

# ENE425 Sustainable Energy and App Development

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## Chapter 7

# Sustainable energy. Hydrogen

In this chapter we study the role that hydrogen will play in the future energy system. The chapter is organized as follows:

1. Watch a video and discuss the **main points** that we will study during the chapter
2. Electrolysis. The chemical process
3. Study the production of hydrogen by analyzing the **types of electrolyzers**, and the main components in a **hydrogen production plant**
4. Study the main **cost challenges** faces by the hydrogen industry
5. Study the interaction between **hydrogen and the rest of renewable energy**
6. Analyze the role of hydrogen increasing **flexibility** in the energy system

### 7.1 Discussion

To motivate the chapter, we start by watching the video What Is Green Hydrogen And Will It Power The Future?

Based on that video, we discuss the next questions:

1. Why are the main **types of hydrogen**?
2. Which is the difference between **green hydrogen** and the other hydrogen types?
3. Which are the **investments** required to boost the adoption of hydrogen? Which **countries** are investing in hydrogen?
4. Which will be the **role of hydrogen** in the future energy system?
  - Transport: cars, trucks, planes, boats.
  - Energy storage: long vs. short term.
  - Industry
  - Heating system
5. Which are the main **challenges** that face the development of hydrogen? Electrolyzers, storage of hydrogen, transport of hydrogen, electricity cost?

Other videos that are very useful to know the technical particularities of the production of hydrogen are:

The Truth about Hydrogen

Energy Storage in Hydrogen : Does this beat batteries?

## 7.2 Motivation

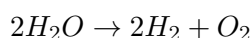
As more countries pursue deep decarbonisation strategies, hydrogen will have a critical role to play. This will be particularly so where direct electrification is challenging and in harder-to-abate sectors, such as steel, chemicals, long-haul transport, shipping and aviation. In this context, hydrogen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

## 7.3 Electrolysis

This section is based on the video: Electrolysis.

The electrolysis is a process where **electricity** is used to make a **chemical change** happen that **wouldn't** happen otherwise.

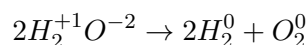
1. **Electrolysis of water** ( $H_2O$ ). The **balance equation** can be written as:



$H_2$  and  $O_2$  are **diatomic elements**: always form groups of two. You will never find just one alone. Other diatomic elements:  $B_2$ ,  $I_2$ ,  $N_2$ ,  $Cl_2$ ,  $H_2$ ,  $O_2$ ,  $F_2$ .

The balance equation represents an **oxidation reduction process**: Electrons are transferred to form new elements.

2. How do the **electrons move** during the reduction process? To understand that process, it is useful to write the **oxidation numbers**:



To satisfy the balance equation:

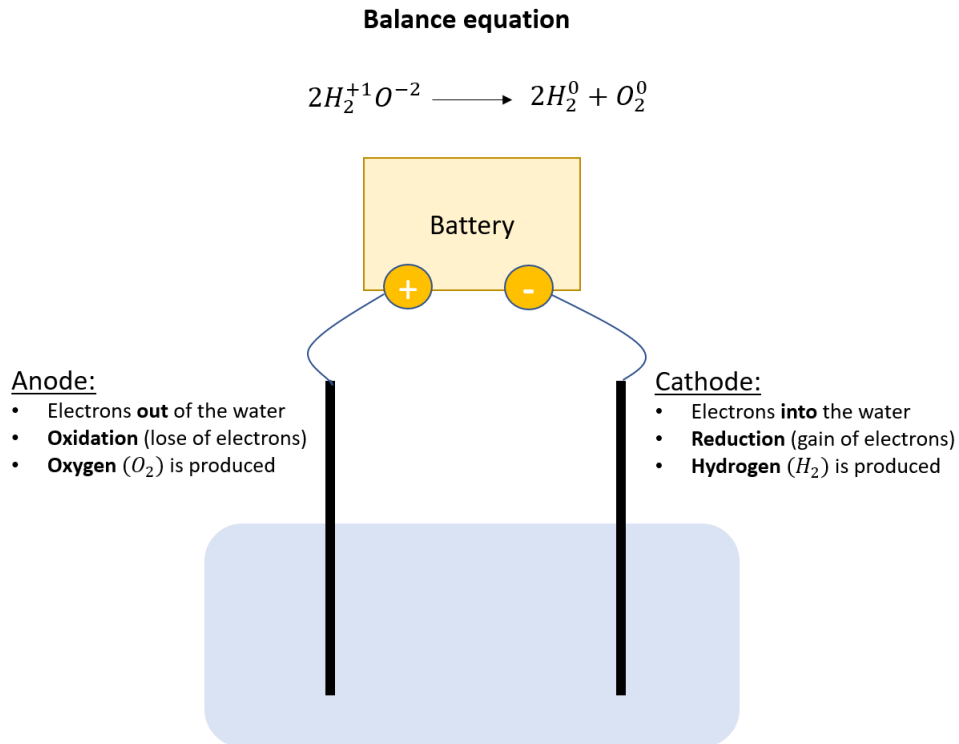
- The **hydrogen** need to be **reduced** (gains electrons).
- The **oxygen** need to be **oxidized** (loses electrons).

3. This process does not happen on its own. An **electrical current** can force this to happen. The **device** used to facilitate that process is called **electrolyser** (figure 7.1).

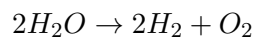
An electrolyser consists on a **battery** and **two electrodes**: A cathode, and an anode:

- a. **Cathode**: Electrons go **into** the water  $\rightarrow$  It will be the place of reduction:  $H_2$  is produced.
- b. **Anode**: Electrons go **out** the water  $\rightarrow$  It will be the place of oxidation:  $O_2$  is produced.

Figure 7.1: Electrolyser



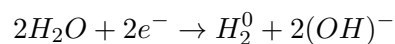
It will produced twice as much hydrogen gas as oxygen gas (balance equation):



4. To fully understand the process, it is necessary to take a look of the **half reactions**:

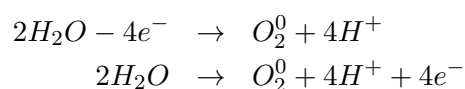
a. **Reduction of hydrogen:**

- In the balance equation, the hydrogen has a positive charge. Therefore, to become neutral, it needs to **gain one electron**.
- In the electrolysis, that electron comes from the **cathode**. Therefore, the **hydrogen** is formed in the cathode.
- In equations:



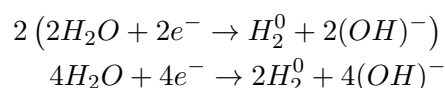
b. **Oxidation of oxygen:**

- In the balance equation, the oxygen has a negative charge. Therefore, to become neutral, it needs to **lose two electrons**.
- In the electrolysis, that electron goes away at the **anode**. Therefore, the **oxygen** is formed in the anode.
- In equations:

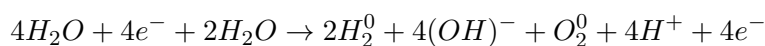


5. **Combining the two half equations** and making some **algebra**:

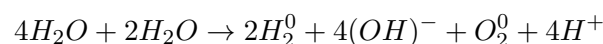
- a. Multiplying the reduction equation by 2.



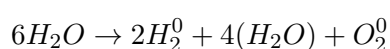
- b. Summing the reduction and the oxidation equations:



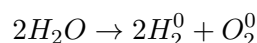
- c. The electrons can be cancelled out



- d. By arranging terms:



- e. By cancelling terms:



The last equation is the **balance equation**, where for each atom of oxygen two atoms of hydrogen are produced.

Other useful videos to understand the electrolysis process:

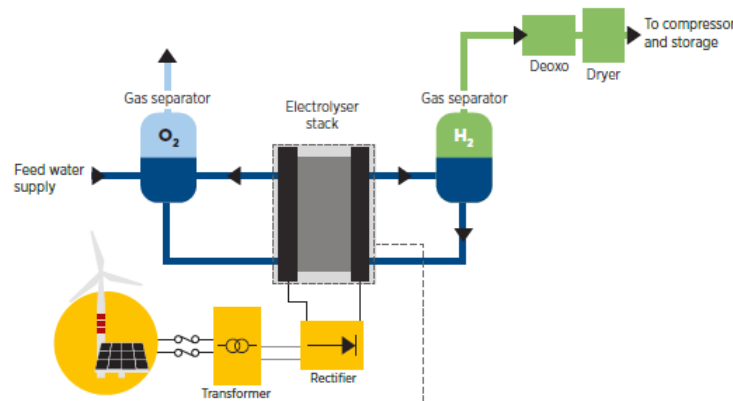
- [What Is Electrolysis | Reactions | Chemistry | FuseSchool](#)
- [Electrolysis of Water and Hydrochloric Acid | Reactions | Chemistry | FuseSchool](#)

## 7.4 Electrolyser: Technology characterisation

Water electrolyzers are electrochemical devices used to split water molecules into hydrogen and oxygen by passage of an electrical current. They can be fragmented in **three levels** (see figure 7.2:

- The **cell** is the core of the electrolyser and it is where the electrochemical process takes place. It is composed of the two electrodes (anode and cathode) immersed in a liquid electrolyte or adjacent to a solid electrolyte membrane, two porous transport layers (which facilitate the transport of reactants and removal of products), and the bipolar plates that provide mechanical support and distribute the flow.
- The **stack** has a broader scope, which includes multiple cells connected in series, spacers (insulating material between two opposite electrodes), seals, frames (mechanical support) and end plates (to avoid leaks and collect fluids).
- The **system level** (or balance of plant) goes beyond the stack to include equipment for cooling, processing the hydrogen (e.g. for purity and compression), converting the electricity input (e.g. transformer and rectifier), treating the water supply (e.g. deionization) and gas output (e.g. of oxygen).

Figure 7.2: Electrolysers components



Source: IRENA (2020a)

Purified water is fed into the system using circulating pumps, or also by gravity. The water then reaches the electrodes by flowing through the bipolar plates and through the porous transport layers. At the electrode, the water is split into oxygen and hydrogen, with ions (typically  $H^+$  or  $OH^-$ ) crossing through a liquid or solid membrane electrolyte. The membrane or diaphragm between both electrodes is also responsible for keeping the produced gases (hydrogen and oxygen) separated and avoiding their mixture. This general principle has remained the same for centuries, but the technology has evolved since William Nicholson and Anthony Carlisle first developed it in 1800.

The principle of water electrolysis is simple, yet it allows the construction of different technological variations based on various physicalchemical and electrochemical aspects. **Electrolysers are typically divided into four main technologies** (figure 7.3). These are distinguished based on the **electrolyte** and **temperature of operation**, which in turn will guide the selection of different materials and components.

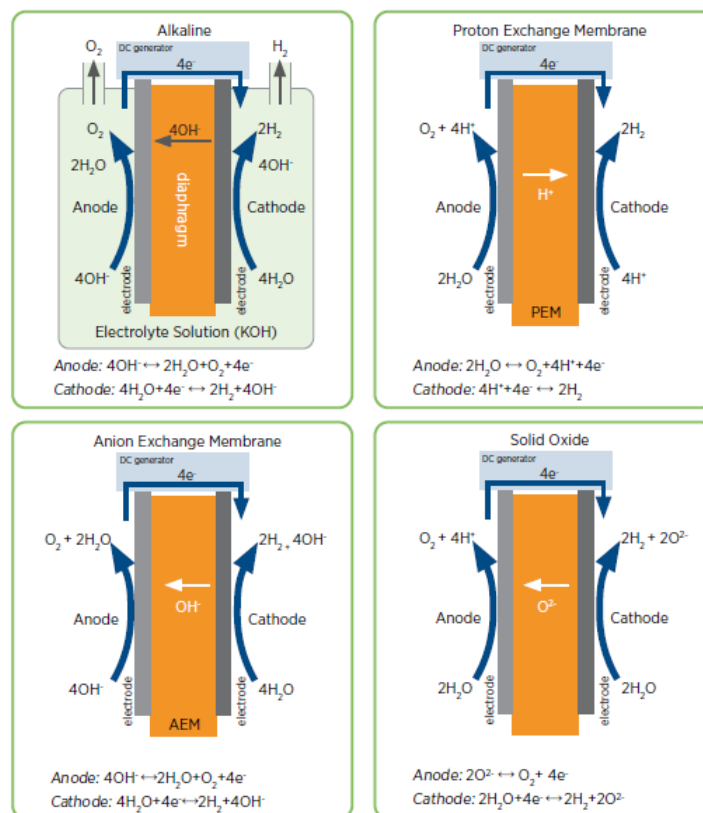
#### 7.4.1 Cell level for each type of electrolyser

1. **Alkaline electrolysers:** These have a simple stack and system design and are relatively easy to manufacture. Currently, they have electrode areas as high as 3 square metres ( $m^2$ ). They operate with high concentrate KOH (typically 57 moles of solute per litre of solution [ $mol \cdot L^{-1}$ ]) as electrolyte, robust  $ZrO_2$  based diaphragms and nickel (Ni) coated stainless-steel for the electrodes. The ionic charge carrier is the hydroxyl ion  $OH^-$ , with KOH and water permeating through the porous structure of the diaphragm to provide functionality for the electrochemical reaction. This allows the intermixing of the produced gases (hydrogen and oxygen –  $H_2$  and  $O_2$ ) that are dissolved in the electrolyte, limiting lower power-operating range and the ability to operate at higher pressure levels.

Some important considerations:

- To prevent this, thicker (0.252 millimetre [mm]) diaphragms are used, but this creates a higher resistance and lower efficiencies.
- Spacers are sometimes included by some manufacturers between electrodes and diaphragms to further avoid the intermixing of gases.
- These thick diaphragms and added spacers result into high ohmic resistances across the two electrodes, drastically reducing current density at a given voltage.

Figure 7.3: Electrolysers types



Source: IRENA (2020a)



- Today's advanced designs, using zero gap electrodes, thinner diaphragms and different electrocatalyst concepts to increase current density, have already reduced their performance gap in comparison to PEM technology.
- On the other hand, classic and sturdy alkaline designs are known to behave very reliably, **reaching lifetimes above 30 years**.

**2. Polymer Electrolyte Membrane (PEM) electrolyzers.** These use a **thin (0.2 mm) PFSA membrane** and electrodes with advanced architecture that allows achieving higher efficiencies (i.e. less resistance). The perfluorosulfonic acid (PFSA) membrane is also chemically and mechanically robust, which allows for high pressure differentials. Thus, the PEM cells can operate at up to 70 bar with the oxygen side at atmospheric pressure.

Some important considerations:

- The acidic environment provided by the PFSA membrane, high voltages, and oxygen evolution in the anode creates a harsh oxidative environment, demanding the use of materials that can withstand these conditions.
- **Titanium-based materials**, noble metal catalysts and protective coatings are necessary, not only to provide long-term stability to cell components, but also to provide optimal electron conductivity and cell efficiency.
- These requirements have caused PEM stacks to be more expensive than alkaline electrolyzers. PEMs have one of the most compact and simplest system designs, yet they are sensitive to water impurities such as iron, copper, chromium and sodium and can suffer from calcination.
- Today, electrode areas are quickly approaching 2 000 square centimetres (cm<sup>2</sup>), yet this is still far from future concepts of large MW stack units using single stack concepts.
- Last but not least, the reliability and **lifetime characteristics of large-scale**, MW PEM stacks still have to be validated.

### **3. Solid oxide electrolyzers (SOEC).**

Some important considerations:

- These operate at high (700-850°C) temperatures. This enables: the favourable kinetics that allow the use of relatively cheap nickel electrodes; electricity demand decreases and part of the energy for separation is provided through heat (waste heat can be used and apparent efficiencies based on electricity can be higher than 100%); the potential for reversibility (operating as fuel cell and electrolyser); coelectrolysis of CO<sub>2</sub> and water to produce syngas (which is the basic building block for the chemical industry).
- On the downside, thermo-chemical cycling, especially under shutdown/ramping periods, leads to faster degradation and shorter lifetimes. Other issues related to stack degradation include: challenges related to sealing at higher differential pressure; electrode contamination by silica used as sealants; and other additional contaminant sources from piping, interconnects and sealing. SOECs are today only deployed at the kW-scale, although some current demonstration projects have already reached 1 MW.

### **4. Anion Exchange Membranes (AEM).**

Some important considerations:

- This is the latest technology with only a few companies commercialising it, with limited deployment.
- AEM's potential lies in the combination of a less harsh environment from alkaline electrolyser with the simplicity and efficiency of a PEM electrolyser.
- It allows the use of non-noble catalysts, titanium-free components, and, as with PEM, operation under differential pressure.
- The reality, however, is that the AEM membrane has chemical and mechanical stability problems, leading to unstable lifetime profiles.
- Moreover, performance is not yet as good as expected, mostly due to low AEM conductivity, poor electrode architectures and slow catalyst kinetics.
- Performance enhancement is typically achieved by tuning membrane conductivity properties, or by adding a supporting electrolyte (e.g. KOH, or sodium bicarbonate [NaHCO<sub>3</sub>]).
- Such tuning could lead to decreased durability, however. The OH<sup>-</sup> ion is intrinsically three-fold slower (lower conductivity) than H<sup>+</sup> protons within PEM, which forces AEM developers to either make thinner membranes, or ones with higher charge density.

#### 7.4.2 System level for each type of electrolyser

##### System Components

The system components are in figure 7.2.

##### Hydrogen processing unit: Compression

Hydrogen from the electrolyser is in gaseous form, conventionally from atmospheric pressure to 30 bar, while higher pressures are possible. To facilitate hydrogen transport, a lower volume is needed. This means either increasing the pressure, liquefying the gas, or converting it for liquid organic hydrogen carriers. Compression can make a large difference. Going from atmospheric to 70 bar (a typical pressure for transmission pipelines) can already reduce the gas volume by a factor of 65. Compressing it to 1 000 bar (a typical pressure for storage in tanks) can reduce the volume by a factor of 625 compared to atmospheric, and liquefaction by a factor of 870.

Compression can be done in mainly **three ways**:

- Using a standard separate compressor.
- By changing the operating pressure of the electrolyser.
- Using a separate electrochemical device.

##### Power supply system

Power supply system cost can decline through economies of scale, standardised designs and participation of specialised electrical equipment suppliers instead of electrolyser manufacturers.

## Water and land use for green hydrogen production

**Water use** is not barrier to scaling up electrolysis. Even in places with water stress, sea water desalination can be used with limited penalties on cost or efficiency.

For the **land area**, there are no real projects of more than 100 MW in water electrolysis (the largest one, as of November 2020, is 20 MW, in Becancour, Canada). Thus, so far, land area estimates rely on engineering estimates, rather than plot optimisation based on real experience. Yet, there are a couple of estimates available:

- A study funded by the German government in 2014 estimated that a 100 MW electrolyser plant would occupy about 6 300 m<sup>2</sup>.
- Siemens estimated back in 2017 that a 300 MW electrolyser plant would occupy about 180 metres (m) x 80 m (15 000 m<sup>2</sup>).
- ITM estimated in 2017 that one 100 MW electrolyser would occupy about 40 m x 87 m (3 500 m<sup>2</sup>), with the possibility of using multiple layout options to fit different applications and of replicating this easily by having a standardised design.
- In 2018, McPhy proposed a 100 MW facility (composed of five modules of 20 MW each) with a plot size of 4 500 m<sup>2</sup>.

To put these numbers in perspective, a global capacity of 1 000 GW of electrolysers, which would be enough to replace the entire current pure and mixed hydrogen fossil-based production, would occupy a land area of the size of Manhattan, New York, using the most conservative estimate (i.e. 0.17 km<sup>2</sup>).

Another reference is that this energy density of almost 7 500 MW/km<sup>2</sup> is almost 1 500 times larger than a relatively good onshore wind density of 5 MW/km<sup>2</sup>, which means the electrolyser would only be a fraction of the space occupied by the renewable electricity input, highlighting the need to use hydrogen only for applications that are hard to electrify and reduce the upstream renewable capacity needed to satisfy the same demand.

### 7.4.3 Trade-offs to consider in the design of the electrolyser

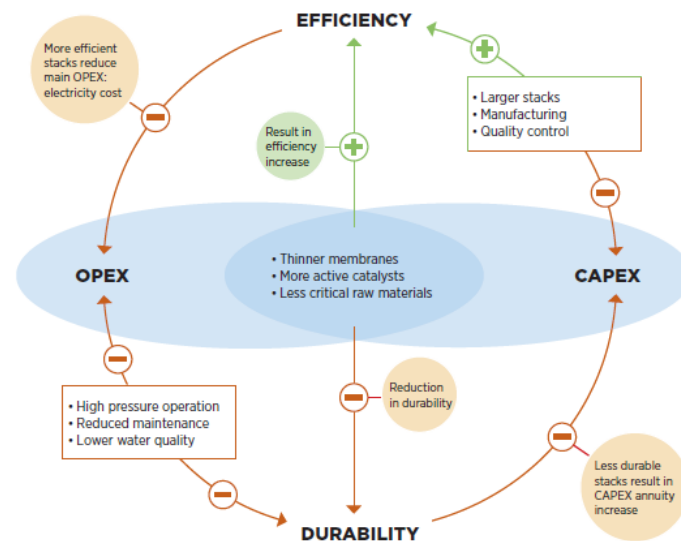
On the supply side, the prospects for green hydrogen depend on the **performance of the electrolyser**. The key dimensions that *R&D* strategies need to address are:

- The **efficiency** increase at the cell, stack, and system level (this reduces operational cost).
- The **current to the stack** is directly related to cell and stack capacity and therefore to hydrogen production.
- A **durability** increase to more than 100 000 hours for any developed system concept.
- An **investment cost** reduction (both stack and system).

These four dimensions are related to each other, however, and improvement in one of them usually leads to a poorer performance in another.

For example, a thicker membrane is mechanically stronger and leads to longer lifetime profiles, but it also increases the resistance to the transport of charges, which in turn decreases the efficiency. While the longer lifetime results in a lower cost contribution of the investment component, the lower efficiency results in a higher operating cost given the higher electricity

Figure 7.4: Trade-offs between efficiency, durability and cost for electrolyzers



Source: IRENA (2020a)

consumption. Figure 7.4 shows the positive or negative effect (arrows + colour) some of the independent choices during manufacturing and research (green boxes) can have on each dimension.

Another **two important aspects** are the use of **more active catalysts** and the **specific business case for the electrolyser**.

The use of more **active catalysts** that are able to improve efficiency levels, but could have negative impact on durability. One example is ruthenium catalysts, which are more active than iridium, but suffer from long-term stability. Moreover, any catalyst free of critical raw materials needs to be aimed at higher efficiencies, but this typically result in catalysts that are less robust and more prone to dissolution.

The **specific business case for the electrolyser** will also affect the optimisation of these parameters. For example, an electrolyser that is coupled with PV could only operate typically less than 2 000 hours in a year, making the capital cost a critical parameter to tackle. With such limited operating hours, durability might be less of an issue, since a short operating lifetime still translates into a longer actual lifetime. This could lead to using materials that are cheaper, but degrade faster. This case is different to one where the electrolyser is coupled with a concentrated solar power that has higher operating hours in a year, but that delivers a higher electricity price, making efficiency more important to reduce the operational cost.

### Lifetime aspects related to materials and components

The lifetime of electrolyser technologies is a function of the cumulative current passing through the stack, which can be represented by the **number of full load hours** as well as the **number of operating hours** – the number of hours during which the facility is on, regardless of load operating levels.

1. **Alkaline electrolyzers** are the most robust, with proven lifetimes of over 30 years.
2. **PEM electrolyzers** have reported lifetimes of more than 50 000 hours.

3. **SOEC electrolyzers** can achieve lifetimes of 20 000 hours, but under constant power and well-defined operating conditions (i.e. not coupled to variable renewable energy [VRE]).

The main degradation mechanism is the thermal cycling, due to the high operating temperatures and need to cool down in case of dynamic operation.

Reversible operation of solid oxide cells (electrolysis + fuel cell) could help increase the hours of operation and thus keep the system at operating temperature.

Deploying SOEC at large scale would require larger cells than currently used (up from 300 cm<sup>2</sup> to more than 1 000 cm<sup>2</sup>), which renders them more prone to failure.

Another important aspect is silica contamination and the instabilities of sealing concepts.

4. **AEM electrolyzers** suffer from a short lifetime, while limited information about their long-term operation, reliability and robustness is available.

The stability of the AEM polymer used to fabricate membrane and catalyst layers is well recognised as a major issue, especially when operated with KOH as the supporting electrolyte.

The main degradation mechanism is hydroxide (OH<sup>-</sup>) attack on the polymer backbone, which leads to membrane collapse and catalyst layer dissolution within a few days.

One solution is cross-linking chemical methods, but this comes at a cost of cell efficiency. Another approach is by operating the stack without a supporting electrolyte (i.e. using only pure water), which can lead to a durability beyond 5 000 hours, but this results in much lower efficiencies, or current densities.

## Efficiency of a hydrogen production facility

The system efficiency of a green hydrogen production facility, measured in units of kilowatt hours consumed per kilograms of hydrogen produced (kWh/kgH<sub>2</sub>), is a result of the individual efficiencies of the **cell**, **stack** and **balance of plant**, as follows.

1. **Cell:** The efficiency profile decreases linearly from lower to higher load levels, so the higher the current input, the lower the stack efficiency.

Naturally, the higher the hours of operation, the lower will be the efficiency due to degradation, though the aforementioned dynamic remains.

At the operational level, the cell voltage is the element actually measured to infer the system performance, in such a way that, the higher the cell voltage, the lower the stack efficiency.

2. **Balance of plant:** A range of system elements such as cooling, purifiers, thermal management, water treatment and others, consume power in order to operate, which also needs to be considered in the facility's overall efficiency.

**Efficiency losses can be minimised by:**

- Designing the electrolyser facility while taking a whole-of-system perspective.
- Using commercially-available components rather than custom made ones.
- Maximising system efficiency including balance of plant, tailored for the specific application.

## 7.5 Production costs

### 7.5.1 Cost abatement as key enabler for hydrogen development

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

**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 for producing 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.

Low electricity cost is not enough by itself for competitive green hydrogen production, however, and **reductions in the cost of electrolysis facilities are also needed.** This is the second largest cost component of green hydrogen production and is the focus of this report, which identifies key strategies to **reduce investment costs for electrolysis plants from 40% in the short term to 80% in the long term.** These strategies range from the fundamental design of the electrolyser stack to broader system-wide elements, including:

1. **Electrolyser design and construction:** Increased module size and innovation with increased stack manufacturing have significant impacts on cost. Increasing the plant from 1 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 between manufacturers. The optimal system design also depends on the application that drives system performance in aspects such as efficiency and flexibility.
2. **Economies of scale:** Increasing stack production to automated production in GW- 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.
3. **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 GW-7.5 GW 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, 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.

4. **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.

5. **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 in significant costs to deliver hydrogen to the end-user.
  - 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.
6. **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, 2020b). 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.

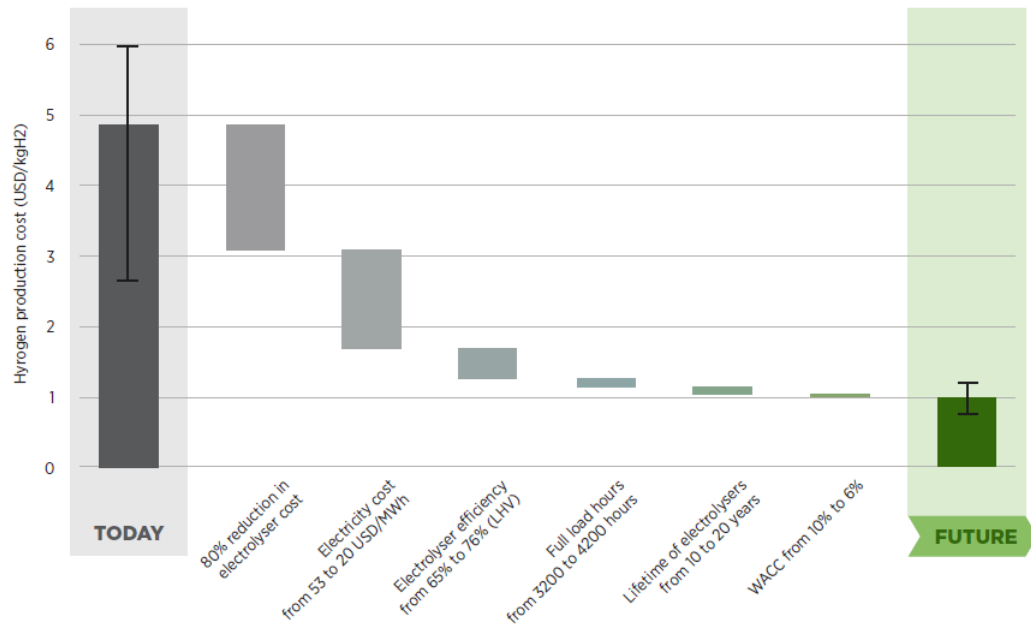
Figure 7.5 shows how up to 85% of green hydrogen production costs can be reduced in the long term by:

1. Access to cheaper electricity.
2. Electrolyser capex investment.
3. Increasing efficiency.
4. Optimising operation of the electrolyser.

**Figure 7.6 illustrates the potential green hydrogen production cost reduction between 2020 and 2050** for a range of electrolysers cost and deployment levels. In the best-case scenario, green hydrogen can already be produced at costs competitive with blue hydrogen today, using **low cost renewable electricity**, i.e. around USD 20 per megawatt-hour (MWh).

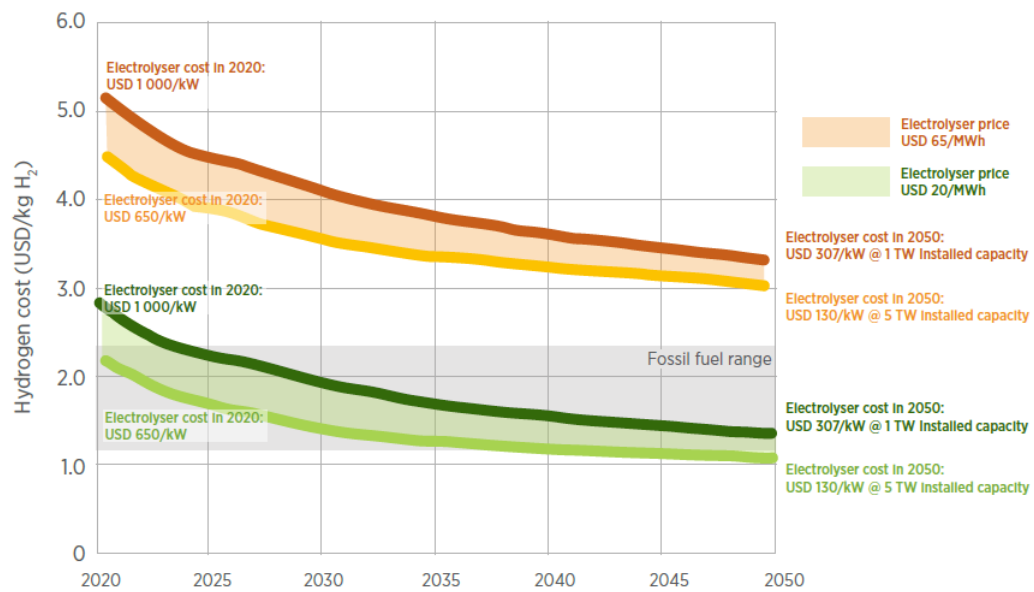
**A low electricity price is essential for the production of competitive green hydrogen, and, as illustrated in figure 7.6, cost reductions in electrolysers cannot compensate for high electricity prices.** Combined with low electricity cost, an aggressive electrolyser deployment pathway can make green hydrogen cheaper than any low-carbon alternative (i.e. < USD 1/kg), before 2040. If rapid scale-up takes place in the next decade, green hydrogen is

Figure 7.5: Hydrogen cost reduction



Source: IRENA (2020a)

Figure 7.6: Hydrogen cost reduction trends



Source: IRENA (2020a)



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 figure 7.7). Alkaline and PEM electrolyzers are the most advanced and already commercial, while each technology has its own competitive advantage. Alkaline electrolyzers have the lowest installed cost, while PEM electrolyzers have a much smaller footprint, combined with higher current density 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 10 ha-17 ha using alkaline. **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 complete water and electricity supply system to be included, high purity hydrogen for fuel cell applications and high output pressure. Normally, numbers for system costs include not only cell stack, but also balance of stacks, power rectifiers, the hydrogen purification system, water supply and purification, cooling and commissioning – yet exclude shipping, civil works and site preparations.

### 7.5.2 Innovation

Innovation is crucial to reduce cost and improve the performance of the electrolyser. 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.
3. Increase durability to extend the equipment lifetime and spread the cost of the electrolyser facility over a larger hydrogen production volume.

### 7.5.3 Government support

Governments can support innovation in electrolyzers by issuing clear long-term signals that support policy on:

1. 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.
2. Establishing regulations and design markets that support investments in innovation and 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.

Figure 7.7: Electrolysers cost components (four technologies)

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

Source: IRENA (2020a)

3. Supporting research, development and demonstration (*RD&D*) to: reduce the use of iridium and platinum in the manufacture of PEM electrolyzers; 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.
4. Fostering coordination and common goals along the hydrogen value chain, across borders, across relevant sectors and between stakeholders.

## 7.6 Hydrogen and renewables

Hydrogen is only one option in **decarbonising hard-to-abate sectors**. Energy efficiency is key to reducing the energy supply and renewable capacity upstream, while bioenergy might be suitable, not only in the form of biofuels for those transport sectors that have limited fuel alternatives (especially aviation), but also as a source of carbon for synthetic fuels. Direct electrification is more efficient from a systems perspective, leading to lower cost, with this already commercially deployed in many areas (e.g. heating or passenger vehicles). Carbon capture and storage (CCS) might be attractive for existing assets that are still in early stages of their lifetime (the case for many assets in Asia) and process emissions (e.g. from cement production). Even for the most ambitious scenarios, these technological choices might not be enough, however, and behavioural changes might be needed to push energy demand even lower. Thus, for energy transition, hydrogen is one solution amongst others and should be tackled in parallel. Hydrogen is part of a wider technology portfolio to be adapted to domestic conditions in each country, with this report further exploring this pathway.

Once produced at scale and competitive cost, green hydrogen can also be further **converted into other energy carriers**, such as ammonia, methanol, methane and liquid hydrocarbons. As a fuel, hydrogen can be used in fuel cells (i.e. an electrochemical device that combines hydrogen with oxygen from the air and produces electricity), but also combusted in engines and turbines. Fuel cells can be used for stationary applications in large-scale power plants, microgrid or backup generation (e.g. in data centres), or for a wide range of transport applications – as is already done in fuel cell electric vehicles (FCEV), trucks, light-duty vehicles, forklifts, buses, ferries and ships. As a chemical, green hydrogen can reduce greenhouse gas (GHG) emissions from sectors where hydrogen from fossil fuel is widely used today, including oil refining, methanol and ammonia production.

Green hydrogen is only one of the production pathways. Hydrogen can also be produced from **bioenergy, methane, coal or even directly from solar energy**. Most of the production today is based on methane and coal (about 95%) (IRENA, 2019) and could be made low carbon with the use of CCS. CCS might be suitable for regions with low-cost natural gas and suitable underground reservoirs. In the short term, CCS might also be a good fit for large-scale applications in industry, given the relatively small scale of deployment for electrolysis.

Low-carbon hydrogen can also be produced from **methane pyrolysis**, where the carbon ends up as solid rather than as CO<sub>2</sub>, with 4-5 times lower electricity consumption than electrolysis and potentially lower hydrogen production cost. Each pathway has its own limitations. Bioenergy might be best suited for other applications, considering its limited nature and the low inherent hydrogen yield. CCS does not lead to zero emissions, requires significant infrastructure for the CO<sub>2</sub>, does not enable sector coupling, is still exposed to the price fluctuations characteristic of fossil fuels, and could face social acceptance issues. In addition, methane leakages associated with production and transportation of the gas have been increasingly under scrutiny as significant contributors to the acceleration of climate change. Methane has 86 times higher global warming potential compared to CO<sub>2</sub> over a 20-year time horizon. Pyrolysis is still at the pilot scale stage

and would require high-temperature renewable or low carbon heat. Hence, considering the sector, green hydrogen is one of the most attractive options, given its nature and renewable character, and as such, it is the focus of this report.

### 7.6.1 Strategies focused on electrolyzers scale-up

A few selected hydrogen strategies are highlighted here, in particular those with a clear focus on electrolyzers scale-up.

1. **Australia:** National hydrogen strategy sets a vision for a clean, innovative, safe and competitive hydrogen industry, with the aim of positioning it as a major player by 2030. The strategy outlines an adaptive approach that equips Australia to scale up quickly as the hydrogen market grows. The strategy includes a set of nationally coordinated actions involving governments, industry and the community. Australia has adopted eight international standards to shape its hydrogen future, as it bids to use the fuel to enhance energy security and build a billion dollar export industry. The rules have the potential not only to support the safety of users – with guidance on storage, transport and refuelling – but also to facilitate international trade, as the nation aims to assume a major role in the global hydrogen economy.

As mentioned above, one of the key targets is “H2 under 2”, which targets a production cost of AUD 2/kg (USD 1.4/ kg) for hydrogen to be competitive across various applications. By 2019, when the national strategy was launched, the government had committed over AUD 500 million (USD 355 million) towards hydrogen projects. Additionally, the government has announced an investment package of AUD 1.9 billion (USD 1.35 billion) to support new energy technologies, including hydrogen, with AUD 70.2 million (USD 49.8 million) dedicated specifically to hydrogen export hubs.

2. **European Union:** On July 8, 2020, the European Commission published its hydrogen strategy for a climate neutral Europe. This aims to boost the clean production of hydrogen to be used as a feedstock, fuel, energy carrier, and ultimate storage alternative for European renewables. The drivers for hydrogen are carbon neutrality, job creation, economic growth and technology leadership (especially for electrolyzers). the strategy has explicit electrolyser capacity targets of 6 GW by 2024 and 40 GW by 2030, as well as production targets of 1 million and 10 million tonnes of renewable hydrogen per year for those two milestone years. Reaching these production targets would require a larger capacity than the 6 GW and 40 GW specified, which implies additional import from neighbouring countries. Investments in renewable hydrogen are estimated to be in the order EUR 220-340 billion (USD 280- 430 billion) for the electricity production and EUR 24-42 billion (USD 30.5-53 billion) for the electrolyzers by 2030.

Hydrogen is seen by the European Commission as a key vector across energy sectors and this strategy was released together with a strategy called “Energy System Integration”, highlighting this function. The Clean Hydrogen Alliance (CHA), a platform that brings together multiple stakeholders from industry, government, civil society and academia, was also launched the same day. Besides bringing actors together, the CHA is also meant to provide a robust pipeline of projects that will support the scale-up process. The commission’s economic recovery plan, “Next Generation EU”, highlights hydrogen as an investment priority to boost economic growth and resilience, creating local jobs and consolidating the EU’s global leadership. The total fund is EUR 750 billion (about USD 950 million) and while only a small share of this is expected to be used for hydrogen, it could represent a large step towards the 2024 goal of 6 GW.

3. **Japan:** This was the first country to adopt a “basic hydrogen strategy” and with specific plans to become a “hydrogen society”. The Japanese strategy primarily aims to achieve cost parity with competing fuels, such as gasoline in the transportation sector or liquefied natural gas (LNG) in power generation. The strategy also covers the entire supply chain, from production to downstream market applications.

Given limited natural resources and limited land availability, hydrogen import plays a key role in the Japanese strategy. The approach has been to pursue parallel demonstration projects with multiple sources, hydrogen carriers and enduse sectors to derisk future imports and increase the flexibility of supply. There are projects with Australia (coal with CCS and liquid hydrogen<sup>5</sup>), Saudi Arabia (oil and ammonia), Brunei (gas and liquid organic carriers) and Norway (hydropower and liquid hydrogen). Japan’s strategy could have a positive global impact and contribute to the creation of new synergies regarding international energy trading and business cooperation. These will be crucial in driving development and making technologies more affordable. According to the roadmap of the Japanese Ministry of Economy, Trade and Industry (METI), Japan expects hydrogen technologies to become profitable by 2030. METI has set specific targets<sup>6</sup> for green hydrogen in terms of electrolyser cost (USD 475/kW), efficiency (70%, or 4.3 kWh per normal cubic metre [Nm<sup>3</sup>]) and finally production cost (USD 3.3/kg) by 2030.

## 7.7 Flexibility of green hydrogen production facilities

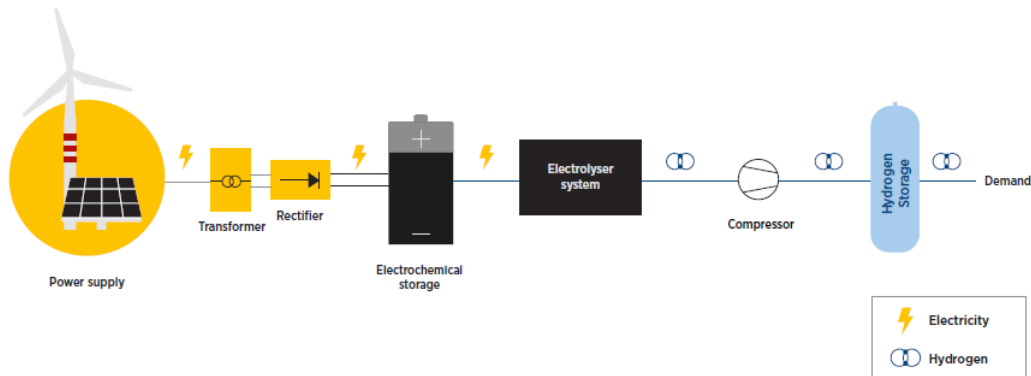
To ensure that green hydrogen supply cost is as low as possible, a holistic approach needs to be applied to system design and operations. System design can be optimised to **minimise cost** and **increase flexibility** as necessary, depending on a variety of factors. These can include:

1. The variability of electricity supply (i.e. constant consumption of grid electricity, or direct feed from variable solar or wind farms).
2. The technology used for the stack (e.g. alkaline, PEM and AEM being more flexible than solid oxide).
3. The flexibility of hydrogen demand (e.g. constant demand for chemical processes, general annual demand for export without hourly or daily constraints).
4. Storage can significantly help to decouple variable supply from hydrogen demand. This can come in the form of electrochemical storage for short-term fluctuations (before the electrolyser stack), or in the form of hydrogen storage for long-term fluctuations (after the stack, before the downstream off-taker). Similarly, hydrogen storage in tanks, caverns and pipelines can help decouple variable hydrogen production from inflexible hydrogen demand (e.g. to produce ammonia).

The type of electricity supply and hydrogen demand will drive system design, where no single electrolyser technology is better than any other, as the combination with electricity and hydrogen storage can effectively provide any level of flexibility, as illustrated in figure 7.8.

Where hydrogen has a significant role to play in terms of **flexibility provision** in future decarbonised power systems is in long duration storage and system adequacy. The seasonality of solar, wind and hydropower resources can provide challenges in terms of adequacy – if not every year, at least in unusual weather years (e.g. dry years, or years with extended periods of low wind). Hydrogen from renewable power can be stored cost effectively – for example, in salt caverns – and can be used for power generation in these particular periods.

Figure 7.8: Green hydrogen production facility with electricity and hydrogen storage



Source: IRENA (2020a)

Due to the near zero short run marginal cost of solar and wind, when they reach significant generation share in a market interval (e.g. in a one hour period), they drive down electricity prices. Figure 7.9 shows how hydrogen production follows renewable electricity availability, highlighting an important seasonality in the production of hydrogen.

The key message is that hydrogen production from electrolyzers can be uniquely positioned to provide seasonal flexibility to the power system – something that no other resource can effectively provide. This can play a significant role in balancing a power system with high shares of solar and wind, not only instantaneously and intra-day, but also across seasons. To be able to provide such services, electrolyzers must be designed not to operate at full capacity the entire year, but rather to purchase electricity when green and affordable. This is only possible if they are sufficiently oversized to avoid purchasing non renewable electricity, or prohibitively expensive electricity, just to be able to meet hydrogen demand.

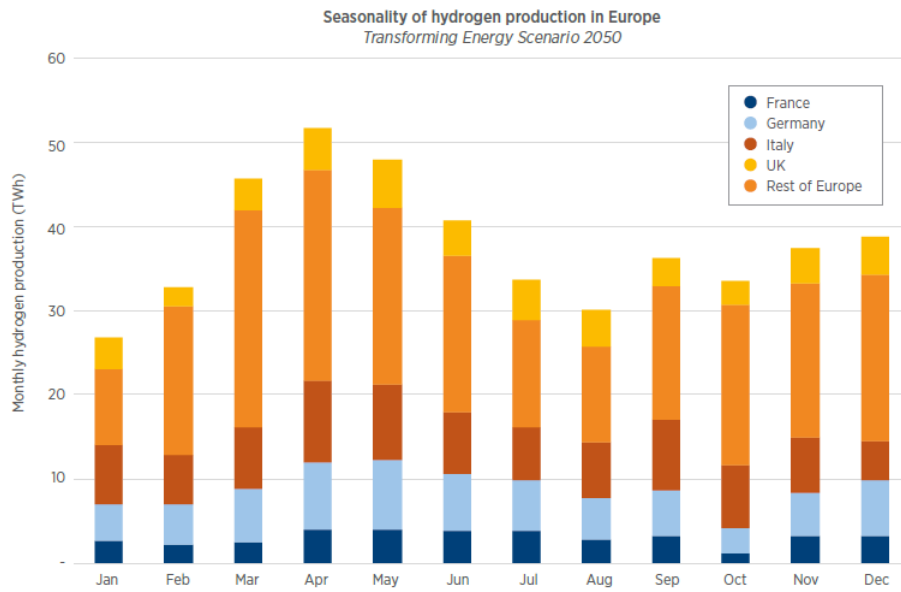
Hydrogen can be **stored** and **transported** in multiple ways. In terms of flexibility services, electrolyzers have been evaluated in terms of:

1. The time they take to respond to a change in power set-point.
2. The time they take to settle after a power set-point change.
3. The rate at which they can change power consumption.
4. The lower operation limit, or the minimum turn down level.
5. The time they take to start up and shut down.

A **report** (Eichman, Harrison and Peters, 2014) has found that:

1. Small electrolyser systems (around 40 kW units) begin changing their electricity demand within milliseconds of a set-point change.
2. The settling time after a set-point change is in the order of seconds.
3. Electrolysers can reduce their electrical consumption to zero for an unlimited amount of time.
4. Electrolysers exhibit low part load operation capabilities.

Figure 7.9: Seasonality of hydrogen production in Europe (IRENA simulation)



Source: IRENA (2020a)

5. Electrolysers can start up and shut down in several minutes.

From the point of view of **short-term flexibility** alkaline and PEM water electrolyzers still present the most interesting technical capability, as they have proven to provide very fast dynamics among all available electrolysis process.

For **congestion management**, large scale electrolyzers can contribute to the reduction of critical peak loads by reducing their electricity demand, or even by completely interrupting operation. This service should be remunerated adequately, however, to compensate for the economic incentive to operate the electrolyser as many hours as possible to reduce the contribution of the investment cost to the total cost. Moreover, such an application can also have its limitations, since several industrial processes cannot be stopped when integrated with the electrolyser facility, therefore limiting flexibility of operations based on the size of the hydrogen storage.

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