Environment Agency

# Review of emerging techniques for hydrogen production from electrolysis of water

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# 1. Introduction

## 1.1 Policy and wider legislative context

In 2019, the UK passed Net Zero legislation to “bring all greenhouse gas emissions to net zero by 2050” [Ref. 1]. Subsequent policy papers have set out a key role for hydrogen in the delivery of Net Zero.

The ten-point plan for a green industrial revolution, 2020 [Ref. 2] ‘Point 2: Driving the Growth of Low Carbon Hydrogen’, said “our aim is for the UK to develop 5 GW of low carbon hydrogen production capacity by 2030”. (The Low Carbon Hydrogen Standard [Ref. 7] says a greenhouse gas (GHG) emissions intensity of 20gCO2e/MJLHV or lower is required for hydrogen to be considered low carbon.)

The Hydrogen Strategy [Ref. 3] identified a major role for hydrogen in meeting future energy demand – a twin-track approach supports both ‘blue’ hydrogen from steam-methane reforming (SMR) with carbon capture usage and storage (CCUS) and ‘green’ hydrogen from the electrolysis of water.

The Net Zero Strategy [Ref. 4] identified hydrogen as the “least-cost option to decarbonise harder to electrify sites, processes, and sectors” with the greatest potential from chemicals and iron and steel sectors.

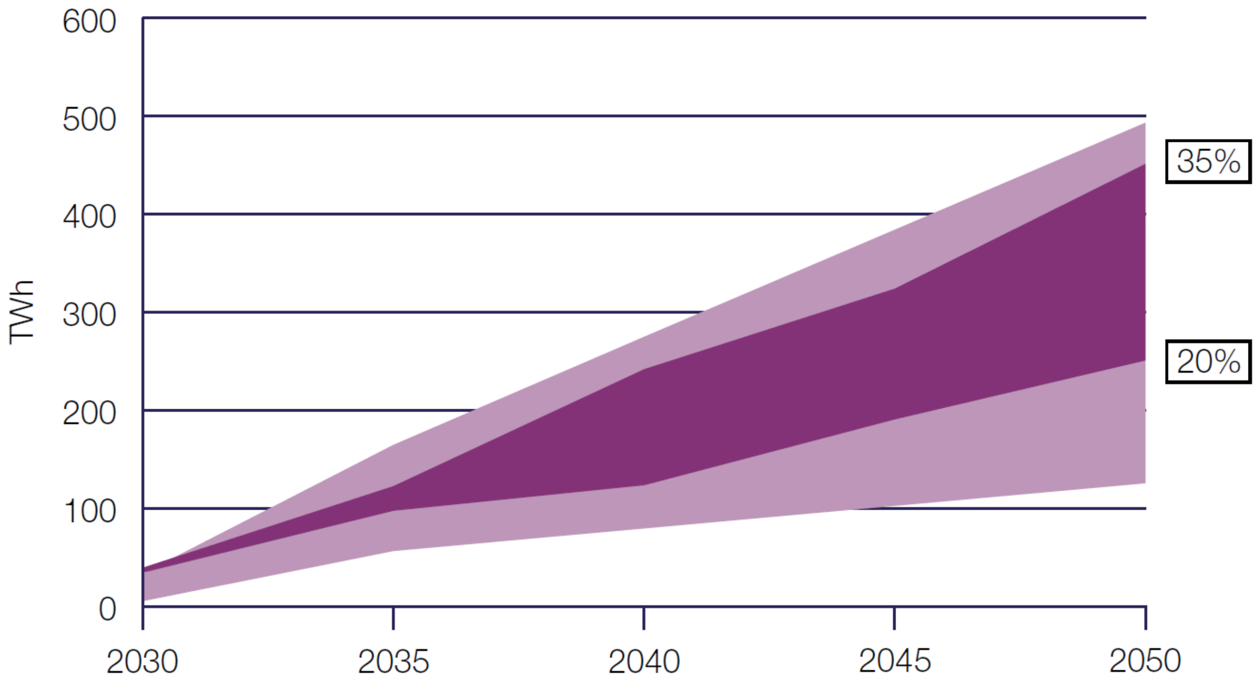
The British Energy Security Strategy [Ref. 5] said we “will double our UK ambition for hydrogen production to up to 10GW by 2030, with at least half of this from electrolytic hydrogen.

Powering up Britain [Ref. 6] contained key hydrogen announcements, including:

- a shortlist of projects for the first electrolytic hydrogen allocation round, supporting up to 250MW of new electrolytic hydrogen production capacity
- an intention to launch a second electrolytic allocation round in 2023, supporting up to 750MW capacity
- an intention to publish a hydrogen production delivery roadmap by end of 2023

**Figure 1 – Hydrogen demand and proportion of final energy consumption in 2050 (Ref. 3)**

This chart shows analysis by BEIS for Carbon Budget 6 (CB6) which suggests 250-460TWh of hydrogen could be needed in 2050, making up 20-35 per cent of UK final energy consumption.



% = hydrogen as proportion of total energy consumption in 2050.

Source: Central range – illustrative net zero consistent scenarios in CB6 impact assessment. Full range – based on whole range from UK Hydrogen Strategy Analytical Annex. Final energy consumption from ECUK (2019).

## 1.2 Purpose of document

An initial review of electrolysis technology for hydrogen production from water by the Environment Agency [Ref. 10] concluded that:

- studies of the environmental impacts having been limited to theoretical and comparative analysis, for relatively small-scale production
- the nature of environmental impacts may change, with improvements as the technology is upscaled
- more detailed primary data for the upstream and downstream processes would improve evaluation of environmental impacts

Due to the early stage of development of electrolysis of water technologies, this report refers to emerging techniques rather than best available techniques (BAT). The UK environmental regulators intend to use this report to develop guidance for emerging techniques. It is a step towards the future development of BAT guidance and standards which can be developed once data from operating plant are available.

The UK environmental regulators are:

- the Environment Agency in England
- the Scottish Environment Protection Agency (SEPA) in Scotland
- Natural Resources Wales (NRW) in Wales
- the Northern Ireland Environment Agency (NIEA), an executive agency of the Department of Environment, Agriculture and Rural Affairs, in Northern Ireland

This report describes the key environmental aspects to address and provides information on best practice for hydrogen production from electrolysis. Following industry consultation, the regulators consider these techniques to be those most likely to be proposed by permit applicants in the short- to medium-term (1 to 5 years). Guidance is based on publicly available information and on information provided by industry stakeholders.

Where there is no relevant BRef, or where related BAT conclusions do not address all the potential environmental effects, the regulator must set permit conditions, including emission limit values, on the basis of best available techniques that it has determined for the activities or processes. This shall be after prior consultations with the operator following the requirements in Article 14(6) of the Industrial Emissions Directive 2010/75/EU (IED) and give special consideration to the criteria for determining BAT in Annex III of the IED.

These criteria include, amongst others, review of comparable processes, types and quantity of emissions, energy efficiency, efficient use of raw materials and prevention or reduction of overall impact of emissions on the environment.

The UK regulators have commissioned this emerging techniques evidence review to support development of emerging techniques guidance. There are no existing best available techniques (BAT) reference documents (BRefs) or guidance which cover the production of hydrogen from water by electrolysis.

The current BRef for large volume inorganic chemicals (2007) [Ref. (32)] mentions hydrogen produced via electrolysis of water in relation to ammonia production (Section 4.26) but concluded at that time that the process was not considered economically viable. The BRef for the production of chlor-alkali (2014) [Ref. (33)] covers the production of hydrogen as a co-product with chlorine and sodium hydroxide by the electrolysis of brine and relevant techniques but not via the electrolysis of water.

These are emerging technologies and there is limited evidence or data available for performance of comparable sites, especially at larger scale.

The guidance is not a regulatory requirement. It does not have the same regulatory status as BAT reference documents or related BAT conclusions. However operators would need to explain and justify where alternatives to methods and performance described in the guidance are proposed. Operators are encouraged to make contact with the appropriate regulator at the earliest possible opportunity.

Where an emission level associated with the best available technique (BAT-AEL) applies from a relevant BRef, these may also be set, although a derogation may be granted for up to 9 months if the technology is considered emerging, to allow testing and use (IED Article 15(5)). Permit conditions will be set to protect the environment by ensuring environmental quality standards are met (Article 18).

The UK regulators envisage that the emerging techniques review and emerging techniques guidance will be used by:

- operators when designing their plants and preparing their application for an environmental permit
- their own staff when determining environmental permits
- any other organisation or members of the public who want to understand how the environmental regulations and standards are being applied

The scope of this review and guidance is limited to preventing or reducing emissions into the environment and does not cover other aspects such as safety, except where relevant in respect of accidents to the environment.

The guidance document will provide a framework for applications and permits and is based on information available at this time. Further information about the performance of the processes will become available as they are further developed and commence operation. The UK regulators will keep BAT and emerging techniques under review as required by Article 19 of IED.

## 1.3 Stakeholder engagement

Stakeholders engaged in the preparation of this guidance include manufacturers, project developers and trade associations. A request for information (RFI) document was prepared to request technical and operational information, including relating to energy use, emissions to atmosphere and liquid discharges.

Following review and acceptance of this report by the UK regulators’ technical working group, the document was issued for initial review by a focussed group of stakeholders and final review by a wider group of stakeholders, including government departments, academic institutions, further trade associations and professional bodies.

The UK regulators and Costain, the consultants who were commissioned to work on this report, would like to thank those who have provided data and supported production of this report.

# 2. Study approach

## 2.1 Definition of scope boundaries

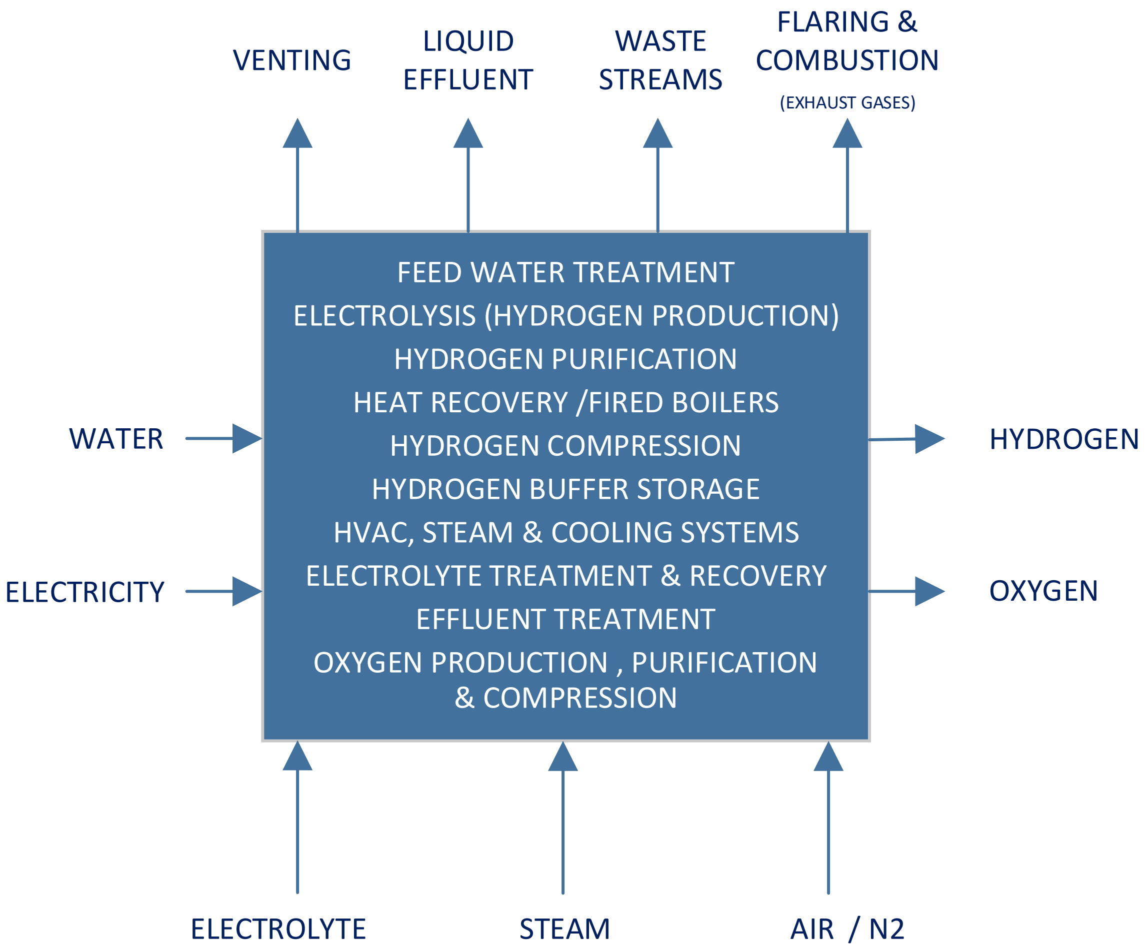
This guidance considers production of hydrogen from electrolysis. The various process units in the scope boundary and interfaces are shown in Figure 2.

Key exclusions from this guidance include:

- generation, transmission, and distribution of electrical power supply to electrolysers
- pipelines or other means of transmission and distribution of hydrogen product, including associated storage systems
- hydrogen end use applications, for example in generating power or heat, or use in transport applications

**Figure 2 – Scope boundaries**

This shows a list of processing units within the scope of this evidence review. It also shows the inputs of raw materials and services and outputs of products, emissions and effluents. These are described in more detail in sections 2.4, 2.5 and 2.6.



## 2.2 Scope boundaries – technologies

Potential electrolyser technologies are identified, considering:

- technologies that can achieve production scales meeting the requirements of industrial applications.
- technologies with a suitable level of readiness for deployment, that is mature technologies applied in equivalent service, at the required scale and operating parameters. The list below excludes those technologies with low readiness levels.
- technologies known currently to be under consideration by UK project developers.

Based on these criteria, the following electrolyser technologies have been considered in developing this guidance:

- alkaline
- polymer electrolyte membrane (PEM)
- solid oxide electrolyser cell (SOEC)
- lower TRL (technology readiness level) technologies: anion exchange membranes (AEM) and others

This guidance is focussed on onshore applications. It may also be applicable to nearshore operations, for example within the UK territorial water limit of 12 nautical miles from the low-water line along the coast limit.

## 2.3 Scope boundaries – plant scale

This guidance is appropriate to production scales anticipated in the UK in the near term. To date, typical installations are under 1 MWe, primarily supplying hydrogen for transport applications. A number of UK developments have been proposed in the 10 to 100 MWe range, equivalent to around 4 to 40 t/day of hydrogen.

Larger electrolyser installations are already found in countries with a large renewable power resource (for example Norway with hydro-electric power) or in countries without indigenous gas supplies for steam reforming (for example Japan). Recent installations include a facility in Canada using Cummins electrolysers (20 MWe) and in Germany at the Shell Rhineland facility using ITM Power electrolysers (10 MWe) [Ref. 11]. Capacity is achieved via multiple electrolyser stacks in modular arrays. Any differences in approach for production at gigawatt (GWe) scale will be considered in future guidance.

## 2.4 Scope boundaries – feed and products

The feed and product boundaries, basis and exclusions considered in producing hydrogen through electrolysis of water are summarised in the following.

**Water**

Description: Feed water is typically treated by reverse osmosis and other polishing technologies to produce demineralised water for use in electrolysis. There is potential for re-use of industrial wastewater, ground water, surface water and seawater treated by desalination to be used as feed water.

Exclusions: Upstream water abstraction/collection, off-site processing and transport to the hydrogen production site.

Notes or basis: Including treatment to achieve required purity. Typically, electrolysers will require removal of impurities for production of demineralised water to a level similar to boiler feedwater quality.

**Hydrogen**

Description: Hydrogen product quality suitable for either fuel cell electric vehicles (FCEVs) or heat grade for combustion as industrial or domestic fuel. Includes hydrogen compression.

Exclusions: Hydrogen transmission and distribution networks.

Notes or basis: For example, typical proposed specification [Ref. 28] for:

- fuel cell vehicles, $H_2 \geq 99.97$ vol%
- combustion, $H_2 \geq 98$ vol%

Pressure as delivered from production and purification process. Compression may be required for transportation or delivery to users, local storage or requirement for downstream process.

**Oxygen**

Description: Oxygen is co-produced when water is electrolysed to produce hydrogen. Includes oxygen compression and purification where oxygen is utilised.

Exclusions: Oxygen transmission and distribution networks.

Notes or basis: Oxygen utilisation should be considered, recognising that the viability of such utilisation will be project specific. There are potential uses in industry that may be complementary to the hydrogen production. In the majority of cases, some or all of the oxygen produced will be discharged to atmosphere, together with any hydrogen impurity it contains.

## 2.5 Scope boundaries – utilities

Utilities requirements for the electrolytic processes are identified as follows.

### Electrical supply

Typical description: Alternating current (AC) electrical supply is delivered to electrolyser rectifier for conversion to direct current (DC).

Notes or basis: Electrical power supply may be direct from an intermittent renewable source (for example wind, solar). Excluding electrical supply for transportation and distribution infrastructure. Associated greenhouse gas emissions are dependent on the source of electrical power, typically with a high percentage of renewable power, supplied directly or via the grid.

### Water supply

Typical description: In addition to feed water for the electrolyser, there may be requirements for cooling water make up.

Notes or basis: Low temperature electrolysers require cooling to extract heat resulting from inefficiency in the electrolysis process. Different cooling methods can be employed, as described below, with the greatest requirements for make up where cooling water is used with an evaporative cooling tower.

### Instrument air

Typical description: Process instrumentation and control can be pneumatic in certain electrolyser applications.

Notes or basis: Includes air compression, associated cooling and drying.

### Cooling

Typical description: Process cooling requirements to remove heat generated in electrolysis process.

Notes or basis: Cooling can be achieved against ambient air, closed-loop cooling water systems, evaporative cooling water systems or once-through (direct) cooling systems. Process temperature needs to be controlled at optimum for the technology used, so heating/cooling load may depend on ambient temperature.

### Heat or steam

Typical description: At pressure levels to suit process requirements (for example heat recovery) for SOEC technology.

Notes or basis: Generated within plant boundary in heat exchange with process streams or from fired boiler or flue gas heat recovery systems (for example for SOEC). This is an area of potential integration with other industrial facilities for import or export of steam, particularly for SOEC technology.

### Nitrogen

Typical description: Nitrogen required primarily for purging.

Notes or basis: Includes storage requirements.

### HVAC

Typical description: HVAC (heating, ventilation and air conditioning).

Notes or basis: Required for indoor installations to maintain a safe working environment.

### Flare or vent

Typical description: For safe combustion or release of non-routine controlled or emergency releases.

Notes or basis: An elevated or ground flare system may be required to handle any controlled releases from planned and unplanned operations, such as start-up operation, planned or unplanned shutdown operation.

## 2.6 Scope boundaries – emissions, effluents and wastes

Boundaries in terms of emissions, effluents and wastes are identified as follows.

### Gaseous emissions

Description: Gaseous emissions from venting, flaring, or other processes to atmosphere.

Scope: Includes:

- venting or combustion or flaring releases during normal operation
- continuous or intermittent venting or flaring – for example on start-up
- fugitive emissions or emissions due to loss of containment

### Liquid effluents

Description: Liquid effluents and potential requirements for effluent treatment.

Scope: Includes:

- from feed water treatment systems
- from electrolyser systems, cooling systems (for example water or ethylene glycol) and steam systems, including requirements for purging
- water condensed in process
- aqueous effluents generated from waste water treatment processes

### Solid and liquid wastes

Description: Any solid or liquid waste streams from operation and subsequent treatment.

Scope: Includes:

- spent cartridges and solid waste cakes from water treatment, catalysts and adsorbents, ion exchange resins considering recovery and recycling
- electrolyser stack components replaced following degradation
- wastewater included in effluents section

## 2.7 Key considerations for emerging techniques

Assessment of BAT criteria and emerging techniques should consider the following aspects where appropriate in technology selection, overall plant design, and development of operational philosophies and procedures.

Technology selection should include, but shall not be limited to, the following key environmental considerations:

- emissions to air
- emissions to water
- conversion efficiency and energy efficiency
- source of water
- optimisation of water usage
- use of scarce raw materials for electrolyser manufacture
- waste minimisation and waste treatment (liquid and solid waste streams)
- abatement techniques to reduce emissions (for example emissions to air, waste water, other wastes)
- noise (for example equipment such as pumps, compressors, fans and flares)

Plant design and operations should consider the points above and those below, with reference to existing relevant standards where appropriate:

- monitoring standards for stack emissions – for example to account for hydrogen losses in vented oxygen (including averaging periods)
- monitoring standards for discharges to water (including averaging periods and arrangements for flow monitoring)
- air dispersion modelling standards
- ambient or deposition monitoring standards
- maximising energy efficiency (including heat integration and optimisation, considering for example opportunities for heat recovery from the electrolysers and compression systems)
- water use efficiency (for process use and cooling systems)
- optimisation of use of raw materials including water re-use
- minimisation of waste (using water hierarchy that is prevention, re-use, recycling, recovery of wastes)
- treatment of hydrogen (dependent on quality requirements)
- start-up and shutdown of operations (including variable production rates rates)
- other than normal operating conditions
- accident management, leak monitoring and containment arrangements
- future proofing of technology for climate change resilience

## 2.8 Existing BAT reference (BRef) documentation

Best Available Techniques (BAT) Reference Document for the Production of Chlor-Alkali, 2014

Reference Document on Best Available Techniques for Energy Efficiency, European Commission, February 2009

Best Available Techniques (Bat) Reference Document for Common Waste Water And Waste Gas Treatment/Management Systems In The Chemical Sector, European Commission, 2016

Best Available Techniques for The Manufacture of Large Volume Inorganic Chemicals – Ammonia, Acids and Fertilisers, 2007

Integrated Pollution Prevention and Control Reference Document on Best Available Techniques on Emissions from Storage, European Commission, July 2006

General Principles of Monitoring Bat Reference Document, 2003

# 3. Technology review

## 3.1 Overview

Electrolysis has for a long time been used at an industrial scale, to split water ($H_2O$) into its constituent hydrogen ($H_2$) and oxygen ($O_2$) molecules by applying a controlled electrical current. Whilst today accounting for only 0.03% of global hydrogen production [Ref. 12], the use of renewable electricity to produce low carbon hydrogen means the number of electrolyser installations is growing quickly.

This guidance report considers the applicability of the following electrolysis technologies:

- alkaline
- polymer electrolyte membrane (PEM)
- solid oxide electrolyser cell (SOEC)

Section 3.4.2 considers other electrolyser technology types considered, which are less mature technologies at a lower TRL (technology readiness level).

There is currently no overall leading technology, with selection dependent on factors such as:

- required hydrogen production rate and end-use
- safety considerations
- operational flexibility requirements, such as speed of response
- requirement or options to integrate with nearby facilities, for example for supply of heat
- commercial considerations, for example cost, lead time

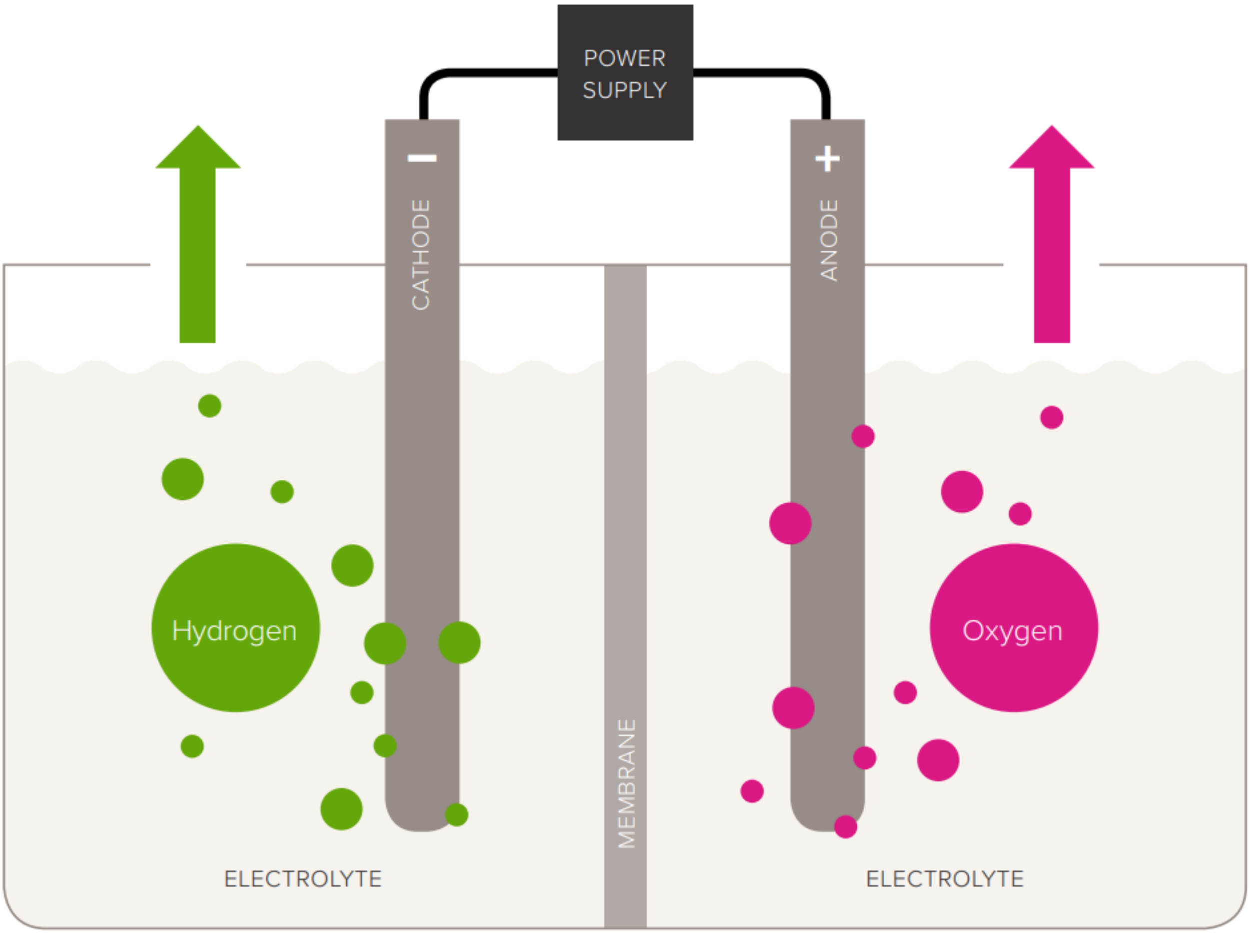
## 3.2 Principles of electrolysis

An electrolyser is composed of:

- the cell where the electro-chemical process takes place. This typically consists of two electrodes (anode and cathode) with electrolyte separated by membrane or diaphragm which facilitates transport of reactants whilst preventing gas transfer. Bipolar plates provide mechanical support and distribute the flow
- the stack which generally consists of multiple cells connected in series, spacers (insulating material between two opposite electrodes), seals, frames (for mechanical support) and end plates (to avoid leaks and collect fluids)
- the balance of the plant which may include power supply (for example transformer and rectifier), water supply and purification (for example demineralisation), hydrogen purification and compression

**Figure 3 – Typical electrolysis cell (The Royal Society, Ref. 13)**

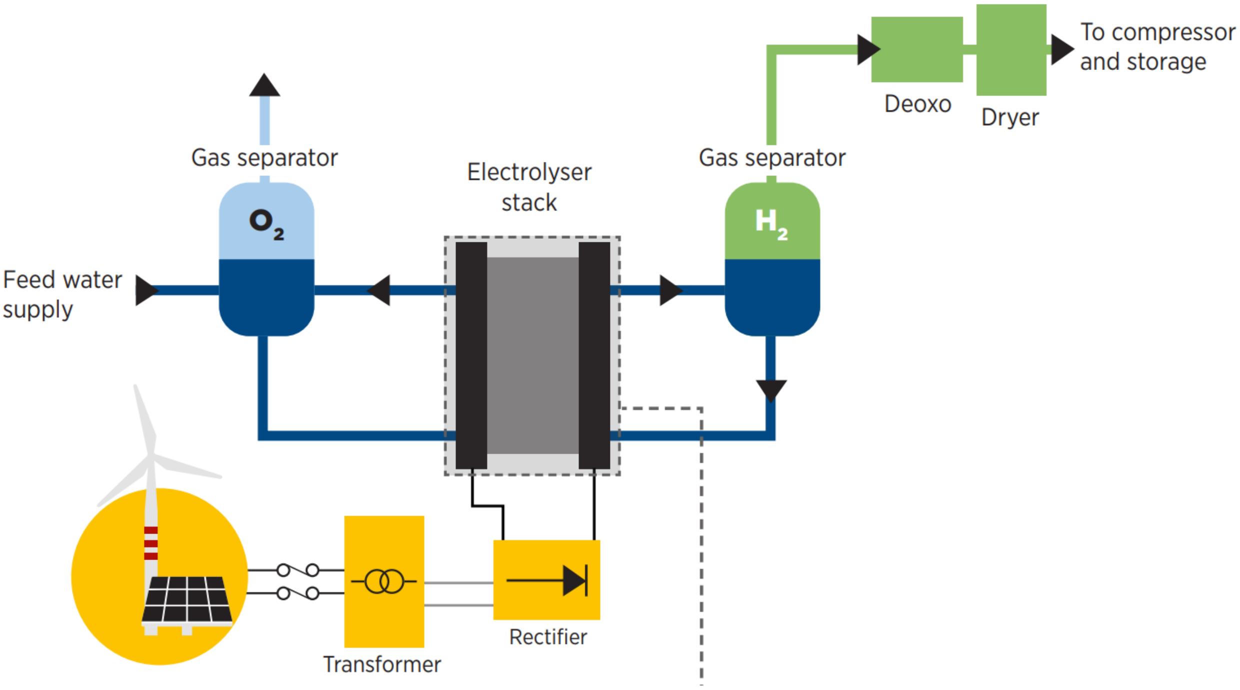
The figure is a diagram of a basic electrolysis cell showing a power supply to the cathode and anode submerged in an electrolyte with hydrogen being produced from the cathode and oxygen being produced from the anode. A membrane separates the cathode from the anode.



Feed water is first purified to removal all mineral content, and is then pumped to feed the electrolyser system. At the electrode, water is split into oxygen and hydrogen. Depending on the technology, $H^+$ (positive) or $OH^-$ (negative) ions cross though the diaphragm or separator. The membrane or diaphragm between the electrodes keeps the produced gases (hydrogen and oxygen) separate.

**Figure 4 – Typical overall process for hydrogen by electrolysis (IRENA, Ref. 14)**

The figure is a basic process flow diagram of an electrolyser stack or unit showing direct current electricity and feed water supply to the stack with oxygen gas separator with oxygen vent to atmosphere and hydrogen gas separator with hydrogen to deoxidiser and dryer prior to compression and storage.



## 3.3 Electrolyser technologies

Individual technologies are reviewed in this section, with further details included in Appendix A.

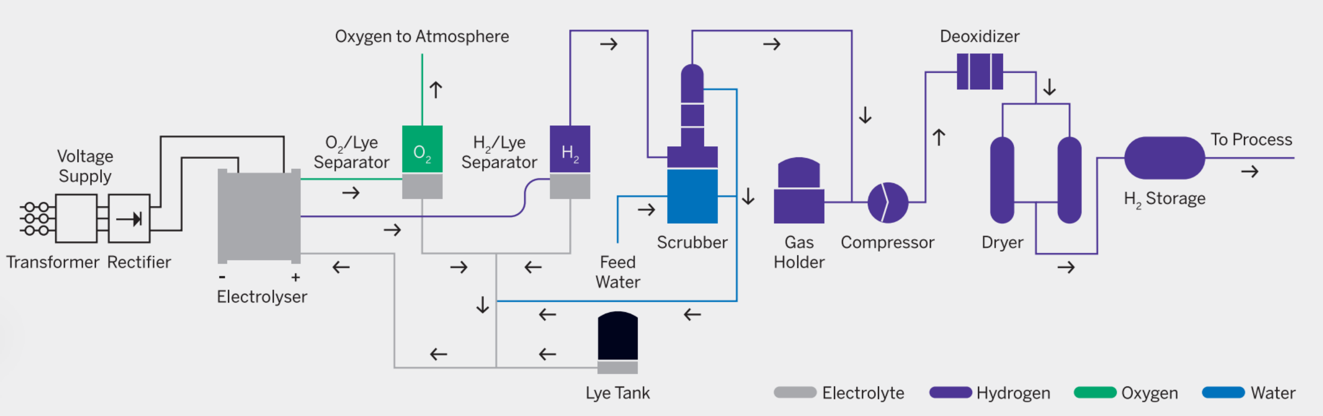
### 3.3.1 Alkaline

Alkaline electrolysis is a long-established means of hydrogen production. There are hundreds of operational units, with many at industrial scale (above 10 MWe). The process is similar to chlor-alkali electrolysis, which is employed at even larger scale for the simultaneous production of chlorine, sodium hydroxide and hydrogen from brine. Typical operating temperature is 70 to 90°C, with operating pressure from atmospheric to 30 barg.

Historically, these systems have not been required to respond rapidly to electrical supply variations. Improving start-up and response times is a focus area for research and development.

**Figure 5 – Alkaline electrolysis system, typical (Nel, Ref. 15)**

This figure is a process flow diagram of a typical atmospheric alkaline electrolysis plant from electricity and water inputs. It shows the flow of alkaline electrolyte and detail of the hydrogen treatment, drying and compression before storage. This is described in more detail in Appendix A1.



### 3.3.2 Polymer electrolyte membrane or proton exchange membrane (PEM) electrolysers

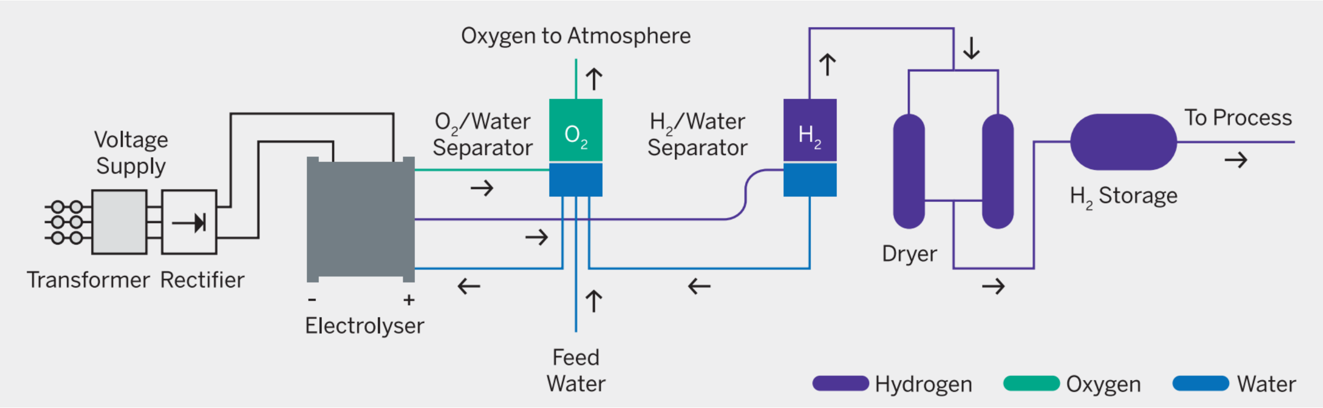
PEM electrolysers were developed in the 1960s. These use a thin perfluoro-sulfonic acid (PFSA) membrane which is mechanically robust, allowing for high pressure differentials across the membrane with hydrogen typically at elevated pressure and the oxygen side at a lower pressure, sometimes atmospheric. Typical operation is at relatively low temperatures (50 to 80°C).

PEM electrolysers are typically installed as a single stack, or multiple stacks to achieve higher production rates. At smaller capacities, the electrolysers are typically supplied as packages, often containerised, with all supporting equipment including hydrogen production, electrical equipment, water purification and cooling systems. Electrolyser stacks of 1 to 2 MWe are available commercially and multiple stacks are used to achieve larger capacities.

High turndown capability, rapid start-up and response to load changes make PEM technology a good candidate for connection to renewable power sources such as wind and solar.

**Figure 6 – PEM electrolysis system, typical (Nel, Ref. 15)**

This figure is a process flow diagram of an electrolyser stack or unit showing direct current electricity and feed water supply to the stack. It shows an oxygen gas separator with oxygen vent to atmosphere and hydrogen gas separator with hydrogen to deoxidiser and dryer prior to compression and storage.



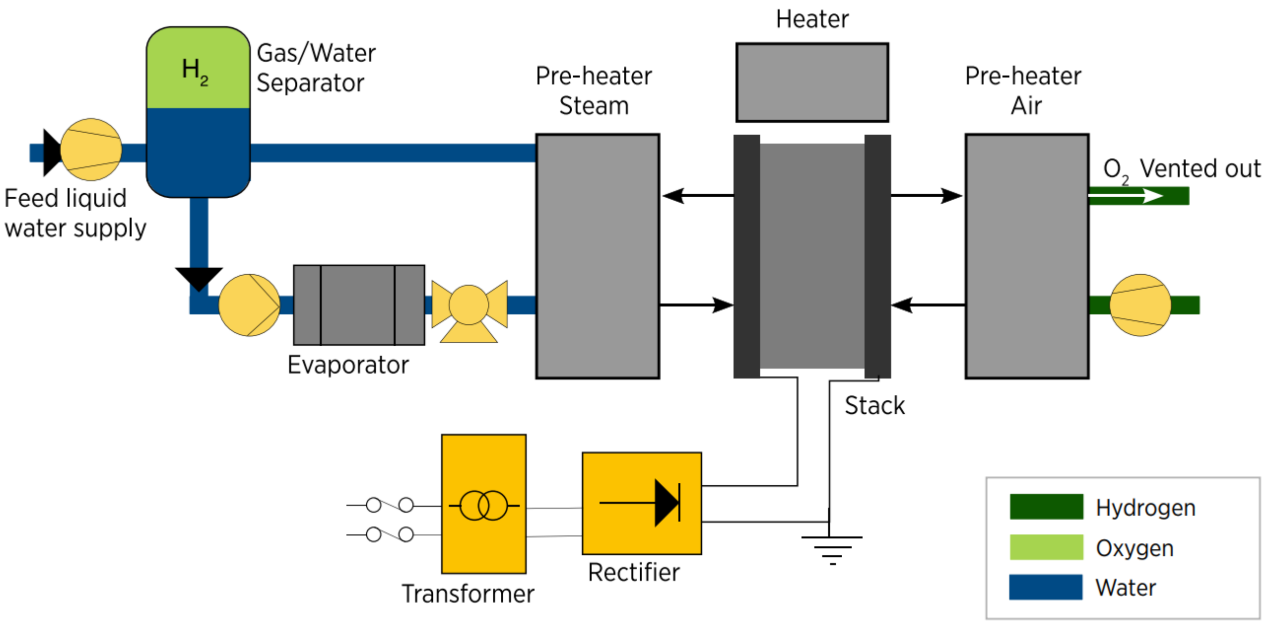
## 3.3.3 Solid oxide electrolyser cell (SOEC)

SOEC electrolysers are currently at a relatively low TRL but offer the potential for high electrical efficiency, with a proportion of the energy required being supplied as heat, and for large-scale integration with other industrial processes.

SOEC electrolysers offer the potential for more efficient operation than alkaline or PEM electrolysers. Operation at elevated temperatures (500 to 1,000°C) results in faster reaction kinetics and could enable lower cost electrode materials to be used. With less operational flexibility than other electrolyser technologies, SOEC applications are likely to be in large installations co-located with industrial processes where heat requirements can be integrated.

**Figure 7 – System diagram for generic SOEC electrolysis (IRENA)**

This figure shows a basic process flow diagram of a solid oxide electrolyser stack or unit showing direct current electricity and feed water supply to the stack. Steam is supplied to increase the temperature at which the electrolyser operates. There is an air heater and oxygen vent to atmosphere. There is a hydrogen gas and water separator.



### 3.3.4 Lower TRL technologies

**Anion exchange membranes (AEM)**

AEMs have potential for future developments, but are currently a less mature technology, with lower TRL than alkaline, PEM or SOEC electrolysers. Fewer technology companies and original equipment manufacturers (OEMs) are involved in their commercialisation.

Potential advantages include:

- less corrosive electrolyser conditions compared to alkaline electrolysers, potentially offering opportunity for lower cost materials of construction and/or reduced levels of degradation
- similar simplicity and efficiency to PEM electrolysers. Response time is faster than SOEC due to low temperature operation
- use of non-noble catalysts and titanium-free components leading to lower capital cost compared with current technologies with costly materials of construction

**Other technologies**

Other lower TRL technologies identified include:

- direct photo-electrolysis
- membrane-free electrolyser
- super-critical electrolysis
- microbial electrolysis
- plasma electrolysis

## 3.4 Technology

### 3.4.1 Evaluation criteria

The considerations most relevant to environmental performance are examined in more detail in section 4:

- hydrogen production rate
- electrical efficiency
- capital cost
- materials and resources used in manufacture (including rare earth metals and PFAS)
- operational flexibility – including speed of response
- emissions and effluents
- component design life – including degradation in use, frequency and cost of major outages for repairs/replacement of worn out components
- water quality
- hydrogen product conditions for example pressure, purity
- decommissioning, ease of recycling

There are trade-offs in design, such as stack size (for example technical considerations of combining multiple smaller stacks together for large projects) and materials vs. cost, electrical efficiency and design life. Also, there are some key differences in the performance of alternative technologies, such as start-up and response time. The selection and optimisation of the electrolyser technology will depend on project-specific requirements including safety, technology maturity and commercial considerations.

### 3.4.2 Technology maturity

The technology landscape has potential to evolve rapidly. Technologies currently with low technology readiness level (TRL) have potential benefits that could make them more attractive than established technologies. Established technologies can also improve through further research and development (R&D) and focus on changing market needs.

For the purposes of this guidance, technologies with different TRL are grouped according to maturity, as follows:

- **Mature** – Technology proven at large scale. Scale-up of some elements may still be required.
- **Novel at Scale** – Technology proven at a smaller scale or deployed in other industries for example chemical production.
- **Low** – Technology at Research and Development level and not yet proven at a pilot scale.

Technology maturity for the electrolyser technologies considered is summarised in Table 1.

Table 1 – Electrolyser technology maturity

| Technology | Current readiness level | Industries used |
|---|---|---|
| **Alkaline** | Mature – with recent developments for increased operating pressure | Hydrogen, Chlor-alkali |
| **PEM** | Mature – at least at smaller scale, with scope for development at larger scale | Hydrogen |
| **SOEC** | Novel at Scale | Hydrogen, Ammonia |
| **AEM** | Low – development expected in short term | Hydrogen |
| **Membrane-free electrolyser** | Low | Hydrogen |
| **Direct photoelectrolysis** | Low | Research stage |
| **High-pressure electrolyser** | Low | Research stage |
| **Microbial electrolysis** | Low | Research stage |
| **Plasma electrolysis** | Low | Research stage |

## 3.5 Performance

### 3.5.1 Electrolyser key parameters

Electrolyser efficiency depends on a range of variables including:

- load: stack efficiency decreases as load levels increase
- voltage: cell voltages are monitored to determine system performance and efficiency
- process conditions: higher stack pressures can decrease performance for PEM, alkaline, SOEC and AEM. Performance increases with temperature up to an optimal point, beyond which additional cooling is required
- electrolyte concentration: can be increased to improve efficiency without extra energy input up to an optimal range or concentration difference between anode and cathode [Ref. 17]
- membrane or diaphragm thickness: thinner membranes in PEM electrolyser (or alkaline electrolyser membrane or diaphragm) improve efficiency
- deterioration: performance deterioration of the order of 1% has been reported by technology suppliers for PEM and alkaline. SOEC yet to be determined

Some factors are competing and need to be optimised, such as:

- thinner membranes increase the risk of pinhole failures due to the build-up of solid deposits from electrodes
- higher operating pressure generally reduces stack efficiency. It also potentially impacts safety and required separation distances. Conversely, higher pressures may reduce hydrogen compression requirements

These factors will typically impact the operational or capital costs for the project.

### 3.5.2 Key performance indicators (KPIs) for electrolyser system

Several KPIs have been identified relating to electrolyser performance:

- **specific power consumption, kWh/kgH$_2$:** electrical energy supplied to the rectifier supplying the electrolyser per unit mass of hydrogen produced. Electrolyser efficiencies reported by IRENA [Ref. 14], Haldor Topsoe [Ref. 16] and E4Tech [Ref. 18] are largely consistent with KPIs developed by the European Energy Research Alliance [Ref. 19]
- **stack efficiency (also known as DC efficiency):** this is the product of Faraday efficiency (also known as current efficiency) and the voltage efficiency. Note that these may or may not include factors such as rectification losses and other plant electrical power demands (such as for water treatment, cooling, auxiliary packages, hydrogen compression and hydrogen purification), or for provision of electrical power for buildings
- **electrolyser system efficiency:** typically calculated as a percentage total electrical energy input produced as hydrogen (based on heating value). It must be stated whether the efficiency is based on the higher heating value (HHV) or lower heating

value (LHV). The efficiency of the electrolyser stack and the balance of plant (BOP) systems can also be considered separately

- **electrical current density:** higher current density leads to increased hydrogen production for a given stack size but reduces electrical efficiency. The optimisation between current density and efficiency is the focus of research and development activities
- **balance of plant:** based on the downstream application, the use of compression, liquefaction and transport system bring about inefficiencies. Varying loads will cause equipment to operate at different points on their performance curves

**Table 2 – Electrolyser performance comparison**

| KPI or parameter | Units | Alkaline | PEM | SOEC |
|---|---|---|---|---|
| **Cell temperature** | °C | 70 – 90 | 50 – 80 | 700 – 850 |
| **Pressure** | barg | < 30 | < 30 | 1 |
| **Current density** | A/cm$^2$ | 0.2 – 1.0 (present)<br>> 2 (2050) | 1 – 3.3 (present)<br>4 – 6 (2050) | 0.3 – 1.0 (present)<br>> 2 (2050) |
| **Hydrogen purity (post drying)** | % | 99.9 – 99.9998 | 99.9 – 99.9999 | 99.9 |
| **Voltage** | V | 1.4 – 3 | 1.4 – 2.5 | 1.0 – 1.5 |
| **Voltage efficiency (LHV) (Note 1)** | % | 50 – 75 | 50 – 68 | 75 – 85 |
| **Stack power requirement (Note 1)** | kWh/kg $H_2$ | 45 – 66 | 45 – 66 | 35 – 50 |
| **Lifetime** | h | 60 – 80k | 50 – 80k | < 20k |
| **Stack size (Note 2)** | MWe | 1 – 20 | 1 – 2 | 0.005 |
| **Cold start** | min | < 50 | < 20 | > 600 |
| **Minimum load** | turndown % | 15 | 5 | 30 |

Notes:

1) Efficiency dependent on % operating load
2) Maximum stack size for alkaline water electrolyser is dependent on operating pressure
3) References for Table 2 from IRENA, Technology Supplier Data, E4Tech

## 3.6 Electrolyser production

### 3.6.1 Demand

Estimates of current worldwide manufacturing capacity vary from 1.2 to 4.5 GWe/year. Predicted demand for hydrogen will require significant increases in electrolyser manufacturing capacity [Ref. 20]; in response, manufacturers have announced plans to step up production rates sharply over the next decade.

Cost reduction of approximately 50% is anticipated once 1,000 units of 1 MWe capacity are produced per year [Ref. 14]. As the rate of electrolysers manufacture increases, the capacity of recycling facilities will also need to increase in parallel.

### 3.6.2 Materials of construction

Electrolyser systems, regardless of technology type, require specific materials for their manufacture. This presents a growing challenge due to the scarcity of these materials and the geo-political complexities of the supply chain. Processing of these materials may also have significant energy requirements, thus generating emissions with high lifecycle global warming potential.

Alkaline electrolysers avoid the use of precious metals but require significant nickel content to withstand caustic conditions. Current designs use 800 kg of nickel per MWe [Ref. 21] although this is low compared to batteries. Per MWe capacity, they may also require 100 kg zirconium, 500 kg aluminium and 10 tonnes of steel in addition to lower quantities of cobalt and copper catalysts. Some designs incorporate platinum group metals.

PEM electrolysers place significant demand on platinum and iridium resources. Current use ranges from 0.3 -1.0 kg per MWe platinum and 0.7 kg per MWe for iridium. Future reduction to 10% of current levels could be possible [Ref. 20] with tantalum a potential alternative for the cathode coating. Continued reduction of precious metal loading remains a focus. PEM electrolysers may contain PFAS if used in membranes/seals

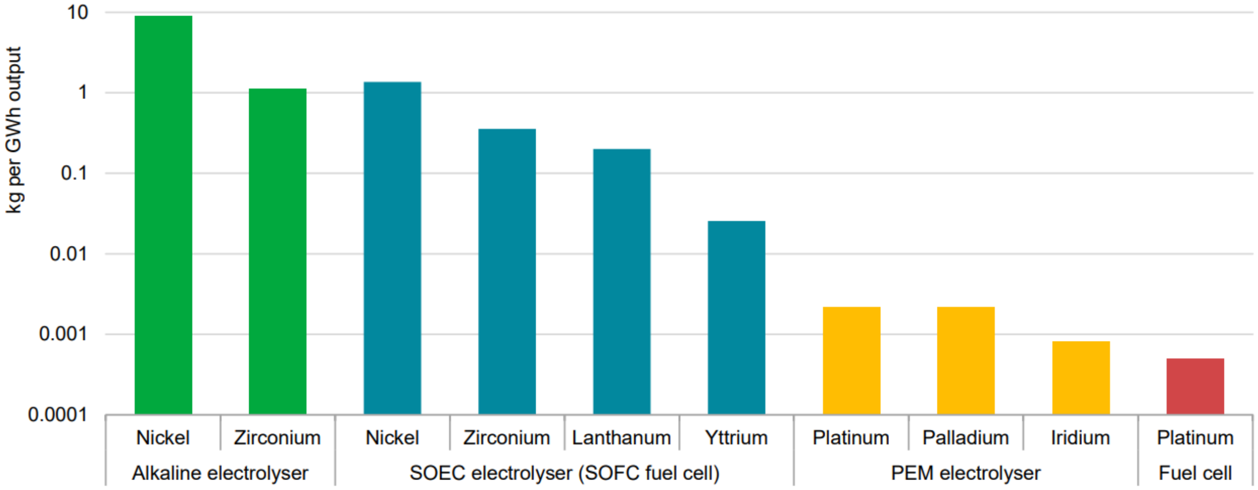
SOEC electrolysers include materials exclusively obtained from a limited range of global sources. Nickel content currently required is 150-200 kg per MWe but with potential to reduce to below 10 kg per MWe.

The IEA report ‘The Role of Critical Materials in Clean Energy Transitions’ [Ref. 14] outlined the levelized demand for selected materials used in electrolysers noting that effective end-of-life recycling will play a key part in reducing the use of critical materials as will reducing the quantity of material used in manufacture. A report by the British Geological Survey [Ref. 37] noted Iridium in particular could become a limitation for PEM technology, unless improvements are made to efficiency (using less metal) and recycling.

Production of electrolyser materials is concentrated in a small number of countries. Platinum and iridium are predominantly mined in South Africa [Ref. 37], with several minerals being produced solely in China.

### Figure 8 – Electrolyser material requirements (IEA, Ref.21)

This graph shows estimated levelised demand for selected materials in electrolysers and fuel cells. This is indicative of the types and amounts of metals in kg per GWh of output which could be needed for different types of electrolysers and fuel cells.



Recycling processes need to be developed at scale to maximise the end-of-life re-use of critical materials. Appropriate recycling technologies may include hydrometallurgy, pyrometallurgy, transient electrochemical dissolution, selective electrochemical dissolution, and acidic process.

**Figure 9 – Lifecycle GWP of critical materials (IRENA, Ref. 14)**

This graph shows the lifecycle global warming potential and cumulative energy demand for a selection of critical materials used for electrolysers.

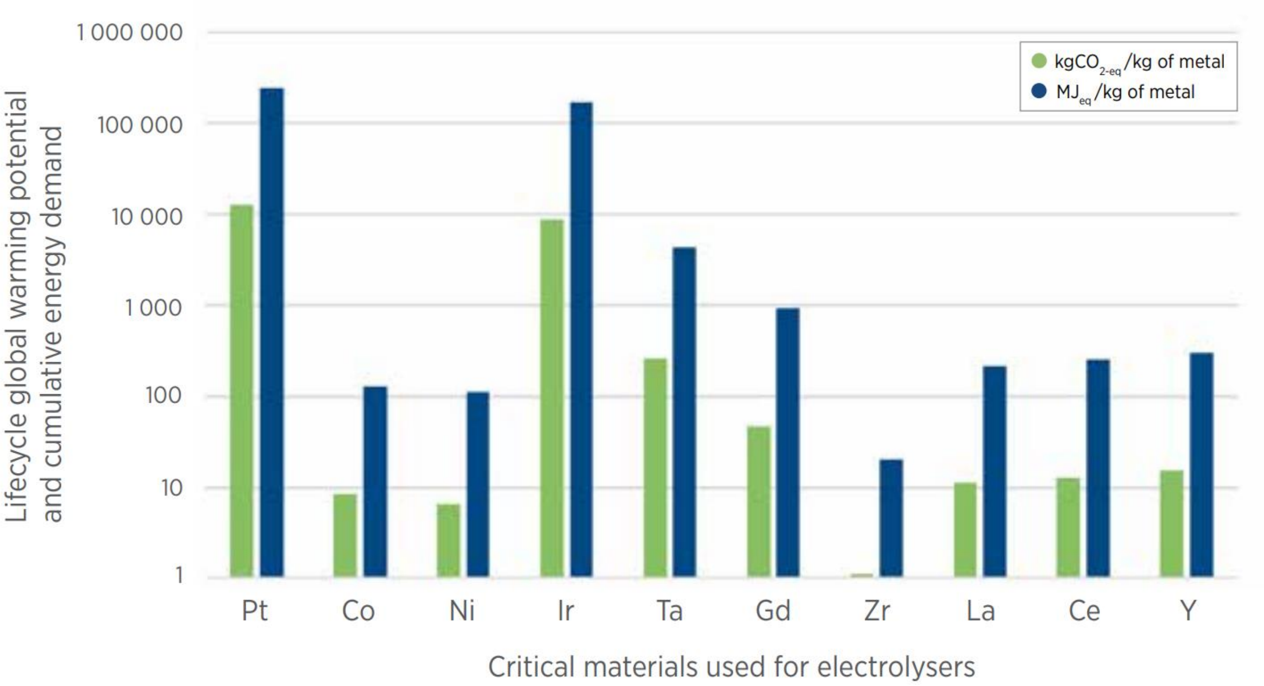
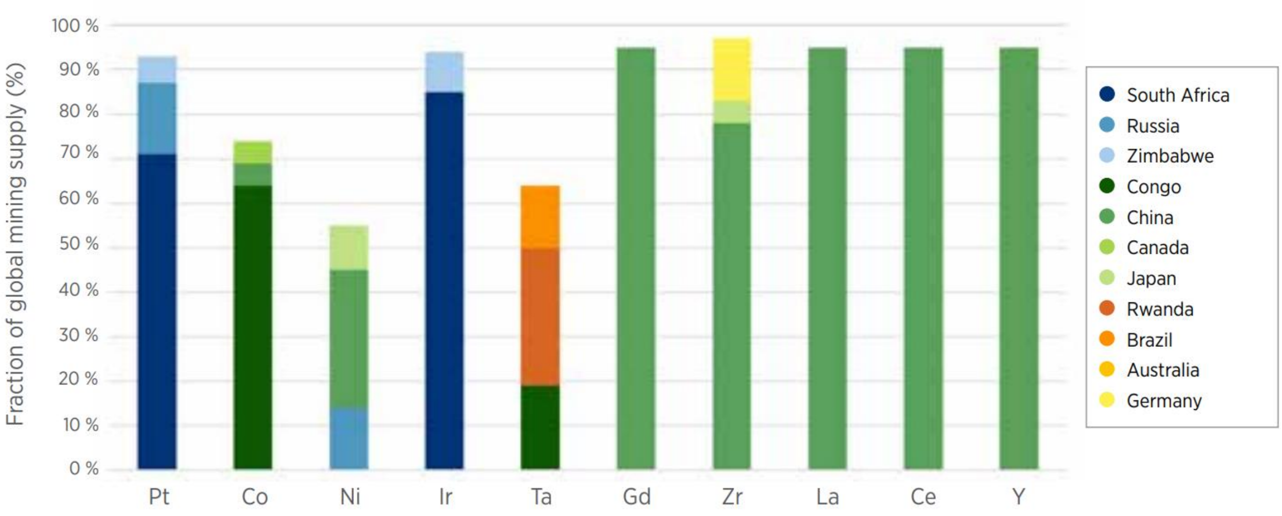


**Figure 10 – Source country of critical materials (IRENA, Ref. 14)**

This graph shows the source countries of critical materials which may be used in electrolysers. It shows the fraction of global mining supply by country for a selection of critical metals.



# 4. Environmental considerations and guidance

## 4.1 Production scale

### 4.1.1 Electrolyser system modularity

With demand for higher production rates, electrolyser manufacturers have focused on the scale-up of the stack components. This reduces the number of components, footprint and capital cost, although multiple parallel stacks may still be required to achieve larger capacities.

Smaller units (for example < 2MWe) are often supplied complete with all supporting systems, typically in a containerised package. At larger capacities, common cooling water systems, hydrogen purification and compression systems, and water treatment systems are often justified.

The increase in potential for environmental impact is not fully linear with the increase in capacity (MWe) of the facility and as it will depend on the specific design and integration of the facility at a particular location. Additionally, at larger scale there is greater potential to justify additional investment in equipment that can improve environmental performance for example more efficient water demineralisation, recovery and use of waste heat, and systems for disposal or recovery to avoid vented hydrogen.

In the near term, an increasing number of small-scale electrolyser installations (< 2 MWe) might be expected in the UK, producing hydrogen for transport use. For industry, larger scale units are likely to be proposed.

Electrolyser systems are typically described by the maximum MW electrical power (MWe) provided to the electrolysers only. This does not account for any power requirements for the rest of the installation.

Typical values quoted: (rule of thumb hydrogen production rate 1MWe ~ 150 tonne/y ~17 kg/h)

- <2 MWe e.g., for supply to fuel-cell electric vehicle (FCEV) fleet
- A number of these already have environmental permits.
- 2 to 20 MWe e.g., for on-site industrial use, chemical production or oil refining. Also for regional transport fuel hubs and for wastewater treatment.
- >20 MWe e.g., for wider supply to industry via hydrogen networks and/or injection into natural gas networks

Future developments in the medium to long-term of up to 3 GW scale have been proposed.

### 4.1.2 Safety

The scope of this review and guidance is limited to preventing or reducing emissions into the environment and does not cover other aspects such as safety. However, safety will need to be considered as part of any project, such as major accident hazard potential increases with production scale, particularly where this leads to increased onsite hydrogen inventories, for example for compressed hydrogen storage.

Facilities with large hydrogen inventories will need to be managed as COMAH (Control of Major Accident Hazard) sites: lower tier at > 5 tonnes hydrogen, upper tier at > 50 tonnes. Larger inventories lead to increased safety separation distances with impact on land requirements. Other safety legislation may also apply, such as DSEAR (The Dangerous Substances and Explosive Atmospheres Regulations).

## 4.2 Overall system design and integration

Integration of water, electrolyte heat recovery, hydrogen storage and utility systems with the electrolysers will need to be considered. As a guiding principle, the overall system should be designed to achieve the required operational flexibility with maximum efficiency, taking into account the overall environmental impact.

A list of considerations identified includes:

- high efficiency and low environmental impact of the whole facility in addition to individual equipment items.
- input from OEMs, particularly electrolyser suppliers, to ensure that environmental consequences of operation/maintenance are considered.
- potential inclusion of battery electrical storage to provide a steady power supply to the installation when there is intermittent availability of renewable power, such as from wind or solar.
- higher pressure operation may increase safety concerns, potentially introducing requirements such as blast walls located between electrolysers.
- leak detection and management (including potential for leak-free valve designs) to reduce potential emissions, which have both environmental and safety-related impacts.
- assessment of pressurised storage requirements to manage hydrogen supply and demand
- understanding of overall system design and performance under a range of operating conditions.
- seeking opportunities to simplify the system design where possible
- ensuring equipment is appropriately sized (including design margins) to give best efficiency and minimise energy use, water use and heat loss. As electrolysers operate more efficiently at reduced load, load sharing control between individual electrolysers should allow optimal operation of the overall facility.
- consideration of differently sized parallel units to cover a range of duty points
- designing the system to operate safely and efficiently for the range of operating scenarios. Optimising efficiency of operation for the most common operating conditions is key to minimising environmental impact

- review potential for heat recovery and re-use through structured review of the system design
- consideration of water recovery within the installation
- utility systems optimisation
- consideration of environmental impacts to include design of equipment and control schemes for associated equipment
- evaluation of water supply source including options such as treated industrial wastewater

## 4.3 Water

### 4.3.1 Water demand

As water is converted electrochemically to produce hydrogen and oxygen, 9 kg of water is consumed per kg of hydrogen produced. In practice, requirements to make up losses such as from feed water purification, vapour losses with the hydrogen and oxygen products, and losses from cooling water systems, mean the water demand will be higher. Water resource uncertainties may be a limiting factor to any proposal, depending on local factors, so should be a key consideration at the design stage.

Opportunities to recover, recycle and re-use water should be taken where possible. An example is re-use of the water recovered from hydrogen dehydration. All wastewater streams should be identified including effluents such as cooling water blowdown, collected rainwater run-off, water treatment effluent and water used for cleaning. Suitable segregation strategies and methods of treatment to meet discharge consent limits should be defined. There may opportunities to integrate oxygen produced in electrolysis with the biological treatment processes used to treat wastewater.

### 4.3.2 Feed water treatment and associated effluent

Impurities in water (for example iron, chromium, copper, silicon, aluminium, boron, and chlorides) affect performance in both alkaline and PEM electrolysers. The required quality of feed water and the associated water treatment is therefore a key consideration. Water may be sourced from surface water, ground water, potable water, sea water or effluent.

Raw water quality will typically be required to produce water of sufficient quality to feed the electrolysers. This may be achieved using filtration, reverse osmosis, and ion exchange (or other technology that can achieve equivalent purity), with a portion of the raw water feed, containing the impurities, rejected as effluent.

Higher levels of impurities in the raw water will typically lead to reduced recovery and higher raw water use, or more complex treatment requirements, including the disposal of streams containing rejected impurities. There could be an environmental trade off to consider between the quality of raw water versus the increase in effluent load from water treatment plants. It is possible however to desalinate sea water to produce demineralised water of a suitable quality, as proposed in offshore applications, and this could also be practiced onshore to reduce use of fresh water supplies.

Power requirements for production of demineralised water from fresh water feed are estimated to be less than 0.05% of the associated electrolyser power input, based on use of reverse osmosis and continuous electro-deionisation. Desalination of sea water would have three to five times the power requirement, but would still not be a major contributor to overall energy efficiency [Ref. 38].

Future electrolyser developments have potential to reduce water treatment requirements, effluent from water treatment, and overall raw water demand. These developments include allowing the use of lower quality feed water and the use of by-product water from the electrolysis operation.

The BRef document for Common Waste Water and Waste Gas Treatment/Management Systems in the Chemical Sector [Ref. 24] should be referred to.

## 4.4 Venting and flaring

### 4.4.1 Hydrogen release

Any hydrogen releases (whether planned or unplanned from leaks, failures and accidents) have an environmental impact. A recent study [Ref. 25] estimated the 100-year window for the GWP of hydrogen is 11 ± 5, significantly higher than previous estimates.

There may be opportunities to recover hydrogen from vented off-specification gas from such sources as:

- purging and venting of off-specification hydrogen including at start-up, shutdown or deviation from normal operation. If the electrolyser is operated intermittently this would lead to greater volumes of vented hydrogen
- venting due to hydrogen cross-over, that is where a small amount of hydrogen migrates across the electrolyser membrane to the anode and is ultimately vented. (Cross-over of oxygen is less likely though must be avoided to prevent potentially explosive mixtures developing)
- purging required for regenerating units used for hydrogen purification (for example PSA)

A report commissioned by BEIS [Ref. 26] estimated the amount of hydrogen vented from electrolyser processes to be in the range 3% of production (50% confidence interval) to 9% of production (99% confidence interval). At start-up, air in the cathode side is vented to avoid an explosive mixture being generated. Similarly, at shutdown it is vented again to remove moisture and prevent an explosive gas mixture from forming. Minimising off-specification hydrogen production is preferable, as regular venting impacts overall operating efficiency and increases emissions of hydrogen.

Venting of hydrogen impurity in the oxygen byproduct is another potential source of emissions. Losses of hydrogen with the vented oxygen stream should be assessed, particularly at low load conditions (operation at which is otherwise desirable from an energy efficiency perspective), also considering the impact of degradation of the membrane. Where oxygen is utilised, this will also impact purification requirements.

Venting of streams containing hydrogen and oxygen must be performed safely. Purging with nitrogen may also be required, particularly for cold start-ups, resulting in more hydrogen being discharged to the environment. Opportunities to recycle should be sought using such strategies as capturing, storing and recycling off-specification hydrogen and/or oxygen. Combustion in air or oxygen, or alternative conversion techniques, for example recombination of hydrogen and oxygen to reduce hydrogen emissions.

Combustion of waste streams, for example in a flare system, would avoid emission of hydrogen gas with global warming potential, although recovery of hydrogen would be preferable to both flaring and venting. A flare system could be considered for disposal of hydrogen, subject to suitable design and controls to ensure safe operation.

Hydrogen product buffer storage capacity may be considered to reduce intermittent operation and avoid one of the causes of hydrogen venting. Connection to a pipeline distribution network, providing both buffer volume and more diversity of use, may also reduce intermittent operation. However, increased on site hydrogen storage capacity would have implications for risk of accidents.

### 4.4.2 Oxygen

Oxygen is co-produced via water electrolysis at a rate of 8 kg of oxygen per kg of hydrogen. As there are well established alternative production methods, it is likely to be vented in smaller installations.

Considerations associated with oxygen venting include local oxygen enrichment of air close to the discharge point. The vent should be located to aid dispersion to minimise fire and explosion risk.

Options to purify and/or utilise the oxygen should be assessed, potentially improving the resource efficiency and economics of a given scheme. This could also offset the energy used to produce oxygen by other means, for example air separation using membrane, pressure swing adsorption or cryogenic processes.

Consideration should also be given to oxygen purification to remove small quantities (0.5 to 1.0 vol%) of hydrogen.

As SOEC technology produces an oxygen enriched air stream, with around 50 vol% oxygen, use of this for combustion of fuels may be more advantageous.

Potential oxygen uses include:

- medical: a techno-economic study by the Italian national energy advisory service (ITAE) assessed the potential to produce oxygen for several hospitals nearby, concluding such a scheme could be economically viable [Ref. 27]
- hydrogen production: for example via auto-thermal reactor (ATR) or partial oxidation (POX)
- industrial: for example steel, glass, pulp and paper, metal refining, pharmaceuticals, ethylene dichloride via oxychlorination.
- oxy-combustion: potentially including carbon capture
- biomass gasification: hydrogen production
- wastewater (sewage) treatment processes
- use of oxygen-enriched air to reduce combustion emissions

## 4.5 Electricity

Electrical demand increases with electrolysis plant scale and dominates other requirements.

Sources of electricity supply for electrolysis include:

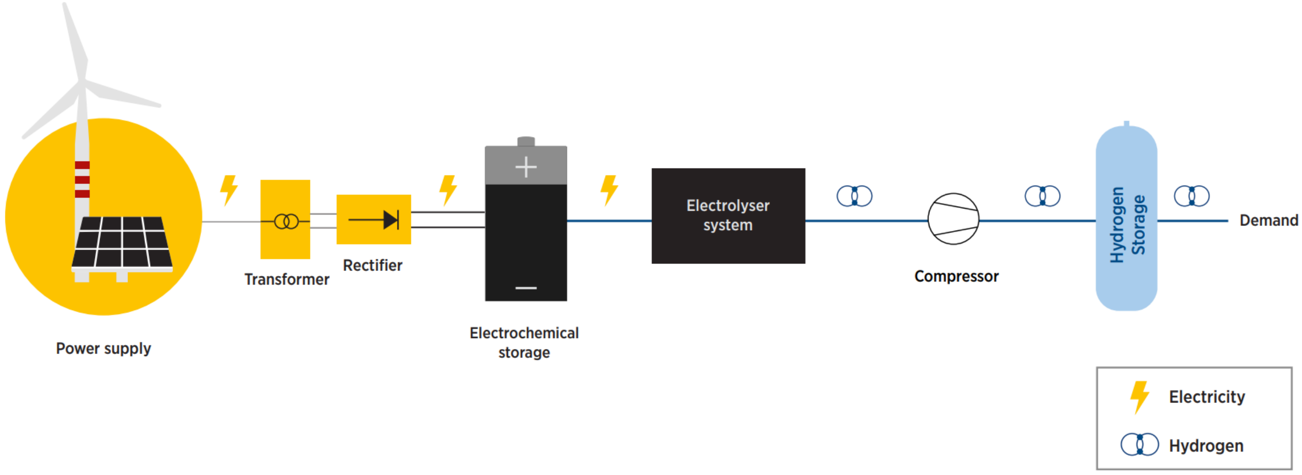
- grid-connected: with commercial agreement for electricity purchase from specific generators or use of grid electricity with carbon intensity at time of use
- off-grid: with private wire connection to renewable generation with potential to include battery storage. Electrolysers can ‘time shift’ the use of renewable power as the hydrogen produced can be more easily stored than the electricity. Intermittent renewable generation can however impact electrolyser operation and lead to a need for hydrogen venting

Each option has practical considerations relating to cost, grid connection (location and capacity) and distance from generation facilities.

In addition to electrolysers, there is also demand from auxiliary/supporting services. These introduce a standby load when the electrolysers are not producing hydrogen. If turndown capability is needed, parallel systems can be considered.

**Figure 11 – Potential scheme for electrolysis via renewable power (IRENA, Ref. 14)**

The figure is a basic system schematic of a hydrogen production facility which shows a renewable power supply to electrochemical storage supplying an electrolyser system before compression and storage.



## 4.6 Electrolyte supply, treatment and recovery

Electrolytes are contained in a closed, recirculating loop. These require periodic recharging and replenishment. Electrolyte should be appropriately stored, transferred and recycled or treated for disposal to minimise the risk of release to ground or surface waters and to minimise wastes.

## 4.7 Hydrogen product specification

Hydrogen product specifications will reflect users' requirements. Although use in combustion (for example for heat) requires lower purity than for use fuel cells (for example for transport applications), hydrogen from electrolysis will typically be of higher purity than required. Whilst 99.999 mol% hydrogen is often quoted for fuel-cell applications, the relevant ISO standard [Ref. 28] requires 99.97 mol%, with specific limits on individual components which can impact operation or life of fuel cells.

Further unit operations may be used to condition the hydrogen produced, including:

- deoxidisers – for example with catalytic reaction of hydrogen with oxygen if necessary, at elevated temperature upstream of dehydration
- compression systems – for example with reciprocating compressors for delivery to pipeline or into pressurised storage
- dehydration systems – for example using glycol absorption or temperature swing adsorption

Higher hydrogen purities require additional treatment with implications for costs (capital and operating) and the potential for additional emissions, for example in tail gas from regeneration of pressure swing adsorption (PSA) purification unit.

The current focus in the UK is the production of gaseous hydrogen. Liquefaction is also a possibility in future for transportation of hydrogen, and for end use in mobility applications (for example aviation). This would require liquefaction facilities which would be inside the scope of this guidance if located with the electrolyser installation. Technology would likely include complex refrigeration cycles with multiple compressors or turbo-expanders for pre-cooling and liquefaction, as well as impurity removal, and catalytic ortho- to para-conversion, to facilitate low pressure storage at cryogenic temperatures of around -253°C (20K).

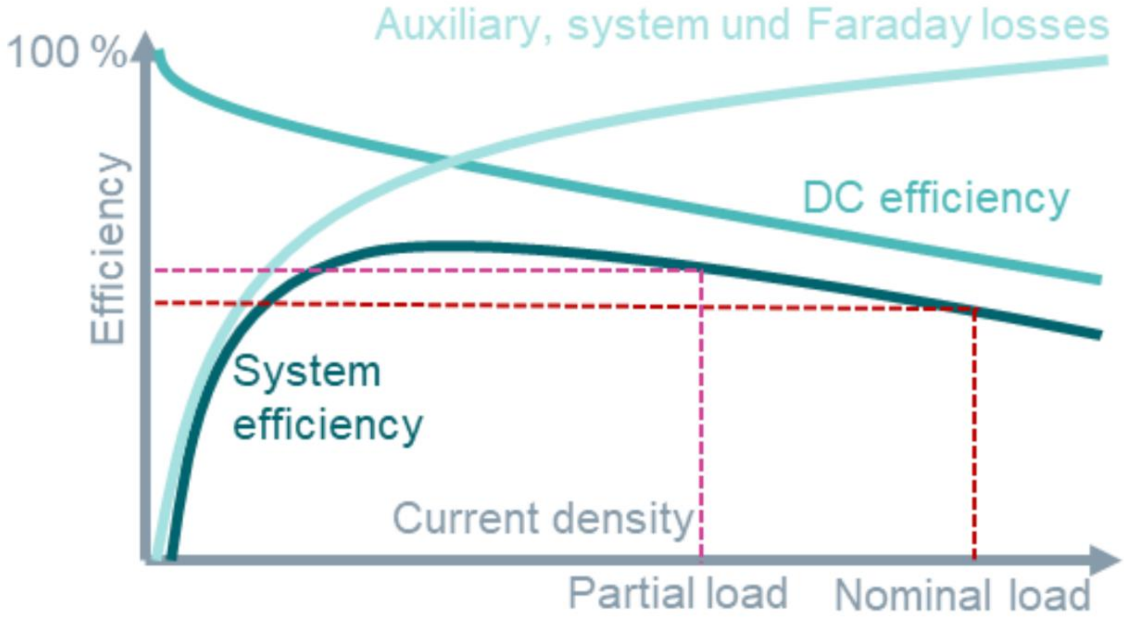
## 4.8 Electrolyser

### 4.8.1 Operation and performance

Electrolyser efficiency depends on its operating point.

**Figure 12 – System efficiency, PEM and alkaline electrolysers (Siemens, Ref. 29)**

This figure is a graphical representation showing a typical electrolyser system efficiency against system load and its schematic shape. This is described in this section.



Understanding electrolyser performance at steady state will enable an optimal operating point to be established. Performance at best efficiency point, maximum capacity and minimum turndown should also be identified. At steady state, emissions should be limited to surplus oxygen produced which has not been captured for utilisation (including any hydrogen content) and any continuous or intermittent purges.

Factors influencing the requirement for flexible (non-steady state) operation include:

- upstream power supply: intermittent input from directly connected renewable generation or from grid electricity (for load shedding and grid balancing).
- downstream hydrogen demand: from a steady state user (for example industrial facility) or from an intermittent user (for example heat, transport).

Dynamic operation will affect the utilities required from auxiliary equipment including water, electricity, cooling, heating and purging. It is anticipated that nitrogen will be required for purging, whether generated on- or off-site. At low operating load, significant losses in efficiency are in part due to the performance of the rectifier in the electrical equipment.

The need for rapid transition between operating points should be established. Performance at non-steady state conditions could make a significant contribution to the overall efficiency and environmental impact of an electrolyser scheme, impacting the amount of hydrogen discharged or resulting in changes in energy efficiency and water usage.

Both PEM and alkaline electrolysers are recognised as technologies that can be integrated effectively through the provision of multiple stacks, potentially each with its own rectifier. The response times for PEM:

- start-up from full shutdown (with nitrogen purge): 40 to 60 minutes
- start-up time from low pressure (with nitrogen purge): 10 to 20 minutes
- time to respond after an operating load change: 1 to 5 seconds

SOEC is a less operationally flexible technology, due to higher operating temperatures. There are much longer cold start-up and shutdown times due to the time taken to either warm up or cool down the process. This increases the likelihood of pairing SOEC technology with industrial users requiring hydrogen, since these typically generate steadier demand.

SOEC warm start-up from elevated temperatures is immediate but a cold start-up could take around 6 hours.

Whilst a wide operating range (5% to 100%) is possible for some PEM and alkaline electrolyser models, operation of some electrolysers at turndown is more limited, requiring more frequent stop-start operation with associated purging. SOEC electrolysers can operate with turndown to 10 to 30% of maximum capacity, depending on the capacity of the unit.

### 4.8.2 Lifetime, reliability and availability

Maximising equipment life is key to maximising hydrogen production and represents best use of scarce resources and of the embedded carbon in the materials of construction. Equipment lifetime is largely determined by the period of time which the electrolyser stack can continue to operate safely and efficiently. There is a difference between electrolyser stack lifetime and overall system lifetime: electrolyser stacks can be replaced when degradation makes their continued use uneconomical. Components requiring periodic replacement in the electrolyser stack produce solid waste, which need to be recycled or managed appropriately.

Electrolyser manufacturers for alkaline, PEM and SOEC indicate a design life of 20 to 30 years depending on the model type and periodic servicing or replacement of electrolyser stack. As alkaline electrolysers have been in commercial operation for much longer than PEM, lifetime values quoted are based on operational data rather than based on estimates. The reliability and lifetime characteristics of large-scale (MW-scale) stacks will be understood better once they have been in operation for a number of years.

Electrolyser availability is dependent upon the reliability of the equipment, and its mode of operation, notably the average time-weighted load and the degree of dynamic operation. Based on central range estimates for alkaline and PEM technologies [Ref. 18], some 8,500 hours/year operation could be reasonably expected, at an availability of 95 to 97%.

Expected lifetimes vary from 50,000 to 80,000 hours for PEM and 60,000 to 80,000 hours for alkaline. Lower values for SOEC have been reported at around 20,000 hours [Ref. 18]. Whilst 93,000 hours have been reported at laboratory scale for SOECs [Ref. 31], in real-world applications, elevated temperatures and thermal cycling could lead to increased degradation. UK ambient temperatures are not expected to impact significantly on this aspect.

Mechanical and electrical equipment is subject to downtime, for both planned (for example maintenance) and unplanned events. The environmental impact of equipment non-availability should be identified, with the need for planned maintenance, redundancy and buffer storage considered to reduce the frequency and/or impact of other than normal operating conditions (OTNOC). A risk-based OTNOC management plan should be implemented which identifies potential scenarios, mitigation measures, monitoring and periodic assessment.

## 4.9 Heat recovery and cooling systems

Recovery of low-grade heat from electrolysers can reduce energy usage (and associated emissions) for the generation of heat outside of the installation or can offer improved overall energy efficiency for the facility itself. Opportunities to export warm water or steam to other nearby industrial users, businesses or municipal buildings are likely to increase as heat networks become commonplace. Consideration may be given to integration of lower grade heat with heat pumps or organic Rankine cycles (ORC) for power generation.

The attractiveness of heat recovery will depend largely on the amount and quality (temperature) of heat available, and whether this can be made available to an end user in a cost-effective manner. The elevated operating temperatures of SOECs, with a proportion of the required energy provided via heat rather than electrical power, make these a strong candidate for heat integration and heat recovery, especially if co-located with other industrial processes. Co-locating ammonia production is an example where heat recovered could be used effectively in hydrogen production. There is potential to integrate the steam system for SOECs with wider steam generation and distribution systems to maximise efficiency, or to minimise the use of natural gas for heating. Heat exchange and recovery within the SOEC process should be optimised to minimise external heat requirements.

The choice of cooling technology (for example direct air cooling, cooling water with evaporative cooling towers, or cooling water with closed loop non-evaporative cooling systems) will be specific to the process cooling requirements, plant location and water availability for make-up of evaporative losses [Ref. 30].

Consideration should also be given to any chemicals used in the process or in management of cooling water quality. Energy used and water consumed (raw, demineralised, other) after extended shutdown periods should also be considered.

## 4.10 Noise

Noise will originate continuously from such equipment as compressors, pumps, fans, rectifiers, piping and continuous vents. Also, from intermitted flaring or venting operations. Equipment generating noise should be identified at the design stage and their environmental performance should be considered for intended operations. A noise management plan will be required if appropriate as a permit condition and an assessment based on BS4142 may be needed.

## 4.11 Monitoring

### 4.11.1 Operational

Monitoring should be developed as part of the operating strategy. Clearly defined operating limits should be developed for individual equipment and operation should observe these limits supported using automated alarms and trips. This would include leak detection, flame detection, online analysers for oxygen in hydrogen product and hydrogen in oxygen produced.

Monitoring systems gather data on operational performance of the electrolyser and supporting balance of plant. Automated data collection is typical from modern control systems and should be considered at the design phase including:

- process performance for example electrolyser operating parameters
- energy efficiency (calculated as KPI from process parameters)
- mechanical performance and mechanical degradation, where this could impact efficiency, fugitive emissions, etc.
- emissions to air and water

A preventative maintenance programme to inspect equipment in line with vendor recommendations should be implemented. As an example, catalyst de-activation of the electrodes, which can reduce performance over time, has been prevented in some systems via small, idle protective currents to avoid reverse potentials at cathodes.

### 4.11.2 Safety and environmental monitoring

Gas permeation and local hotspots caused by impurities carried over from the electrode coating could lead to pinhole failures: these can be identified by monitoring of hydrogen concentration in the oxygen stream, which would be required in any case to ensure levels remain below flammable limits. Whilst new generation diaphragms and membranes can mitigate this issue, thicker designs improve stack lifetime but also reduce efficiency.

It should be possible to monitor environmental performance of the system in real time, comparing KPIs with operational data collected. This would provide a view of both instantaneous and longer-term performance. Energy used per kg hydrogen produced would be a fundamental parameter to measure, for example. Vented or fugitive hydrogen losses to atmosphere will also be a key parameter to monitor in order to prevent, minimise or abate emissions.

Monitoring of emissions to water will be required based on appropriate methods of measuring. Monitoring standards for discharges to water may follow the BAT conclusions for Common Waste Water and Waste Gas Treatment or Management System in the Chemical Sector (2016/902/EU) [Ref. 24] or the UK equivalent. Operating companies should monitor and record waste emissions, the physical and chemical composition of waste, its hazardous characteristics and handling precautions.

A site condition report, monitoring and remediation plan will be required as part of the environmental permit.

# 5. Request for information response

## 5.1 Response

This guidance document has been developed including information provided by stakeholders in response to a request for information (RFI) document [Ref. 34]. Following a limited response, further information is requested as outlined in section 5.2.

It is in the interest of stakeholders to engage in the ongoing process of developing guidance, and further information will be gathered where available to support further revisions of this document.

## 5.2 Information requested from industry and other stakeholders

It would be helpful to obtain information on energy efficiency and environmental impacts, including quantitative description and quantities of:

- electrical consumption (kWh/kg of hydrogen)
- gaseous emissions
- liquid effluents
- solid wastes

Also, technical information on typical electrolyser configuration and equipment, including:

- electrolyser features for specific technology route
- deoxidiser systems (for example catalytic reaction with oxygen)
- hydrogen compression, dehydration and storage
- equipment included to minimise venting of hydrogen
- heat recovery systems, including lower grade heat with technology such as heat pumps or organic Rankine cycles
- cooling systems
- safety and environmental techniques and procedures

This information is needed both for normal operation and operation at OTNOC including performance during:

- start-up, from a cold or warm start, including time to start and any purging requirements
- ramp-up and ramp-down
- shutdown, including time to shut-down, and impact on product quality and venting requirements. as a specific example, the requirement to vent off-specification hydrogen when not in steady state operation is an area that requires greater definition through supplier and operator data
- operation at minimum turndown capacity, design capacity and maximum capacity
- more information is requested on plans for future decommissioning and ability to recycle and/or re-use plant and equipment, including whether structures could be re-coated and re-used

- information is requested on the impact of ambient temperature and whether performance of electrolysis plant is affected and therefore should not be located near other heat -generating equipment. Implications especially for climate change adaptation reasons (designing for future impacts) are similarly requested

Per- or poly-fluorinated alkyl substances (PFAS) are a group of chemicals compounds used in products which are often referred to as ‘forever chemicals’ because of their extreme persistence in the environment. Some forms of PFAS can take over 1000 years to degrade. Information is requested on the implications of using PFAS, in electrolysis schemes, for instance in equipment seals [Ref. 35].

# 6. References

1. GOV.UK, UK becomes first major economy to pass net zero emissions law, 27 June 2019, https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law, Accessed: 14 April 2023
2. GOV.UK, The ten point plan for a green industrial revolution becomes first major economy to pass net zero emissions law, November 2020, https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution, Accessed: 14 April 2023
3. GOV.UK, UK hydrogen strategy, August 2021, https://www.gov.uk/government/publications/uk-hydrogen-strategy, Accessed: 14 April 2023
4. GOV.UK, Net Zero Strategy: Build Back Greener, October 2021, https://www.gov.uk/government/publications/net-zero-strategy, Accessed: 14 April 2023
5. GOV.UK, British energy security strategy, April 2022, https://www.gov.uk/government/publications/british-energy-security-strategy, Accessed: 18 April 2023
6. GOV.UK, Powering up Britain, March 2023, https://www.gov.uk/government/publications/powering-up-britain, Accessed: 18 April 2023
7. GOV.UK, UK Low Carbon Hydrogen Standard: emissions reporting and sustainability criteria, 2022, https://www.gov.uk/government/publications/uk-low-carbon-hydrogen-standard-emissions-reporting-and-sustainability-criteria, Accessed: 18 April 2023
8. GOV.UK, Review of emerging techniques for hydrogen production from methane and refinery fuel gas with carbon capture, January 2023, https://www.gov.uk/government/publications/review-of-emerging-techniques-for-hydrogen-production-from-methane-and-refinery-fuel-gas-with-carbon-capture, Accessed: 14 April 2023
9. Legislation.gov.uk, The Environmental Permitting (England and Wales) (Amendment) (EU Exit) Regulations 2019, https://www.legislation.gov.uk/uksi/2019/39/schedule/made, Accessed: 18 April 2023
10. Environment Agency, What are the environmental risks associated with the different types of hydrogen production using electrolysis? – literature review, April 2022
11. Reuters, Shell opens 10 MW German hydrogen electrolyser to boost green fuel output, July 2021, https://www.reuters.com/business/energy/shell-opens-10-mw-german-hydrogen-electrolyser-boost-green-fuel-output-2021-07-02/, Accessed: 17 April 2023
12. Global Hydrogen Review, International Energy Agency (IEA), October 2021, https://www.iea.org/reports/global-hydrogen-review-2021, Accessed: 18 April 2023
13. Options for Producing Low-Carbon Hydrogen at Scale – policy briefing, The Royal Society, ISBN 978-1-78252-318-5, January 2018, https://royalsociety.org/~/media/policy/projects/hydrogen-production/energy-briefing-green-hydrogen.pdf, Accessed: 14 April 2023

14. IRENA, Green Hydrogen Cost Reduction – Scaling Up Electrolysers to Meet the 1.5°C Climate goal, ISBN 978-92-9260-295-6, 2020, https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf, Accessed: 14 April 2023
15. Nel, Nel Hydrogen Electrolysers, 2021, https://nelhydrogen.com/resources/electrolysers-brochure/, Accessed: 14 April 2023
16. Haldor Topsoe, SOEC High-Temperature Electrolysis Factsheet, https://info.topsoe.com/green-hydrogen, Accessed: 14 April 2023
17. Effect of Electrolyte Concentration Difference in Hydrogen Production during PEM Electrolysis, J. Electrochem. Sci. Technol., 2018, 9(2), 991-108, April 2018.
18. E4 Tech, Study on development of water electrolysis in the EU, February 2014, https://www.fch.europa.eu/sites/default/files/FCHJUElectrolysisStudy_FullReport%20(ID%20199214).pdf, Accessed: 17 April 2023
19. European Energy Research Alliance, Key Performance Indicators (KPIs) For FCH Research And Innovation, 2020 – 2030, August 2020, https://www.eera-fch.eu/news-and-resources/2121:the-jp-fch-kpis.html, Accessed: 18 April 2023
20. Henry Royce Institute, Materials for the Energy Transition – Materials for Low-Carbon Methods for Generation of Hydrogen and Other Related Energy Carriers and Chemical Feedstocks, September 2020, https://www.royce.ac.uk/content/uploads/2020/10/M4ET-Low-Carbon-Production-Hydrogen-Roadmap.pdf, Accessed: 18 April 2023
21. International Energy Agency (IEA), The Role of Critical Minerals in Clean Energy Transition, March 2022, https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions, Accessed: 18 April 2023
22. Institute for Sustainable Process Technology, Hydrohub GigaWatt Scale Electrolyser, 2020, https://ispt.eu/projects/hydrohub-gigawatt/, Accessed: 18 April 2023
23. energypost.eu, Hydrogen production in 2050: how much water will 74EJ need?, 2021, Hydrogen production in 2050: how much water will 74EJ need? – Energy Post, Accessed: 19 April 2023
24. European Commission, Best Available Techniques (BAT) Reference Document for Common Waste Water and Waste Gas Treatment/Management Systems in the Chemical Sector, https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/CWW_Bref_2016_published.pdf, Accessed: 18 April 2023
25. Haldor Topsoe, Green Hydrogen – High Temperature Electrolysis (Guidance for Emerging Techniques, Hydrogen from Electrolysis of Water – Response to Request for Information document), March 2022.
26. Frazer-Nash, Fugitive Hydrogen Emissions in a Future Hydrogen Economy, FNC 012865-53172R Issue 1, March 2022, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1067137/fugitive-hydrogen-emissions-future-hydrogen-economy.pdf, Accessed: 18 April 2023
27. CNR-ITAE, Italian national energy advisory service (ITAE), Oxygen from Electrolysis for Medical Use: An Economically Feasible Route, https://iaee2021online.org/download/contribution/fullpaper/1130/1130_fullpaper_20210428_111608.pdf, Accessed: 18 April 2023

28. International Standards Organisation, Hydrogen Fuel Quality – Product Specification, ISO 14687, First Edition 2019.
29. Siemens, Efficiency – Electrolysis, White paper, January 2019, https://assets.siemens-energy.com/siemens/assets/api/uuid:5342163d-2333-4c8d-ae85-2a0e8d45db56/white-paper-efficiency-en.pdf
30. European Commission, Integrated Pollution Prevention and Control (IPPC), Reference Document on the application of Best Available Techniques to Industrial Cooling Systems, 2001, https://eippcb.jrc.ec.europa.eu/reference/industrial-cooling-systems, Accessed: 19 April 2023
31. Swedish Electromobility Centre, energiforsk (Sweden), Technology review – Solid Oxide Cells 2019, Report 2019:601, ISBN 978-91-7673-601-2.
32. European Commission, Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals – Ammonia, Acids and Fertilisers, 2007, Large Volume Inorganic Chemicals – Ammonia, Acids and Fertilisers | Eippcb (europa.eu) Accessed: 25 May 2023
33. European Commission, Best Available Techniques for the production of chlor-alkali, Production of Chlor-alkali | Eippcb (europa.eu), Accessed: 25 May 2023
34. Costain, UK Environmental Regulators – Request for Information, BAT for Hydrogen Production from Electrolysis of Water, 27 January 2022.
35. Position Paper on PFAS, The importance of fluoropolymers across the hydrogen value chain, impacts of the proposed PFAS restriction for the hydrogen sector, Author: Hydrogen Europe , January 2023, https://hydrogeneurope.eu/wp-content/uploads/2023/02/Hydrogen-Europe-position-paper-on-PFAS-ban_v12_FINAL.pdf, Accessed July 2023.
36. SGN Feasibility Study into Water Requirement for Hydrogen Production, Ramboll/SGN, 18 Nov 2022, https://www.energy-uk.org.uk/wp-content/uploads/2023/03/Report_JEP21WT02_V1.pdf, Accessed Aug 2023.
37. Scoping Report on the Material Requirements for a UK Hydrogen Economy, British Geological Society, Open Report OR/23/017, 2023, https://ukcmic.org/downloads/reports/ukcmic-scoping-report-on-the-material-requirements-for-a-uk-hydrogen-economy-or12017.pdf, Accessed Aug 2023.
38. Power requirements for demineralised water production – Costain calculation.

# Appendix 1 – Electrolyser technologies summary

## A. Emerging technologies with higher technology readiness level (TRL)

### A1. Alkaline water

Alkaline electrolysers operate by transporting hydroxide ions (rather than hydrogen ions) through the electrolyte from the cathode to the anode leading to hydrogen generation on the cathode side. Providing an alkaline electrolyte such as potassium hydroxide (KOH) with improved conductivity increases the mobility of ions and the effectiveness of the electrolysis process. KOH is generally used instead of sodium hydroxide (NaOH) due to its higher conductivity. Nickel is often used as the material of construction for the electrodes due to its chemical resistance, low cost compared to rare metals, good activity and availability.

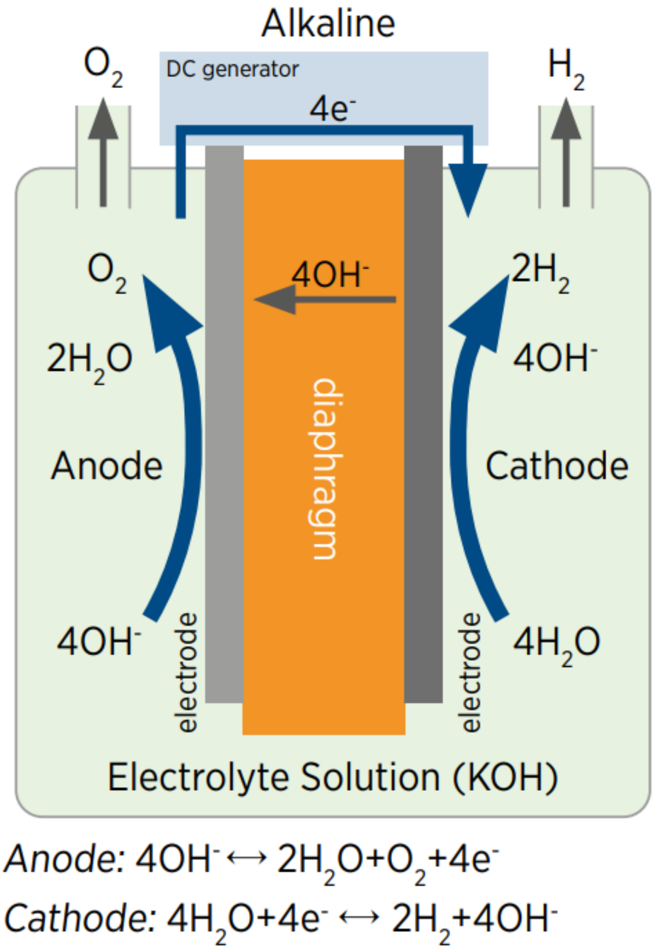
Effectiveness and efficiency of the electrolyser system, reflects the resistances of the following components:

- boundary layers at the electrode surface
- electrode phase
- electrolyte phase
- separator
- circuit

The reactions at the electrodes are heterogeneous that is not in the same phase. Reactions take place at the interface between the electrode (usually a solid) and the electrolyte phase (usually liquid or molten). It is in the interphase region, which can be thought of as a boundary layer where the efficiency of electrolysis as an operation is largely dependent on electrolyte velocity, concentration of the electroactive species and the electrical potential difference and its variance with distance from the electrode. Each of these factors represents a different influence on the boundary layer near the electrode surface. At the micro level, the interactions influence the mass transfer at the boundary layer, which determines the level of resistance to the electrolysis process taking place.

**Figure A1.1 – Alkaline electrolysis (IRENA, Ref. 29)**

This figure is a basic representation of an electrolytic cell for alkaline electrolysis, showing the anode and cathode separated by a diaphragm with a potassium hydroxide electrolyte. Hydroxide ions are transferred from cathode to anode via the diaphragm and oxygen is produced at the anode and hydrogen at the cathode. The anode and cathode reaction equations are shown.



Whilst this is a mature technology, there are recent and ongoing developments focused on improving efficiency and supporting higher current densities, which are limited by bubble formation in the liquid electrolyte, which decreases the effective area of the electrode. Manufacturers are seeking to reduce this effect through their design.

Potential improvements through the effects of centrifugal gravity fields, magnetic fields, ultrasound and microwaves, are being researched, although their potential in commercial applications is yet to be confirmed.

The development of more effective materials of construction for the membrane or diaphragm may achieve lower gas crossover rates and hydrogen losses.

## A2. Polymer electrolyte membrane (PEM)

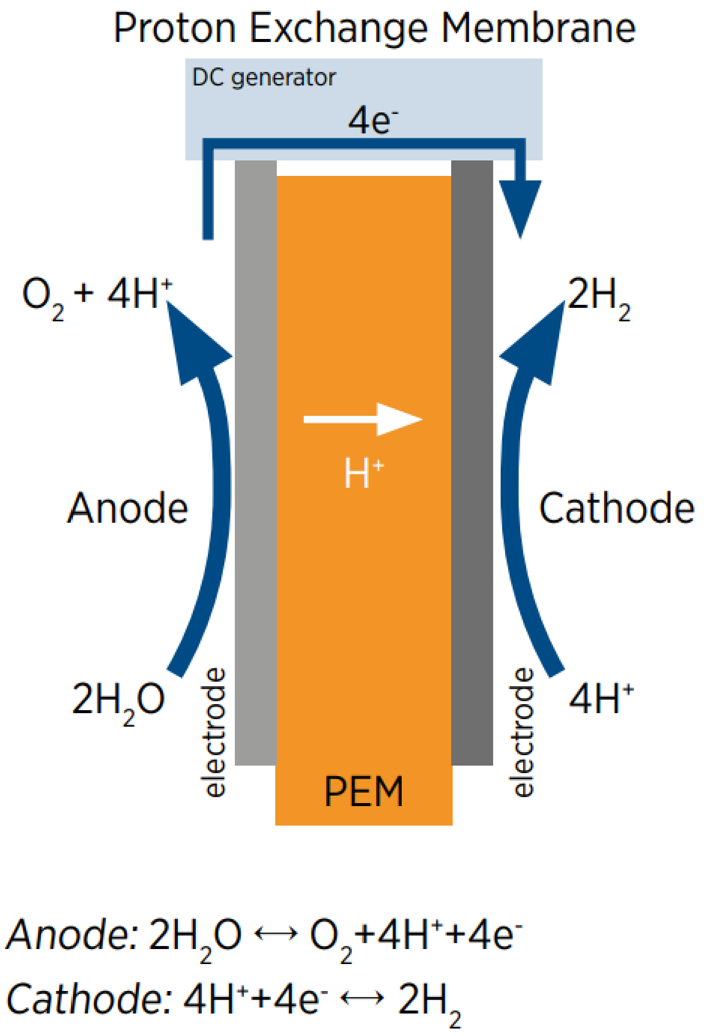
In a PEM electrolyser, water is pumped to the anode where it is split electrochemically into oxygen, hydrogen ions ($H^+$ that is protons) and electrons (e-). The protons travel via the conducting membrane to the cathode side. Electrons exit from the anode, providing the potential difference (voltage). Hydrogen ions (protons) and electrons then combine at the cathode, producing hydrogen.

Materials of construction need to withstand an oxidative environment created by the PFSA membrane, high voltages and oxygen evolution in the anode. Titanium-based materials, noble metal catalysts and protective coatings are used to provide optimal electron conductivity and cell efficiency whilst ensuring long-term stability of cell components. Electrodes may be constructed from Platinum or Palladium at the cathode and Iridium or Rubium at the anode. There is a research and development focus on reducing use of these rare and costly materials.

PEM electrolysers are sensitive to water impurities such as iron, copper, chromium and sodium and can suffer from calcination. Therefore, appropriate water treatment, typically with reverse osmosis and ion exchange (or equivalent), is essential.

**Figure A2.1 – PEM electrolysis (IRENA, Ref. 29)**

The figure is a basic representation of an electrolytic cell for proton exchange membrane electrolysis, showing the anode and cathode separated by a membrane which acts as a solid electrolyte. Hydrogen ions are transferred from anode to cathode via the membrane. Oxygen is produced at the anode and hydrogen at the cathode. The anode and cathode reaction equations are shown.



$$\textit{Anode: } 2H_2O \leftrightarrow O_2 + 4H^+ + 4e^-$$

$$\textit{Cathode: } 4H^+ + 4e^- \leftrightarrow 2H_2$$

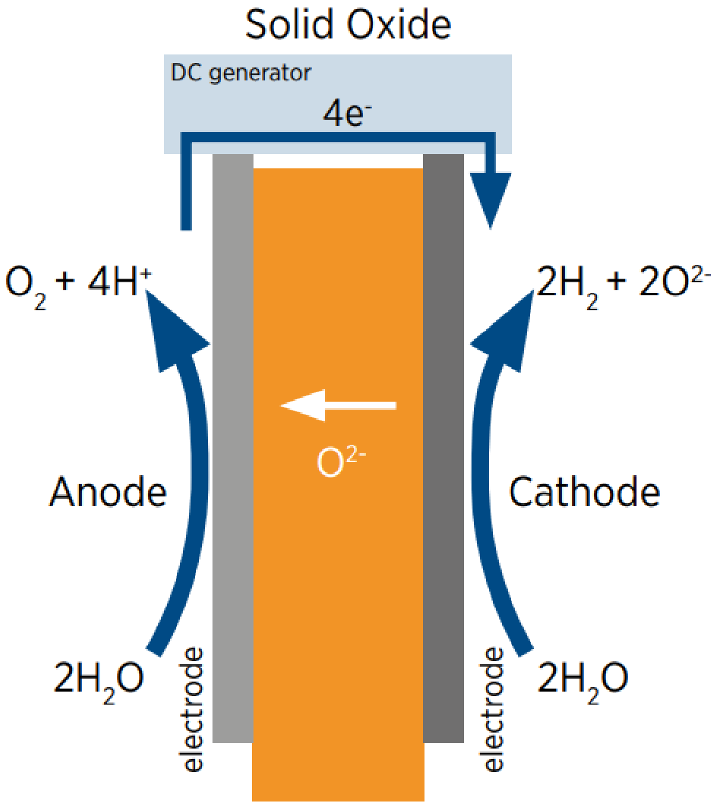
Hydrogen is typically generated at pressures up to 30 barg, direct from the electrolyser, although pressures as high as 70 barg are possible. Delivery at high pressure reduces downstream compression power requirements, and in some use cases, compression may be avoided. Oxygen is produced at lower pressure, typically close to atmospheric pressure. The membrane prevents hydrogen and oxygen mixing, thereby avoiding production of flammable mixtures, and so must be of high integrity.

### A3. Solid oxide electrolyser cell (SOEC)

For SOECs, different cell designs are available, with different materials used in the load bearing layer, determining the maximum operating temperature.

**Figure A3.1 – Schematic representation of SOEC electrolysis (IRENA)**

The figure is a basic representation of an electrolytic cell for solid oxide electrolysis showing the anode and cathode separated by a solid oxide layer acting as the electrolyte. Oxide ions are transferred via the solid oxide. Oxygen is produced at the anode and hydrogen at the cathode. The anode and cathode reaction equations are shown.



$$\text{Anode: } 2O^{2-} \leftrightarrow O_2 + 4e^-$$

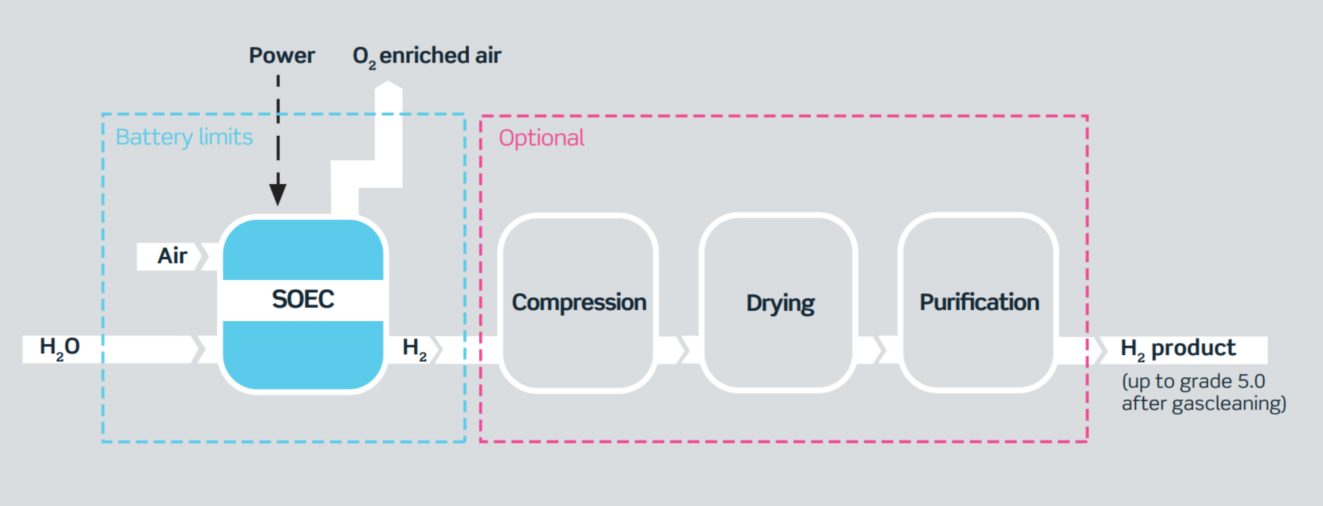
$$\text{Cathode: } 2H_2O + 4e^- \leftrightarrow 2H_2 + 2O^{2-}$$

Opportunities to integrate heat recovery effectively, and also to directly produce gases used in chemical synthesis through the electrochemical process, mean that they could be readily combined with a high temperature synthesis reaction such as methanation; methanol synthesis or ammonia synthesis. SOEC may suit integration with steam and electricity generation from nuclear power generation. There is potential for electrochemical production of feedstocks such as CO from $CO_2$ (for example for methanol synthesis), or nitrogen from air (for example for ammonia).

There is also the potential to combine SOEC with concentrated solar power (CSP) in future, as this could simultaneously provide electricity and heat needed for the SOEC electrolyser.

**Figure A3.2 – SOEC System, typical (Haldor Topsoe, Ref. 16)**

This figure is a basic process flow diagram of a solid oxide electrolysis cell system. Inputs are electricity, air and water with compressed, dried and purified hydrogen and oxygen enriched air as outputs.



## B. Emerging technologies with lower technology readiness level (TRL)

### B1. Anion exchange membrane

Each cell, defined by the bipolar plates which allow the cells to be connected to form a stack, is divided by an anion exchange membrane (AEM). Water travels from the anode through the membrane to the cathode, where hydrogen is produced and released via a gas diffusion layer. OH- moves back to the anode via the membrane, and oxygen is produced from OH- at the anode and is released via a gas and liquid diffusion layer. The hydrogen can be produced a pressure of around 30 barg, with pressure differential preventing oxygen cross-over, giving high purity hydrogen.

The process operates in a mild alkaline environment, with dilute potassium hydroxide circulating on the anode side of the cell. The cathode remains dry, with the hydrogen produced having low moisture content. The electrolyser does not require platinum catalysts or titanium bipolar plates.

AEM electrolysers are currently a less mature technology than alkaline, PEM or SOEC electrolysers.

Current challenges include:

- membrane chemical and mechanical stability for extended lifetime
- optimisation of ion conductivity of the membrane which limits current density
- trade-offs between performance and durability

### B2. Direct photo-electrolysis

Direct solar water splitting, or photolytic processes use solar energy to split water into hydrogen and oxygen. These processes are at various stages of early research but offer long-term potential for sustainable hydrogen production with low environmental impact.

In photoelectrochemical (PEC) water splitting, hydrogen is produced from water using sunlight and specialized materials which use light energy to directly dissociate water molecules into hydrogen and oxygen. The semiconductor materials are similar to those used in photovoltaic solar electricity generation, but for PEC applications the semiconductor is immersed in a water-based electrolyte, where sunlight energizes the water-splitting process. PEC water splitting is a promising solar-to-hydrogen pathway, offering the potential for high conversion efficiency at low operating temperatures using cost-effective semiconductor materials. Production methods with microbial processes breaking down biomass may also use sunlight (see section B5).

### B3. Membrane-free electrolyser

In a conventional water-splitting electrolyser, where hydrogen is formed at the cathode and oxygen at the anode, an ion-conductive polymer membrane sits between the two electrodes. One of its key roles is to prevent an explosion by keeping the two gases apart. Such membranes are expensive to produce, require routine replacement and because they are only stable at high acidities, require expensive metals such as platinum or iridium.

In a membrane-free electrolyser, the two parallel electrode plates are coated with hydrogen and oxygen evolution catalysts with plates separated by a tiny gap. When electrolyte flows between the catalytic plates, hydrogen and oxygen evolve at their corresponding electrodes. The lift forces in the narrow passage push the gases towards the wall they evolved from (Segré–Silberberg effect) and hence prevents them from forming a flammable mixture. Each product can then be collected at its specific outlet. A proprietary technology being developed combines membrane-free technology with cryogenic separation to deliver pure hydrogen and pure oxygen as separate gases.

The manufacturer states that it is constructed from readily available, reusable, or recyclable materials, and does not require precious metals such as Palladium or Platinum for membranes or powerful catalysts. The technology is claimed to be scalable for a wide variety of applications, and when supplied by renewable electricity, delivers green hydrogen.

### B4. High-pressure electrolyser

High-pressure electrolysers operate at intermediate temperature and pressure, delivering gases at over 200 barg, removing the requirement for hydrogen compressors. This is a low TRL technology currently at laboratory scale, expected to move demonstration outside the laboratory environment in 2023. Future development will use catalytic oxygen reduction, with the object of creating 99.999% purity hydrogen product.

One manufacturer has reported electrolyser performance with a cell efficiency of 32.2kWh/kg of hydrogen. This relates to a current density of 662mA/cm$^2$ @ 1.2V. With further development of heat recirculation it is anticipated the full system efficiency could be 42kWh/kg of hydrogen, potentially reducing to 33kWh/kg of hydrogen with a waste heat source. This type of electrolyser does not have membranes, can be constructed without use of rare earth metals or PFAS, and does not require water for stack cooling.

Effluent from the pre-treatment for this unit would be a hydroxide-based water effluent. At current stage of development this would be 0.5M (molar) concentration. A respondent identified that they are intending to develop a full water recirculation system, recovering heat and unconverted water back the input of the electrolyser. This flow will be actively monitored and if pollutant concentration increases, a recycle stream purge will be required.

### B5. Microbial electrolyser

Production of hydrogen by microbial processes is in the early stages of development. The microbial substrate is oxidised by microbes, producing $CO_2$, protons and electrons (Ref. 6). Microbes such as bacteria and microalgae can produce hydrogen through biological reactions using sunlight or organic matter. The algae and bacteria could be grown in water that cannot be used for drinking or for agriculture and could potentially even use wastewater.

Hydrogen production via biological methods is currently at the R&D or pilot stage, but in the long term has the potential to provide sustainable, low-carbon hydrogen production. This method can be broken down into microbial biomass conversion and photobiological: microbial processes use the ability of microorganisms to consume and digest biomass and release hydrogen whilst photobiological processes use microorganisms and sunlight to turn water, and sometimes organic matter, into hydrogen.

There are several technical challenges to be addressed, including high internal resistance, and the choice of electrode materials, before this can become commercially viable.

# Appendix 2 – Definition of BAT

Best available techniques (BAT) means the most effective and advanced stage in the development of activities and their methods of operation, which indicates the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where that it is not practicable, to reduce emissions and the impact on the environment as a whole.

‘Techniques’ includes both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned.

‘Available techniques’ means those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into account the costs and advantages, whether or not the techniques are used or produced inside the United Kingdom, as long as they are reasonably accessible to the operator. (‘Member State in question’ was amended to ‘United Kingdom’ by the Environmental Permitting (England and Wales) (Amendment) (EU Exit) Regulations 2019 [Ref. 9].)

‘Best’ means most effective in achieving a high general level of protection of the environment as a whole.

# Abbreviations

| | |
|---|---|
| AC | alternating current |
| AEM | anion exchange membrane |
| ATR | auto-thermal reactor |
| BAT | best available techniques |
| BAT-AEL | best available technique associated emission level |
| BEIS | (Department for) Business, Energy and Industrial Strategy |
| BOP | balance of plant |
| BRef | BAT reference document |
| CAPEX | capital expenditure |
| CCS | carbon capture and storage |
| CCUS | carbon capture utilisation and storage |
| COMAH | Control of Major Accident Hazards |
| CSP | concentrated solar power |
| DC | direct current |
| DSEAR | (The) Dangerous Substances and Explosive Atmospheres Regulations |
| EA | Environment Agency |
| EU | European Union |
| FCEV | fuel cell electric vehicle |
| GW | gigawatt (1 x 109 watt) |
| GWe | gigawatt of electricity |
| GWP | global warming potential |
| HHV | higher heating value |
| HVAC | heating, ventilation and air conditioning |
| IEA | International Energy Agency |
| IED | Industrial Emissions Directive |
| IRENA | International Renewable Energy Agency |
| ISO | International Organization For Standardization |
| ITAE | Istituto di Tecnologie Avanzate Per L'energia (Italy) |
| KOH | potassium chloride |
| KPI | key performance indicator |
| kWh | kilowatt-hour |
| LHV | lower heating value |
| MW | megawatt |

| | |
|---|---|
| MWe | megawatt of electricity |
| NIEA | Northern Ireland Environment Agency |
| NRW | Natural Resources Wales |
| OEM | original equipment manufacturer |
| ORC | organic Rankine cycle |
| OTNOC | other than normal operating conditions |
| PEC | photoelectrochemical |
| PEM | polymer electrolyte membrane or proton exchange membrane |
| PFAS | per- or poly-fluorinated alkyl substances |
| PFSA | perfluoro sulfonic acid |
| POX | partial oxidation |
| PSA | pressure swing adsorption |
| R&D | research and development |
| RFI | request for information |
| SEPA | Scottish Environment Protection Agency |
| SMR | steam methane reforming |
| SOEC | solid oxide electrolyser cell |
| TRL | technology readiness level |
| UK | United Kingdom |