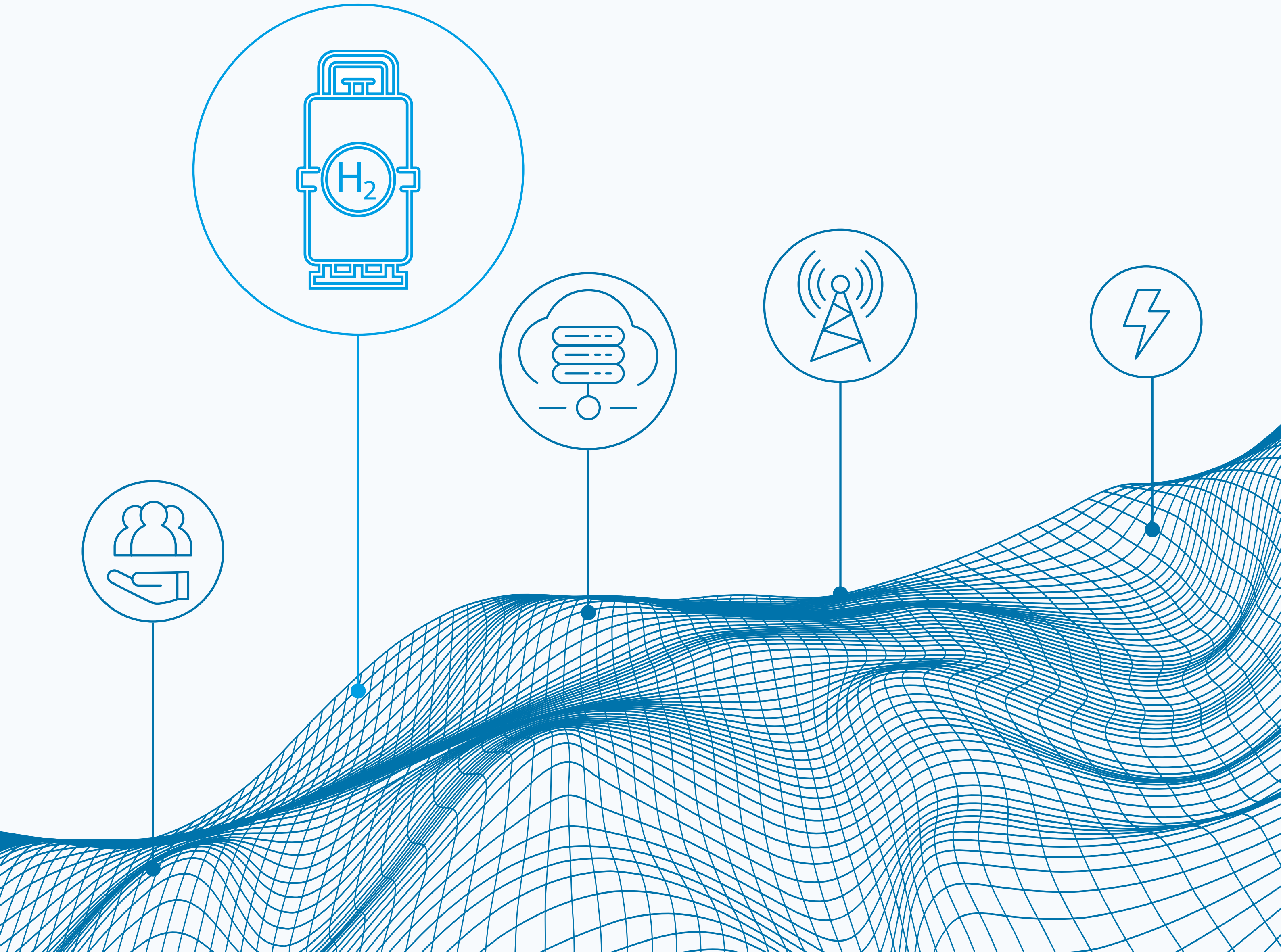
IRENA
International Renewable Energy Agency

RENEWABLE POWER-TO-HYDROGEN

INNOVATION LANDSCAPE BRIEF



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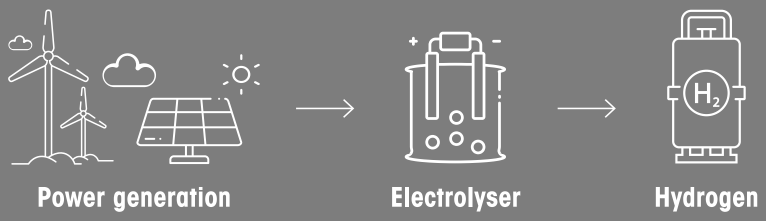
1 BENEFITS

Converting variable renewable energy (VRE) sources to hydrogen via electrolysis can contribute to power sector transformation in several ways:



- Reducing VRE curtailment
- Long-term energy storage
- Providing grid-balancing services via the electrolyser
- Using clean H_2 as fuel in other sectors
- Transporting renewable power over long distances as H_2

2 KEY ENABLING FACTORS

- Reducing production costs
- Improving revenue-stream opportunities
- Developing hydrogen infrastructure
- Implementing supportive hydrogen policies
- Developing safety-related regulations

3 SNAPSHOT

- ➜ 4% of global hydrogen supply is produced via electrolysis (with the rest being fossil fuel-based)
- ➜ $P2H_2$ projects are located in Australia, Austria, Canada, Chile, Denmark, France, Germany, Japan and the United Kingdom
- ➜ In 2017, Enel built a micro grid in Chile with a 450 kWh $P2H_2$ storage system
- ➜ The European Marine Energy Centre installed $P2H_2$ storage for excess tidal and wave energy in Scotland (UK)

WHAT IS POWER-TO-HYDROGEN ?

Hydrogen can be produced by electrolysis, a process that uses electricity to **split water** into hydrogen and oxygen. When **renewable power** is used for this process, hydrogen becomes a **complementary carrier** of renewable energy.

RENEWABLE POWER-TO-HYDROGEN

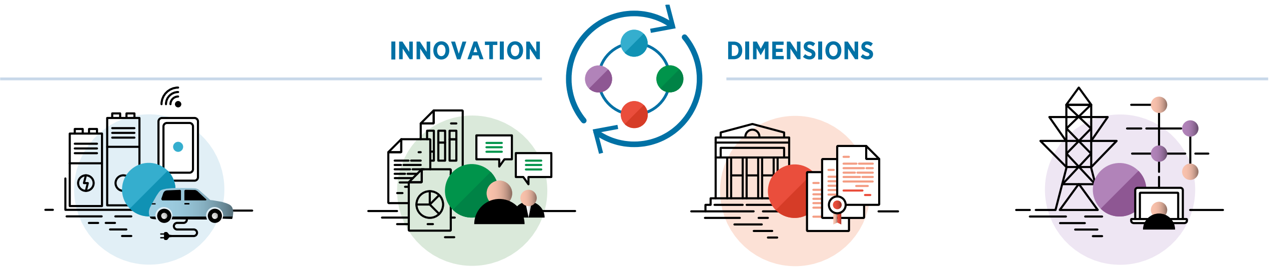
Hydrogen produced with excess solar PV and wind power can be **stored for later use** – as a fuel for transport, industry and other sectors. Hydrogen production can be used as a 'smart' load to **increase power system flexibility** and help to decarbonise the overall economy.

ABOUT THIS BRIEF

This brief is part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019), illustrates the need for synergies among different innovations to create actual solutions. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.



● ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

● BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

● MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

● SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

This brief provides an overview of the concept of power-to-hydrogen ($P2H_2$) and its role in increasing the share of renewable energy in the power sector. $P2H_2$ can provide grid balancing services and long-term storage to manage the variation in power supply from wind and solar photovoltaic (PV) technologies. $P2H_2$ can also enable the use of clean hydrogen, produced from renewable energy sources, as feedstock in industrial processes and thereby help decarbonise other sectors. This brief focuses on the production of hydrogen as a provider of grid balancing services, as well as its use as a carrier and storage medium.

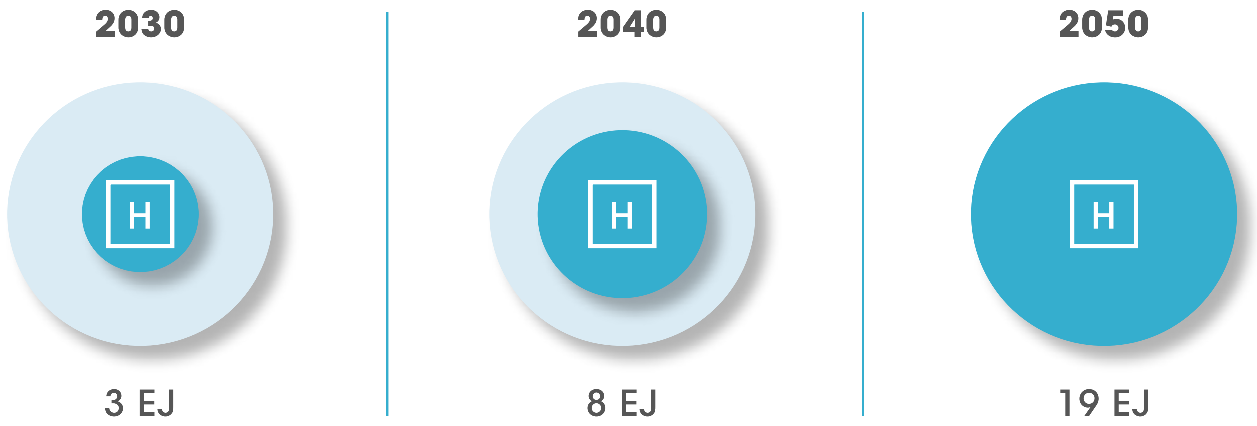
For a more in-depth study of hydrogen technology status and development, and its applications in end-use sectors, please refer to the IRENA Technology Outlook: "Hydrogen from renewable power" (IRENA, 2018a).

The brief is structured as follows:

I. DESCRIPTION

The hydrogen industry is well-established and has decades of experience in industrial sectors that use hydrogen as a feedstock. Hydrogen can be produced via several processes, such as steam methane reforming (SMR), coal gasification, renewable liquid reforming (using ethanol) and electrolysis. This brief focuses on hydrogen produced from renewable electricity through electrolysis, i.e. renewable power-to-hydrogen, an approach regaining attention especially in power systems with high shares of VRE. IRENA analysis indicates that hydrogen production with renewable electricity should reach 19 EJ in 2050, in order to achieve the global energy transformation and decarbonisation targets (IRENA, 2019b).

Figure 1: Growth in hydrogen production with renewable electricity in Paris Agreement-aligned scenario



Source: IRENA, 2019b

Table 1 Brief description of electrolysers

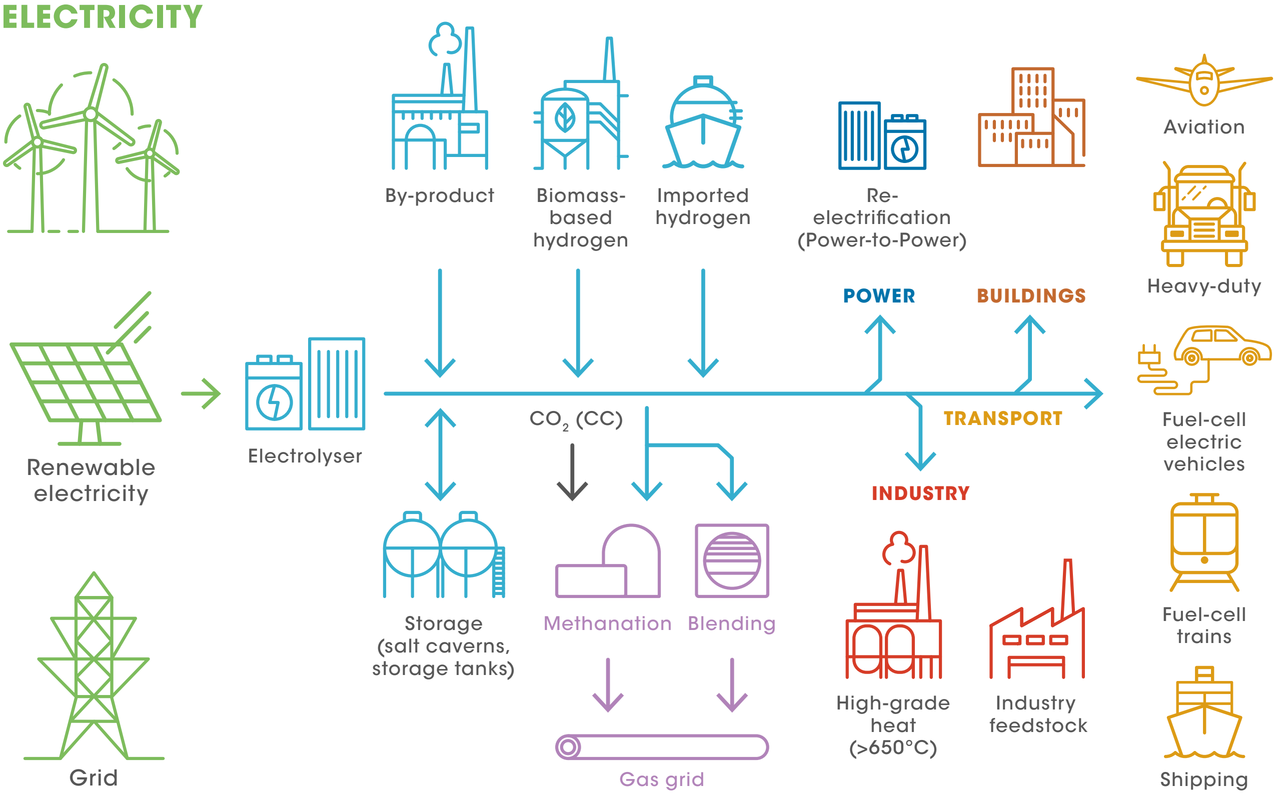
	Type of electrolyser		
	Alkaline	**PEM**	**SOE**
Development status	Commercial	Commercial, small- and medium-scale applications (< 300 kW)	Undergoing research
Brief description	• Transport of hydroxide ion through electrolyte • Hydrogen generated at cathode • A liquid alkaline solution of sodium or potassium hydroxide used as electrolyte	• Water reacts at the anode to form oxygen and hydrogen ions (protons) • Electrons flow through an external circuit and hydrogen ions selectively move across the PEM to the cathode • Electrolyte is a solid speciality plastic material	• Water at the cathode combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions • The oxygen ions pass through the solid ceramic membrane and react at the anode to form oxygen gas and generate electrons for the external circuit • A solid ceramic material used as the electrolyte
Operating temperature	100–150 °C	70–90 °C	700–800 °C

Sources: Bertuccioli et al., 2014; Office of Energy Efficiency & Renewable Energy, 2018.

An electrolyser is a device that splits water into hydrogen and oxygen using electricity. When electricity produced from renewable energy sources is used in this process, the hydrogen becomes a carrier of renewable energy, complementary to electricity. As described in Table 1, there are three main types of electrolyser: an alkaline electrolyser; a proton exchange membrane (PEM) electrolyser; and a solid oxide electrolyser (SOE).

Hydrogen produced during the process of electrolysis can be used as a medium for energy storage and for applications such as producing heat for buildings, refuelling fuel cell vehicles and as a source of feedstock for industry (Figure 2). An important distinction between hydrogen and other forms of energy storage is that hydrogen can be stored and transported through the existing natural gas network. Little investment is needed to adapt natural gas infrastructure to transport hydrogen. Blending hydrogen with other gases means that pure hydrogen is no longer available for direct use in different applications, *e.g.* fuel cell vehicles. Extracting pure hydrogen from blended gas is possible, but it is expensive and complicated, so there is an economic trade-off to be made between the various hydrogen applications.

Figure 2: Concept of $P2H_2$ and the end-use applications of hydrogen



Source: IRENA, 2018a

As Figure 2 illustrates, hydrogen contributes to “sector coupling” – on the one hand between the power system and on the other between the industrial, buildings and transport sectors. Sector coupling creates extra loads that represent new markets for hydrogen produced from VRE sources, furthering the integration of high shares of VRE in the power system.

Well-defined safety standards, appropriate ventilation and leak detection are required to ensure safe operations with hydrogen. It is a highly flammable gas[1] and can burn at a wide range of concentrations. These standards already exist for various industrial applications, but they may need to be streamlined considering emerging new applications of hydrogen, for example as a fuel for cars.

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[1] The US National Fire Protection Association gives hydrogen a 4, the highest flammability rating, denoting materials “that completely vaporise at normal pressure and temperature and burn readily”.

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

Producing hydrogen from renewable power, especially when there is excess renewable electricity generation in the system, helps avoid curtailment and thereby improves the return on investment for VRE asset owners.

Electrolysis can also enhance the reliability of power supply by providing flexibility services when needed. With increasing penetration of VRE resources such as solar PV and wind, large-scale storage solutions and grid stability management are becoming critical issues in system operation.

Electrolysers can help integrate VRE into power systems, as their electricity consumption can be adjusted to follow wind and solar PV power generation, where hydrogen becomes a medium of storage for renewable electricity.

Thus, electrolysers offer a flexible load and can also provide grid balancing services (upwards and downwards frequency regulation). The hydrogen produced can be further used in the industrial and transport sectors and as a fuel, or it can be stored and then converted back into electricity. Moreover, stored hydrogen may enable the efficient distribution of energy across regions, facilitating VRE consumption in areas where VRE generation is difficult or direct electrification of an end-use energy application.

Reducing curtailment of excess VRE generation

At times that renewable energy cannot be fed into the power grid due to network constraints or low demand, it could be supplied to electrolysers for production of hydrogen via electrolysis. Procuring excess renewable energy (that is likely to be curtailed or sold at near zero marginal prices) can significantly help improve the economics of hydrogen production. Offtake of excess renewable energy also enables VRE asset owners to gain incremental revenues and reduces their exposure to volatility in power prices.

This option, however, requires great availability of renewable power (especially at relatively low cost) to ensure a good load factor at the electrolysis facility. Low load factors yield a high levelized cost of hydrogen (LCOH), as the CAPEX of the electrolyser, a key component of the hydrogen cost, needs to be allocated to low production volumes (IRENA, 2018a). Figure 3 showcases different LCOH at current technology cost levels and in 2025 for an Alkaline electrolyser connected to the Danish grid.

In Spain, for example, demonstration projects are using hydrogen for the municipal bus fleet on islands, which is cost-efficient thanks to cheap electricity from solar PV combined with grants for the buses, translating into breakeven costs with the conventional buses (today already). In Sweden, hydrogen is used to decarbonise the steel industry with the goal of decarbonising the industry by 2035. By 2030, it is estimated that the share of VRE curtailment will be around 10–30% in Sweden, which provides more incentives for renewable hydrogen[2].

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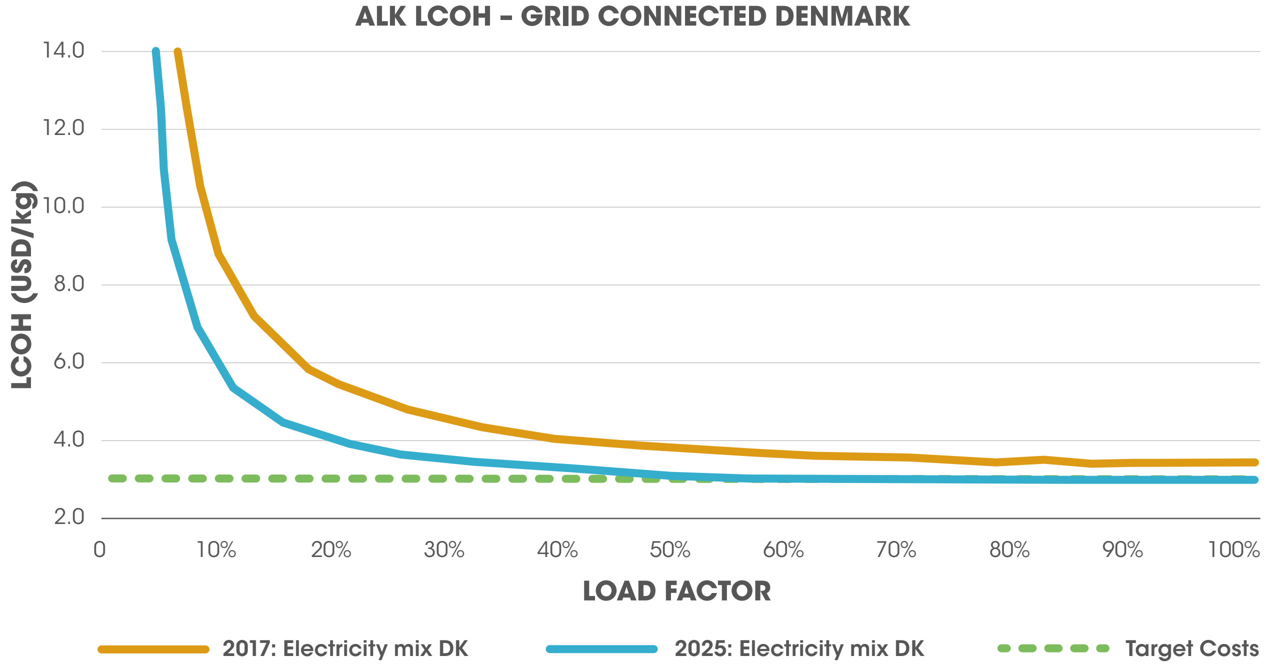
[2] Based on discussions during the IRENA Online workshop: Identifying challenges for achieving 100% renewable power systems by mid-century, June 2019.

Figure 3: Levelised cost of hydrogen (LCOH) produced via alkaline electrolyser in Denmark



Source: IRENA, 2018a

Providing long-term energy storage

While intraday imbalances caused by VRE generation might be better managed with batteries in economic terms, seasonal variations need long-term storage solutions such as $P2H_2$ (Eichman and Flores-Espino, 2016). Hydrogen can serve as a long-term storage medium, with the capability of storing energy for several months. Table 2 below provides a comparison of various energy storage technologies and their storage capability.

Long-term storage options can help countries with significant seasonal differences between power demand and renewable power generation to integrate more renewable power into the grid. For example, Germany's energy demand is 30% higher in winter than in summer. However, renewable energy sources generate around 50% less power in winter than in summer (Hydrogen Council, 2017a). $P2H_2$ can therefore potentially assist in shifting the supply of renewable energy from seasons with low demand to seasons with high demand.

Currently, storing power in the form of hydrogen is not financially viable[3]. Given that a main advantage of VRE-based hydrogen is that it reduces carbon dioxide (CO_2) emissions, policy measures that account for the cost of CO_2 emissions would improve the economic case for hydrogen storage and its subsequent use for power generation. The economics are expected to improve due to technological development. For example, the Hydrogen Council expects the cost of power storage in the form of hydrogen to fall to EUR 140 per megawatt hour (MWh) by 2030[4], which is lower than the projected cost for pumped hydro storage (about EUR 400 per MWh) (Hydrogen Council, 2017a).

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[3] Currently, the cost of emissions is generally not included while analysing the financial viability of any project. One of the methods to improve the technology's financial viability is to price in the emissions, while encouraging hydrogen storage for power generation and discouraging conventional power generation.

[4] The cost quoted is for power-to-hydrogen-to-power.

Table 2 Comparison of various energy storage technologies and their storage capability

Storage technology	Efficiency (%)	Typical storage capacity	Typical discharge time	Maturity of technology
Hydrogen energy storage	**30–45%**	**< 1 GW**	**< 1 h–1 000+h**	**Under RD&D**
Batteries	70–85%	< 100 MW	< 5 h	Under R&D in some regions and commercialised in United States, United Kingdom and Australia
Compressed air energy storage (CAES)	45–70%	< 10 MW	5–100 h	RD&D
Flywheels	85–100%	< 1 MW	< 30 min	R&D
Pumped hydro storage (PHS)	70–85%	0.1–1 GW	10–500 h	Commercialised

Note: GW = gigawatt; h = hour; min = minute; MW = megawatt; R&D = research and demonstration; RD&D = research, development and demonstration.
Source: Adapted from California Hydrogen Council, 2015; NREL, 2014; IEA, 2014

Providing grid balancing services

Frequent fluctuations in power generation from variable sources call for rapid-response balancing options. The electrolyser systems used to produce hydrogen can be cycled up and down rapidly as a flexible load, providing grid services such as frequency regulation. The performance of alkaline and PEM electrolyser technologies differs when used to provide specific grid services. In general, alkaline electrolysers offer less flexibility as compared to PEM electrolysers, as shown in Table 3 below. Alkaline electrolysers are unlikely to offer grid services with an activation time of less than 30 seconds (Tractebel, ENGIE and Hinicio, 2017).

Table 3 Flexibility capability of electrolysers

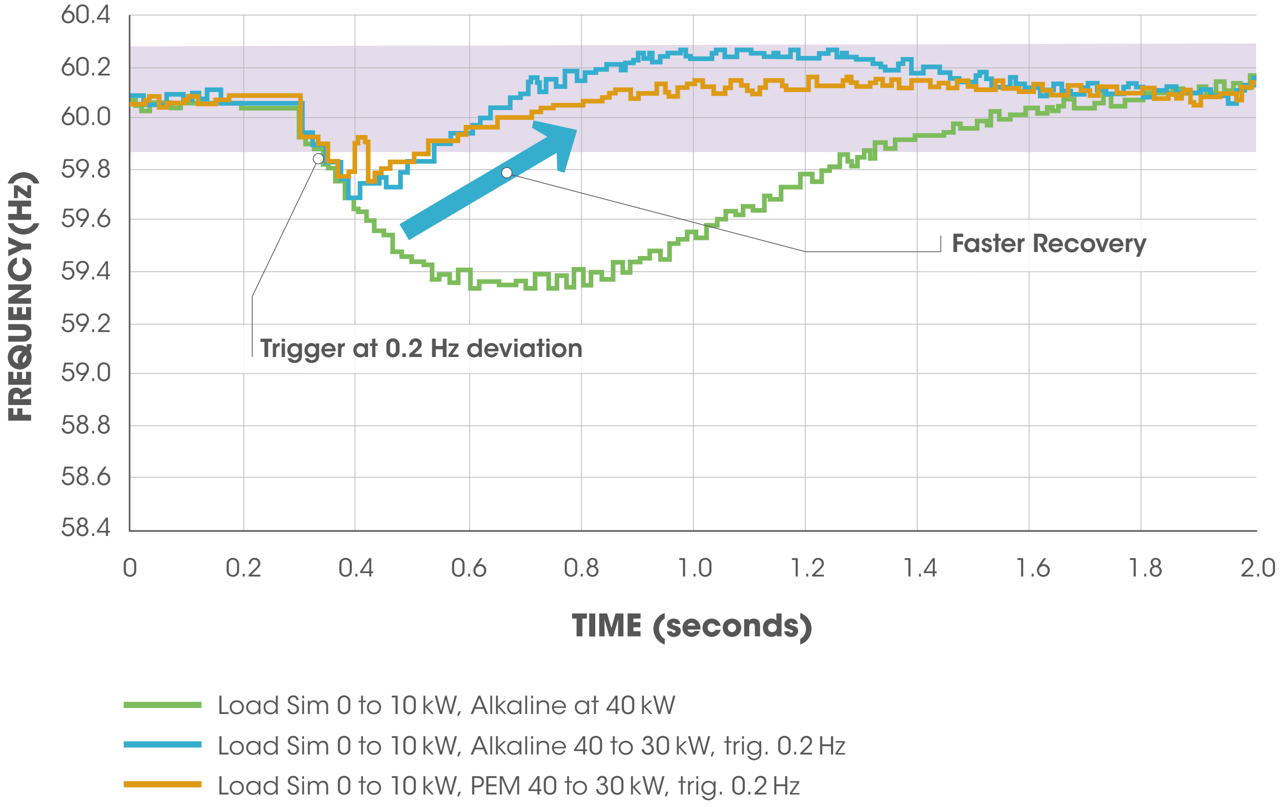
	Alkaline electrolyser	PEM electrolyser
Load range	15–100% of nominal load	0–160% of nominal load
Start-up	1–10 minutes	1 second–5 minutes
Ramp-up	0.2–20% per second	100% per second
Ramp-down	0.2–20% per second	100% per second
Shutdown	1–10 minutes	Seconds

Note: The ramp-up and ramp-down figures are percentage of nominal load.

Experimental analysis done by the US National Renewable Energy Laboratory (NREL) demonstrates the use of electrolyser technology for utility-scale grid stabilisation services. The experiment shows that electrolysers can rapidly change their load point in response to grid needs and at the same time accelerate recovery in case of frequency deviation (Gardiner, 2014). Figure 4 shows the result of the experiment conducted to maintain the frequency of the system at 60 Hz.

A load simulator was used to generate harmonics on the grid (green line on Figure 4), which reduces the frequency below the lower limit of 59.8 Hz. A control signal is generated when the frequency reaches a defined point, and that signal is transmitted to the electrolysers to reduce power consumption. The red and blue lines in the graph show the response of the electrolysers (by reducing their power consumption) once the frequency deviates by 0.2 Hz. The time taken for such response was less than a second.

Figure 4: Use of electrolyser for fast frequency response



Note: Hz = hertz.
Source: Gardiner, 2014

Supporting sector coupling strategies by increasing the use of renewable power in other sectors

Hydrogen can be used to couple renewable electricity with other energy use sectors as depicted in Figure 2. Some of the applications of hydrogen are listed below.

- **As feedstock:** Hydrogen can be used as feedstock in the chemical industry. It is a key input to the production of ammonia, synthetic fuels and various types of fertiliser. It can also be used in the methanation process to produce methane from CO_2. Hydrogen is also used to produce synthetic liquid fuels from biomass, which increases the efficiency of biomass utilisation significantly. Hydrogen can also be used to replace fossil fuels and act as a reducing agent in heavy industries such as steel. In Sweden, for instance, the HYBRIT project aims to replace coking coal with hydrogen in the ore-based steelmaking process.[5]

- **As fuel:** Hydrogen can be directly used as a fuel in the transport sector or to provide power using fuel cells. For example, Europe hosts 95 hydrogen stations where a fuel cell can be refuelled in three minutes for a range of 500–800 kilometres (H_2 live, 2019). Another way to use hydrogen as a fuel is to blend it with natural gas in the existing natural gas pipelines. Standards suggest blending up to 10% hydrogen (by volume),[6] with a potential to increase it to 20% (Hydrogen Strategy Group, 2018) (NREL, 2015) (IRENA, 2018a). However, the appropriate blend may vary significantly between pipeline network systems and natural gas compositions and must therefore be assessed on a case-by-case basis (NREL, 2013; ARENA, 2018). The current limit on hydrogen in gas turbines and engines is 1–2%, which can be increased to 10–15% with minor retrofitting (Maroufmashat and Fowler, 2017).

Enabling distribution of renewable power across regions and globally

Transporting energy in the form of hydrogen can allow renewable energy to be supplied to regions with scarce renewable energy resources (Hydrogen Council, 2017a).

Hydrogen can be transported using a gas pipeline network or vessels. Transporting renewable power in the form of hydrogen over long distances could be an economically attractive option in the long term, especially in those cases where the electricity grid has insufficient capacity or where building new infrastructure would be too impractical or expensive. This might be the case for offshore wind generation, where hydrogen could be produced offshore and then transported to the shore via natural gas pipelines, either converting existing offshore pipelines or using newly installed pipelines where the costs are lower than laying submarine cables.

Also, regions with abundant and cheap renewable energy sources but not enough demand could produce hydrogen to be transported to regions with limited renewable generation but high demand. Transport of renewable energy via hydrogen could be developed at different scales, from local to international. The latter option is being investigated in several countries that either have abundant renewable energy potential (*e.g.* Australia) or limited indigenous renewable energy potential, such as Japan (IRENA, 2018a). Several pilots are being conducted to find out the most cost-effective or economical way to transport hydrogen over long distances. One example is the Hydrogen Energy Supply Chain (HESC) pilot project being undertaken in Japan (Hydrogen Strategy Group, 2018).

Also, harnessing the high potential of solar energy in equatorial countries, storing it in the form of hydrogen, and transporting it to regions with high energy demand, such as Europe,[7] might be economical (Hydrogen Council, 2017a).

Micro-grids and fuel cell applications

Due to their modularity, fuel cells typically are employed in decentralised applications, offering electricity grid support and black start capability for micro-grids (Steinberger-Wilckens et al., 2017; Gardiner, 2014). In Japan, residential fuel cell systems are deployed to provide consumer grid independence. The government of Japan aims to install 1.4 million residential co-generation fuel cell systems by 2020, and 5.3 million by 2030. Currently, more than 220 000 residential fuel cells systems are installed in Japan (Bloomberg New Energy Finance, 2017; FCHEA, 2019).

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[5] The HYBRIT project is a joint venture of SSAB, LKAB and Vattenfall established in 2016. The project aims to drastically change the steelmaking process with a goal to provide fossil-free steel by 2035.

[6] For most infrastructure components (IRENA, 2018a).

[7] Analysis by the Hydrogen Council assumes that renewable energy is harnessed at the highest potential of solar energy in equatorial countries and transported to regions with high energy demand in the form of hydrogen. The report also assumes that the cost of solar power in the Netherlands is double the production cost of solar in the sunbelt regions.

III. KEY FACTORS TO ENABLE DEPLOYMENT

Reducing production costs and improving revenue-stream opportunities

Electrolysers have been long used in several industries. They are regarded as a "mature" technology for industrial applications. However, their potential in energy applications is still evolving (FCH JU, 2014). $P2H_2$ requires performance improvement and cost reduction, accompanied by unlocking and monetising the value streams from the use of the electrolysers and the hydrogen.

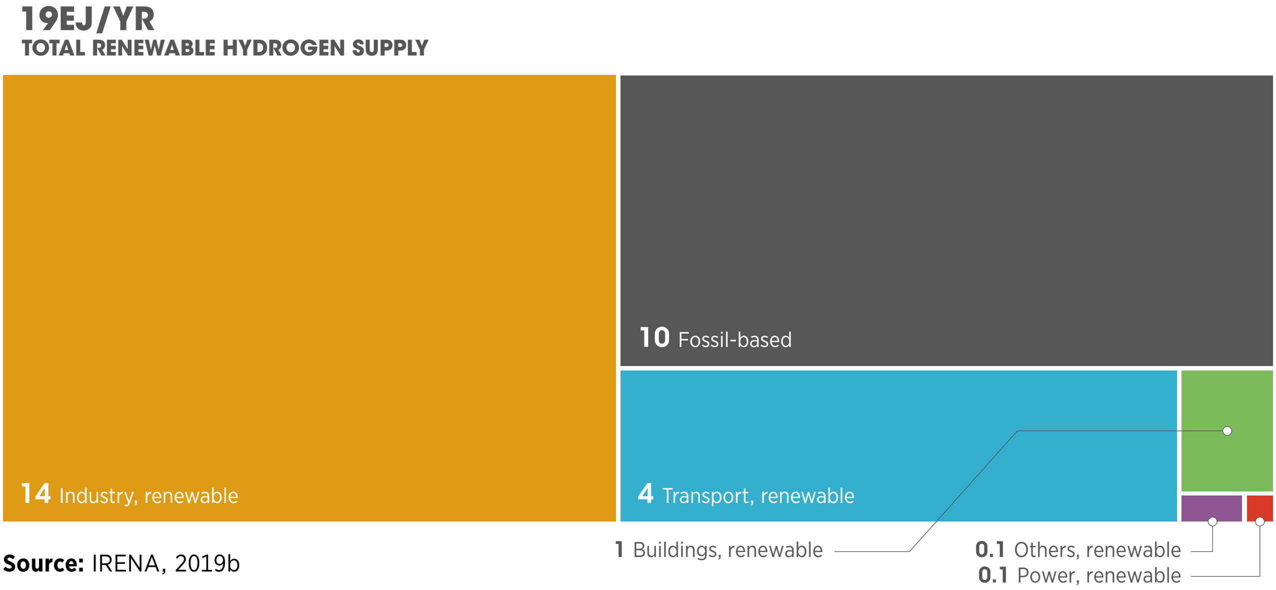
A market for hydrogen needs to be established for $P2H_2$ to be deployed successfully. As discussed, hydrogen can be used across many different sectors: transport, power sector, industrial feedstock, and producing heat for residential as well as industrial purposes.

IRENA analysis shows that by 2050 hydrogen has the potential to supply nearly 29 EJ of global energy demand, two-thirds of which would come from renewable sources (Figure 5).

In the industrial sector, 14 EJ of renewable hydrogen would be consumed in 2050, largely in the iron and steel subsectors, and also for ammonia production.

In the transport sector, hydrogen can be used in fuel cell electric vehicles (FCEVs), mostly for heavier freight transport but also for some passenger transport. The transport sector would be the second largest user of renewable hydrogen (after the industry sector) at around 4 EJ per year by 2050.

Figure 5: Hydrogen supply in 2050 by source of production (EJ/yr)



Source: IRENA, 2019b

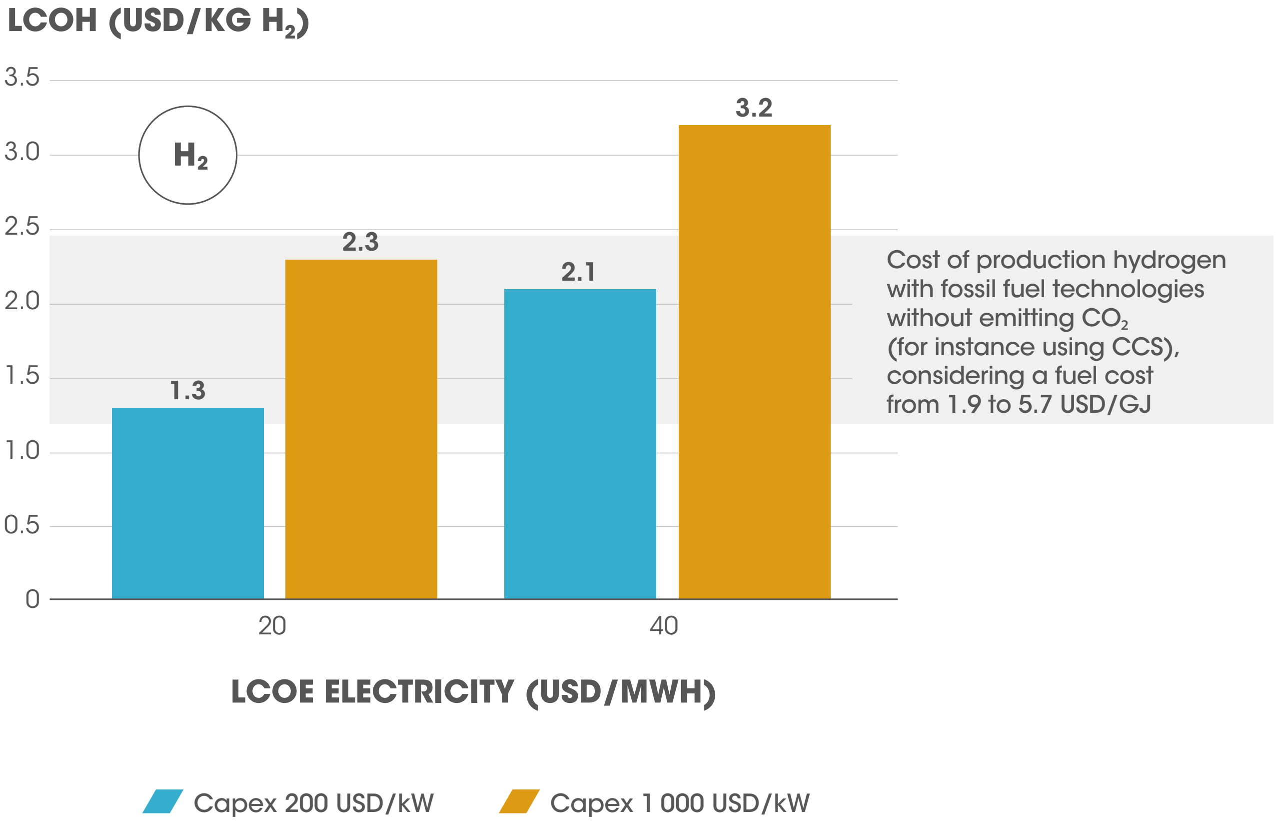
In the buildings sector, hydrogen can be blended with natural gas or combined to produce synthetic methane and injected in gas grids. The gas grid in this scenario would function as an existing large-scale storage asset, accommodating and distributing low cost renewable electricity (IRENA, 2019b).

Upfront capital costs can be substantial in setting up hydrogen infrastructure such as electrolysers, transport infrastructure and storage. These costs, coupled with high tariffs for electricity (procured from utilities, VRE generators or the wholesale market), make hydrogen even more expensive to produce through electrolysis. Technology and infrastructure costs must therefore be continually reduced, while existing regulatory and market frameworks must be adjusted or redesigned to accommodate the potential of $P2H_2$.

The cost of producing hydrogen from electrolysis is currently in the range of EUR 2.4–6.7 per kilogram (kg) depending on geography and various operating parameters, compared to EUR 1.3–3.0 per kg via SMR process (Tractebel, ENGIE and Hinicio, 2017). Electricity costs alone constitute a major part of the total cost of producing hydrogen from electrolysis. Electricity's contribution to the overall cost of hydrogen depends on the cost of electricity itself, the size of the installation, load hours and the location of the electrolyser. While the cost of electricity is on average 30% of the total cost of producing hydrogen, in some cases it may be as high as 60% (Ainscough, Peterson and Miller, 2014). The levelised cost of hydrogen (LCOH) (USD/ KgH_2) is directly proportional to electrolyser load factors. The higher the load factor, the lower would be the share if fixed cost and the higher is the share of electricity cost in the LCOH. Therefore, lower electricity costs enhance the cost effectiveness of electrolytic hydrogen, for example by using excess renewable power that is expected to be curtailed or by placing hydrogen electrolysis plants in locations with very low renewable electricity costs.

IRENA analysis shows that hydrogen produced from electricity can be competitive if the price of electricity falls to below USD 30/MWh or if electrolyser costs decline significantly (IRENA, 2019b).

Figure 6: Levelised cost of hydrogen (USD/kgH_2)produced at different electricity prices (USD/GJ) and electrolyser CAPEX (USD/kW



Note: the analysis considers electrolyser running full load hours per year
Source: IRENA, 2019b

Since electricity is an important cost factor, the trend of rapid reductions in the cost in electricity from wind and solar PV technologies creates an important opportunity for hydrogen production in locations with abundant solar and wind resources. Policies related to managing curtailment, remunerating seasonal balancing capacity and taxation should be reassessed.

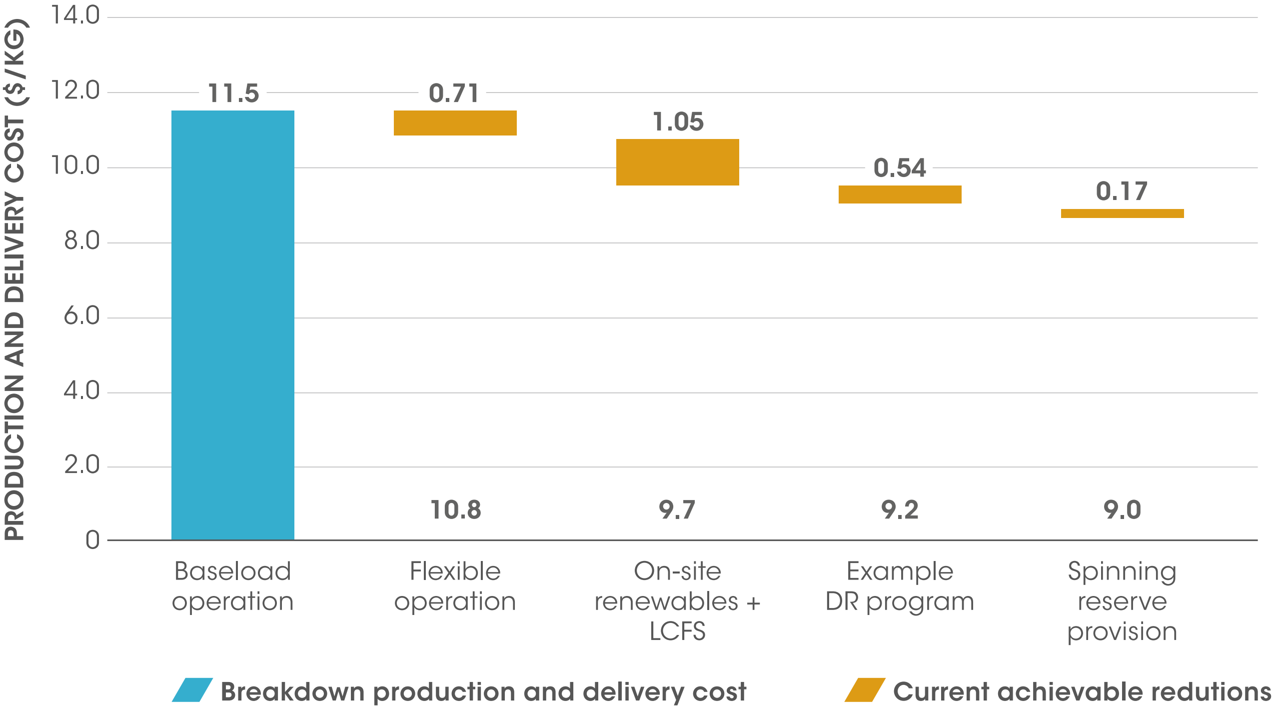
Policy makers should aim to provide a platform to monetise the flexibility offered by electrolysers, while also allowing revenue stacking from all services provided by the electrolyser. This may lead to greater economic viability for electrolysers. For instance, a study done for California shows that a potential cost reduction of 21% could be achieved for the production and delivery of electrolysed hydrogen if electrolysers were allowed to provide ancillary services to power systems, in addition to their participation in electricity markets (Figure 7) (Eichman and Flores-Espino, 2016).

Develop a hydrogen infrastructure

For P2H_2 to contribute to power sector transformation, hydrogen-related infrastructure needs to be developed in such a way as to promote the creation of a hydrogen ecosystem. This would enable the sustained development of all the necessary stages: production, transmission, storage and consumption.

One of the key challenges in the adoption of hydrogen fuel is the lack of cost-efficient storage options. Hydrogen storage is very expensive on a small scale and is currently unavailable for large-scale use. Moreover, the transport of hydrogen by means other than road or pipeline is still in the early phases of development. New ship designs may be required to carry liquefied hydrogen on sea routes – for example, new designs are being built as part of the HESC pilot project in Victoria (Hydrogen Strategy Group, 2018). Some companies are in the process of developing alternative means of hydrogen transport by conveying it in a liquid carrier, such as Hydrosil by HysiLabs, or developing a cartridge-based storage solution for hydrogen, such as STOR-H by Aaqius. Investment in research and development to create mature storage solutions may enable the rapid adoption of hydrogen for a variety of purposes.

Figure 7: Summary of cost impact on electrolytic hydrogen production in California



Note: DR = demand response; LCFS = Low Carbon Fuel Standard.
Source: Eichman and Flores-Espino, 2016

Pursue supportive policies for renewable hydrogen usage

Deployment of hydrogen infrastructure needs a co-ordinated approach between various stakeholders. Furthermore, many of the investments in hydrogen infrastructure rely on a relatively long time commitment of 10–20 years for financial viability. Hence, a strategic road map is required to mitigate the risks and realise the benefits of hydrogen deployment. Governments could consider adopting national/regional action plans for the sector, with clear goals to stimulate the deployment of a renewable hydrogen infrastructure.

To achieve rapid scale-up, a stable and supportive policy framework is needed to encourage the appropriate private investments. This is the case across the entire supply chain (equipment, manufactures, infrastructure operator, vehicle manufacturers etc). In the transport sector, a holistic approach is needed to drive the sector towards a hydrogen-fuelled zero-emissions scenario, taking into account all stakeholders: customers, car manufacturers, hydrogen producers and transporters (supply trucks and ships), equipment suppliers (*e.g.* electrolysers, liquefiers, storage tank manufacturers) and infrastructure developers. Figure 8 summarises the key challenges facing the hydrogen industry at every step of the value chain, and proposes a set of policy measures to overcome them (IRENA, 2018a).

Several countries are already developing road maps to convert renewable energy to hydrogen and use it in various applications. Chile, Australia, Uruguay and Argentina[8] aim to convert their surplus renewable energy into hydrogen, and Japan aims to develop supply chains to import hydrogen from these countries and use it for various applications such as transport, industrial processes and power generation (IRENA, 2018a; Hydrogen Strategy Group, 2018; METI, 2017). In 2016 Noordelijke Innovation Board released a document entitled “The green hydrogen economy in the Northern Netherlands”, with a high-level road map for a hydrogen economy detailing hydrogen production projects, markets and various issues related to infrastructure and society (NIB, 2016).

More pilot studies would be useful to better understand different technical and operational challenges of $P2H_2$. Pilots[9] or demonstration projects should ideally focus on improving the conversion efficiency of power to hydrogen and vice versa. Currently the conversion efficiency of $P2H_2$ systems is in the range of 50–70% (Energy Storage Association, 2018; IRENA, 2018a). Improving system efficiency will help reduce the cost of hydrogen produced through electrolysis.

Develop and enforce regulations related to safety

Hydrogen is a highly flammable gas. The US federal government has already specified safety regulations for the handling and storage of hydrogen. Some of these regulations should be reassessed to reflect technological advancement in decentralised hydrogen storage, and while there are adequate safety regulations regarding traditional uses of hydrogen, the lack of safety regulation for upcoming uses of hydrogen (such as cartridge-based storage solutions for road vehicles) acts as a barrier to commercialisation.

Pilot studies are needed to understand various issues related to hydrogen handling, especially when existing infrastructure is retrofitted or repurposed for use in hydrogen applications, such as converting natural gas pipelines to transport pure hydrogen, as is being currently considered in the Netherlands, Spain and in the United Kingdom.

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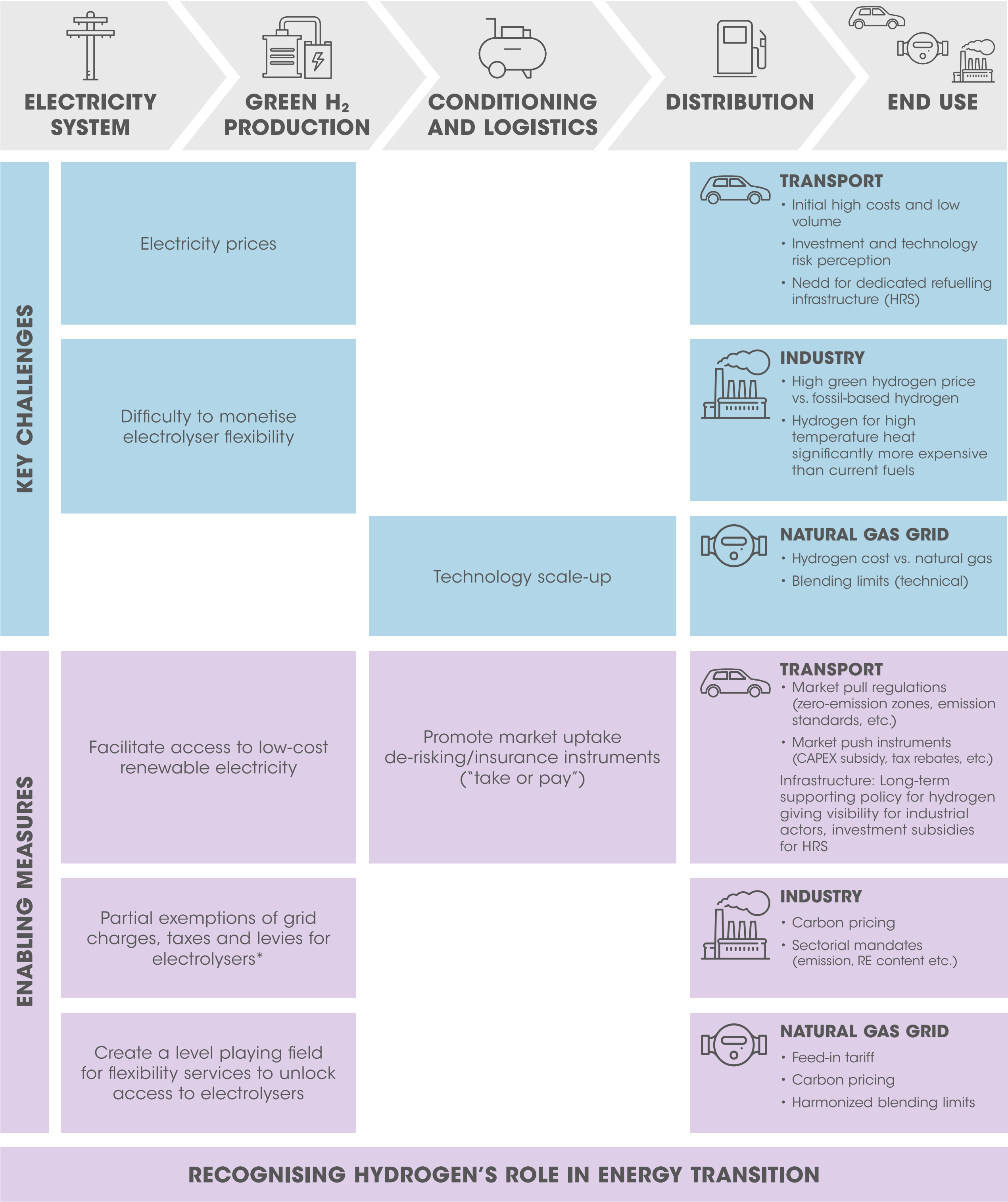
[8] Chile and Australia aim to convert excess solar power into hydrogen, while Uruguay and Argentina aim to convert excess wind power into hydrogen.

[9] For some countries pilots may still be needed, but given the number of pilots and demonstrations that have been done, some jurisdictions are looking at going from the pilot/demonstration stage to commercial-scale projects. The Northern Netherlands is looking to put in 100–1 000 MW of renewable energy sources to generate hydrogen for industry and transport applications while replacing the use of natural gas. Japan is building a port facility to import liquefied hydrogen from Australia derived from brown coal, and from Brunei, for transport and energy uses.

Figure 8: Key challenges and overview of possible enabling measures for power-to-hydrogen



ELECTRICITY SYSTEM | **GREEN H_2 PRODUCTION** | **CONDITIONING AND LOGISTICS** | **DISTRIBUTION** | **END USE**

KEY CHALLENGES

Electricity prices

Difficulty to monetise electrolyser flexibility

Technology scale-up

TRANSPORT
- Initial high costs and low volume
- Investment and technology risk perception
- Nedd for dedicated refuelling infrastructure (HRS)

INDUSTRY
- High green hydrogen price vs. fossil-based hydrogen
- Hydrogen for high temperature heat significantly more expensive than current fuels

NATURAL GAS GRID
- Hydrogen cost vs. natural gas
- Blending limits (technical)

ENABLING MEASURES

Facilitate access to low-cost renewable electricity

Partial exemptions of grid charges, taxes and levies for electrolysers*

Create a level playing field for flexibility services to unlock access to electrolysers

Promote market uptake de-risking/insurance instruments (“take or pay”)

TRANSPORT
- Market pull regulations (zero-emission zones, emission standards, etc.)
- Market push instruments (CAPEX subsidy, tax rebates, etc.)

Infrastructure: Long-term supporting policy for hydrogen giving visibility for industrial actors, investment subsidies for HRS

INDUSTRY
- Carbon pricing
- Sectorial mandates (emission, RE content etc.)

NATURAL GAS GRID
- Feed-in tariff
- Carbon pricing
- Harmonized blending limits

RECOGNISING HYDROGEN’S ROLE IN ENERGY TRANSITION

*Provided that they run in system beneficial mode

Source: IRENA, 2018a.

IV. CURRENT STATUS AND EXAMPLES OF ONGOING INITIATIVES

Key facts about the developments in power to hydrogen are presented in Table 4, followed by some pilot projects.

Table 4 Key facts about power-to-hydrogen

Description	Key facts
Share of hydrogen produced by electrolysis	4% of the global hydrogen supply is produced via electrolysis (the rest is fossil fuel-based)[1]
Cost of hydrogen production from electrolysis	• Cost of hydrogen production from electrolysis, through PEM, in 2017: EUR 6.7/kg of H_2; potential to drop to EUR 4.1/kg in 2025[2] (PEM technology is better-suited to provide flexibility) • PEM CAPEX cost is expected to decrease from EUR 1 200/kW (2017) to EUR 700/kW (2025)[1] • Alkaline CAPEX cost is expected to decrease from EUR 750/kW (2017) to EUR 480/kW (2025)[1]
Cost of hydrogen infrastructure (including production, logistics for distribution)	USD 8–10/kg (current estimates) USD 2–4/kg (expected in near future)[1]
Key countries with $P2H_2$ applications	$P2H_2$ projects are located in (inter alia) Australia, Austria, Canada, Chile, Denmark, France, Germany, Japan, United Kingdom and United States
Countries with goals for introducing hydrogen in transport sector	China, France, Germany, Netherlands, Japan, Korea, United Kingdom and United States[4]
Hydrogen demand expected in future by sector	**World:** Total demand for hydrogen to increase from almost 8 EJ today[1] to 29 EJ in 2050[5]. **Europe:** 2.8 GW of electrolyser capacity expected by 2025[2] **Japan:** 300 000 tonnes per year (target by 2030)[6]

Note: CAPEX = capital expenditure.
Source: [1] IRENA, 2018a, [2] Tractebel, ENGIE and Hinicio, 2017; (note that prices are for the European market only); [3] CORFO, 2018; [4] based on IPHE presentation at IRENA Innovation Day, Uruguay, June 2019; [5] IRENA, 2019; [6] METI, 2017.

Examples of projects using hydrogen to reduce VRE curtailment

GRHYD demonstration project, France

A consortium led by ENGIE is demonstrating a hydrogen energy storage project in France, named GRHYD. As France aims to meet 23% of its gross end-user energy consumption from renewable sources by 2020, the GRHYD project plans to convert surplus energy generated from renewable energy sources into hydrogen. The hydrogen is blended with natural gas to create a product called Hythane(1), and then used within the existing infrastructure. The project aims to demonstrate the technical, economic, environmental and social advantages of mixing hydrogen with natural gas as a sustainable energy solution. Hythane(1) is being injected into the natural gas distribution network of Le Petit Village and is also fed to a natural gas vehicle refuelling station in Dunkirk (ENGIE, 2018).

HyBalance (FCH JU) project, Denmark

The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) is supporting research, technological development and demonstration activities in fuel cell and hydrogen energy technologies in Europe, with the aim of accelerating their commercialisation. The HyBalance project is one of several under the FCH JU. It aims to demonstrate the use of hydrogen in the energy system in Denmark. Excess wind power is used to produce hydrogen by electrolysis, which helps to balance the grid. The hydrogen is then used in the transport and industrial sector in Hobro, Denmark. The project is expected to help identify potential revenue streams from hydrogen and changes to the regulatory environment needed to improve the financial feasibility of $P2H_2$.

Examples of projects using hydrogen to provide balancing services to the grid

"Plug and Play" micro-grid, Chile

In 2017 Enel started operating a micro-grid in Chile comprising a 125 kW-peak solar PV facility combined with a total of 582 kilowatt hours (kWh) of energy storage capacity, using a lithium-ion battery (132 kWh) and $P2H_2$ systems (450 kWh). This micro-grid system can provide 24 hours of clean energy without any diesel-based power back-up system. The main advantage of this system is that it can work with both on-grid and off-grid systems. It can also be moved geographically to provide power at any location – small community, camps, etc. The project demonstrates that hydrogen can help provide a power back-up option in micro-grids, which are traditionally supported by diesel generators (Enel, 2017; Brasington, 2018).

H2Future (FCH JU) project, Austria

H2Future is an FCH JU project under which a 6 MW electrolyser was installed by Siemens at the Voestalpine Linz steel production site in Austria. The project aims to study the use of electrolysers to provide grid balancing services, such as primary, secondary and tertiary reserve, while also providing hydrogen to the steel plant. Hydrogen is produced using electricity during off-peak hours to take advantage of time-of-use power prices (European Commission, 2018).

REFHYN (FCH JU) project, Germany

REFHYNE is an FCH JU project that has seen a 10 MW electrolyser installed at a large oil refinery in the Rhineland, Germany. It aims to provide hydrogen necessary for refinery operations, produced using electricity instead of natural gas. Producing hydrogen with electricity generated from renewable power sources could help significantly reduce CO_2 emissions from the Shell Rheinland refinery. The electrolyser, at the same time, is expected to balance the internal electricity grid of the refinery and provide primary control reserve service to the German transmission system operators (FCH JU, 2018).

Examples of projects using hydrogen as a renewable energy carrier

Surf ‘N’ Turf Initiative – Orkney, United Kingdom

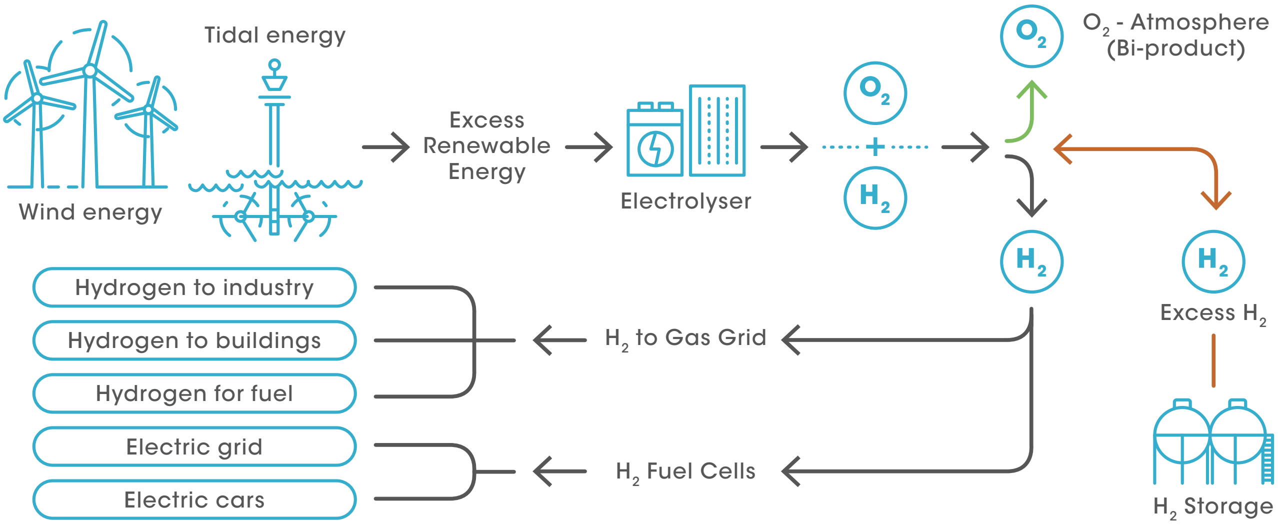
The Surf ‘N’ Turf initiative uses power generated from tidal and wind energy produced on the island of Eday, Orkney. Eday is home to 150 people who collectively own a 900 kW wind turbine. The turbine was vulnerable to curtailment for various reasons. The Surf ‘N’ Turf initiative converts excess wind and tidal energy into hydrogen via a 500 kW electrolyser on the island; the hydrogen is then transported from Eday on ships to Mainland Orkney (Surf ‘N’ Turf Initiative, n.d.). The hydrogen produced can either be used in industries and households during emergencies, or during lean seasons when renewable energy generation is low. Figure 9 shows the schematic structure of the initiative.

Subsequently, a further 1 MW electrolyser was added on the island of Shapinsay. The hydrogen produced is transported to Kirkwall for multiple purposes, which include producing auxiliary power, heat for ferries in Kirkwall harbour, fuelling a fleet of hydrogen range-extended light vehicles, and heating for buildings in the Kirkwall area (BIG HIT, n.d.).

Stone Edge Farm Micro-grid, California, United States

The Stone Edge Farm micro-grid in California was not able to export excess renewable power to the California Independent System Operator (CAISO) market in an economically viable way. One of the challenges in exporting power was to comply with the minimum threshold of 0.5 MW set by CAISO and meeting CAISO’s requirements to install onsite weather forecasting. The micro-grid developer is now using hydrogen to export its power. It has set up a bank of onsite electrolysers, which converts the excess electricity into hydrogen. This hydrogen is then used in fuel cell electric vehicles. When required, the hydrogen is also used to produce power using fuel cells (Forni, 2017).

Figure 9: Illustrative structure of the Surf ‘N’ Turf Initiative



Adapted from: Surf‘n’ Turf Initiative, 2018

Source: Surf ‘N’ Turf Initiative, n.d.

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS

Hardware:

- Electrolyser technology to produce hydrogen from renewable electricity
- Hydrogen fuel cells to convert hydrogen into electricity when required
- Conversion units to use renewable hydrogen and convert into other substitutes such as methane
- Hydrogen transport vessels such as ships and trucks
- Transport infrastructure (*e.g.* existing natural gas infrastructure)
- Storage facilities for hydrogen (in form of high-pressure or liquid hydrogen storage)

POLICIES NEEDED

- Recognise hydrogen's role in energy transition
- Promote use of hydrogen produced via electrolysis from renewable energy sources for the decarbonisation of the economy
- Adopt policies that encourage the use of renewable hydrogen in end-use sectors (for example, implement market pull regulations in transport sector, such as zero emission zones, emission standards etc)
- Allow hydrogen mixed with natural gas to be used in existing natural gas infrastructure by defining a remuneration mechanism to encourage renewable hydrogen injection into gas networks
- Develop appropriate mechanisms to price the emissions of greenhouse gases, which would encourage decarbonisation of the economy

REGULATORY REQUIREMENTS

- Allow use of existing gas networks for transporting renewable hydrogen and set relevant standards, including safety standards (*e.g.* encourage blending of hydrogen with natural gas in appropriate proportions, harmonise blending limits)
- Provide the necessary incentives for hydrogen to offer flexibility services (*e.g.* exemption from taxes, levies and grid fees for electrolysers providing flexibility to the grid)
- Allow electrolysers to participate across the power sector (*e.g.* in some countries, only generators can access frequency containment reserves and frequency restoration reserves)

STAKEHOLDER ROLES AND RESPONSIBILITIES

Public sector:

- Adopt clear policies to decarbonise economies
- Encourage and fund pilot programmes to work as a test bed and for dissemination of results
- Promote innovations in reducing the cost of electrolysis

Private sector:

- Work together with the public sector on innovative projects
- Disseminate information about the contribution of renewable hydrogen to power sector transformation and VRE integration
- Develop new business models for the power sector and VRE integration

ABBREVIATIONS

CAPEX	capital expenditure
CAISO	California Independent System Operator
CO_2	carbon dioxide
EJ	exajoule
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
GW	gigawatt
h	hour
HESC	Hydrogen Energy Supply Chain
Hz	hertz
kg	kilogram
kW	kilowatt
kWh	kilowatt hour
MW	megawatt
PEM	proton exchange membrane
PV	photovoltaic
$P2H_2$	power to hydrogen
R&D	research and demonstration
RD&D	research, development and demonstration
SMR	steam methane reforming
SOE	solid oxide electrolyser
VRE	variable renewable energy

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