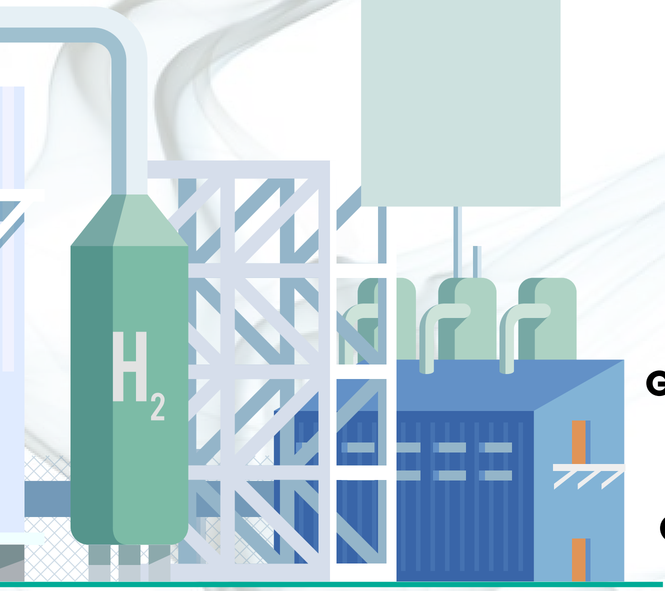
IRENA
International Renewable Energy Agency

MAKING THE BREAKTHROUGH

Green hydrogen policies and technology costs



Highlights and excerpts from

GREEN HYDROGEN: A guide to policy making

Green hydrogen cost reduction

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- ***Green hydrogen: A guide to policy making*** (IRENA, 2020; ISBN 978-92-9260-286-4)
- ***Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5°C climate goal*** (IRENA, 2020; ISBN 978-92-9260-295-6)

About IRENA

The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation, a centre of excellence, a repository of policy, technology, resource and financial knowledge, and a driver of action on the ground to advance the transformation of the global energy system. An intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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FOREWORD

Francesco La Camera
Director-General, IRENA

While 2020 may be remembered for the tragic COVID-19 crisis, it was also an unprecedented year for the global energy transition and the growing momentum of hydrogen technology. Many countries, in aligning their pandemic response with longer-term goals, have announced strategies to develop hydrogen as a key energy carrier. In parallel, numerous countries, cities and companies have adopted net-zero targets for energy-related carbon dioxide emissions, bringing the need for hydrogen to the forefront.

But not all types of hydrogen are compatible with sustainable, climate-safe energy use or net-zero emissions. Only "green" hydrogen – produced with electricity from renewable sources – fulfils these criteria, which also entail avoiding "grey" and hybrid "blue" hydrogen. Green hydrogen uptake is essential for sectors like aviation, international shipping and heavy industry, where energy intensity is high and emissions are hardest to abate.

Green hydrogen, however, is still not ready to take off without widespread and co-ordinated support across the value chain. The Collaborative Framework on Green Hydrogen, set up by the International Renewable Energy Agency (IRENA) in mid-2020, offers a platform to strengthen support in co-operation with IRENA's member countries and partners.

The past two years have witnessed increased momentum, with around 20 countries adopting a national hydrogen strategy or announcing their intention to do so. Industry investors plan at least 25 gigawatts of electrolyser capacity for green hydrogen by 2026. Still, far steeper growth is needed – in renewable power as well as green hydrogen capacity – to fulfil ambitious climate goals and hold the rise in average global temperatures at 1.5 degrees Celsius.

Green hydrogen, on average, costs between two and three times more to make than blue hydrogen, with the true potential and viability of the latter requiring further investigation. With electricity input accounting for much of the production cost for green hydrogen, falling renewable power costs will narrow the gap. Attention, meanwhile, must shift to the second-largest cost component, electrolysers.

With larger production facilities, design standardisation and insights from early adopters, the proposed strategies could cut costs by 40% in the short term and up to 80% in the long term, this study finds.

In price terms, the resulting green hydrogen could fall below the USD 2 per kilogram mark – low enough to compete – within a decade. This opens the way for large-scale manufacturing capacity, new jobs and economic growth. But getting there depends on defining the right business model, creating markets, and optimising the supply chain in a way that both developed and developing countries, equally, can enjoy the transition to a clean, resilient energy system.

IRENA stands ready to help countries worldwide, whatever their energy challenges or level of economic development, make the leap.

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KEY FINDINGS

As global economies strive for carbon neutrality, cost-competitive renewable hydrogen is possible within the decade.

Green hydrogen, produced by renewable power, can help eliminate carbon dioxide (CO_2) emissions in challenging sectors like steel, chemicals, long-haul transport, shipping and aviation. Thanks to the decline in renewable power costs, hydrogen could become a cost-competitive clean energy carrier worldwide by 2030.

Green hydrogen can cut emissions from heavy industry and transport

However, ongoing innovation and consistent policy attention are needed to make green hydrogen viable as part of a sustainable energy mix. Regulations, market design, and the costs of power and electrolyser production will all come into play.

The International Renewable Energy Agency (IRENA) has released two in-depth studies on how to scale up hydrogen production based on renewable power sources in time to meet climate goals:

- ***Green hydrogen: A guide to policy making*** (Nov 2020)
- ***Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5°C climate goal*** (Dec 2020)

The present overview encompasses key findings from the two studies. It aims to highlight the challenges and assist in the crucial decision making needed to cut production costs and bring green hydrogen into the energy mainstream.

As the world strives to cut greenhouse gas emissions and reach carbon neutrality by 2050, energy-intensive industries and transport present a major challenge. Emissions are especially hard to abate in sectors such as steelmaking and cement, aviation and long-haul shipping. Hydrogen based on renewables, or *green* hydrogen, has emerged as a vital clean energy carrier.

This is the only hydrogen type fully compatible with net-zero emission targets and sustainable, climate-safe energy use. *Grey* and hybrid *blue* hydrogen can also boost energy supply, but without eliminating fossil fuel use. Blue hydrogen, while cleaner than grey, still relies on carbon capture and storage (CCS).

Energy planning has recently started to include green hydrogen for several reasons:

- It results in no residual greenhouse gas emissions.
- It can increase system flexibility, particularly through seasonal storage, helping to integrate higher shares of solar and wind power.
- Although currently expensive, it will become more competitive due to rapidly falling costs for electricity from renewables. Solar photovoltaic (PV) and wind power costs have already declined 80% and 40%, respectively, in the last decade, with these trends expected to continue.

Hydrogen, meanwhile, can be converted into other energy carriers like methanol, ammonia and synthetic liquids for a broadening range of uses.

Green hydrogen now costs USD 4-6/kilogram (kg), 2-3 times more than grey hydrogen. The largest single cost driver is renewable electricity, which is becoming cheaper every year. But electricity itself is not the only factor to consider.

Electrolysers – which split water into hydrogen and oxygen – must also be scaled up and improved to make green hydrogen cost-competitive. Their costs, having fallen 60% since 2010, could fall another 40% in the short term and 80% in the longer term, the latest IRENA analysis indicates. Achieving these reductions hinges on innovation to improve electrolyser performance, scaling up manufacturing capacity, standardisation, and growing economies of scale.

This could bring green hydrogen costs below the USD 2/kg mark – a crucial milestone for cost competitiveness – before 2030 (see Figure 1).

While renewable power keeps getting cheaper, electrolyser costs must also fall

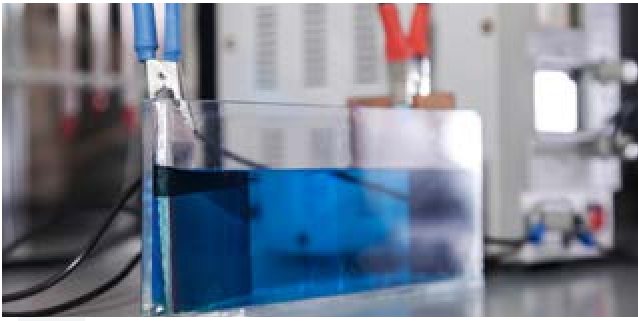
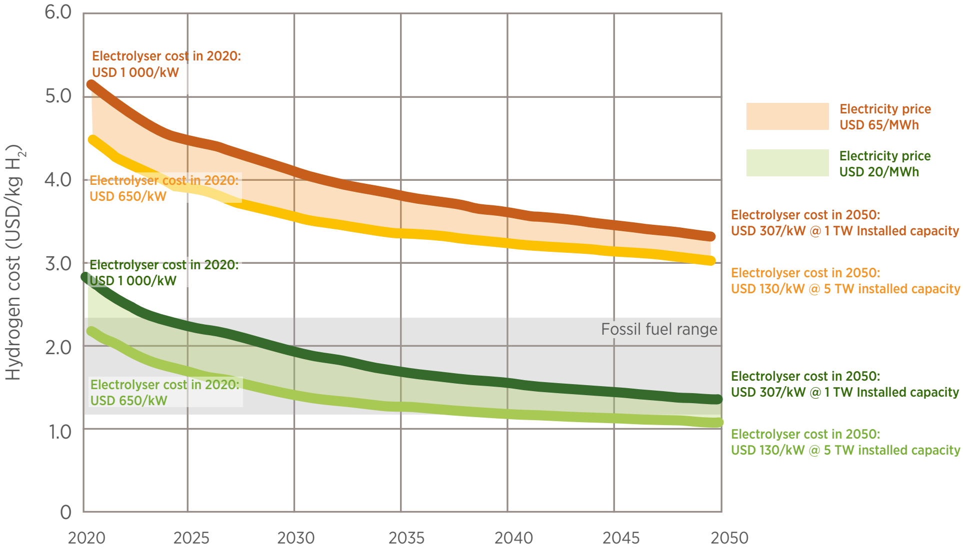


Figure 1 **How electrolyser scale-up drives down costs**



Note: Efficiency at nominal capacity is 65%, with an LHV of 51.2 kilowatt-hours per kilogram of hydrogen (kWh/kg H_2) in 2020 and 76% (at an LHV of 43.8 kWh/kg H_2) in 2050, a discount rate of 8% and a stack lifetime of 80 000 hours. The electrolyser investment cost for 2020 is USD 650-1 000/kW. Electrolyser costs reach USD 130-307/kW as a result of 1-5 TW of capacity deployed by 2050.

Assuming average (USD 65/MWh) and low (USD 20/MWh) electricity prices, constant over the period 2020-2050.

Based on IRENA analysis.

Four policy pillars would help move green hydrogen from niche to mainstream:

- **Developing national hydrogen strategies.** These define each country's level of ambition and can provide a valuable reference for private investment and project finance.
- **Setting priorities.** Along with use as a fuel or re-conversion to electricity, hydrogen can support a wide range of end uses for industry and transport. Policy makers must identify the applications that provide the highest value. Industrial uses, for example, could be prioritised over low-grade heat or fuel blending.
- **Requiring guarantees of origin.** Clear labels are needed to reflect carbon emissions over the whole life cycle of hydrogen. This would increase consumer awareness and allow incentives for green hydrogen use.
- **Adopting enabling policies.** With the right overall policy framework, green hydrogen can create significant industrial, economic and social value, including new jobs.

Green hydrogen promises to become a game changer for energy efficiency and decarbonisation. To achieve its potential, it needs to be widely affordable, including for developing economies seeking affordable ways to build sustainable future energy systems. With the right policies put in place now, it could soon become a cornerstone of the world's shift away from fossil fuels.

Green hydrogen costs could fall below USD 2/kg before 2030

1 GREEN HYDROGEN AND CLIMATE GOALS

The challenge of climate change has prompted the need for rapid adoption of new technologies. The global community in 2015 committed to taking action to keep global temperature rise this century well below 2 degrees Celsius (°C) in relation to pre-industrial levels. Growing numbers of countries are pledging to reach net-zero carbon dioxide (CO_2) emissions by mid-century with the goal of limiting temperature rise to 1.5°C. Achieving the deep or full decarbonisation of economies will require concerted and wide-ranging action across all economic sectors.

The necessary emission reductions have barely begun. An estimated 8.8% less CO_2 was emitted in the first six months of 2020 than in the same period in 2019, following the COVID-19 pandemic and the consequent lockdowns (Liu *et al*., 2020). But for continued long-term reduction, the need for structural and transformational changes in our global energy production, consumption and underlying socio-economic systems cannot be understated.

Dramatic emission reductions will be both technologically feasible and economically affordable. IRENA's *Global Renewables Outlook* offers viable options for reaching net-zero emissions in the 2050-2060 time frame. The Deeper Decarbonisation Perspective suggests possibilities for accelerated action to reduce CO_2 emissions while bringing an economic payback of between USD 1.5 and USD 5 for every USD 1 spent on the energy transition (IRENA, 2020a).

The energy transformation requires a major shift in electricity generation from fossil fuels to renewable sources like solar and wind, greater energy efficiency, and the widespread electrification of energy uses, from cars to heating and cooling in buildings. Still, not all sectors or industries can easily make the switch from fossil fuels to electricity. Hard-to-electrify (and therefore hard-to-abate) sectors include steel, cement, chemicals, long-haul road transport, maritime shipping and aviation (IRENA, 2020b).

Green hydrogen can provide a link between growing renewable electricity generation and sectors where emissions are hardest to abate (IRENA, 2018). Hydrogen in general is a suitable energy carrier for applications remote from electricity grids or that require a high energy density, and it can serve as a feedstock for chemical reactions to produce a range of synthetic fuels and feedstocks.

Green hydrogen brings other, system-wide benefits. These include potential for additional system flexibility and storage, which support further deployment of variable renewable energy (VRE); contribution to energy security; reduced air pollution; and other socio-economic benefits such as economic growth and job creation, and industrial competitiveness.

Yet key barriers must be addressed to realise the full potential of green hydrogen. Chief among those is cost. 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.

An integrated policy approach is needed. This can help reduce initial resistance and reach the minimum threshold for market penetration, resting on four central pillars: building national hydrogen uptake strategies, identifying policy priorities, establishing a governance system and enabling policies, and creating a system for guarantee of origin for green hydrogen.

As more countries pursue deep decarbonisation strategies, hydrogen will have a critical role to play. This will be particularly so where direct electrification is challenging and in harder-to-abate sectors, such as steel, chemicals, long-haul transport, shipping and aviation. In this context, **hydrogen needs to be low carbon** from the outset and ultimately green (produced by electrolysis of water using renewable electricity).

In addition to regulations and market design, the cost of production is a major barrier to the uptake of green hydrogen. Costs are falling – due largely to falling renewable power costs – but green hydrogen is still 2-3 times more expensive than blue hydrogen (produced from fossil fuels with CCS), and further cost reductions are needed.[1]

The largest single cost component for on-site production of green hydrogen is the cost of the renewable electricity needed to power the electrolyser unit. This renders production of green hydrogen more expensive than blue hydrogen, regardless of the cost of the electrolyser.

A low cost of electricity is therefore a necessary condition to produce competitive green hydrogen. This creates an opportunity to produce hydrogen at locations around the world that have optimal renewable resources, in order to achieve competitiveness.[2]

Low electricity cost is not enough by itself for competitive green hydrogen production, however. **Reductions are also needed in the cost of electrolysis facilities.**

This is the second-largest cost component of green hydrogen production. The potential exists to reduce investment costs for electrolysis plants by **40% in the short term and 80% in the long term.**

1.1 **ELECTROLYSER** COST REDUCTION

Key strategies to reduce electrolyser costs range from the fundamental design of the electrolyser stack to broader system-wide elements, including:

- **Electrolyser design and construction:** Increased module size and innovation with increased stack manufacturing have significant impacts on cost. Increasing the plant from 1 megawatt (MW) (typical today) to 20 MW could reduce costs by over a third. Cost, however, is not the only factor influencing plant size, as each technology has its own stack design, which also varies among manufacturers. The optimal system design also depends on the application that drives system performance in aspects such as efficiency and flexibility.
- **Economies of scale:** Increasing stack production through automated processes in gigawatt-scale manufacturing facilities can achieve a step-change cost reduction. At lower manufacture rates, the stack is about 45% of the total cost, yet at higher production rates, it can go down to 30%. For polymer electrolyte membrane (PEM) electrolysers, the tipping point seems to be around 1 000 units (of 1 MW) per year, where this scale-up allows an almost 50% cost reduction in stack manufacturing. The cost of the surrounding plant is as important as the electrolyser stack, and savings can be achieved through standardisation of system components and plant design.

1 *In the context of decarbonisation, hydrogen produced from fossil fuels without capturing most of the CO_2 emissions does not fulfil the criteria of renewable energy, although it represents the vast majority of hydrogen production today.*

2 *The trend over the last decade of falling renewable electricity prices is expected to continue; 82%, 47% and 39% for solar photovoltaic (PV), offshore and onshore wind respectively (IRENA, 2020c).*

- **Procurement of materials:** Scarce materials can represent a barrier to electrolyser cost and scale-up. Current production of iridium and platinum for PEM electrolysers will only support an estimated 3 gigawatts (GW) to 7.5 GW of annual manufacturing capacity, compared to an estimated annual manufacturing requirement of around 100 GW by 2030. Solutions that avoid the use of such materials are already being implemented by leading alkaline electrolyser manufacturers, however, and technologies exist to significantly reduce the requirements for such materials in PEM electrolysers. Anion exchange membrane (AEM) electrolysers do not need scarce materials in the first place.

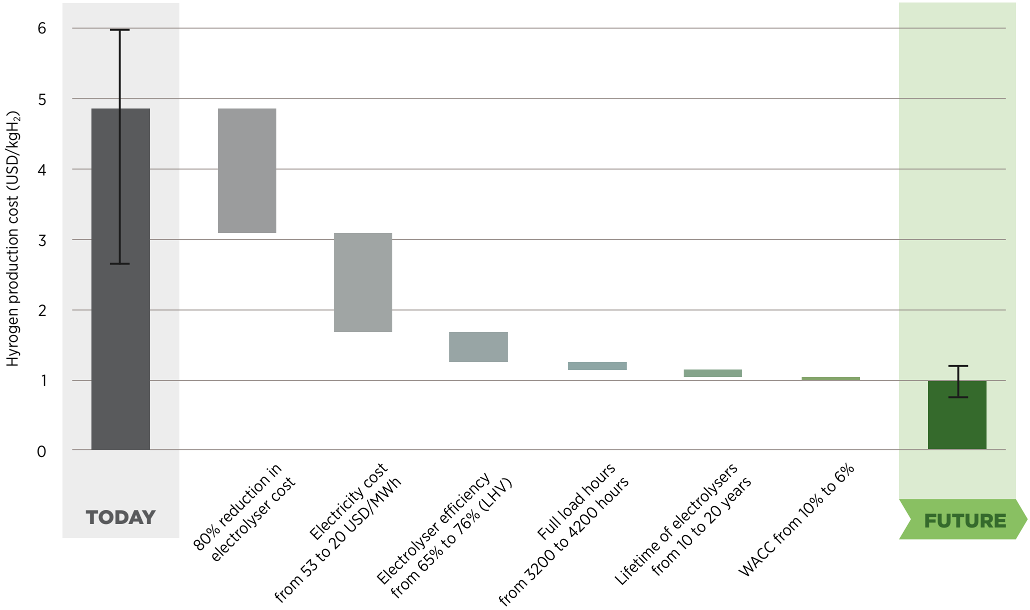
- **Efficiency and flexibility in operations:** Power supply represents large efficiency losses at low load, limiting system flexibility, from an economic perspective. A modular plant design with multiple stacks and power supply units can address this problem. Compression could also represent a bottleneck for flexibility, since it might not be able to change its production rate as quickly as the stack. One alternative to deal with this is an integrated plant design with enough capacity to deal with variability of production through optimised and integrated electricity and hydrogen storage. Green hydrogen production can provide significant flexibility for the power system, if the value of such services is recognised and remunerated adequately. Where hydrogen will play a key role in terms of flexibility, as it does not have any significant alternative sources to compete with, will be in the seasonal storage of renewables. Although this comes at significant efficiency losses, it is a necessary cornerstone for achieving 100% renewable generation in power systems with heavy reliance on variable resources, such as solar and wind.

- **Industrial applications:** Electrolysis system design and operation can be optimised for specific applications. These can range from: large industry users requiring a stable supply and with low logistics costs; large-scale, off-grid facilities with access to low-cost renewables, but that incur significant costs to deliver hydrogen to the end user; and decentralised production that requires small modules for flexibility, which compensate for higher investment per unit of electrolyser capacity with reduced (or near-zero on-site) logistic costs.

- **Learning rates:** 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%. This is significantly lower than the 36% learning rates experienced over the last 10 years for PV (IRENA, 2020c). 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.

Up to **85% of green hydrogen production costs** can be reduced in the long term by a combination of cheaper electricity and lower electrolyser capital costs, along with increased efficiency and optimised electrolyser operation (see Figure 2).

Figure 2 **Electricity and electrolysers: Potential to cut hydrogen costs by 80%**



Note: 'Today' captures best and average conditions. 'Average' signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, full load hours of 3 200 (onshore wind) and a weighted average cost of capital (WACC) of 10% (relatively high risk). 'Best' signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4 200 (onshore wind) and a WACC of 6% (similar to renewable electricity today).

Based on IRENA analysis

1.2 COST REDUCTION **POTENTIAL**

In the best-case scenario, green hydrogen can already be produced at costs competitive with blue hydrogen today. This is possible using low-cost renewable electricity, *i.e.,* around USD 20 per megawatt-hour (MWh). The potential exists for green hydrogen cost reduction to varying degrees between 2020 and 2050, depending on electrolyser costs and deployment levels.

Cost reductions of 60% could be achieved by 2030 through a combination of manufacturing scale, learning rate, technological improvements and increased module size (Hydrogen Council, 2020).

Figure 3 illustrates IRENA's scenarios for electrolyser cost reduction by 2030 and 2050.

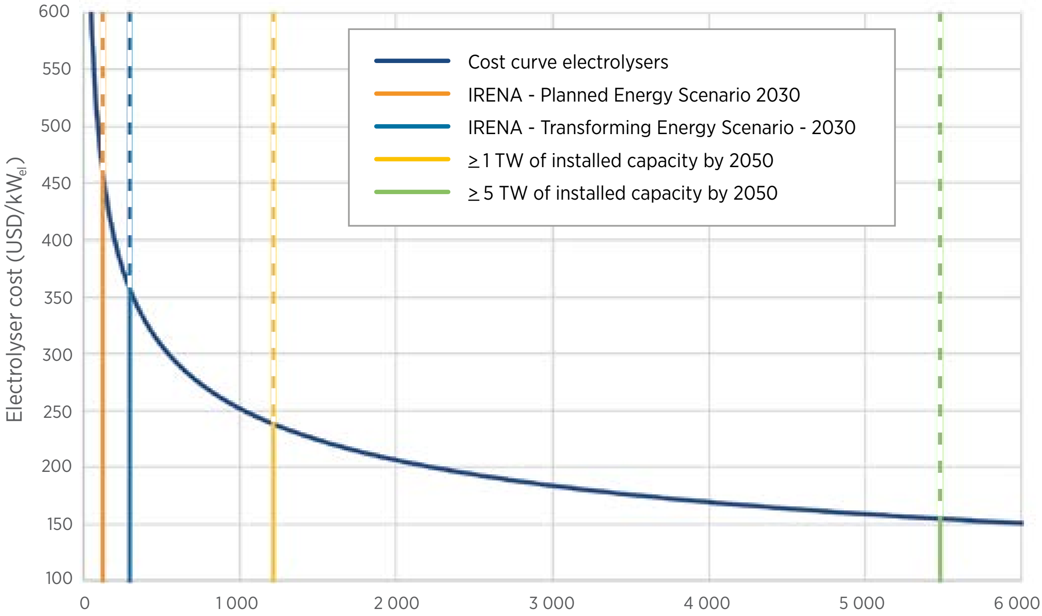
A low electricity price is essential for the production of competitive green hydrogen, cost reductions in electrolysers cannot compensate for high electricity prices. Combined with low electricity cost, an aggressive electrolyser deployment pathway[3] can make green hydrogen cheaper than low-carbon alternatives (*i.e.,* < USD 1/kg), in markets with low electrolyser costs, before 2040.

If rapid scale-up takes place in the next decade, green hydrogen is expected to start becoming competitive with blue hydrogen by 2030 in a wide range of countries – *e.g.,* those with electricity prices of USD 30/MWh – and in applications.

Today's cost and performance are not the same for all electrolyser technologies (see Table 1).

3 Meaning 5 terawatts (TW) of installed capacity by 2050.

Figure 3 **Electrolyser cost reduction by 2030 and 2050, based on IRENA scenarios**



Notes: 1 TW of installed capacity by 2050 is about 1.2 TW of cumulative capacity due to lifetime and replacement. Similarly, 5 TW by 2050 is equivalent to 5.48 TW of cumulative capacity deployed.

Based on IRENA analysis.

Alkaline and PEM electrolysers are the most advanced and already commercial, while each technology has its own competitive advantage.

Alkaline electrolysers have the lowest installed cost, while PEM electrolysers have a much smaller footprint, combined with higher production rate and output pressure.

Meanwhile, solid oxide has the highest electrical efficiency. As the cell stack is only part of the electrolyser facility footprint, a reduced stack footprint of around 60% for PEM compared to alkaline translates into a 20%-24% reduction in the facility footprint, with an estimated footprint of 8 hectares (ha) – 13 ha for a 1 GW facility using PEM, compared to between 10 ha and 17 ha using alkaline (ISPT, 2020).

Gaps in cost and performance are expected to narrow over time as innovation and mass deployment of different electrolysis technologies drive convergence towards similar costs.

The wide range in system costs is expected to remain, however, as this is very much dependent on the scale, application and scope of delivery. For instance, a containerised system inside an existing facility with existing power supply is significantly lower cost than a new building in a plot of land to be purchased, with a complete water and electricity supply system included, high-purity hydrogen for fuel cell applications and high-output pressure.

Normally, numbers for system costs include not only the cell stack, but also the balance of stacks, power plant rectifiers, the hydrogen purification system, water supply and purification, cooling and commissioning – yet exclude shipping, civil works and site preparations.

Table 1 **Key performance indicators for four electrolyser technologies today and in 2050**

	2020				2050			
	Alkaline	PEM	AEM	SOEC	Alkaline	PEM	AEM	SOEC
Cell pressure [bar]	< 30	< 70	< 35	< 10	> 70	> 70	> 70	> 20
Efficiency (system) [kWh/kgH_2]	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_{el}]	270	400	-	> 2 000	< 100	< 100	< 100	< 200
Capital cost range estimate for the entire system, >10 MW [USD/kW_{el}]	500-1000	700-1400	-	-	< 200	< 200	< 200	< 300

Note: PEM = polymer electrolyte membrane (commercial technology); AEM = anion exchange membrane (lab-scale today); SOEC = solid oxide electrolysers (lab-scale today).

Based on IRENA analysis.

Notably, the 2020 numbers are cost estimates for a system ordered in 2020, given the lowest price possible (on the limit of zero profit). As the market scales up rapidly in the initial phase, the investment in manufacturing facilities must be recovered based on falling production costs. Therefore the gap between cost and price is currently higher than it will be 10 or 20 years from now. As a reference, an estimated investment of EUR 45 million to EUR 69 million (about USD 54 million to USD 83 million) is needed per gigawatt of manufacturing capacity (Cihlar *et al.*, 2020).

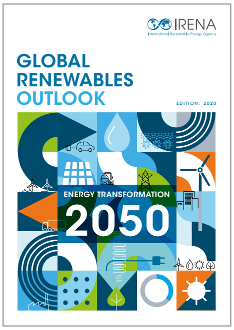
1.3 FOSTERING **INNOVATION**

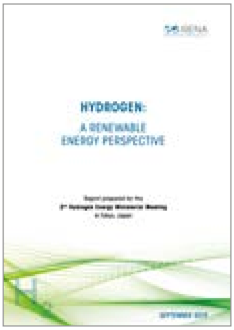
Innovation is crucial to reduce cost and improve the performance of electrolysers. The ultimate goals are to: 1) reduce cost by standardising and simplifying manufacturing and design to allow for industrialisation and scale-up; 2) improve efficiency to reduce the amount of electricity required to produce one unit of hydrogen; and 3) increase durability to extend the equipment lifetime and spread the cost of the electrolyser facility over a larger hydrogen production volume.

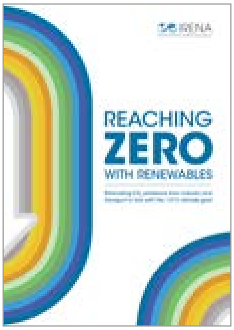
Governments can drive further innovation in electrolysers by issuing clear long-term policy signals on:

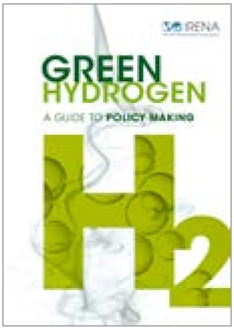
- **Facilitating investment** in production, logistics and utilisation of green hydrogen, including all areas that will help this low-carbon energy carrier to become competitive; technology cost and performance improvements, material supply, business models and trading using common standards and certifications.
- **Establishing regulations and designing markets** that support investments in innovation and help scale up the production of green hydrogen. This includes approaches such as setting manufacturing or deployment targets, tax incentives, mandatory quotas in hard-to-decarbonise sectors and other de-risking mechanisms, while enabling new business models that can guarantee predictable revenues for the private sector to invest at scale.
- **Supporting ongoing research, development and demonstration (RD&D)** to: reduce the use of iridium and platinum in the manufacture of PEM electrolysers; transition all alkaline units to be platinum- and cobalt-free; and, in general, mandate reduced scarce materials utilisation as a condition for manufacturing scale-up.
- **Fostering co-ordination and common goals** along the hydrogen value chain, across borders, across relevant sectors and among stakeholders.

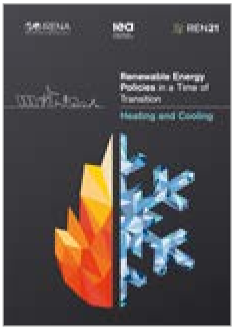
RECENT STUDIES ON GREEN HYDROGEN AND DEEP DECARBONISATION

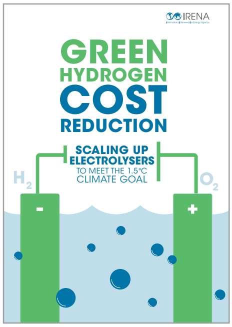












The recent green hydrogen studies complement a range of work aimed at providing analytical insights and outlining options to accelerate the energy transition.

The *Global Renewables Outlook* (IRENA, 2020a) provides detailed global and regional roadmaps for emission reductions alongside assessment of the socio-economic implications. The 2020 edition includes the Deeper Decarbonisation Perspective, detailing options for net-zero or zero emissions. The next edition will provide further analysis of a pathway consistent with a 1.5°C goal.

Building on that technical and socio-economic assessment, the International Renewable Energy Agency (IRENA) has continued assessing specific facets of that pathway, including the policy and financial frameworks needed.

This includes the roles of direct and indirect electrification, the implications for power systems, the role of green hydrogen and of biomass, and options for specific, challenging end-use sectors.

Other publications relevant to green hydrogen strategies include: *Hydrogen: A renewable energy perspective* (IRENA, 2019a); *Reaching zero with renewables* (IRENA, 2020b) and *Renewable energy policies in a time of transition: Heating and cooling* (IRENA, IEA and REN21, 2020).

IRENA also continues to convene experts and stakeholders through Innovation Weeks, Policy Days and Policy Talks as well as through the **Collaborative Framework on Green Hydrogen**, which brings together a broad range of member states and other stakeholders to exchange knowledge and experience.

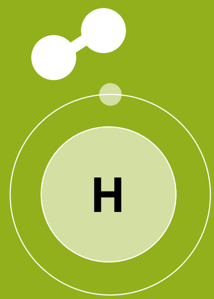
2 STATUS, DRIVERS AND BARRIERS

H

Hydrogen 1.01

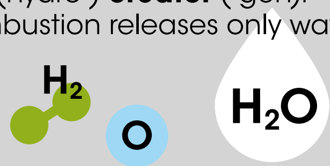
Henry Cavendish discovered the element in **1766**

Most abundant chemical structure in the universe



The first industrial water electrolyser was built in **1888**

Hydrogen means **water** (hydro-) **creator** (-gen): its combustion releases only water



KEY POINTS

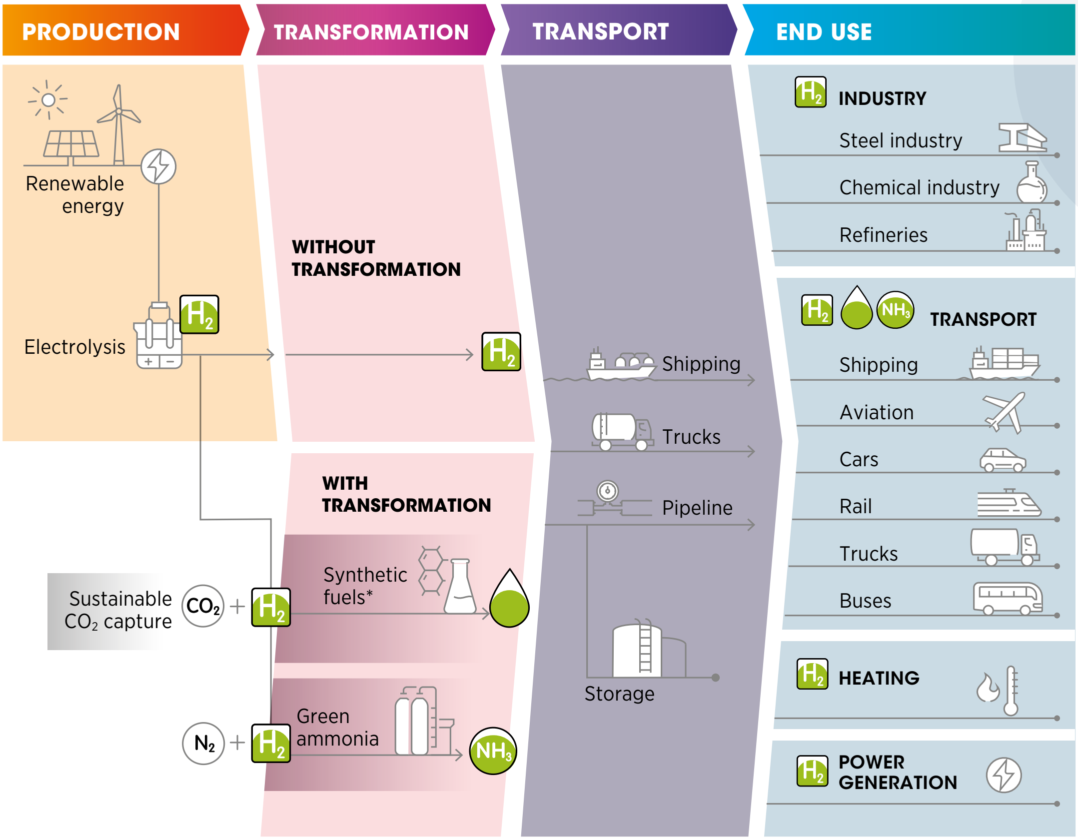
- Hydrogen is already in widespread use, mainly as an industrial feedstock for methanol and ammonia. It is produced mostly from natural gas and coal, which account for more than 95% of pure hydrogen production today.
- Green hydrogen is the only type of hydrogen compatible with a long-term sustainable energy system. To differentiate this from other pathways, a certification scheme is needed to track greenhouse gas (GHG) emissions across the entire value chain. This should reflect life-cycle emissions in a standard taxonomy with clear boundaries and thresholds.
- Recent interest in hydrogen, unlike previous waves, is driven by a competitive renewable electricity supply (already available), the focus on net-zero energy systems and growing recognition of hydrogen's versatility. These factors have prompted support from a wide range of stakeholders.
- Major challenges remain: prohibitive costs across the value chain; infrastructure gaps, from pipelines to storage and shipping; and energy losses requiring more power uptake. As a new energy carrier for many applications, hydrogen is not yet included in most current policy frameworks.

Green hydrogen is an energy carrier that can be used in many applications (see Figure 4). However, its actual use is still very limited. Each year around 120 million tonnes of hydrogen are produced globally, of which two-thirds are pure hydrogen and one-third is in a mixture with other gases (IRENA, 2019a).

Hydrogen output is mostly used for crude oil refining and for ammonia and methanol synthesis, which together represent almost 75% of the combined pure and mixed hydrogen demand.

Today's hydrogen production is mostly based on natural gas and coal, which together account for 95% of production. Electrolysis produces around 5% of global hydrogen, as a by-product of chlorine production. Currently, there is no significant hydrogen production from renewable sources: green hydrogen has been limited to demonstration projects (IRENA, 2019a).

Figure 4 **Green hydrogen production, conversion and end uses across the energy system**



Source: IRENA (2020f).

Note: N_2 = nitrogen; NH_3 = ammonia

* *The term synthetic fuels refers here to a range of hydrogen-based fuels produced through chemical processes with a carbon source (carbon monoxide (CO) and CO_2 captured from emission streams, biogenic sources or directly from the air). They include methanol, jet fuels, methane and other hydrocarbons. The main advantage of these fuels is that they can be used to replace their fossil fuel-based counterparts and in many cases be used as direct replacements – that is, as drop-in fuels. Synthetic fuels produce carbon emissions when combusted, but if their production process consumes the same amount of CO_2, in principle it allows them to have net-zero carbon emissions.*

2.1 DIFFERENT **SHADES** OF HYDROGEN

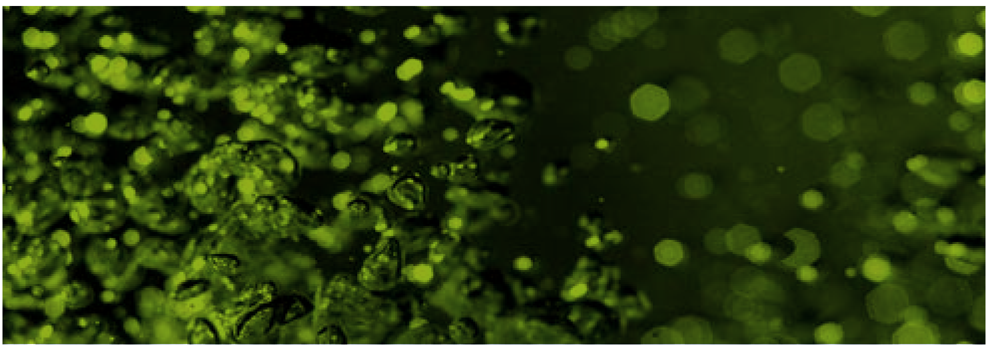
Hydrogen can be produced with multiple processes and energy sources; a colour code nomenclature is becoming commonly used to facilitate discussion (see Figure 5). Policy makers should use an objective measure of impact based on life-cycle greenhouse gas (GHG) emissions, especially since there might be cases that do not fully fall under one colour (*e.g.,* mixed hydrogen sources, electrolysis with electricity from the grid).

Figure 5 **Main shades of hydrogen**

Colour	**GREY** HYDROGEN	**BLUE** HYDROGEN	**TURQUOISE** HYDROGEN*	**GREEN** HYDROGEN
Process	SMR or gasification	SMR or gasification with carbon capture (85-95%)	Pyrolysis	Electrolysis
Source	Methane or coal	Methane or coal	Methane	Renewable electricity

Note: SMR = steam methane reforming.

** Turquoise hydrogen is an emerging decarbonisation option.*



GREY HYDROGEN

GREY HYDROGEN[1] is produced with fossil fuels (*i.e.,* hydrogen produced from methane using steam methane reforming (SMR) or coal gasification). The use of grey hydrogen entails substantial CO_2 emissions, which makes these hydrogen technologies unsuitable for a route towards net-zero emissions.

BLUE HYDROGEN

During early stages of the energy transition, the use of **BLUE HYDROGEN** (*i.e.,* grey hydrogen with carbon capture and storage [CCS]) could facilitate the growth of a hydrogen market. Around three-quarters of hydrogen is currently produced from natural gas. Retrofitting with CCS would allow the continued use of existing assets while still achieving lower GHG emissions. This is an option to produce hydrogen with lower GHG emissions while reducing pressure on the renewable energy capacity installation rate to produce green hydrogen. Notably, industrial processes like steel production may require a continuous flow of hydrogen; blue hydrogen could be an initial solution while green hydrogen ramps up production and storage capacity to meet the continuous flow requirement.

However, blue hydrogen has limitations that have so far restricted its deployment: it uses finite resources, is exposed to fossil fuel price fluctuations and does not support the goals of energy security. Moreover, blue hydrogen faces social acceptance issues, as it is associated with additional costs for CO_2 transport and storage and requires monitoring of stored CO_2. In addition, CCS capture efficiencies are expected to reach 85-95% at best,[2] which means that 5-15% of the CO_2 will still be emitted. And these high capture rates have yet to be achieved.

In sum, the carbon emissions from hydrogen generation could be reduced by CCS but not eliminated. Moreover, these processes use methane, which brings leakages upstream, and methane is a much more potent GHG per molecule than CO_2. This means that while blue hydrogen could reduce CO_2 emissions, it does not meet the requirements of a net-zero future. For these reasons, blue hydrogen should be seen only as a short-term transition to facilitate the uptake of green hydrogen on the path to net-zero emissions.

TURQUOISE HYDROGEN

TURQUOISE HYDROGEN combines the use of natural gas as feedstock with no CO_2 production. Through the process of pyrolysis, the carbon in the methane becomes solid carbon black. A market for carbon black already exists, which provides an additional revenue stream. Carbon black can be more easily stored than gaseous CO_2. At the moment, turquoise hydrogen is still at the pilot stage (Philibert, 2020; Monolith, 2020).

GREEN HYDROGEN

Among the different shades of hydrogen, **GREEN HYDROGEN** – meaning hydrogen produced from renewable energy – is the only suitable one for a fully sustainable energy transition. The most established technology option for producing green hydrogen is water electrolysis fuelled by renewable electricity. Other renewables-based solutions to produce hydrogen exist.[3] However, except for SMR with biogases, these are not mature technologies at commercial scale yet (IRENA, 2018). Green hydrogen production through electrolysis is consistent with the net-zero route and allows the exploitation of synergies from sector coupling, thus decreasing technology costs and providing flexibility to the power system. Low solar and wind power costs and technological improvement are decreasing the cost of production of green hydrogen. For these reasons, green hydrogen from water electrolysis has been gaining increased interest.

1 *Sometimes referred to as black or brown hydrogen.*

2 *An alternative route to SMR could be a process called autothermal reforming, for which a capture rate of up to 94.5% of the CO_2 emitted is estimated to be possible (H-vision, 2019).*

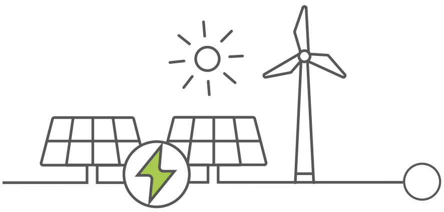
3 *For example, biomass gasification and pyrolysis, thermochemical water splitting, photocatalysis and supercritical water gasification of biomass, combined with dark fermentation and anaerobic digestion.*

2.2 NEW DRIVERS FOR GREEN HYDROGEN

There have been several waves of interest in hydrogen in the past. These were mostly driven by oil price shocks, concerns about peak oil demand or air pollution, and research on alternative fuels. Hydrogen can contribute to energy security by providing another energy carrier with different supply chains, producers and markets; this can diversify the energy mix and improve the resilience of the system.

Hydrogen can also reduce air pollution when used in fuel cells, with no emissions other than water. Its uptake promotes economic growth and job creation given the large investment needed to develop hydrogen as an energy carrier from an industrial feedstock.

As a result, more and more energy scenarios are giving green hydrogen a prominent role, albeit with significantly different volumes of penetration (see Box 1). The new wave of interest is focused on delivering low-carbon solutions and additional benefits that only green hydrogen can provide. The drivers for green hydrogen include:



1. Low solar and wind electricity costs. The major cost driver for green hydrogen is the cost of electricity. The price of electricity procured from solar PV and onshore wind plants has decreased substantially in the last decade. In 2018, solar energy was contracted at a global average price of USD 56/MWh, compared with USD 250/MWh in 2018. Onshore wind prices also fell during that period, from USD 75/MWh in 2010 to USD 48/MWh in 2018 (IRENA, 2019b). New record-low prices were marked in 2019 and 2020 around the world: solar PV was contracted at USD 13.12/MWh in Portugal (Morais, 2020) and USD 13.5/MWh in the United Arab Emirates (Abu Dhabi) (Shumkov, 2020); onshore wind was contracted at USD 21.3/MWh in Saudi Arabia (Masdar, 2019), while in Brazil, prices ranged between USD 20.5 and 21.5/MWh (BNEF, 2019). With the continuously decreasing costs of solar PV and wind electricity, the production of green hydrogen is increasingly economically attractive.

2. Technologies ready for scale-up. Many of the components in the hydrogen value chain have already been deployed on a small scale and are ready for commercialisation, now requiring investment to scale up. The capital cost of electrolysis has fallen by 60% since 2010 (Hydrogen Council, 2020), resulting in a decrease in hydrogen cost from a range of USD 10-15/kg to as low as USD 4-6/kg in that period.

Many strategies exist to bring down costs further and support the wider adoption of hydrogen (IRENA, 2020d). The cost of fuel cells[4] for vehicles has decreased by at least 70% since 2006 (US DOE, 2017).

While some technologies (such as ammonia-fuelled ships) are yet to be demonstrated at scale (IRENA, 2020b), scaling up green hydrogen could make those pathways increasingly cost-effective and attractive.

4 Fuel cells use the same principles as an electrolyser, but in the opposite direction, for converting hydrogen and oxygen into water in a process that produces electricity. Fuel cells can be used for stationary applications (e.g., centralised power generation) or distributed applications (e.g., fuel cell electric vehicles). Fuel cells can also convert other reactants, such as hydrocarbons, ethers or alcohols.

3. **Benefits for the power system.** As the share of solar and wind power, or variable renewable energy (VRE), rapidly increases in various markets around the world, the power system will need more flexibility. The electrolysers used to produce green hydrogen can be designed as flexible resources that can quickly ramp up or down to compensate for fluctuations in VRE production, by reacting to electricity prices (Eichman *et al.*, 2014). Green hydrogen can be stored for long periods, and can be used in periods when VRE is not available for power generation with stationary fuel cells or hydrogen-ready gas turbines. Flexible resources can reduce VRE curtailment, stabilise wholesale market prices and reduce the hours with zero or below-zero electricity prices (or negative price), which increases the investment recovery for renewable generators and facilitates their expansion. Finally, hydrogen is suitable for long-term, seasonal energy storage, complementing pumped-storage hydropower plants. Green hydrogen thus supports the integration of higher shares of VRE into the grid, increasing system efficiency and cost-effectiveness.

4. **Government aims to create net-zero energy systems.** By mid-2020, seven countries had already adopted net-zero GHG emission targets in legislation, and 15 others had proposed similar legislation or policy documents. In total, more than 120 countries have announced net-zero emission goals (WEF, 2020). Among them is China, the largest GHG emitter, which recently pledged to cut its net carbon emissions to zero within 40 years. While these net-zero commitments have still to be transformed into practical actions, they will require cutting emissions in the "hard-to-abate" sectors where green hydrogen can play an important role.

5. **Broader use of hydrogen.** Previous waves of interest in hydrogen were focused mainly on expanding its use in fuel-cell electric vehicles (FCEVs). In contrast, the new interest covers many possible green hydrogen uses across the entire economy, including the additional conversion of hydrogen to other energy carriers and products, such as ammonia, methanol and synthetic liquids. These uses can increase the future demand for hydrogen and can take advantage of possible synergies to decrease costs in the green hydrogen value chain. Green hydrogen can, in fact, improve industrial competitiveness, not only for the countries that establish technology leadership in its deployment, but also by providing an opportunity for existing industries to have a role in a low-carbon future. Countries with large renewable resources could derive major economic benefits by becoming net exporters of green hydrogen in a global green hydrogen economy.

6. **Interest among multiple stakeholders.** As a result of all the above points, interest in hydrogen is now widespread in both public and private institutions. These include energy utilities, steel makers, chemical companies, port authorities, car and aircraft manufacturers, shipowners and airlines, multiple jurisdictions and countries aiming to use their renewable resources for export or to use hydrogen to improve their own energy security. These many players have also created partnerships and ongoing initiatives to foster collaboration and co-ordination of efforts.[6]

Yet green hydrogen uptake continues to face various barriers.

5 *System flexibility is here defined as the ability of the power system to match generation and demand at any time scale.*

6 *The Hydrogen Council is an example of a private initiative. Launched in 2017, it includes over 90 member companies positioned across the supply chain. The Hydrogen Initiative under the Clean Energy Ministerial is an example of a public initiative, where nine countries and the European Union (EU) are collaborating to advance hydrogen. The Fuel Cell and Hydrogen Joint Undertaking is an example of private-public partnership in the EU.*

Box 1 **Roles for green hydrogen in different energy transition scenarios**

The role given to green hydrogen in existing regional and global energy transition scenarios differs greatly due to a number of factors.

First, not all scenarios aim for the same GHG reduction target. The more ambitious the GHG reduction target, the greater is the amount of green hydrogen expected in the system. For low levels of decarbonisation, renewable power and electrification might be enough. But with deeper decarbonisation targets, green hydrogen would play a larger role in the future energy mix.

Second, not all scenarios rely on the same set of enabling policies. The removal of fossil fuel subsidies, for example, would increase the space for carbon-free solutions.

Third, the technology options available vary among scenarios. Scenarios that give greater weight to the social, political and sustainability challenges of nuclear, carbon capture, use and storage, and bioenergy anticipate limited contributions from those technologies to the energy transition, and thus require greater green hydrogen use.

Fourth, the more end uses for green hydrogen included in a scenario, the higher the hydrogen use will be. Scenarios that cover all hydrogen applications and downstream conversion to other energy carriers and products provide more flexibility in ways to achieve decarbonisation. More hydrogen pathways also help create larger economies of scale and faster deployment, leading to a virtuous circle of increasing both demand and supply.

Finally, cost assumptions, typically input data including capital and operating costs (Quarton *et al.*, 2020) differ among scenarios. Those with the highest ambitions for hydrogen deployment are those with the most optimistic assumptions for cost reduction.

For all these reasons, the role of green hydrogen varies widely among scenarios. However, as more and more scenarios are being developed to reach zero or net-zero emissions, green hydrogen is more prominently present in scenarios and public discourse.

2.3 **BARRIERS** TO GREEN HYDROGEN UPTAKE

Certain barriers apply to all shades of hydrogen. These include a lack of dedicated infrastructure (*e.g.,* transport and storage facilities). Others relate mainly to the production stage of electrolysis for green hydrogen (*e.g.,* energy losses, lack of value recognition, challenges ensuring sustainability and high production costs).

1. HIGH PRODUCTION COSTS. Green hydrogen produced using electricity from an average VRE plant in 2019 would be two to three times more expensive than grey hydrogen. In addition, adopting green hydrogen technologies for end uses can be expensive. Vehicles with fuel cells and hydrogen tanks cost at least 1.5 to 2 times more than their fossil fuel counterparts (NREL, 2020). Similarly, synthetic fuels for aviation are today, even at the best sites in the world, up to eight times more expensive than fossil jet fuel (IRENA, 2019a).

2. LACK OF DEDICATED INFRASTRUCTURE. Hydrogen has to date been produced close to where it is used, with limited dedicated transport infrastructure. There are only about 5 000 kilometres of hydrogen transmission pipelines around the world (Hydrogen Analysis Resource Center, 2016), compared with more than 3 million kilometres for natural gas. There are 470 hydrogen refuelling stations around the world (AFC TCP, 2020), compared with more than 200 000 petrol and diesel refuelling stations in the United States and the EU. Natural gas infrastructure could be repurposed for hydrogen (IRENA, IEA and REN21, 2020), but not all regions of the world have existing infrastructure. Conversely, synthetic fuels made from green hydrogen may be able to use existing infrastructure, although it might need to be expanded.

3. ENERGY LOSSES. Green hydrogen incurs significant energy losses at each stage of the value chain. About 30-35% of the energy used to produce hydrogen through electrolysis is lost (IRENA, 2020d). In addition, the conversion of hydrogen to other carriers (such as ammonia) can result in 13-25% energy loss, and transporting hydrogen requires additional energy inputs, which are typically equivalent to 10-12% of the energy of the hydrogen itself (BNEF, 2020; Staffell *et al.*, 2018; Ikäheimo *et al.*, 2017). Using hydrogen in fuel cells can lead to an additional 40-50% energy loss.

The total energy loss will depend on the final use of hydrogen. The higher the energy losses, the more renewable electricity capacity is needed to produce green hydrogen. The key issue, however, is not the total capacity needed, since global renewable potential entails higher orders of magnitude than hydrogen demand, and green hydrogen developers are likely to first select areas with abundant renewable energy resources. The key issue is whether the annual pace of development of the solar and wind potential will be fast enough to meet the needs for both the electrification of end uses and the development of a global supply chain in green hydrogen, and the cost that this additional capacity will entail.

4. LACK OF VALUE RECOGNITION. There is no green hydrogen market, no green steel, no green shipping fuel and basically no valuation of the lower GHG emissions that green hydrogen can deliver. Hydrogen is not even counted in official energy statistics of total final energy consumption, and there are no internationally recognised ways of differentiating green from grey hydrogen. At the same time, the lack of targets or incentives to promote the use of green products inhibits many of the possible downstream uses for green hydrogen. This limits the demand for green hydrogen.

5. NEED TO ENSURE SUSTAINABILITY. Electricity can be supplied from a renewable energy plant directly connected to the electrolyser, from the grid, or from a mix of the two. Using only electricity from a renewable energy plant ensures that the hydrogen is "green" in any given moment. Grid-connected electrolysers can produce for more hours, reducing the cost of hydrogen. However, grid electricity may include electricity produced from fossil fuel plants, so any CO_2 emissions associated with that electricity will have to be considered when evaluating the sustainability of hydrogen. As a result, for producers of hydrogen from electrolysis, the amount of fossil fuel-generated electricity can become a barrier, in particular if the relative carbon emissions are measured based on national emission factors. Box 2 highlights options to ensure that grid-connected electrolysers deliver hydrogen with minimum emissions.

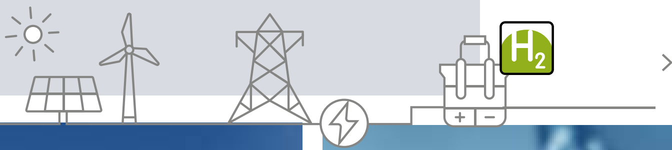
Box 2 **Hydrogen emissions from grid-powered electrolysis**

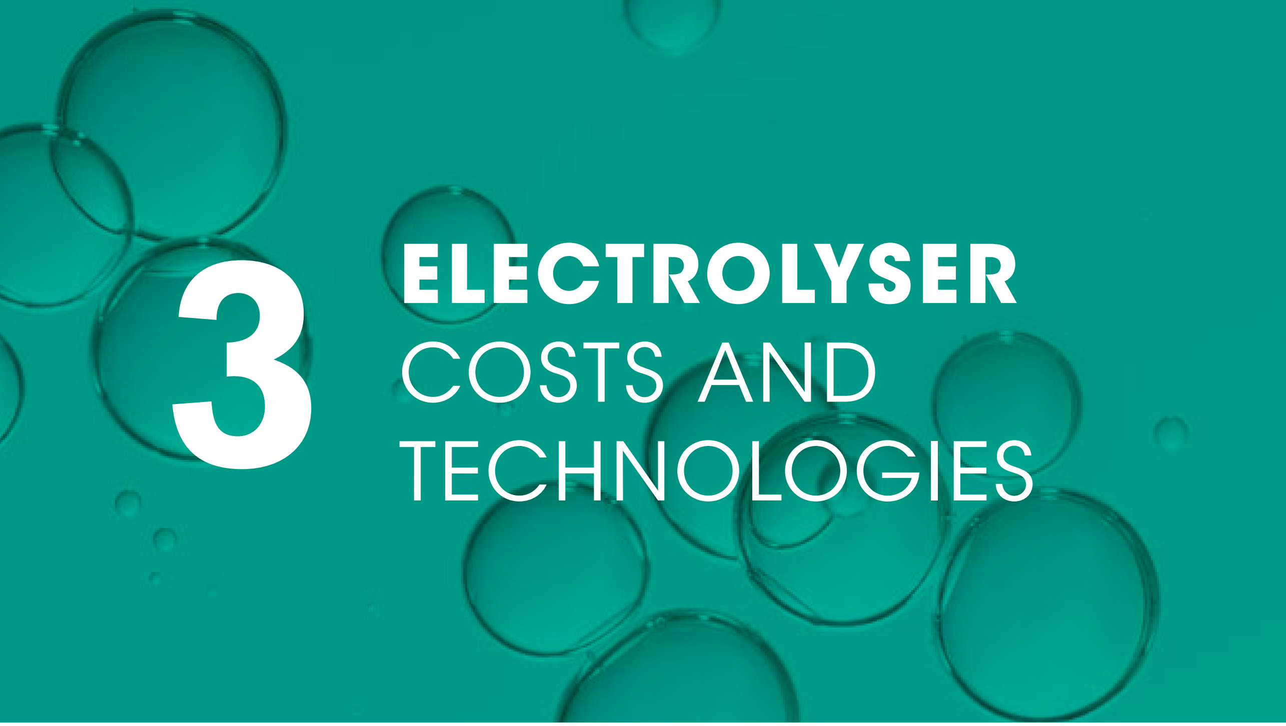
For hydrogen from electrolysis to have lower overall emissions than grey hydrogen, CO_2 emissions per unit of electricity need to be lower than 190 grams of CO_2 per kilowatt-hour (Reiter and Lindorfer, 2015). Only a few countries (mostly benefiting from hydropower) have average CO_2 emissions per kWh below that threshold and thus can ensure the sustainability of electrolytic hydrogen. Most other countries are currently above that threshold.

However, electrolysers can be designed to serve as flexible demand-side resources that can be ramped down or turned off when the national power mix is above a certain threshold of CO_2 emissions, if tracked, and then turned back on when renewable production is higher, and in particular when VRE production would otherwise be curtailed. In general, low electricity prices are a proxy for high renewable energy production (IRENA, 2020e), so that electricity prices can signal electrolyser activities. Moreover, when electricity prices are too high to produce competitive hydrogen, the electrolyser would shut down anyway. The significant (for some countries) and increasing renewable energy share of electricity production will also decrease the carbon footprint of electrolytic hydrogen production.

A hybrid model can also be used, where off-grid solar and wind power generation is the main source of electricity, but grid electricity can top up production to decrease the impact of initial investment costs while causing only a small increase in the carbon footprint of the electrolysis plant.

Power purchase agreements with grid-connected solar and wind plants may also ensure the sustainability of electricity consumption and at the same time make green hydrogen an additional driver for the decarbonisation of the power grid.

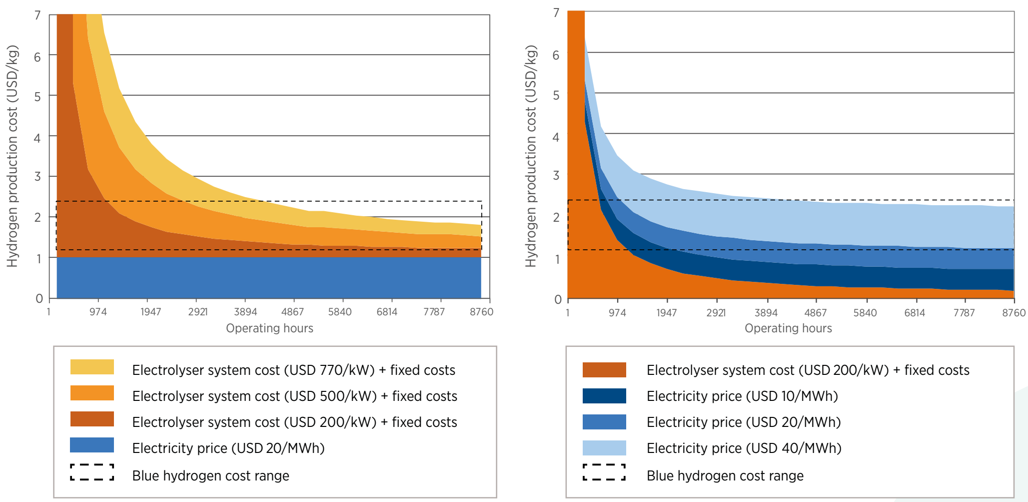




3 ELECTROLYSER COSTS AND TECHNOLOGIES

Transforming the energy system depends on adopting now technologies and practices, which must be developed, scaled up and introduced into mainstream use in ways that ensure cost-effective long-term uptake.

Figure 6 **Hydrogen production cost as a function of investment, electricity price and operating hours**

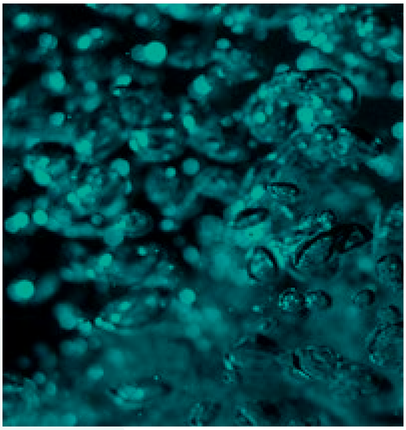


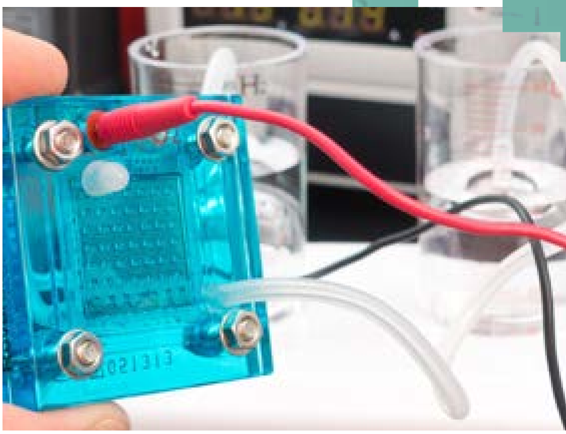
Note: Efficiency at nominal capacity is 65% (with an LHV of 51.2 kWh/kg H_2), the discount rate 8% and the stack lifetime 80 000 hours.
Based on IRENA analysis.

3.1 **NEED FOR** COST REDUCTION

KEY POINTS

- The major cost component for green hydrogen is **electricity supply**. Cost decline in this is already under way through the competitive deployment of renewables.
- There is a need to focus on reducing **procurement and construction costs** and increasing the **performance and durability** of electrolysers to achieve further cost reductions in green hydrogen production.
- Green hydrogen can already achieve **cost-competitiveness with fossil-based hydrogen** today in ideal locations with the lowest renewable electricity costs. Cost reductions in renewable electricity and electrolysers will continue to increase the number of sites where green hydrogen can be produced competitively, however.
- Policy support in recently unveiled **hydrogen strategies** in many countries is mostly in the form of explicit electrolyser capacity targets and, to a more limited extent, cost targets. These have yet to translate into **specific regulatory instruments**. So far, these explicit targets are not enough to be in line with 1.5°C decarbonisation pathways.





3.2 **TECHNOLOGY** CHARACTERISTICS

KEY POINTS

- An **electrolysis stack** (or electrolyser stack) splits water into hydrogen and oxygen, while the balance of plant comprises power and water supplies, water purification, compression and other components.
- Well-designed electrolysers can provide valuable **energy storage** and manage the variability of solar and wind power.
- The **materials and processes** for electrolyser manufacturing require further innovation, especially to reduce performance trade-offs between different components.

The stack is where the actual splitting of water into hydrogen and oxygen takes place. The balance of plant, meanwhile, provides power supply, water supply and purification, compression, possibly electricity and hydrogen buffers, and hydrogen processing. While these two main parts account for similar cost shares, the greater potential for near-term cost reduction is in this balance of plant. Further innovation in needed, through concerted RD&D, to reduce overall costs while boosting performance and durability.

- The flexibility of **alkaline and PEM stacks** is sufficient to follow fluctuations in wind and solar energy supply. The flexibility of the system is limited, however, by the balance of plant (*e.g.,* the compressors) rather than the stack. Furthermore, flexibility in the very short-term time scales involved (*i.e.,* sub-second) is not the key value proposition for electrolysers, as their key system value lies in bulk energy storage. This effectively decouples variability of generation from stability of **hydrogen and power-to-X demand** through hydrogen storage in gas infrastructure (*e.g.,* salt caverns, pipelines) and liquid e-fuels storage.

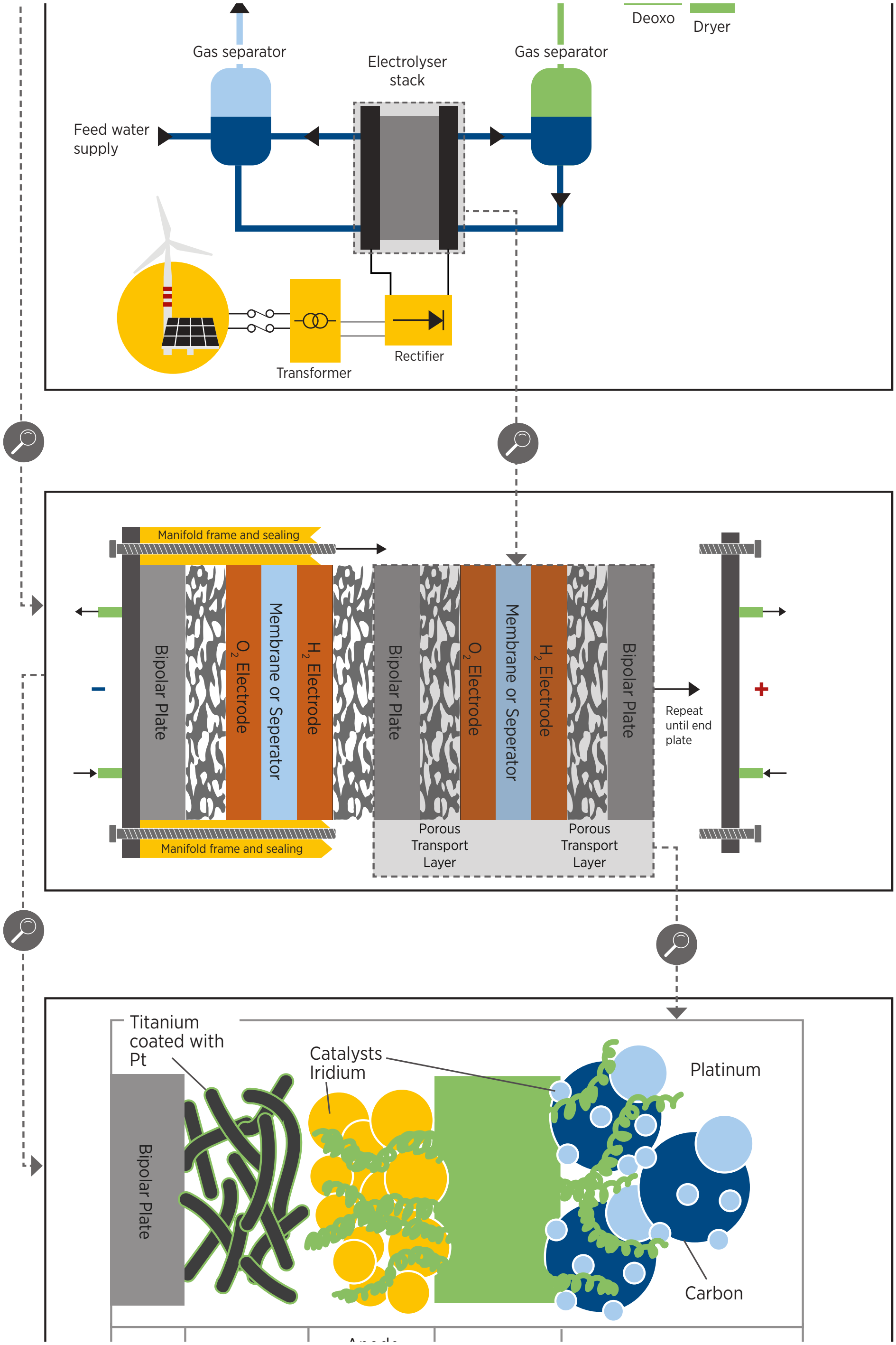
- There is no single electrolyser technology that performs optimally across all dimensions. The future technology mix will depend on **innovation and competition** among key technologies and manufacturers, leading to technological improvements and a better fit for different technologies and system designs in each specific application.

- Water and land use do not represent barriers to scaling up. In places with water stress, the **source of water** for hydrogen production should be explicitly considered in the strategies and further elaborated in project planning. Where access to sea water is available, desalination can be used with limited impact on cost and efficiency, potentially deploying multi-purpose desalination facilities to provide local benefits. A 1 GW plant could occupy about 0.17 square kilometres of land, which means 1 000 GW of electrolysis would occupy an area equivalent to Manhattan (central island of New York City, US).

- Improving the performance of the electrolyser stack in one dimension usually goes along with reduced performance in other parameters (efficiency, cost, lifetime, mechanical strength and manufacturing). This entails **performance trade-offs** that must be tackled through innovation in materials and manufacturing, leading to a set of specific system designs tailored to different applications in the future.

- Potential **breakthroughs in technology development** can be disruptive in terms of accelerating cost reductions for the stack, while for the balance of plant, the challenges are more about economies of scale, standardisation of design and supply chains, and learning-by-doing.

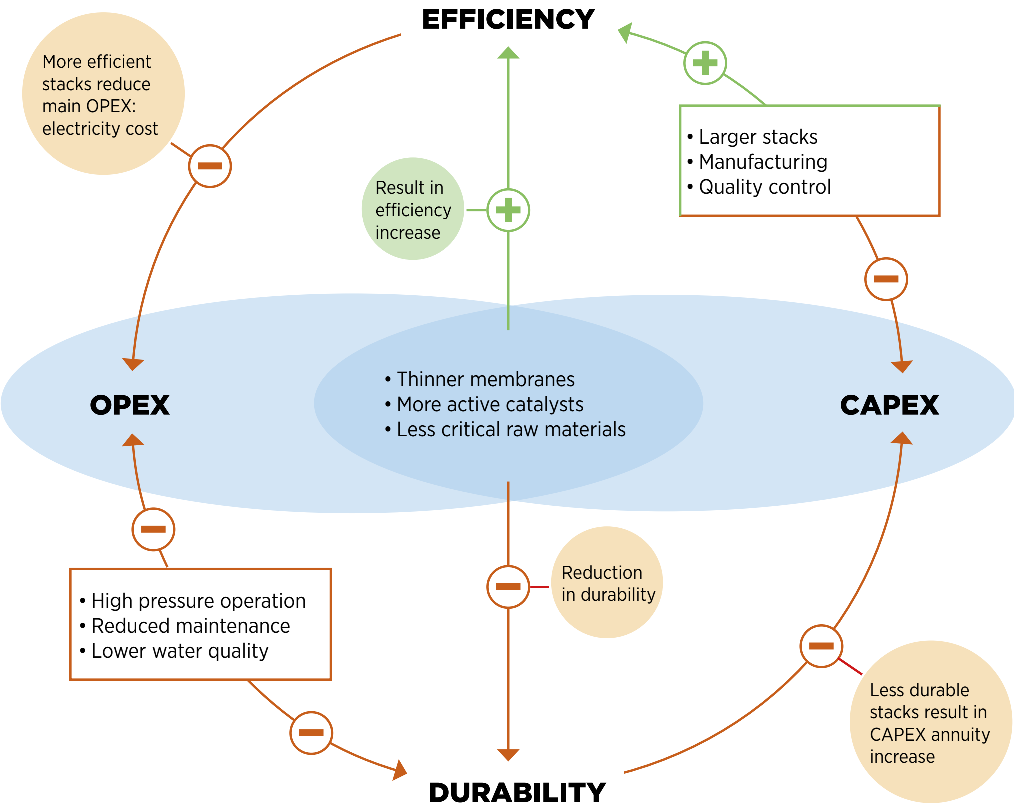
Figure 7 **Basic components of water electrolysers at different levels**



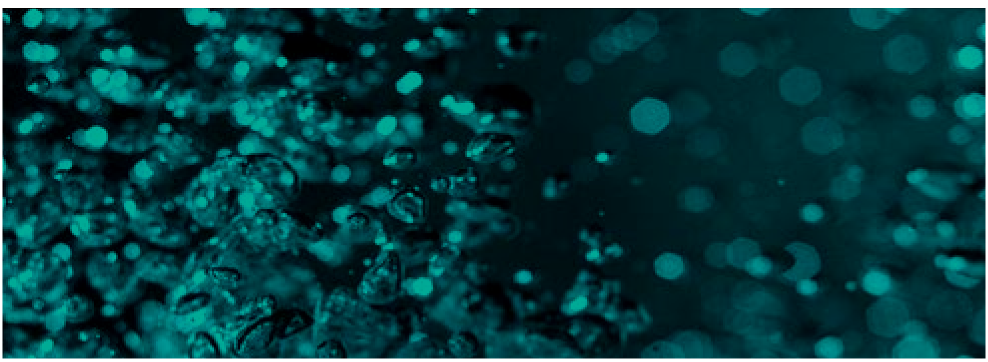
Note: O_2 = oxygen; BP = bipolar plates; PTL = porous transport layer

Based on IRENA analysis.

Figure 8 **Trade-offs between efficiency, durability and cost for electrolysers**



Note: The arrows represent a direct impact or effect from the research and development of a given material or component over each relevant dimension. CAPEX = capital expenditure; OPEX = operational expenditure.



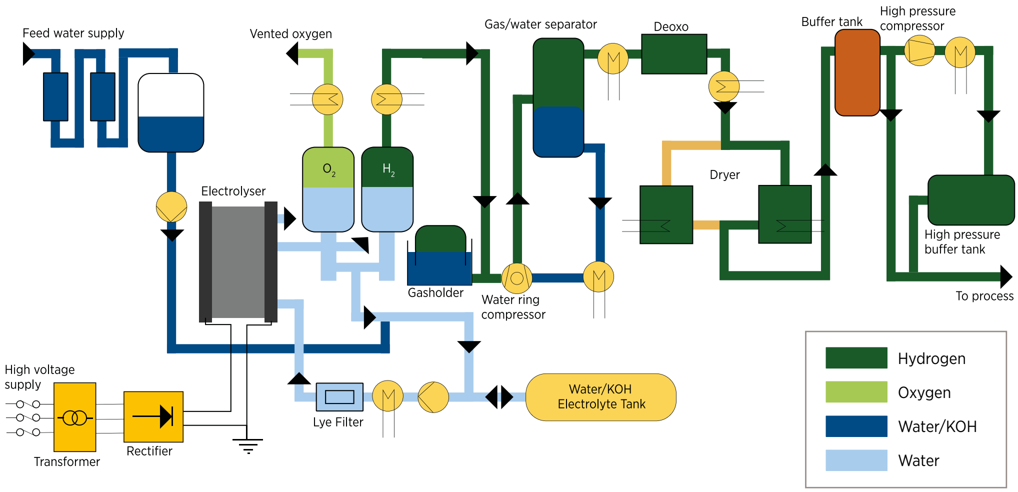
4 COST REDUCTION STRATEGIES

4.1 STACK LEVEL

KEY POINTS

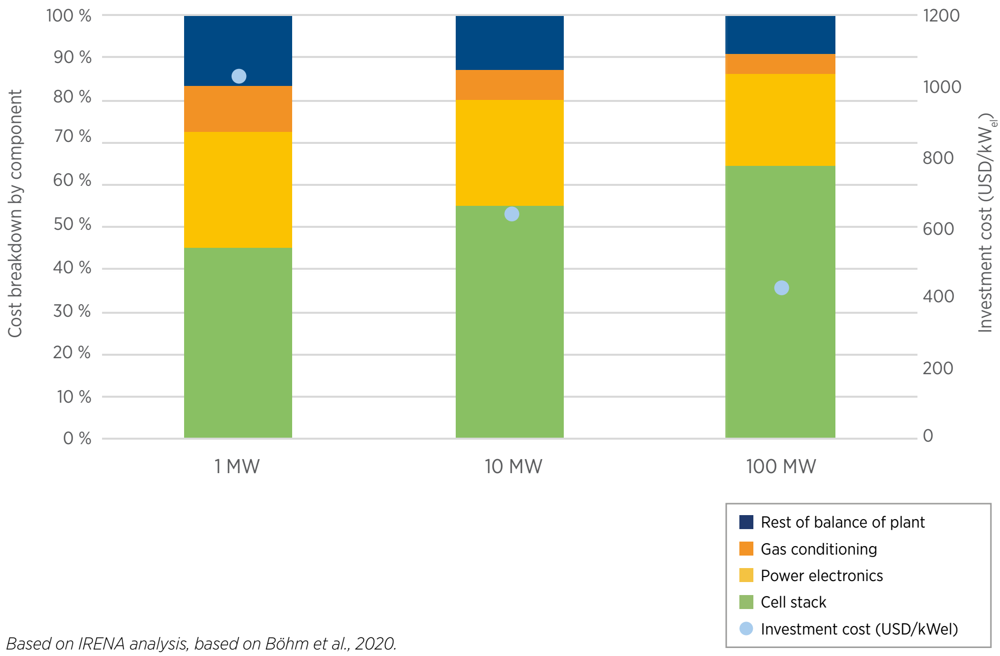
- **Government support for research programmes** is needed to continue improving commercially available technologies and make potential breakthroughs in emerging technologies.
- Given the differences in **design and maturity** among the various technologies, the use of comparable **performance indicators** seems to be a suitable approach to guide innovation efforts. These performance indicators, including **long-term targets**, can be used by governments to benchmark performance of funded projects and to set research programme goals.
- To prevent critical materials from becoming a barrier to scaling up, alkaline systems need to shift to **platinum- and cobalt-free design**. This is already commercially available from some manufacturers today; yet it must become a prerequisite for policy support before scaling up manufacturing capacity. For PEM electrolysers, further efforts are needed to reduce the platinum and iridium content by at least one order of magnitude and, if possible, in the future, replace these with more common materials. Titanium is also a significant cost component that should be reduced in use. Although less scarce than other materials, it is still required in significant quantities for current PEM designs.
- Increasing the **size of a facility** can have the largest cost reduction effect on the balance of plant. Yet facility size is not defined based on cost only, but is also based on the application (*e.g.,* the residential or transport sectors use smaller sizes than industrial applications). Higher cost due to smaller scale can partly be offset by savings in the delivery of the hydrogen, due to on-site production.

Figure 9 **Typical system design and balance of plant for an alkaline electrolyser**



Note: This configuration is for a generic system and might not be representative of all existing manufacturers.
Based on IRENA analysis.

Figure 10 **Cost breakdown by major component for alkaline electrolysers based on current costs**



Based on IRENA analysis, based on Böhm et al., 2020.

Table 2 **Iridium and platinum loading for PEM electrolysers with increased performance and material reduction strategies**

	TODAY	FUTURE
Current density (A/cm^2)	2	5
Electrode area (cm^2)	1200	5 000
Iridium loading (mg/cm^2)	5	0.2
Iridium loading (g/kW)	1.3	0.4
Platinum loading (mg/cm^2)	2	0.05
Platinum loading (g/kW)	0.5	0.1

Based on IRENA analysis.

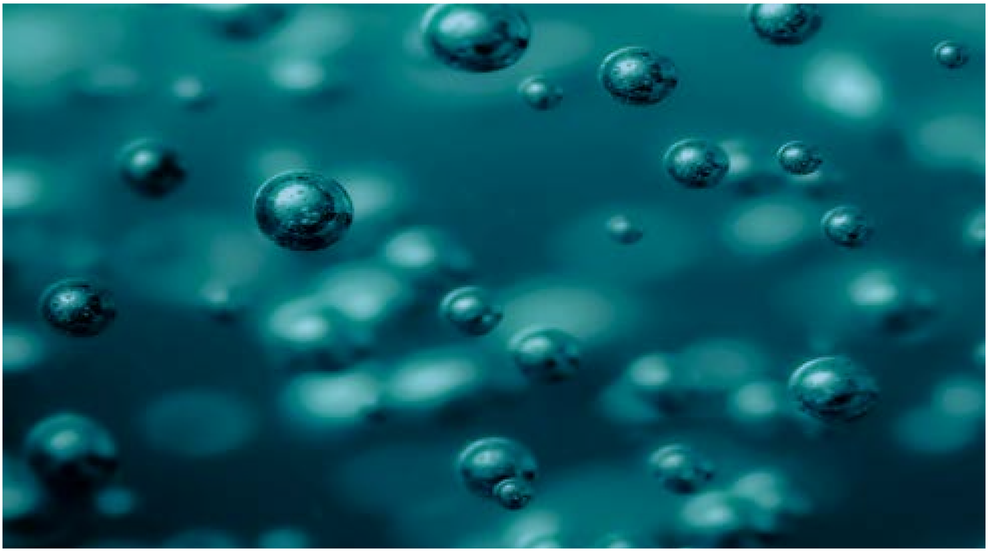


Table 3 **Proposed activities to improve the performance of alkaline electrolysers**

	CHALLENGE	BENEFIT
1. Increase catalyst surface area > 50 m^2/g	Easy	Medium
2. Increase catalyst utilisation > 80%	Moderate	Medium
3. Improve kinetics for both hydrogen and oxygen evolution with novel nickel-based alloys	Moderate	High
4. Mitigate catalyst poisoning/deactivation by foreign elements from electrolyte, and components present in the system	Moderate	Low
5. Design, create and integrate forms of recombination catalysts for gas permeation (crossover)	Moderate	Medium
6. Mitigate critical degradation of catalysts on the anode side to avoid loss of surface area	Difficult	High
7. Mitigate nickel hydrogen (NiH) formation on the cathode side	Difficult	Low
8. Eliminate mechanical degradation of catalyst layers (delamination, dissolution)	Difficult	High
9. Identify stable polymer chemistry that can be used as ionomer (OH- transport) to be used to fabricate electrodes for alkaline electrolysers	Difficult	High
10. Identify and reduce interface resistances from catalyst layer to porous transport layers	Difficult	High

Based on IRENA analysis.

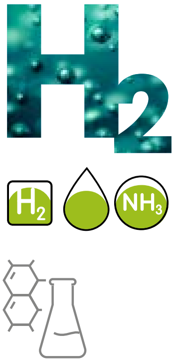


Table 4 **Proposed activities to improve the performance of PEM electrolysers**

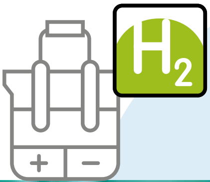
	CHALLENGE	BENEFIT
1. Mitigate membrane poisoning/deactivation by foreign elements from components and system	Easy	Medium
2. Design, create and integrate forms of recombination catalysts for gas permeation (crossover)	Easy	Medium
3. Increase catalyst utilisation of anode and cathode catalysts	Moderate	High
4. Identify and reduce interface resistances from catalyst layer to porous transport layers	Moderate	Medium
5. Reduce the ohmic losses and gas permeation of perfluorinated sulfonic acid (PFSA) membranes	Difficult	High
6. Improve kinetics for oxygen evolution using iridium-free catalysts, maintaining stability like the best iridium	Difficult	High
7. Eliminate mechanical degradation of catalyst layers (delamination, dissolution)	Difficult	Medium
8. Create noble metal free protective layers for porous transport layers	Difficult	High
9. Create titanium-free porous transport layers	Difficult	High

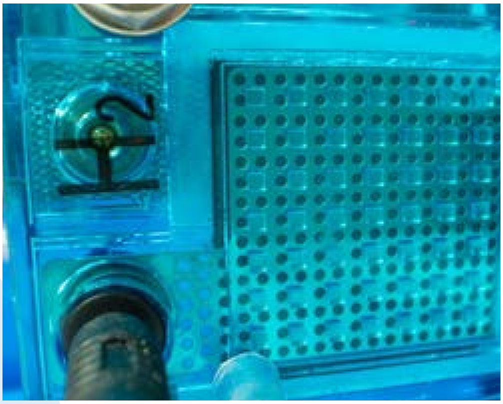
Based on IRENA analysis.

Table 5 **Proposed activities to improve the performance of AEM electrolysers**

	CHALLENGE	BENEFIT
1. Develop cost-effective porous transport layers for AEM electrolysers	Moderate	Medium
2. Identify and reduce interface resistances from catalyst layer to porous transport layers	Moderate	Medium
3. Control the oxidised state of electrocatalysts on the oxygen side (anode)	Moderate	Medium
4. Reduce the ohmic losses and gas permeation of AEM membranes	Moderate	High
5. Improve kinetics for hydrogen and oxygen evolution and maintain long-term stability	Moderate	High
6. Increase AEM membrane durability	Difficult	High
7. Eliminate mechanical degradation of catalyst layers (delamination, dissolution) and improve ionomer/catalyst binding properties	Difficult	High

Based on IRENA analysis.





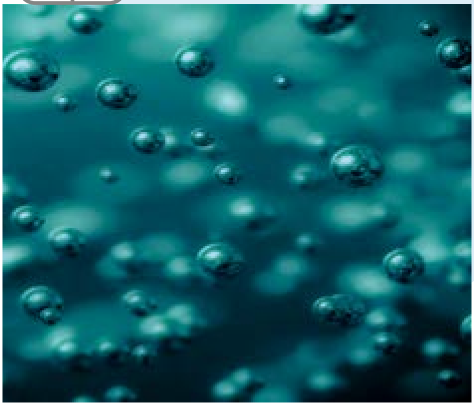
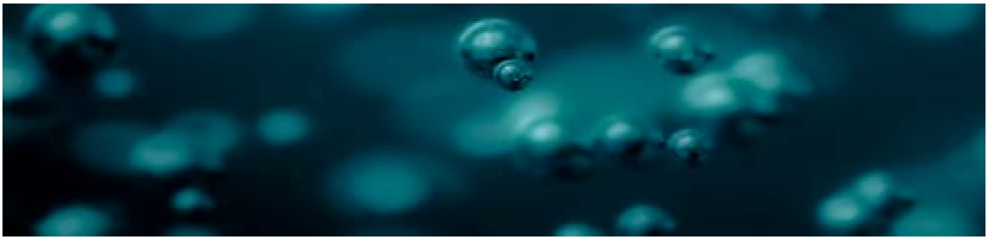


Table 6 **Proposed activities to improve the performance of solid oxide electrolysers**

	CHALLENGE	BENEFIT
1. Stabilise the chemical structure and compatibility of the electrodes	Moderate	Medium
2. Control the oxidation state of electrocatalysts on the oxygen side (anode) or nickel agglomeration	Moderate	Medium
3. Increase the electrocatalytic activity of electrodes at lower temperatures	Moderate	Low
4. Solve challenges related to lanthanum manganite (LSM) or lanthanum ferrite (LSF) delamination from electrolyte	Moderate	High
5. Improve kinetics for hydrogen and oxygen evolution and maintain long-term stability	Difficult	High
6. Eliminate or reduce contamination issues related to silicon dioxide (SiO_2) dissolution from stack sealants	Difficult	Medium
7. Eliminate thermal instability issues caused by an expansion coefficient mismatch between electrolytes and electrodes	Difficult	High
8. Scale up stack components towards larger, MW-size stack units	Difficult	High

Based on IRENA analysis.



4.2 SYSTEM LEVEL

KEY POINTS

- The largest benefits from **economies of scale** in electrolyser manufacturing seem to be reached around the 1GW/year level. Several industrial players claim to have reached this scale or are working towards expansion. One measure governments could take is to set manufacturing capacity targets, manufacturing tax benefits, grants and loans for capacity expansion and work in close collaboration with industry. The Netherlands and the UK are examples of where this is happening.
- A predictable **5-10 year pipeline** of electrolysis projects – driven by green hydrogen demand – will be key for manufacturers to invest in new, larger and automated production facilities. Uncertainties about the demand for green hydrogen versus fossil fuel-based hydrogen is a key obstacle to the scaling up of electrolyser manufacturing: policy makers should carefully assess the balance, as learning from investments in green hydrogen versus blue hydrogen production are not interchangeable.
- Water electrolysis deployment for green hydrogen has been limited so far, which introduces uncertainty around the cost reduction that can be achieved by scaling up. From this limited experience, electrolysers seem to display a similar relationship between **cost decrease and global capacity** as solar PV does – which could result in a **40% cost reduction**, given the capacity targets that governments have already announced. One action that governments could take is to ensure cost is communicated transparently, in order to be able to track progress and identify potential.
- Cost declines are greatest during the current, **early stage of deployment**, when the cumulative capacity deployed is still small and the market is relatively concentrated in a few companies. Current costs suffer from lack of transparency, due to the nascent stage of the industry, which will likely be resolved as large-scale manufacturing facilities come online and large projects get commissioned. This, in turn, will facilitate price discovery and improve cost reduction forecasts.

Table 6 lists key performance indicators (KPIs) for the four-electrolysis technologies considered here, both for the state of-the-art in 2020 and as targets for 2050. The table also indicates which component are specifically related to, or most affect, any given KPI.

Table 7 shows learning rates, by component, for alkaline, PEM and solid oxide electrolysers.

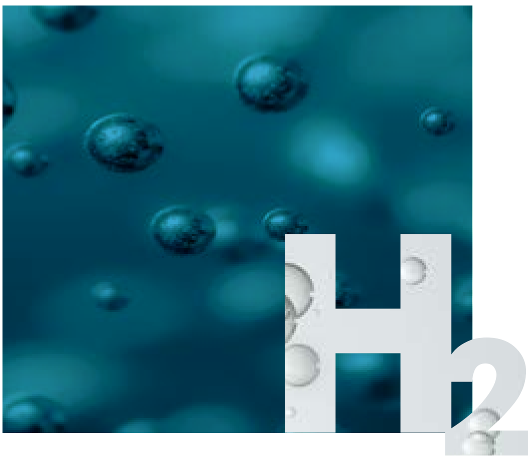


Table 7 **Key performance indicators for electroyser technologies**

	2020	Target 2050	R&D focus
	PEM electrolysers		
Nominal current density	1-2 A/cm²	4-6 A/cm²	Design, membrane
Voltage range (limits)	1.4-2.5 V	< 1.7 V	Catalyst, membrane
Operating temperature	50 – 80°C	80°C	Effect on durability
Cell pressure	< 30 bar	> 70 bar	Membrane, reconversion catalysts
Load range	5% – 120%	5% – 300%	Membrane
H_2 purity	99.9% – 99.9999%	Same	Membrane
Voltage efficiency (LHV)	50% – 68%	> 80%	Catalysts
Electrical efficiency (stack)	47-66 kWh/kg H_2	< 42 kWh/kg H_2	Catalysts/membrane
Electrical efficiency (system)	50-83 kWh/kg H_2	< 45 kWh/kg H_2	Balance of plant
Lifetime (stack)	50 000 - 80 000 hours	100000 - 120000 hours	Membrane, catalysts, porous transport layers
Stack unit size	1 MW	10 MW	Membrane electrode assembly, porous transport layer
Electrode area	1 500 cm²	> 10 000 cm²	Membrane electrode assembly, porous transport layer
Cold start (to nominal load)	< 20 minutes	< 5 minutes	Insulation (design)
Capital costs (stack) minimum 1 MW	USD 400/kW	< USD 100/kW	Membrane electrode assembly, porous transport layers, bipolar plates
Capital costs (system) minimum 10 MW	USD 700 – 1 400/kW	< USD 200/kW	Rectifier, water purification
	Alkaline electrolysers		
Nominal current density	0.2–0.8 A/cm²	> 2 A/cm²	Diaphragm
Voltage range (limits)	1.4–3 V	< 1.7 V	Catalysts
Operating temperature	70-90°C	> 90°C	Diaphragm, frames, balance of plant components
Cell pressure	< 30 bar	> 70 bar	Diaphragm, cell, frames
Load range	15% – 100%	5% – 300%	Diaphragm
H_2 purity	99.9% – 99.9998%	> 99.9999%	Diaphragm
Voltage efficiency (LHV)	50% – 68%	> 70%	Catalysts, temperature
Electrical efficiency (stack)	47–66 kWh/kg H_2	< 42 kWh/kg H_2	Diaphragm, catalysts
Electrical efficiency (system)	50–78 kWh/kg H_2	< 45 kWh/kg H_2	Balance of plant
Lifetime (stack)	60 000 hours	100 000 hours	Electrodes
Stack unit size	1 MW	10 MW	Electrodes
Electrode area	10 000 - 30 000 cm²	30 000 cm²	Electrodes
Cold start (to nominal load)	< 50 minutes	< 30 minutes	Insulation (design)

Table 7 **(continued)**

	2020	Target 2050	R&D focus
	Alkaline electrolysers (continued)		
Capital costs (stack) minimum 1 MW	USD 270/kW	< USD 100/kW	Electrodes
Capital costs (system) minimum 10 MW	USD 500 – 1 000/kW	< USD 200/kW	Balance of plant
	AEM electrolysers		
Nominal current density	0.2 – 2 A/cm²	> 2 A/cm²	Membrane, reconversion catalysts
Voltage range (limits)	1.4 – 2.0 V	< 2 V	Catalyst
Operating temperature	40-60°C	80°C	Effect on durability
Cell pressure	< 35 bar	> 70 bar	Membrane
Load range	5% – 100%	5% – 200%	Membrane
H_2 purity	99.9% – 99.999%	> 99.9999%	Membrane
Voltage efficiency (LHV)	52% – 67%	> 75%	Catalysts
Electrical efficiency (stack)	51.5-66 kWh/kg H_2	< 42 kWh/kg H_2	Catalysts/membrane
Electrical efficiency (system)	57-69 kWh/kg H_2	< 45 kWh/kg H_2	Balance of plant
Lifetime (stack)	> 5 000 hours	100 000 hours	Membrane, electrodes
Stack unit size	2.5 kW	2 MW	Membrane electrode assembly
Electrode area	< 300 cm²	1 000 cm²	Membrane electrode assembly
Cold start (to nominal load)	< 20 minutes	< 5 minutes	Insulation (design)
Capital costs (stack) minimum 1 MW	Unknown	< USD 100/kW	Membrane electrode assembly
Capital costs (system) minimum 10 MW	Unknown	< USD 200/kW	Rectifier
	Solid oxide electrolysers		
Nominal current density	0.3 – 1 A/cm²	> 2 A/cm²	Electrolyte, electrodes
Voltage range (limits)	1.0 – 1.5 V	< 1.48 V	Catalysts
Operating temperature	700-850°C	< 600°C	Electrolyte
Cell pressure	1 bar	> 20 bar	Electrolyte, electrodes
Load range	30% – 125%	0% – 200%	Electrolyte, electrodes
H_2 purity	99.9%	> 99.9999%	Electrolyte, electrodes
Voltage efficiency (LHV)	75% - 85 %	> 85%	Catalysts
Electrical efficiency (stack)	35-50 kWh/kg H_2	< 35 kWh/kg H_2	Electrolyte, electrodes
Electrical efficiency (system)	40-50 kWh/kg H_2	< 40 kWh/kg H_2	Balance of plant
Lifetime (stack)	< 20 000 hours	80 000 hours	All
Stack unit size	5 kW	200 kW	All
Electrode area	200 cm²	500 cm²	All
Cold start (to nominal load)	> 600 minutes	< 300 minutes	Insulation (design)
Capital costs (stack) minimum 1 MW	> USD 2 000/kW	< USD 200/kW	Electrolyte, electrodes
Capital costs (system) minimum 1 MW	Unknown	< USD 300/kW	All

Note: A/cm² = amperes per square centimetre; V = volts; °C = degrees Celsius; kWh/kg H_2 = kilowatt hours per kilogram of hydrogen; MW = Megawatt; cm² = square centimetres; kW = kilowatt

Based on IRENA analysis.

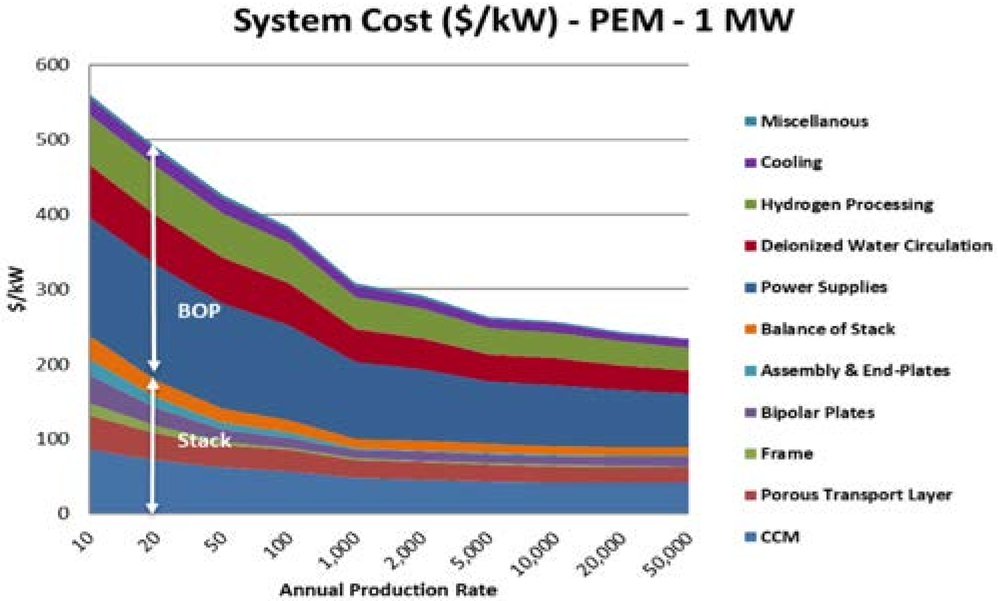
Table 8 **Learning rate by stack component for three types of electrolysers**

TECHNOLOGY	COMPONENT	LEARNING RATE (%)
Alkaline	Structural rings	5
	Polytetrafluoroethylene seal	8
	Bipolar plates	18
	(Pre)electrodes	18
	Membrane	18
	Flanges	5
	Tie rods	5
PEM	Stack assembling	8
	Small parts	5
	MEA manufacturing	8
	Catalysts	8
	Membranes	18
	Current collectors	18
	Bipolar plates	18
	End plates	8
Solid oxide	Stack assembling	8
	Electrolyte	18
	Catalysts	18
	Porous transport layer	18
	Interconnector	18
	Sealings	5
	End and pressure plates	8
Balance of plant	Power supply	12
	Gas conditioning	7
	Small purchased parts	12 – 15
	Machining	10
	Welding	10

MEA = membrane electrode assembly

Source: Bohm et al., 2019.

Figure 11 **Cost breakdown for PEM electrolysers as a function of manufacturing scale (units of 1 MW per year)**



Note: Costs include material, labour, capital, energy, maintenance, buildings and scrap costs.

Source: Mayyas et al., 2019.

5 GUIDANCE FOR POLICY MAKERS

5.1 POLICY PILLARS

KEY POINTS

- Each country needs a long-term hydrogen strategy. This defines national ambitions, outlines the amount of support required, and provides a reference for private investment and finance in green hydrogen development.
- Hydrogen strategies may be preceded by decades of research and demonstration projects and should be followed by impact assessments.
- Such assessments are needed to quantify the costs and benefits of different applications and to identify suitable policy instruments.
- While green hydrogen can be used across the energy system, initial policies and support should focus on the most attractive applications in each local context.
- Guarantee-of-origin schemes require labels of hydrogen and hydrogen products, indicating emissions over the entire product life cycle. Clear labelling would increase consumer awareness and facilitate incentive claims for green hydrogen use.
- As green hydrogen becomes mainstream, policies should cover its integration into the broader energy system. Civil society and industry must be involved to maximise the benefits.
- Each sector entails specific challenges, degrees of competition, and needs for service, along with its own incumbent and alternative technologies. Policy must be tailored to drive green hydrogen uptake across the value chain.

Turning green hydrogen from a niche player into a widespread energy carrier calls for an integrated policy approach to build the market. This rests on four central pillars:

1. **National hydrogen strategies.** These can start with research and development (R&D) programmes, followed by a vision document on "why hydrogen", "why this jurisdiction", and "why now". Next is a roadmap of short-term actions, identifying high-priority research areas and applications. Finally, the strategy sets levels of ambition and of support. It can be followed by economic, social and environmental impact analyses.

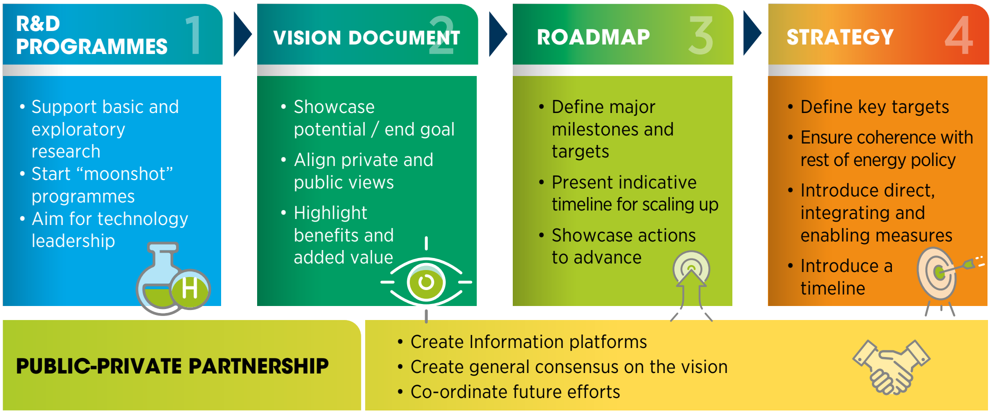
2. **Policy priorities for green hydrogen.** Each country or region should identify its highest-value hydrogen pathways, along with policy goals like reducing air pollution, boosting economic growth or decarbonising hard-to-abate sectors.

   Other decarbonisation alternatives should also be weighed, and renewable power should not be diverted from other, existing productive uses.

3. **A guarantee-of-origin system.** A certification system helps to differentiate, and value, green hydrogen. Common classifications are needed for all hydrogen in use, with life-cycle emissions indicated for any given batch.

4. **Governance system and enabling policies.** These create the socio-economic space for green hydrogen uptake. R&D, workforce and other policies should reflect the systemic and social value of energy choices. New policies can create local value chains and encourage demand for green products. Specific measures can level the playing field with fossil fuels.

Figure 12 **Steps leading to the formulation of a national strategy**

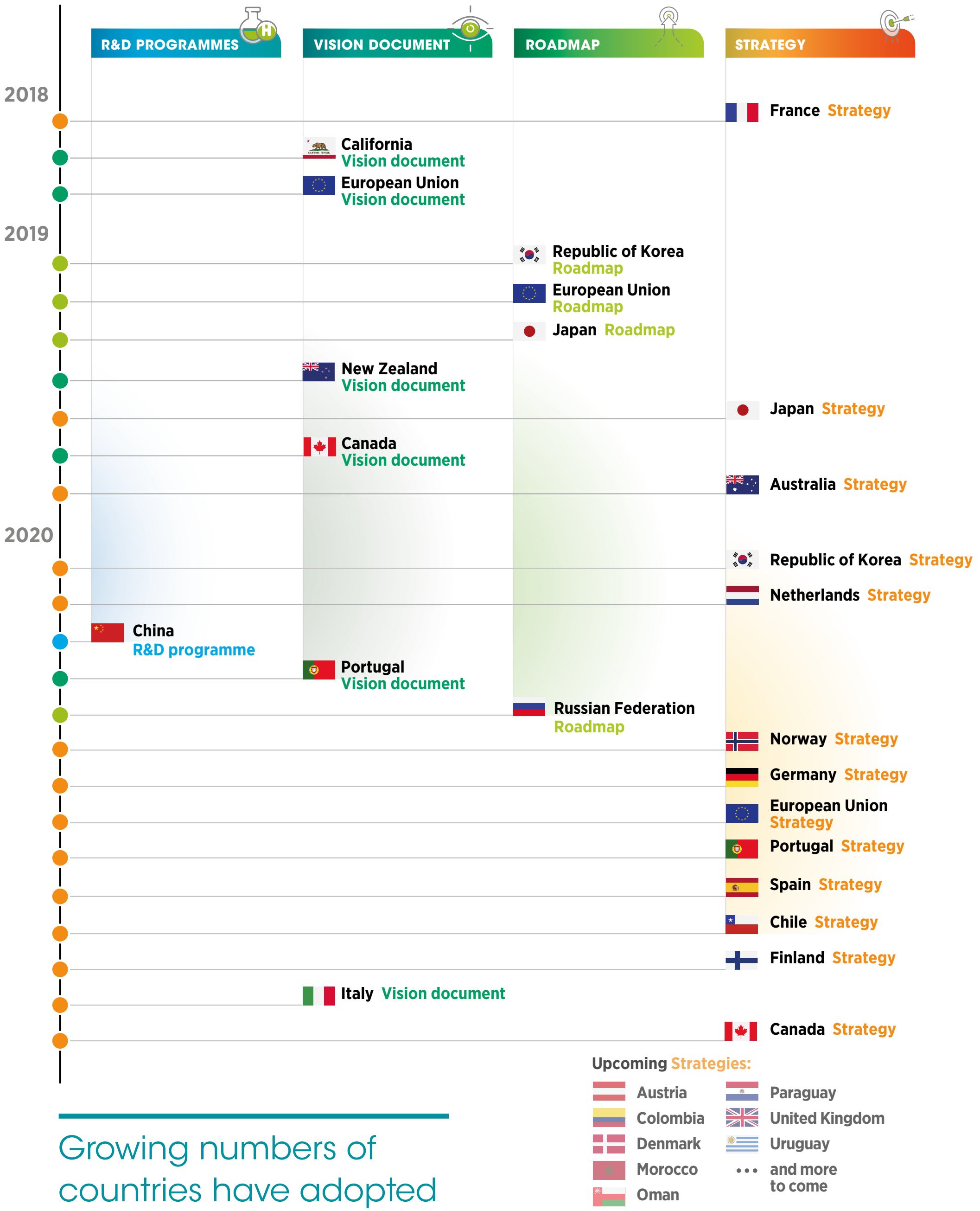


As a follow-up to the strategy, a set of analyses must be carried out to assess the impact of the introduction or change of specific policies. The analyses assess the economic, social and environmental consequences of the implementation of the proposed measures in the strategy. They evaluate alternative timelines and scopes, as well as interactions with other technologies. After these analyses, the actual regulations and laws are introduced, followed by regular revisions to adjust them according to progress and latest trends.

This process from R&D to strategy is far from linear or quick. Moreover, countries can skip the public-facing steps described here and issue a national hydrogen strategy while keeping the investigation activities confidential.

National strategies lay out a clear pathway to increase hydrogen uptake

Figure 13 **Recent hydrogen policies and strategies**



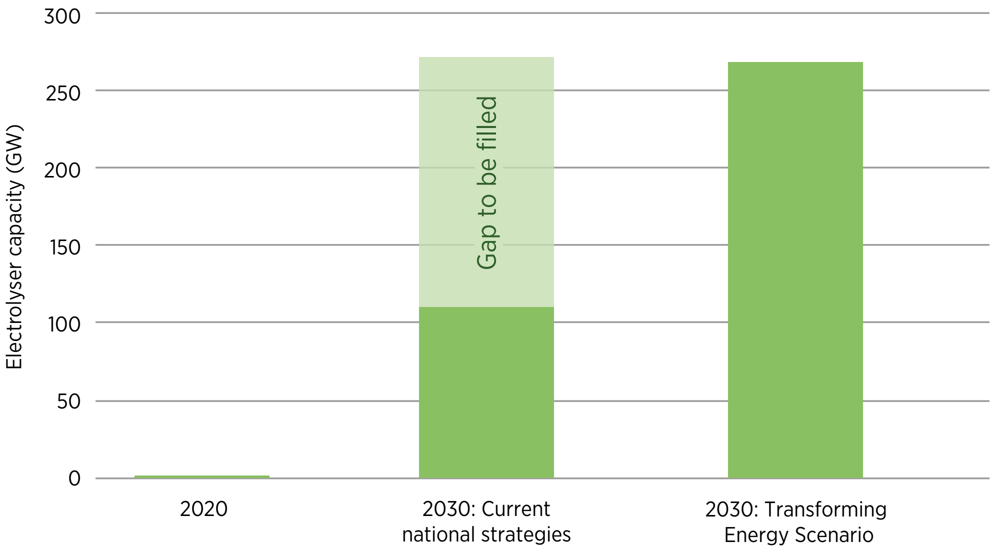
Growing numbers of countries have adopted hydrogen policies and strategies

Note: R&D = research and development

Hydrogen policies are evolving rapidly. While information in this figure is as complete as possible, more countries may have announced, drafted and published vision, roadmap and strategy documents.

Source: IRENA, 2020f), updated.

Figure 14 **Electrolyser capacity in national strategies versus climate-safe scenario for 2030**



Based on IRENA analysis.

Current strategies are insufficient to meet climate goals

Box 3 **The EU hydrogen strategy**

The EU strategy aims for an integrated view of the hydrogen value chain, and establishes a supporting governance system and policy framework to promote hydrogen deployment (see Figure 15).

The ambition of EU policy makers is to make the European industry a global leader, both in green hydrogen equipment and zero-carbon heavy industry. For this reason, the strategy identifies green hydrogen as the only shade of hydrogen compatible with a net-zero emission system.

The strategy aims to create at least 6 GW of electrolyser capacity by 2024, enough to produce up to 1 million tonnes per year (Mt/yr) of green hydrogen. That would increase to 40 GW in EU countries by 2030, with an additional 40 GW of electrolyser capacity in southern and eastern neighbours (*e.g.,* Ukraine or Morocco), from which the EU could import green hydrogen.

The strategy sets a number of actions, including not only regulatory changes indicated by impact assessments, but also supporting investments designed to kick-start deployment.

The strategy adopts a staged approach:

STAGE 1 (2020-2024): Scale up electrolyser capacity to 6 GW and produce up to 1 Mt/yr of renewable hydrogen. The focus is on decarbonising applications that already use hydrogen and facilitating the uptake of green hydrogen in new end-use applications. The hydrogen supply would be mostly local to avoid the need for extensive infrastructure while planning for infrastructure expansion. Some existing hydrogen production is retrofitted with carbon capture. **2020**

STAGE 2 (2025-2030): Scale up electrolyser capacity to 40 GW in EU countries and produce up to 10 Mt/yr of renewable hydrogen. An additional 40 GW of capacity may be commissioned in neighbouring regions, via co-operation. Transporting the green hydrogen will require a pan-European grid infrastructure that could be largely based on existing natural gas infrastructure. International trade with neighbouring regions can also be developed. The hydrogen market is assumed to be efficient in terms of allocation, with unhindered cross-border trade. **2025**

STAGE 3 (2030-2050): Green hydrogen reaches maturity and is deployed at large scale across all hard-to-abate sectors where alternatives have a higher cost. E-fuels made from hydrogen would be used in a wide range of sectors, including aviation and shipping. **2030** **2050**

Reaching the key goals for 2030 requires estimated investments of EUR 24 billion to EUR 42 billion (about USD 29 billion to USD 50 billion) for electrolyser capacity, in addition to between EUR 220 billion and EUR 340 billion (about USD 265 billion to USD 410 billion) for 80-120 GW of additional renewable-based power generation capacity, EUR 65 billion (USD 78 billion) for infra-structure and EUR 11 billion (USD 13 billion) for retrofitting existing natural gas plants.

Figure 15 **Main aspects and instruments mentioned in the EU hydrogen strategy**

SUPPLY

- Use of life cycle CO_2 thresholds
- Threshold for low carbon
- Use of certification schemes
- Adoption of tenders

INFRASTRUCTURE

- Reform of gas market legislation
- Repurposing gas infrastructure
- Provide equal access to all stakeholders

DEMAND

- Revision of ETS
- Introduction of "Carbon Contract for Difference"
- Market-based support schemes
- Quotas of green hydrogen in end uses

INVESTMENT

Important Projects of Common European Interest (IPCEI); REACT-EU; InvestEU programme; European Regional Development Fund and the Cohesion Fund

RESEARCH AND INNOVATION

Larger and more efficient electrolysers; innovative production technologies; assess the repurposing of natural gas infrastructure; environmental impact; safety and materials

INTERNATIONAL DIMENSION

Partnerships with neighbouring regions; IPHE, CEM, MI, IEA, IRENA; global trading; trade policy to avoid market distortions; Euro as benchmark for hydrogen trading

Notes: CEM = Clean Energy Ministerial; ETS = emissions trading system; IEA = International Energy Agency; IPHE = International Partnership for Hydrogen and Fuel Cells in the Economy; MI = Mission Innovation; REACT-EU = Recovery Assistance for Cohesion and the Territories of Europe.

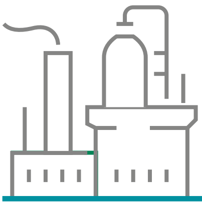
Source: European Commission, 2020.

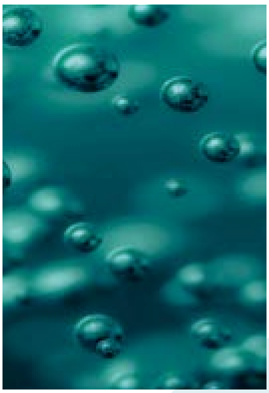
Figure 16 **Ways to decarbonise end-use energy**

	RENEWABLES	DIRECT ELECTRIFICATION	ENERGY EFFICIENCY	GREEN HYDROGEN
HEATING	• Solar water heaters, direct geothermal use, biomass (low-grade heating)	• Heat pumps	• Retrofit of buildings • Technological advancement	• High-grade heating
INDUSTRY	• Solar drying, biomass (productive uses)	• Electric industrial application (*e.g.,* arc furnaces)	• Use of best available technologies	• Steelmaking refineries • Chemical industry
LAND TRANSPORT	• Biofuels	• Battery electric vehicles	• Performance standards • Travel avoidance • Engine design	• Fuel-cell electric vehicles
SHIPPING	• Biofuels • Wind energy	• Short-distance shipping	• Ship design • Operation optimisation • Travel avoidance	• Green ammonia • Methanol
AVIATION	• Biojet fuels	• Short-distance aviation	• Plane design • Travel avoidance	• Hydrogen and synthetic fuels for aviation

Based on IRENA, IEA and REN 21, 2020, and IRENA, 2020b.

Hydrogen is one of several options available to replace fossil fuels





5.2 **SUPPORTING** POLICIES

Green hydrogen is at an early stage in most applications and needs policy support to advance from niche to mainstream and be part of the energy transition. Some barriers to the deployment of green hydrogen in various sectors are relatively consistent across end uses, the cost barrier being the main one.

Other barriers are more sector-specific and call for a tailored approach (see Figure 17).

Once priorities are set, policy makers need to address the barriers specific to the sectors where green hydrogen is expected to be deployed.

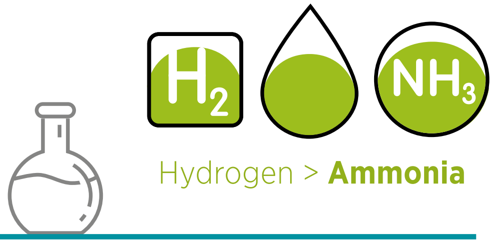


Figure 17 **Key barriers, and policies to address them, across the hydrogen value chain**

	ELECTROLYSIS	INFRASTRUCTURE	INDUSTRY	AVIATION	SHIPPING
BARRIERS	- Capital cost - Electricity cost - Lack of hydrogen market - Barriers to power market	- Limited existing infrastructure - Technical limitations of users - Lack of investment	- High cost - Lack of demand for green products - Global competition and carbon leakage	- High cost - Procurement of sustainable CO_2 - Policy focus on biofuels	- High cost - Technical barriers
POLICY OPTIONS	+ Set capacity targets + Offer loans + Introduce feed-in premium + Allow participation in ancillary markets	+ Collaborate on global trading of hydrogen + Identify priorities for conversion + Align blending targets + Provide financing	+ Offer dedicated loans + Develop public procurement of green products + Phase out high-emission technologies	+ Set targets + Review policy focus + Expand emissions trading system	+ Introduce fiscal incentives + Set targets for zero-emission vessels + Support infrastructure development

6 PROJECTS, MILESTONES AND ROLES

6.1 GREEN HYDROGEN PROJECT PIPELINE

KEY POINTS

- Announcements of **projects coming online in the next five years** add up to a total that is two orders of magnitude greater than today's globally installed capacity. Still, even steeper growth would be needed to be in line with **1.5°C pathways**.
- This requires a further acceleration in the deployment of **renewable power capacity**, which needs to be at least ten times higher in 2050 than it was in 2019.
- To achieve this, hydrogen uptake must be focused on **sectors where direct electrification is more difficult**, to maximise the efficiency of renewable electricity use.

As research and development (R&D) institutions dedicated to green hydrogen emerge, intensified competition could result in faster innovation and significant reductions in costs.

Currently, the field of green hydrogen production is growing so fast that new players can sometimes be difficult to identify. Historically, with a few exceptions, water electrolysers were manufactured by small companies.

Now, large enterprises are active in acquiring and merging small- to medium-sized electrolyser companies into their subsidiary portfolios. This will dramatically and positively increase investment, much more rapidly changing the technology and decreasing costs. Table 8 provides a non-exhaustive list of companies, enterprises and key players involved in the manufacturing and/or commercialisation of water electrolysers.

Table 9 **Some key players involved in manufacturing water electrolyser systems**

COMPANY	MANUFACTURING SITE	ELECTROLYSER TYPE
AQUAHYDREX	Australia, US	Alkaline
AREVAH$_2$	France, Germany	PEM
ASAHI KASEI	Japan	Alkaline
CARBOTECH	Germany	PEM
COCKERILLL JINGLI	China	Alkaline
CUMMINS - HYDROGENICS	Belgium, Canada, Germany	PEM and Alkaline
DENORA	Italy, Japan, US	PEM and Alkaline
ENAPTER	Italy	AEM
GINER ELX	US	PEM
GREEN HYDROGEN SYSTEMS	Denmark	Alkaline
HALDOR TOPSOE	Denmark	Solid Oxide
HITACHI ZOSEN	Japan	Alkaline and PEM
HONDA	Japan	PEM
HYDROGENPRO	Norway	Alkaline
iGAS	Germany	PEM
ITM	UK	PEM
KOBELCO	Japan	Alkaline and PEM
KUMATEC	Germany	Alkaline
MCPHY	France, Italy, Germany	Alkaline
NEL HYDROGEN	Denmark, Norway, US	PEM and Alkaline
PERIC	China	Alkaline
PLUG POWER	US	PEM
SHANGHAI ZHIZHEN	China	Alkaline
SIEMENS ENERGY	Germany	PEM
SOLIDPOWER	Italy, Switzerland, Germany, Australia	Solid Oxide
SUNFIRE	Germany	Solid Oxide
TELEDYNE	US	PEM
THYSSENKRUPP UHDE	Germany	Alkaline
TIANJIN	China	Alkaline
TOSHIBA	Japan	Solid Oxide

PEM electrolysers *Alkaline electrolysers* *AEM electrolysers* *Solid oxide electrolysers*

Based on IRENA analysis.

6.2 **MILESTONES**

KEY POINTS

- Progress towards lower costs is not inherently time-bound. The best **cost reduction pathway** will be defined by how quickly specific key milestones are achieved. This depends on governments setting time-bound targets and measures to support green hydrogen demand, which in turn will promote scale-up (explicitly or implicitly) and increased competition in electrolyser manufacturing and deployment.
- No single cost reduction strategy is recommended to pursue exclusively, and the four strategies presented here can all be considered in parallel. A combination of government **support for research programmes** in parallel with the establishment of **policies and targets**, combined with **private sector moves** towards standardisation and optimised designs, will lead to lower electrolyser costs and ultimately cheaper green hydrogen.
- A 40% cost decline could be achievable in the short term, with a total **80% cost reduction** in the long term when all the targets are achieved.
- Investment cost is only one component of the **total green hydrogen cost**. To achieve cost competitiveness with fossil-based hydrogen, low electricity cost, favourable regulation, higher efficiency and a longer lifetime will be needed.

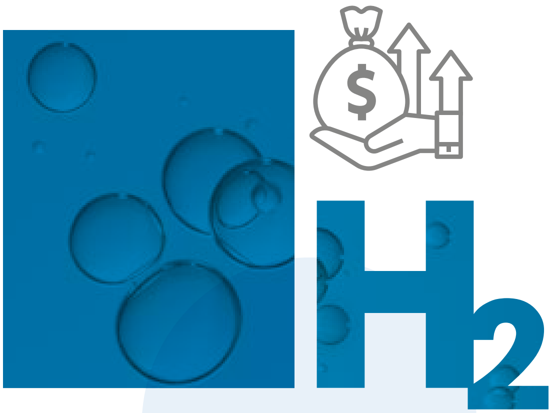
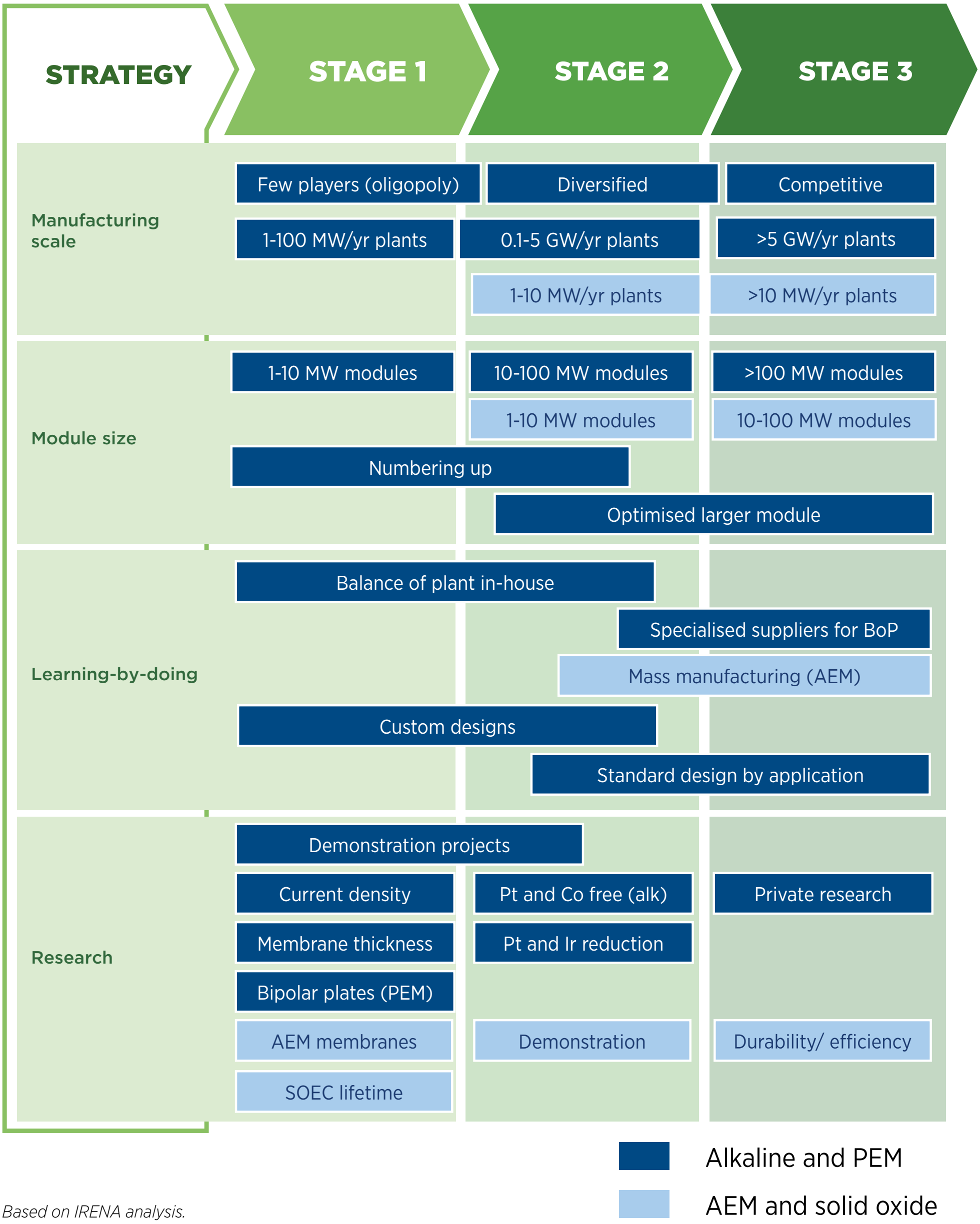


Figure 18 **Milestones for four cost reduction strategies across three stages of deployment for electrolysers**



Based on IRENA analysis.

6.3 STAKEHOLDER ROLES

Today, green hydrogen represents only a limited share of global supply. The transition to a future where green hydrogen has not only displaced fossil-based hydrogen, but also gone beyond the industrial sector to become a versatile energy carrier, will therefore not happen overnight. It will also not happen without participation by multiple stakeholders.

Co-ordination will be crucial in at least four key areas:

1 **Across the value chain**: Hydrogen supply must be scaled up in parallel with infrastructure development and, more importantly, demand. At least during the early stages, when a market has not yet developed, production projects need to be co-developed with an off-taker, since there is no grid or ubiquitous established sink that can absorb all the production. While blending in the gas grid, if combined with tracing and financial compensation, can provide an alternative, it is only an alternative for early stages of development.

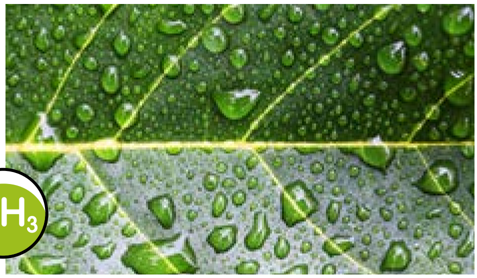
2 **Across borders**: All sectors, from electrolysers to fuel cells, direct reduction of steel to ammonia ships and synthetic fuels, will benefit from global collaboration. This applies to the deployment level – enabling learning from projects to drive costs down – and at the research level, enabling the co-ordination of national programmes.

3 **Across sectors**: Green hydrogen development would benefit from combining different applications to aggregate demand, justifying larger projects and achieving economies of scale that benefit production and, perhaps, infrastructure.

4 **Among multiple stakeholders**: Green hydrogen will not scale up without support from multiple stakeholders. Fortunately, there is already widespread interest in hydrogen from energy utilities, steel makers, chemical companies, port authorities, car and aircraft manufacturers, shipowners and airlines, amongst others, but their actions need to be in the same direction.

For governments, there are multiple actions that could be pursued to promote green hydrogen production. Most of these will have the largest impact in the early stages of deployment (see Figure 19). Some, however, such as market regulation and financing, will be crucial once the market kicks off and the scale-up process begins.

Governments should also adopt a flexible approach in which strategies and targets are frequently reviewed to give consideration to the latest developments. For example, the Australian strategy includes this approach (Strategic Actions 2.1 and 2.2) to remove market barriers and support technology growth, as the market develops.



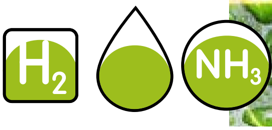
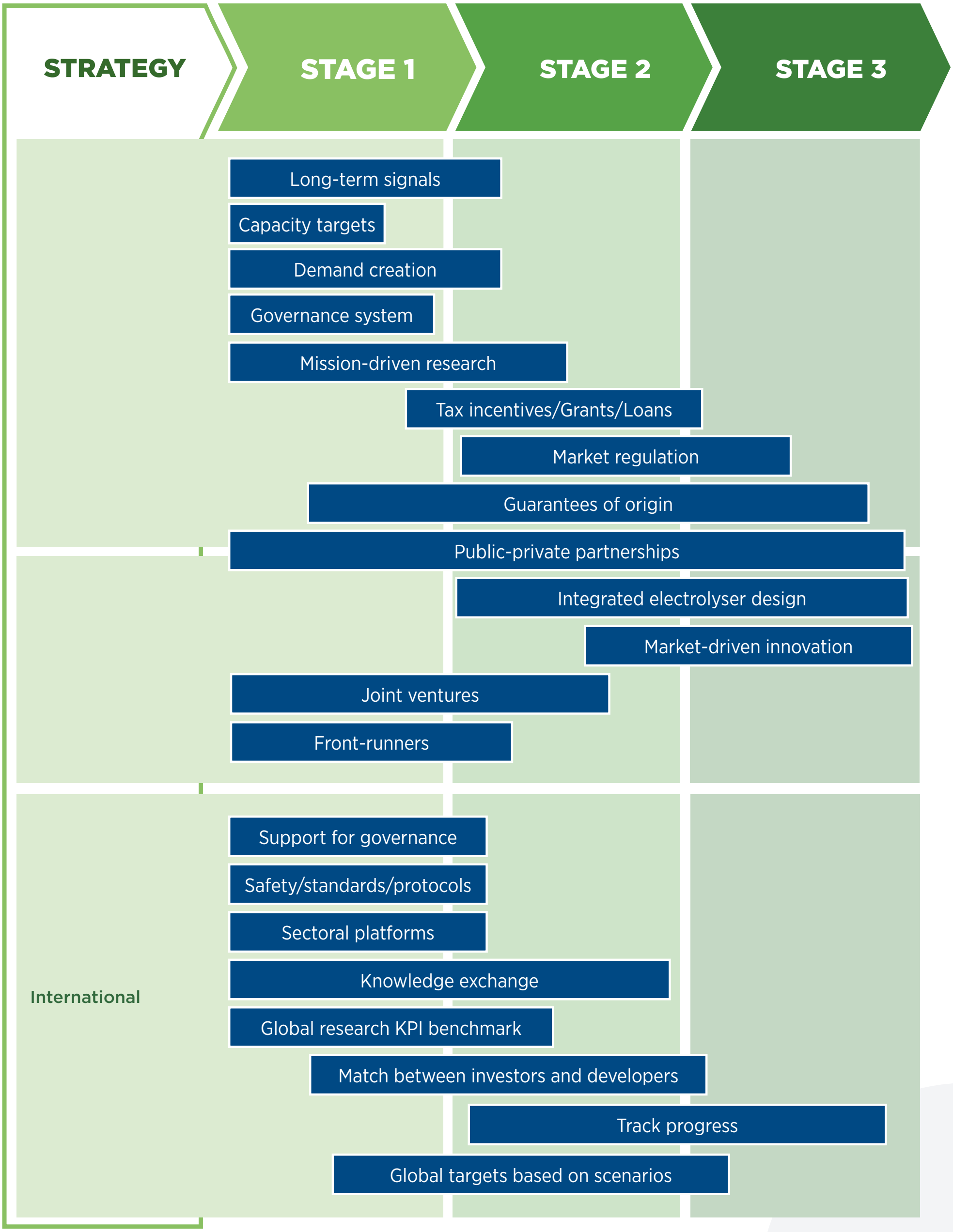


Figure 19 **Main actions and functions for key stakeholders influencing green hydrogen uptake**



Note: KPI = key performance indicator.

Based on IRENA analysis.

WAY FORWARD

	H Hydrogen 1.01	National pledges to achieve net-zero emissions	Broader use of hydrogen
Maturity of relevant technology	Power system flexibility benefits	Low renewable energy cost	Extensive base of interested stakeholders

Global interest is rising in green hydrogen as one of the solutions for an energy transition towards zero or net-zero emissions. Unlike earlier waves of interest in hydrogen, this new wave focuses on creating a link between renewable electricity and hard-to-electrify end uses.

Its drivers include: low renewable electricity costs, the maturity of relevant technology, power system flexibility benefits, national pledges to achieve net-zero emissions, and a more extensive base of interested stakeholders.

Indeed, the years 2019 and 2020 witnessed increased momentum for green hydrogen, with many countries around the world implementing national hydrogen strategies or announcing their intentions to do so. Measures to support green hydrogen have even been included in post-COVID-19 recovery packages.

Although interest in green hydrogen is reaching unprecedented levels, several barriers impede its full contribution to the energy transition. The primary obstacle is the high cost of green hydrogen compared to grey hydrogen and fossil fuel sources. Other barriers include the lack of dedicated infrastructure, the lack of value recognition for reduced GHG emissions, and other barriers related to the development of an emerging industry.

While the hydrogen sector has received attention from governments, more dedicated policy support is needed to ensure technology readiness, market penetration and market growth. IRENA has identified four pillars for green hydrogen policy making: national hydrogen strategies, policy priorities for green hydrogen, guarantee of origin systems and enabling policies.

National hydrogen strategies define a country's level of ambition for hydrogen and outline the amount of support required to achieve such ambition. They serve as a reference for private actors in the hydrogen industry, helping to encourage increased levels of financing. Effective national strategies should lay out a clear pathway to increasing hydrogen uptake.

A wide range of end uses can utilise green hydrogen. To avoid diluting efforts, national policy makers should identify the applications that provide the highest value and prioritise action towards them. By doing so, governments can ensure that their policy efforts provide more immediate benefits, creating higher demand for green hydrogen.

Guarantee-of-origin schemes should be based on life-cycle greenhouse gas emissions. They should be designed to allow policy makers and end users to understand the impact of this energy carrier, ensure consistency and compatibility with emissions for other commodities, and allow comparison with other energy sources.

Enabling policies are economy-wide policies that can help to level the playing field between hydrogen and fossil fuels. These policies should be applied to allow hydrogen actors to provide value to the entire energy system, and to broader economic and social systems.

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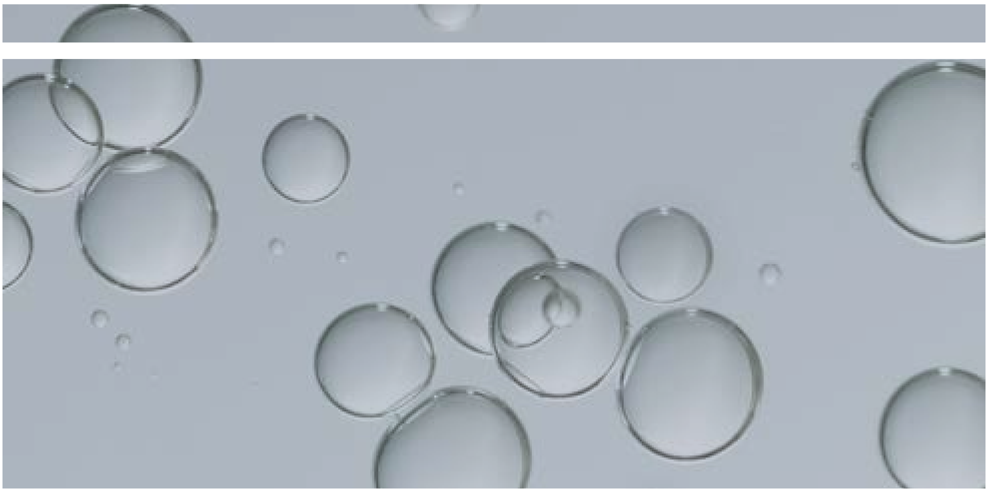

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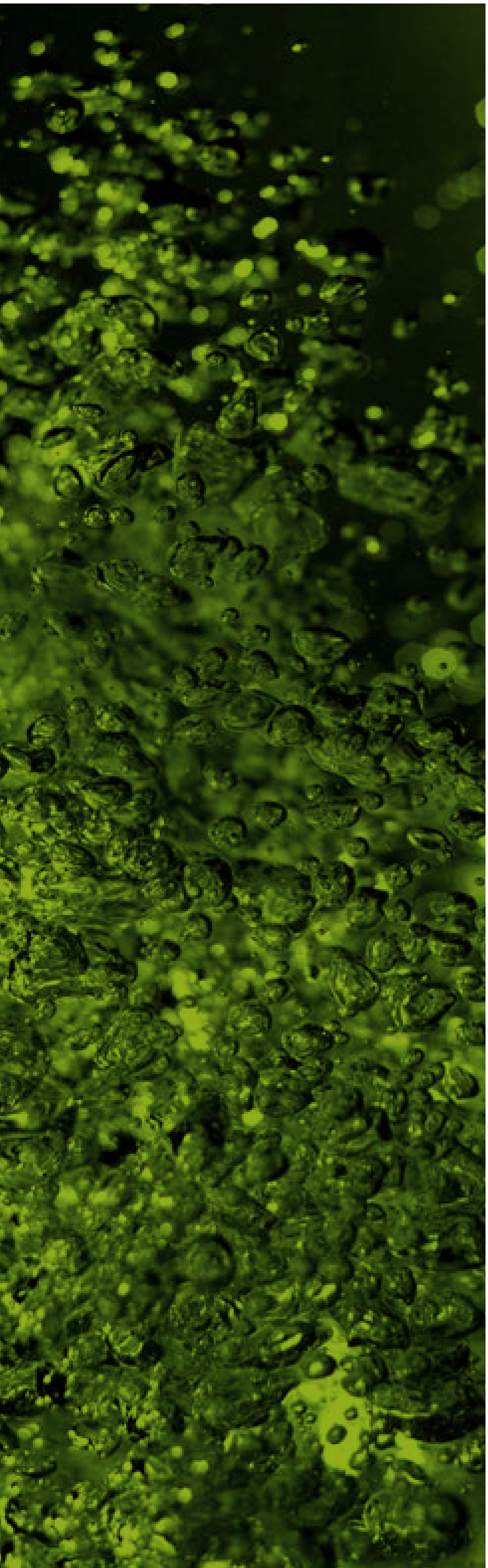


ABBREVIATIONS

AEM	Anion exchange membrane
CCS	Carbon capture and storage
CO_2	Carbon dioxide
EU	European Union
EUR	Euro
H_2	Hydrogen
IRENA	International Renewable Energy Agency
KPI	Key performance indicator
LHV	Lower heating value
PEM	Polymer electrolyte membrane
PV	Photovoltaic
R&D	Research and development
RD&D	Research, development and demonstration
SMR	Steam methane reforming
SOEC	Solid oxide electrolysers
UK	United Kingdom
US	United States
USD	United States dollar
VRE	Variable renewable energy
WACC	Weighted average capital cost

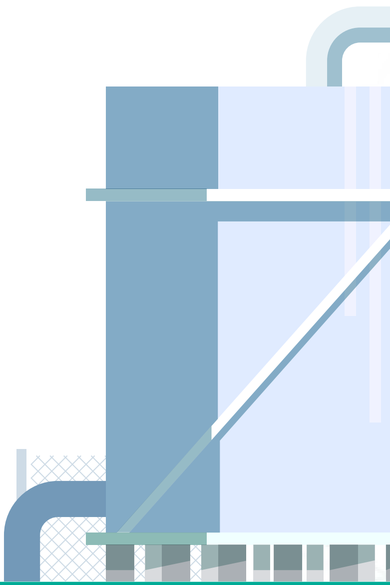
UNITS OF MEASURE

°C	Degrees Celsius
A	Ampere
cm^2	Square centimetre
g	Gram
GW	Gigawatt
ha	Hectare
kg	Kilogram
kW	Kilowatt
kW_{el}	Kilowatt electric
kWh	Kilowatt-hour
Mt	Million tonnes
MW	Megawatt
MWh	Megawatt-hour
TW	Terawatt
V	Volt

IRENA
International Renewable Energy Agency

MAKING THE BREAKTHROUGH

Green hydrogen policies and technology costs



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