Chapter 7. Hydrogen

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Chapter outline

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 electrolysers**, and the main components in a **hydrogen production plant**
4. Study the main **cost challenges** faces by the hydrogen industry
5. Analyze the role of hydrogen increasing **flexibility** in the energy system

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. Which are the main **types of hydrogen**?
2. Which is the difference between **green hydrogen** and the other types of hydrogen?
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
5. Which are the main **challenges** that face the development of hydrogen? Electrolysers, storage of hydrogen, transport of hydrogen, electricity cost?

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).

Electrolysis. The process

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:

$$2H_2O \rightarrow 2H_2 + O_2$$

H_2 and O_2 are **diatomic elements**: always form groups of two. You will never find just one alone.

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

Electrolysis. The process

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

$$2H_2^{+1}O^{-2} \rightarrow 2H_2^0 + O_2^0$$

To satisfy the balance equation:

- The **hydrogen** need to be **reduced** (it needs to **gain electrons**).
- The **oxygen** need to be **oxidized** (it needs to **lose electrons**).

Electrolysis. The process

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 below).

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.

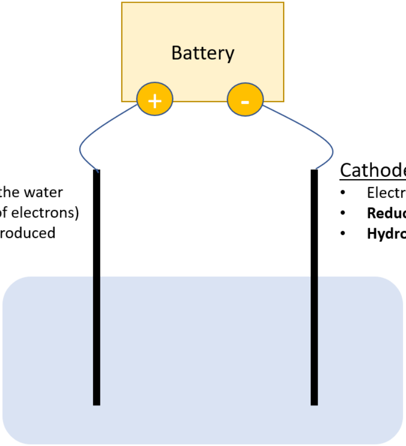
It will produced twice as much hydrogen gas as oxygen gas (balance equation):

$$2H_2O \rightarrow 2H_2 + O_2$$

Electrolysis. The process

Balance equation

$$2H_2^{+1}O^{-2} \longrightarrow 2H_2^0 + O_2^0$$



Anode:

- Electrons **out** of the water
- **Oxidation** (lose of electrons)
- **Oxygen** (O_2) is produced

Cathode:

- Electrons **into** the water
- **Reduction** (gain of electrons)
- **Hydrogen** (H_2) is produced

Electrolysis. The process

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:

$$2H_2O + 2e^- \rightarrow H_2^0 + 2(OH)^-$$

Electrolysis. The process

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:

$$\begin{aligned} 2H_2O - 4e^- &\rightarrow O_2^0 + 4H^+ \\ 2H_2O &\rightarrow O_2^0 + 4H^+ + 4e^- \end{aligned}$$

Electrolysis. The process

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

   a. Multiplying the reduction equation by 2.

$$2\left(2H_2O + 2e^- \rightarrow H_2^0 + 2(OH)^-\right)$$
$$4H_2O + 4e^- \rightarrow 2H_2^0 + 4(OH)^-$$

   b. Summing the reduction and the oxidation equations:

$$4H_2O + 4e^- + 2H_2O \rightarrow 2H_2^0 + 4(OH)^- + O_2^0 + 4H^+ + 4e^-$$

Electrolysis. The process

c. The electrons can be cancelled out

$$4H_2O + 2H_2O \rightarrow 2H_2^0 + 4(OH)^- + O_2^0 + 4H^+$$

d. By arranging terms:

$$6H_2O \rightarrow 2H_2^0 + 4(H_2O) + O_2^0$$

e. By cancelling terms:

$$2H_2O \rightarrow 2H_2^0 + O_2^0$$

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

Electrolyser. Components

Water electrolysers 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 below):

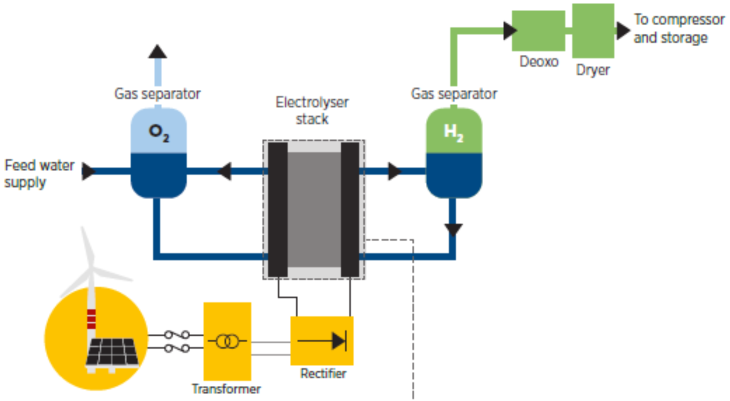
- The cell is the core of the electrolyser and it is where the electrochemical process takes place.

  It is composed of the **two electrode**s (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.

Electrolyser. Components

- 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).

Electrolyser. Components



Electrolyser. System level

1. **Compression**
   - Hydrogen from the electrolyser is in **gaseous form,** conventionally from atmospheric pressure to 30 bar
   - 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 1000 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

Electrolyser. System level

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

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

4. **Land use**. A global capacity of 1000 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

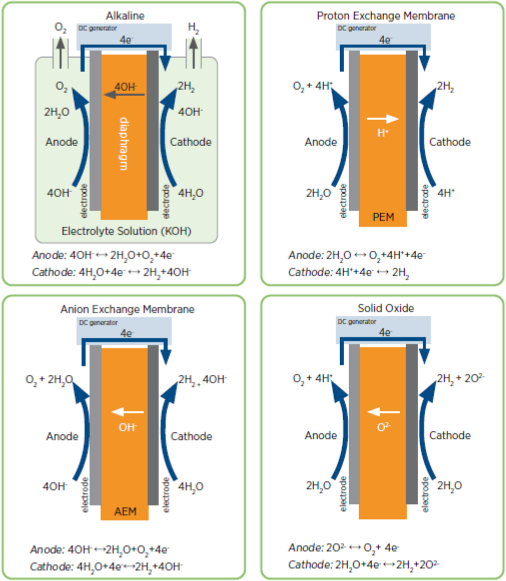
Electrolyser. Cell level

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 below)

These are distinguished based on the **electrolyte** and **temperature of operation**, which in turn will guide the selection of **different materials** and **components**

Electrolyser. Cell level



Electrolyser. Cell level

1. **Alkaline electrolysers:**
    - To prevent the mix of H_2 and O_2, 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
    - 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**

Electrolyser. Cell level

2. **Polymer Electrolyte Membrane (PEM) electrolysers**

- The **acidic environment** provided by the perfluorosulfonic acid (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 electrolysers. 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.
- Last but not least, the reliability and **lifetime characteristics of large-scale**, MW PEM stacks still have to be validated.

Electrolyser. Cell level

3. **Solid oxide electrolysers (SOEC)**.

- These operate at high **(700-850℃) temperatures**. This enables:
  - **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%)
  - Coelectrolysis of CO2 and water to produce **syngas** (which is the basic building block for the chemical industry)
- On the downside:
  - 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.

Electrolyser. Cell level

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

- 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 electrolysers 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

Trade-offs to consider in the design of the electrolyser

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)

Trade-offs to consider in the design of the electrolyser

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 consumption

Trade-offs to consider in the design of the electrolyser

The system efficiency of a green hydrogen production facility 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**

   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

Cost abatement and hydrogen development

1. **The largest single cost component for on-site production of green hydrogen is the cost of the renewable electricity** needed to power the electrolyser unit

This renders production of green hydrogen more expensive than blue hydrogen, regardless of the cost of the electrolyser

A low cost of electricity is therefore a necessary condition 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.

Cost abatement and hydrogen development

2. The cost of **electrolysis facilities** is the second largest cost component of green hydrogen production. There are six strategies to reduce the cost of electrolysis facilities (figure below):

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

   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

Cost abatement and hydrogen development

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

Cost abatement and hydrogen development

4. **Efficiency and flexibility in operations**: Power supply represents large efficiency losses at low load, limiting system flexibility from an economic perspective

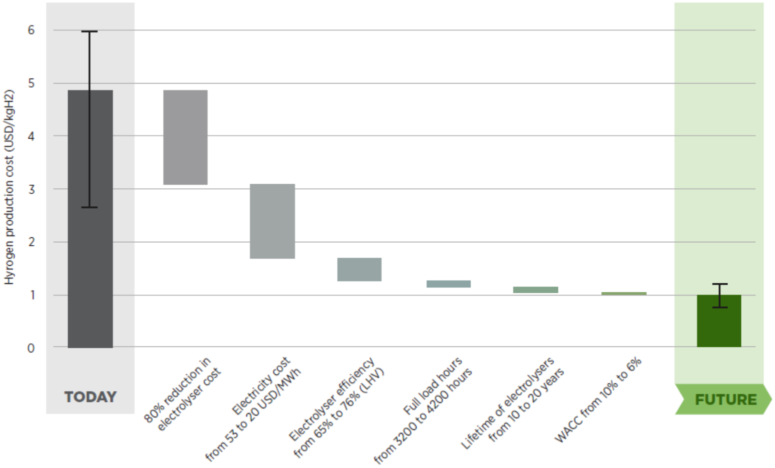
   A modular plant design with **multiple stacks** and **power supply units** can address this problem

   Compression could also represent a bottleneck for flexibility, since it might not be able to change its production rate as quickly as the stack

Cost abatement and hydrogen development

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%

Cost abatement and hydrogen development



Flexibility of green hydrogen production facilities

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.

Flexibility of green hydrogen production facilities

Due to the near zero short run marginal cost of solar and wind, when they are reach significant generation share in a market interval (e.g. in a one hour period), they drive down electricity prices

The figure below shows how hydrogen production follows renewable electricity availability, highlighting an important **seasonality in the production of hydrogen**

Flexibility of green hydrogen production facilities

The key message is that hydrogen production from electrolysers 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, electrolysers 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

Flexibility of green hydrogen production facilities