable for generating green hydrogen because of its high production rates, and it is considered to operate well with the intermittent supply of renewable electricity. The requirement of expensive and stable materials due to the highly acidic environment in the cell makes this technology costly. An electrocatalyst from non-noble materials with a high surface area is required so that the electrolyzer can still operate at a high current density and maximize hydrogen production. Improvements in porous transport layers and membranes can further enhance the performance and durability of this electrolyzer.

SOEC operates at a high temperature, and its cells are made up of ceramics to withstand the temperature. Most of the R&D on SOEC is focused on improving cell and stack performance by improving the materials for the membrane, electrolytes, and electrocatalysts. Another practical challenge is related to the requirement of high temperature. Although it offers a great opportunity for heat integration with exothermic industrial processes, the heating up of the feed water and sweep air up to the desired temperature must be efficient and reliable (L. Wang et al. 2018). Table 10 lists some of the design/engineering challenges and areas for improvement in AE, PEM, SOEC, and AEM electrolyzers.

Table 10 | **Details on design- and material-related challenges in electrolyzer technology**

TECHNOLOGY	CHALLENGES/IMPROVEMENTS
Alkaline	▪ Improvements in the stability and conductivity of the diaphragm separator that will lead to higher efficiency. ▪ Development of robust catalysts and electrodes that can withstand the intermittent operations of renewable energy. ▪ Higher efficiencies could be achieved by increasing the operating temperature. Catalyst stability at and above 100oC can lead to tangible improvements in efficiency.a ▪ Redesign of electrocatalyst composition and electrode architecture for specific areas and utilization rates. ▪ Introduction of novel porous transport layers and electrode concepts.
PEM	▪ New catalyst materials and structures (PGM and non-noble metals) could be developed to improve stability in corrosive conditions. ▪ Reengineering electrodes to decrease catalyst quantities could bring down the cost. ▪ Solutions to problems related to membrane creep, increase in chemical degradation with increasing operating pressure, and high back diffusion are needed. ▪ Removal or substitution of expensive coatings on porous transport layers. ▪ Appropriate choice of manufacturing technology for product design, required production volume, and cost of the technology.
SOEC	▪ Severe material degradation occurs because SOEC operates at high temperature. Stability needs to be improved for longer time periods. ▪ Heat integration with external energy sources such as nuclear reactors and coal-fired power plants. ▪ Upgradation of manufacturing and cutting-edge technologies to improve performance. ▪ Technology advancements for collection of waste heat, which would lower the waste heat and increase the overall process efficiency. ▪ Scaling up stack components toward larger megawatt or gigawatt units
AEM	▪ Establishment of testing, and benchmarking the performance evaluation. ▪ Development of advanced transition-metal-based powder electrocatalysts for better performance. ▪ Cost-effective and highly efficient OER electrocatalysts. ▪ Improve interface interactions in the membrane electrode assembly (MEA) by regulating the fabrication methods and designing the advanced catalyst layer structure. ▪ Regulation of cells to assemble torque, temperature, and pressure to optimize MEA for improving activity.

Note: AE = alkaline electrolysis; AEM = anion exchange membrane; OER = oxygen evolution reaction; PEM = proton exchange membrane; PGM = platinum-group metal; SOEC = solid oxide electrolysis cell.

Sources: Authors' compilation.

a. Ehlers 2023.

3.3 LARGE-SCALE HYDROGEN ELECTROLYZERS

Upscaling electrolyzer manufacturing can help reduce electrolyzer costs and utilize equipment and facilities effectively. The large-scale manufacturing facilities also represent long-term decisions and will boost investor confidence. This ultimately will reduce the cost of hydrogen (IRENA 2020). However, several problems are associated with large-scale electrolyzer manufacturing, such as demand uncertainty, huge investment risk, material availability, and high-technology manufacturing.

Hydrogen has several uses, but uncertainty prevails regarding its uptake in sectors such as mobility, heating, and power. Also, green hydrogen must compete with the traditionally available gray hydrogen as well as with natural gas, oil, and coal to demonstrate that it is a future-ready fuel. The high CAPEX, demand uncertainty, and unclear regulatory framework could prevent potential off-takers from signing long-term offtake contracts and paying a higher price than the market rate for the fuel. The early market players involved in green hydrogen production also face the first mover risk associated with uncertainty in demand and cost competitiveness.

Identification of materials that may be critical for the expected scale-up of electrolyzers is crucial. Research, innovation, and development for reducing or substituting the critical minerals in electrolysis technology are inevitable. The supply-chain-related problems of the minerals used in electrolyzer manufacturing have been discussed in the earlier sections.

Rapid upscaling of, and improvement in, electrolyzers can be achieved using high-tech manufacturing technologies. An automated technology that can enable deposition of atomic thickness catalyst layers will not only improve the material efficiency but will also help achieve excellent standards of quality control at high throughput (TNO 2023).

A strategic roadmap to achieve large-scale electrolyzer deployment is necessary. This roadmap can consider factors such as the available manufacturing capacity, planning for upgrading the module size, targeted R&D, and the learning-by-doing methodology. The key element in upscaling the manufacturing process involves shifting from the manual assembly line to an automatic assembly.

These concerns can also be addressed in parallel by enabling favorable policies and support from governments, setting capacity targets, stimulating international trade, and implementing projects that are in the pipeline, all of which will encourage the upscaling of manufacturing at a higher production rate. The mushrooming of electrolyzer manufacturing and green hydrogen production is directly linked with demand. Hence, the active involvement of the government and supportive policy measures to create demand will play a crucial role.

3.4 INTERMITTENT SUPPLY OF RENEWABLE ENERGY

In terms of energy supply, electrolysis-generated green hydrogen uses renewable energy. Weather-dependent renewable energy sources are variable and show dynamicity in solar intensity or wind speed. The intermittent nature of renewable energy (solar and wind) can create operational breakdowns and affect electrolyzer performance.

Fluctuating current inputs to an electrolyzer change its voltage, gas pressure, gas purity, and the amount of gas generated. The sudden change in electrode potential can in turn cause electrode degradation. The electrolyzer should stop functioning when the electric power drops below the operation range due to operational constraints such as minimum power loads. Renewable energy cannot be used during the shutdown, which lowers the efficiency of all energy use (Kojima et al. 2023).

Alkaline electrolyzers powered by renewable electricity are the cost-effective solution for large-scale hydrogen production. However, the intermittent and fluctuating behavior of renewable energy sources may lead to poor performance of AE at low loads. Due to the high potential of gas cross-over between the anode and cathode at low load, start-stop operations are increased to ensure the system's safety. These frequent start-stops affect the durability of electrodes and can cause severe catalyst deterioration (Xia et al. 2023).

PEM technology operation is flexible, and it can be used with modest power loads and varying power, which makes it most suitable for obtaining direct power with intermittent renewable energy (Scottish Government 2022). Although electrocatalysts made of precious metals are scarce and expensive, technological advancements that allow for a reduction in the quantity of precious-metal catalysts without compromising the electrolyzer's performance or lifespan are necessary. For scaling up electrolyzers, it is crucial to create membranes that can withstand variations in pressure or local heat and cell layouts that can reduce these heterogeneities. Unlike AE electrolyzers, PEM electrolyzers can be operated at low-power loads with fluctuating power, but such operation may lead to performance degradation over time.

Laboratory-scale studies on the durability of, and fluctuating power inputs to, SOEC electrolyzers are described in the literature. As these electrolyzers operate at high temperature, understanding the temperature variation in the cell caused by the intermittent nature of renewable energy will be important (Kojima et al. 2023). Small-scale studies have shown that SOEC electrolyzers are resilient to power fluctuations, although it will be interesting to observe their behavior at a large scale over time.

Durability of the entire electrolyzer system against power fluctuations must be ensured for the long-term deployment of all three electrolyzer technologies. For this, electricity integration into the grid is one of the options for obtaining a stable supply of electricity. Another method is energy storage. Energy sources such as hydropower and natural gas can also be used to balance the variable supply of renewable energy.

3.5 USE OF SEAWATER

Substitution of freshwater with seawater can be a major method of producing green hydrogen. Technologies related to desalination and wastewater treatment are available, and they will require only a negligible amount of additional energy compared with the energy consumed for electrolyzer operation. The desalination process requires <0.1 percent of the energy consumed in electrolyzer operation. It is important now to take the next step forward and switch to seawater for hydrogen production (Beswick et al. 2021).

The use of seawater seems to be a feasible option, but it involves challenges. The two-electron transfer hydrogen evolution reaction (HER) and the four-electron transfer oxygen evolution reaction (OER) are the two main half-reactions involved in water electrolysis. The main problem with seawater electrolysis for HER is that as the current increases, the local pH near the cathode surface rises significantly. This may lead to the formation of precipitates, such as Ca (OH)2 and Mg (OH)2, from the cations in the seawater, which would block the HER active sites. The extreme pH fluctuation problem must be resolved if long-term sea water electrolysis is to succeed. There are currently two possible solutions: including a pH buffer in the seawater electrolysis system to moderate pH variations and constructing suitable saltwater electrolyzers. To obtain high HER selectivity, future catalyst design should consider inhibiting these undesirable electrochemical reactions in a seawater electrolyzer (Gao et al. 2022).

The most challenging task in seawater electrolysis continues to be the creation of active, selective, and stable catalysts. Because real saltwater composition varies from place to place, it is essential to use a standardized composition of electrolytes when assessing the qualities of novel catalysts. The significant problem of ion-induced poor catalyst stability calls for a thorough understanding of the various ions' poisoning mechanisms. Advances in membrane technology will hasten the growth of the saltwater electrolysis sector to meet the rising demand for green hydrogen. More resilient and tolerant seawater electrolyzers could extend electrolyzer lifetimes, lower CAPEX, and lower maintenance costs.

4. RECOMMENDATIONS AND WAY FORWARD

Electrolyzers are a critical technology and play an important role in the energy transition. Projects for installing electrolyzers at locations with excellent solar and wind resources have been launched at many locations, and future large-scale industrial deployments are underway. In this section, the future of green hydrogen production technologies and initiatives that can be adopted by the G20 countries to accelerate low-carbon energy systems are discussed.

4.1 FUTURE OF GREEN HYDROGEN AND ELECTROLYZER MANUFACTURING

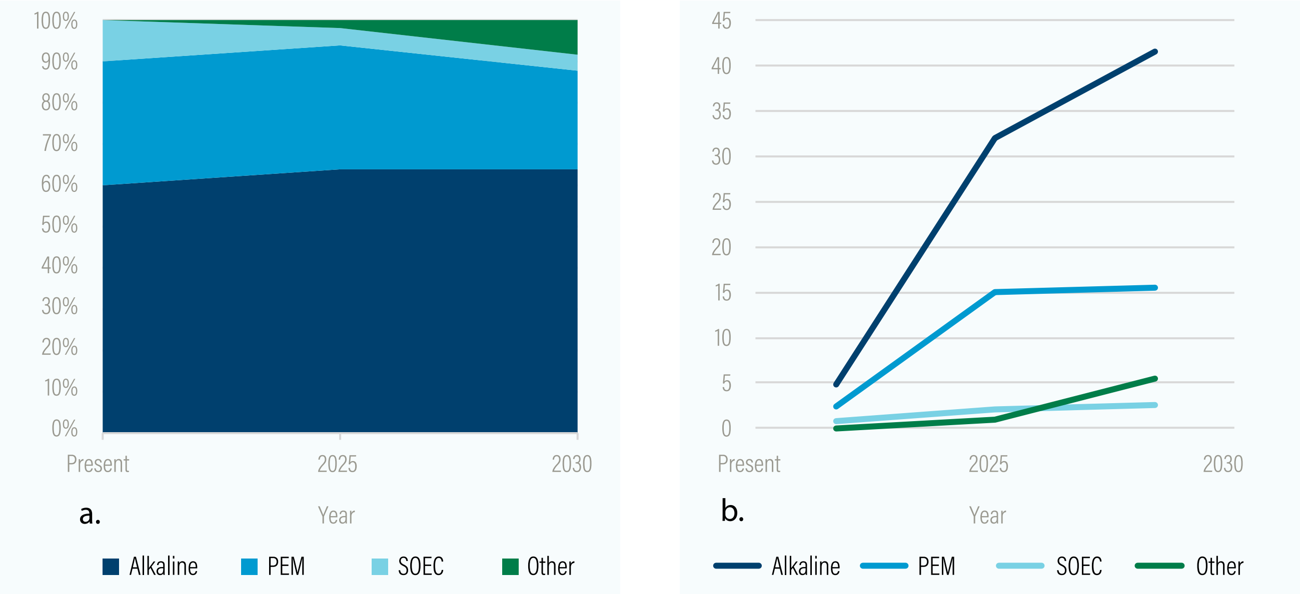
The IEA announced that 520 Mt of clean H_2 is required annually to reach net-zero targets by 2050. According to Bloomberg NEF, the Hydrogen Council expert, and a 1.5°C scenario forecast by IRENA, 500 Mt, 660 Mt, and 614 Mt, respectively, are required (Collins 2023).

The future of global electrolyzer manufacturing relies on supportive policies and initiatives to promote the uptake of hydrogen in different sectors. By 2050, the electrolyzer capacity needs to grow from the current 700 MW to 1.3–3 TW (terawatts) under the announced scenario and to 4–5 TW under the net-zero scenario, which requires an accelerated installation pace of almost 400 GW/yr (IEA 2022; IRENA 2022). In addition to the increased demand, continuous R&D and large-scale manufacturing will help bring down the electrolyzer cost. By 2030, a 70 percent reduction in electrolyzer cost is expected if all the pipeline projects are implemented and electrolyzer manufacturing is upscaled (IRENA 2020).

AE technology, being the most mature technology, held a 60 percent share of the global electrolyzer manufacturing capacity in 2021, followed by PEM and SOEC. By 2030, the share of AE will rise to 64 percent of the global electrolyzer manufacturing capacity, followed by PEM and SOEC with shares of 24 percent and 4 percent, respectively. Figures 6a and 6b give a detailed view of the technology-wise growth and dominance of these technologies in the global electrolyzer manufacturing landscape.

In terms of the rise in production capacities, AE, PEM, and SOEC are likely to see significant growth until 2025–30. However, due to limitations in efficiencies, the use of critical raw materials, and so on, the rise in the production capacities of AE, PEM, and SOEC is projected to stagnate. Electrolyzer manufacturing is a volatile industry with everyday technology advancements and innovation, and this trend could continue. New emerging technologies, such as SOEC and AEM, could solve the emerging challenges and show excellent all-around performance. Globally, regions such as Europe and China, which had a share of 80 percent in 2021, dominate electrolyzer manufacturing. By 2030, this scenario may, however, change as electrolyzer manufacturing becomes increasingly competitive. Countries in North America, Oceania, India, and others can also emerge as key players in global electrolyzer manufacturing.

Figure 6 | a. **Technology-wise share and b. Shift in the global electrolyzer manufacturing landscape**



Note: AE = alkaline electrolysis; AEM = anion exchange membrane; GW = gigawatts; PEM = proton exchange membrane; SOEC = solid oxide electrolysis cell; yr = year.

Sources: Figure created by WRI based on data from IEA (2022), IRENA (2021), Lovegrove (2022), and Raj et al. (2022).

4.2 PRIORITIES FOR POLICIES AND MARKET CONSTRAINTS

Governments, along with diverse stakeholders, are already working to find effective policies to include the role of hydrogen in the clean energy transition. To improve the chances of meeting the infrastructure requirement and achieving the expected investment and growth of green hydrogen and electrolyzer technology, some of the following measures can be considered:

Demand creation

To solve the chicken-and-egg problem, demand creation for green or low-carbon hydrogen is crucial. Policies supporting demand creation can be a key lever to encourage its adoption as a clean energy vector. Closing the price gap between green and gray hydrogen is one of the ways to increase the demand for green hydrogen; alternatively, a legislation that phases out gray hydrogen production by a certain date could be passed in stages, for example, 25 percent elimination by 2030, 50 percent by 2035, and 100 percent by 2040.

Financial support

Policies to mitigate investment risks across the complete green hydrogen value chain and support public-private partnerships for green or low-carbon hydrogen should be formulated. Such policies will reduce the pressure on the government and mitigate risks for both public and private sectors participating in a nascent industry. Applying taxes to gray hydrogen and launching production-linked incentive schemes to promote domestic electrolyzer manufacturing can make green hydrogen cost competitive.

Technology and scale of manufacturing

Supportive policy steps such as promotion of R&D, knowledge sharing, technology transfer, international collaborations, joint demonstration projects, innovation, and scaling of manufacturing are the key drivers that are essential to lower the cost and promote the competitiveness of hydrogen technologies.

International trade

Policies supporting international trade across the green hydrogen value chain can ease the risk related to the uncertainty in domestic demand. Such policies will further boost investors' confidence and ensure that the demand for green or low-carbon hydrogen can be met at the global level. International partnerships, harmonization of standards and certification, and development of hydrogen hubs near ports are some of the initial steps that can be taken to boost international trade.

Harmonization of global standards and certification

Establishing globally harmonized standards, a regulatory framework, and a hydrogen certification system can ensure clean practices, promote international trade, and boost confidence among consumers and investors in green or low-carbon hydrogen markets.

Skill development

Transitioning to green or low-carbon hydrogen will generate new jobs across the complete value chain. It will require a highly skilled workforce that is knowledgeable about hydrogen-based systems. This workforce can be built up by leveraging existing skills and developing new skills among workers across the hydrogen ecosystem, including industries, academia, and government. Training, apprenticeship programs, workshops, and the introduction of new educational courses are some steps that can be taken to support skill development.

4.3 PRIORITIES FOR INDUSTRIAL AND TECHNOLOGICAL ADVANCEMENTS

Poor articulation of market demands, supply chain constraints on required minerals, and inadequate knowledge exchange will hamper the timely development of green hydrogen and electrolyzer manufacturing, which in turn will slow down the energy transition. Collaboration among government, business, and research organizations could lead the way for joint development of green hydrogen.

Target specific gaps in technology

One challenge to the deployment of electrolyzers at large scale is to reach economies of scale in manufacturing. This effort involves finding alternatives to scarce materials, improving efficiency, and mitigating the lack of automated manufacturing. The process supply chain for essential components such as MEAs, gas diffusion layers, and electrode materials is limited. Component suppliers and original equipment manufacturers should make a head start in addressing the critical challenges of electrolyzer manufacturing by solving the problems related to the undersupply of materials and promote technological innovations to increase efficiency, which in turn will increase the output and thus reduce the cost.

Lifetime and Reliability

An important landmark of electrolyzers is to reach a lifetime of 20+ years. Hooking up electrolyzers directly to photovoltaic arrays and wind turbines with no grid connection to stabilize their power supply may pose a real challenge to electrolyzer systems. Manufacturers' data specify the lifetime of components in a certain environment, but in real-world operations the cyclic process could wear the components out many times faster, repeatedly. A combination of modeling and accelerated lifetime testing strategies to quantify sensitivity under various operating conditions could help in understanding the real-world operation challenges.

Demonstrate Functionality

The top priority with any new technology is to indicate its utilization at a large scale in real-world conditions. Lower capital and operating cost, performance evaluation, and suitability for intermittent operation of electrolyzers will justify the initial risk of investing in the equipment. With time, the next challenge will be to demonstrate that an investment in the new technology will deliver returns. This can be achieved if electrolyzers last the course and will not require any unexpected interventions.

Collaboration opportunities
Cooperative and coordinated actions to accelerate the development and deployment of electrolyzers to produce green/low-carbon hydrogen and its derivatives is required for global renewable energy transformation. Collaboration among industries with research organizations and international organizations of G20 nations could leverage the knowledge and expertise for driving low-carbon economic growth and enhance energy security.

Promote new technologies
Supporting electrolyzer technologies that are not yet commercialized could help them reach the market faster. Industry end users and established RE producers can work with electrolyzer OEMs to allow experimentation on and implementation of technologies that are new to the market, such as SOEC and AEM.

4.4 PRIORITIES FOR RESEARCH AND INNOVATION

Research, innovation, and development are needed to improve the efficiency of production of green hydrogen and electrolyzer manufacturing. These efforts will accelerate the energy transition to achieve decarbonization by increasing performance and reducing the cost of electrolyzers.

Platform for green hydrogen
development of a common platform for collaborative analysis, applied research, equipment, and testing protocols can be a solid starting point for the development of sustainable green hydrogen among different nations. Cross-learnings and scaling global climate finance among G20 nations will help boost the green hydrogen ecosystem globally.

Sharing facilities
Shared infrastructure for testing and validation can provide a major boost to the electrolyzer manufacturing industry and help it to develop at a large scale. Sharing could strengthen the infrastructure and set performance criteria for electrolyzers based on scarce material use, sustainability, and recyclability. The G20 nations could also make sharing of data and learnings of subsidized research, demonstrations, and pilot projects mandatory. Data sharing and monitoring of system performance can accelerate learning under the net-zero scenario and should be made available in government-funded projects.

Promoting high-tech manufacturing
Research, innovation, and development could be encouraged in the areas of automated cell/stack manufacturing, high-quality components, quality control, automated defect detection systems, and the use of robotics to reduce the number of manufacturing steps and handle a large volume of cells.

5. CONCLUSION

The potential of hydrogen as a clean and sustainable energy source is infinite. To promote the widespread deployment of this clean fuel, electrolyzers powered by renewable electricity are required for large-scale hydrogen production. Current and future projections of electrolyzer production to meet the hydrogen demand along with identification of gaps in the large-scale deployment of electrolyzer technologies could provide the capabilities the electrolyzer industry needs to thrive in the future.

Diverse stakeholders from different institutions of the G20 countries can work together to address the concerns related to electrolyzers. Policymakers can encourage investment in electrolysis capacity by providing a stable regulatory environment and ongoing assistance. Through technical breakthroughs and innovation, industry participants can concentrate on increasing the production and lowering the cost of hydrogen to make it more competitive than traditional fuel sources. The performance and effectiveness of electrolysis technology can also be enhanced with ongoing research and development, which will make it more appealing and competitive for widespread use, and a uniform standard law could promote international trade and cooperation.

REFERENCES

Ansari, Dawud, Julian Grinschgl, and Jacopo Maria Pepe. 2022. “Electrolyzers for the Hydrogen Revolution: Challenges, Dependencies, and Solutions.” SWP Comments 57. https://doi.org/10.18449/2022C57.

Arcos, Jose M. Marín, and Diogo M.F. Santos. 2023. “The Hydrogen Color Spectrum: Techno-Economic Analysis of the Available Technologies for Hydrogen Production.” Gases 3 (1): 25–46. https://doi.org/10.3390/gases3010002.

ARENA (Australian Renewable Energy Agency). 2014. “Commercial Readiness Index for Renewable Energy Sectors.” Canberra, Australia: ARENA. https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf.

Beswick, Rebecca R, Alexandra M Oliveira, and Yushan Yan. 2021. “Does the Green Hydrogen Economy Have a Water Problem?” ACS Energy Letters 6 (9): 3167–3169. https://doi.org/10.1021/acsenergylett.1c01375.

Castillo, Rodrigo, and Caitlin Purdy. 2022. China’s Role in Supplying Critical Minerals for the Global Energy Transition: What Could the Future

Hold? Leveraging Transparency to Reduce Corruption. https://www.brookings.edu/wp-content/uploads/2022/08/LTRC_ChinaSupplyChain.pdf.

Chandrasekar, Aruna, Damian Flynn, and Eoin Syron. 2021. “Operational Challenges for Low and High Temperature Electrolyzers Exploiting Curtailed Wind Energy for Hydrogen Production.” International Journal of Hydrogen Energy 46 (57): 28900–28911. https://doi.org/10.1016/j.ijhydene.2020.12.217.

Collins, Leigh. 2023. “Global Hydrogen Demand to More than Triple by 2050, Driven by Power Generation, Aviation and Industry: Analyst,” January 27. Hydrogen Insight. https://www.hydrogeninsight.com/production/global-hydrogen-demand-to-more-than-triple-by-2050-driven-by-power-generation-aviation-and-industry-analyst/2-1-1394924.

Ehlers, Johan C., Anders A. Feidenhans’l, Kasper T. Therkildsen, and Gastón O. Larrazábal. 2023. “Affordable Green Hydrogen from Alkaline Water Electrolysis: Key Research Needs from an Industrial Perspective.” ACS Energy Letters 8 (3): 1502–1509. https://doi.org/10.1021/acsenergylett.2c02897.

Esposito, Dan, and Hadley Tallackson. 2022. “The Inflation Reduction Act Upends Hydrogen Economics with Opportunities, Pitfalls.” Utility Dive. https://www.utilitydive.com/news/the-ira-will-accelerate-electrolyzed-hydrogens-future-heres-what-that-me/632925/.

FuelCellsWorks. 2022. “Nine of The Largest Green Hydrogen Projects 2022,” May 12. https://fuelcellsworks.com/news/nine-of-the-largest-green-hydrogen-projects-2022/.

Gao, Fei-Yue, Peng-Cheng Yu, and Min-Rui Gao. 2022. “Seawater Electrolysis Technologies for Green Hydrogen Production: Challenges and Opportunities.” Current Opinion in Chemical Engineering 36: 100827. https://doi.org/10.1016/j.coche.2022.100827.

Hydrogen Council. 2021. Hydrogen Decarbonization Pathways: A Life-Cycle Assessment. Brussels: Hydrogen Council. https://hydrogencouncil. com/wp-content/uploads/2021/01/Hydrogen-Council-Report_Decarbonization-Pathways_Part-1-Lifecycle-Assessment. pdf.

Hydrogen Council. 2022. Hydrogen Insights 2022: An Updated Perspective on Hydrogen Market Development and Actions Required to Unlock Hydrogen at Scale. Brussels: Hydrogen Council. https://hydrogencouncil.com/wp-content/uploads/2022/09/Hydrogen-Insights-2022-2.pdf.

Hydrogen Council. 2023. Hydrogen Insights 2023: An Update on the State of the Global Hydrogen Economy, with a Deep Dive into North America. Brussels: Hydrogen Council. https://hydrogencouncil.com/wp-content/uploads/2023/05/Hydrogen-Insights-2023.pdf

IEA (International Energy Agency). 2019. The Future of Hydrogen: Seizing Today’s Opportunities. Paris: IEA. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf.

IEA. 2021. Global Hydrogen Review 2021. Paris: IEA. https://www.iea.org/reports/global-hydrogen-review-2021.

IEA. 2022. Global Hydrogen Review 2022. Paris: IEA. https://www.iea.org/reports/global-hydrogen-review-2022.

IRENA (International Renewable Energy Agency). 2020. Green Hydrogen Cost Reduction: Scaling up Electrolyzers to Meet the 1.5°C Climate Goal. Dubai: IRENA. https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction.

IRENA. 2022. Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and Way Forward. Abu Dhabi: IRENA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Global_hydrogen_trade_part_1_2022_.pdf.

IRENA and EPO (European Patent Office). 2022. Innovation Trends in Electrolyzers for Hydrogen Production. Patent Insight report. Abu Dhabi: IRENA and Munich: EPO. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_EPO_Electrolyzers_H2_production_2022.pdf?rev=647d930910884e51b60137bcf5a955a6.

Karacan, Cinar, Felix P. Lohmann-Richters, Gareth P. Keeley, Fabian Scheepers, Meital Shviro, Martin Müller, Marcelo Carmo, and Detlef Stolten. 2022. "Challenges and Important Considerations When Benchmarking Single-Cell Alkaline Electrolyzers." International Journal of Hydrogen Energy 47 (7): 4294–4303. https://doi.org/10.1016/j.ijhydene.2021.11.068.

Kim, Yoona, Sang-Mun Jung, Kyu-Su Kim, Hyun-Yup Kim, Jaesub Kwon, Jinhyeon Lee, Hyun-Seok Cho, and Yong-Tae Kim. 2022. "Cathodic Protection System against a Reverse-Current after Shut-down in Zero-Gap Alkaline Water Electrolysis." JACS Au 2 (11): 2491–2500. https://doi.org/10.1021/jacsau.2c00314.

Kojima, Hirokazu, Kensaku Nagasawa, Naoto Todoroki, Yoshikazu Ito, Toshiaki Matsui, and Ryo Nakajima. 2023. "Influence of Renewable Energy Power Fluctuations on Water Electrolysis for Green Hydrogen Production." International Journal of Hydrogen Energy 48 (12): 4572–4593. https://doi.org/10.1016/j.ijhydene.2022.11.018.

Lovegrove, Peter. 2022. "Hydrogen Forecast to 2050," June 14. DNV. https://www.dnv.com/news/hydrogen-at-risk-of-being-the-great-missed-opportunity-of-the-energy-transition-226628.

MarketsandMarkets. 2022. Green Hydrogen Market by Technology, Renewable Source, End-Use Industry, and Region: Global Forecast to 2027. Pune, India: MarketsandMarkets Research. https://www.marketsandmarkets.com/Market-Reports/green-hydrogen-market-92444177.html.

Minary-Jolandan, Majid. 2022. "Formidable Challenges in Additive Manufacturing of Solid Oxide Electrolyzers (SOECs) and Solid Oxide Fuel Cells (SOFCs) for Electrolytic Hydrogen Economy toward Global Decarbonization." Ceramics 5 (4): 761–779. https://doi.org/10.3390/ceramics5040055.

Moberg, Jonas, and Sam Bartlett. 2022. "The Mirage of Blue Hydrogen Is Fading" Blog. Green Hydrogen Organisation. http://gh2.org/blog/mirage-blue-hydrogen-fading.

Olivier, Pierre, Cyril Bourasseau, and Pr Belkacem Bouamama. 2017. "Low-Temperature Electrolysis System Modelling: A Review." Renewable and Sustainable Energy Reviews 78: 280–300. https://doi.org/10.1016/j.rser.2017.03.09.

Patonia, Aliaksei, and Rahmatallah Poudineh. 2022. "Cost-Competitive Green Hydrogen: How to Lower the Cost of Electrolyzers?" Working Paper, OIES Paper: EL No. 47, Oxford Institute for Energy Studies (OIES) Research Papers. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2022/01/Cost-competitive-green-hydrogen-how-to-lower-the-cost-of-Electrolyzers-EL47.pdf.

Radowitz, Bernd. 2022. "Germany Grants Sunfire $68m to Build up Gigawatt-Scale H2 Electrolyzer Production." Recharge | Energy Transition. https://www.rechargenews.com/energy-transition/germany-grants-sunfire-68m-to-build-up-gigawatt-scale-h2-Electrolyzer-production/2-1-1142165.

Raj, Kowtham, Pranav Lakhina, and Clay Stranger. 2022. Harnessing Green Hydrogen: Opportunities for Deep Decarbonisation in India. New Delhi: NITI Aayog and Colorado: Rocky Mountain Institute (RMI). https://www.niti.gov.in/sites/

default/files/2022-06/Harnessing_Green_Hydrogen_V21_DIGITAL_29062022.pdf.

Rosa, Lorenzo, and Marco Mazzotti. 2022. "Potential for Hydrogen Production from Sustainable Biomass with Carbon Capture and Storage." Renewable and Sustainable Energy Reviews 157: 112123. https://doi.org/10.1016/j.rser.2022.112123.

Schalenbach, Maximilian, Aleksandar R. Zeradjanin, Olga Kasian, Serhiy Cherevko, and Karl J. J. Mayrhofer. 2018. "A Perspective on Low-Temperature Water Electrolysis – Challenges in Alkaline and Acidic Technology." International Journal of Electrochemical Science 13 (2): 1173–1226. https://doi.org/10.20964/2018.02.26.

Scottish Government. 2022. Assessments of Electrolyzers: Final Report. Edinburgh: The Scottish Government. https://www.gov.scot/binaries/content/documents/govscot/publications/research-and-analysis/2022/10/assessment-Electrolyzers-report/documents/assessment-Electrolyzers-final-report/assessment-Electrolyzers-final-report/govscot%3Adocument/assessment-Electrolyzers-final-report.pdf.

TNO (Netherlands Organisation for Applied Scientific Research). 2023. "Electrolyzers: Opportunities for the High-Tech Manufacturing Industry – The Case of PEM." https://www.voltachem.com/images/uploads/Electrolyzers_opportunities_for_the_high-tech_manufacturing_industry_20230331.pdf.

United Nations. n.d.-a. "The Paris Agreement." United Nations. https://www.un.org/en/climatechange/paris-agreement. Accessed June 1, 2023.

United Nations. n.d.-b. "For a Livable Climate: Net-Zero Commitments Must Be Backed by Credible Action." Net Zero Coalition. United Nations. https://www.un.org/en/climatechange/net-zero-coalition. Accessed June 1, 2023.

UNEP (UN Environment Programme). 2022. Emissions Gap Report 2022. EGR. Nairobi: UNEP. https ://www.unep.org/resources/emissions-gap-report-2022.

Wang, Ligang, Mar Pérez-Fortes, Hossein Madi, Stefan Diethelm, Jan Van herle, and François Maréchal. 2018. "Optimal Design of Solid-Oxide Electrolyzer Based Power-to-Methane Systems: A Comprehensive Comparison between Steam Electrolysis and Co-Electrolysis." Applied Energy 211: 1060–1079. https://doi.org/10.1016/j.apenergy.2017.11.050.

Wang, Fu, Lei Wang, Yangliang Ou, Xuanmiao Lei, Jinliang Yuan, Xingjiang Liu, and Yingying Zhu. 2021. "Thermodynamic Analysis of Solid Oxide Electrolyzer Integration with Engine Waste Heat Recovery for Hydrogen Production." Case Studies in Thermal Engineering 27: 101240. https://doi.org/10.1016/j.csite.2021.101240.

Xia, Yanghong, Haoran Cheng, Hanghang He, and Wei Wei. 2023. "Efficiency and Consistency Enhancement for Alkaline Electrolyzers Driven by Renewable Energy Sources." Communications Engineering 2 (1): 22. https://doi.org/10.1038/s44172-023-00070-7.

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