ELECTROLYSERS

Introduction

Electrolytic hydrogen is produced by applying electricity to split a pure water source into its component molecules of hydrogen and oxygen. Electrolysers, or more precisely electrolyser stacks, are the primary electrochemical component in an electrolytic hydrogen production system and are supported by auxiliary components required for functions such as water and electricity supply, cooling and purification. The hydrogen produced from the electrolyser stack is purified through separation and drying processes, whilst oxygen is released into the atmosphere or can be captured or stored to supply other industrial processes.

Electrolyser stacks are comprised of two electrodes (a positively charged anode and a negatively charged cathode) that are separated by an electrolyte, which is the medium responsible for transporting the chemical charges (ions) from one electrode to the other. A variety of electrolyser technologies exist that each present their own opportunities and potential challenges.

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Electrolyser Technologies

Technology	Operating Temperature	System Efficiency
PEM	<100°C	c. 60%
AE	<100°C	c. 60%
SOE	500-850°C	80-90%

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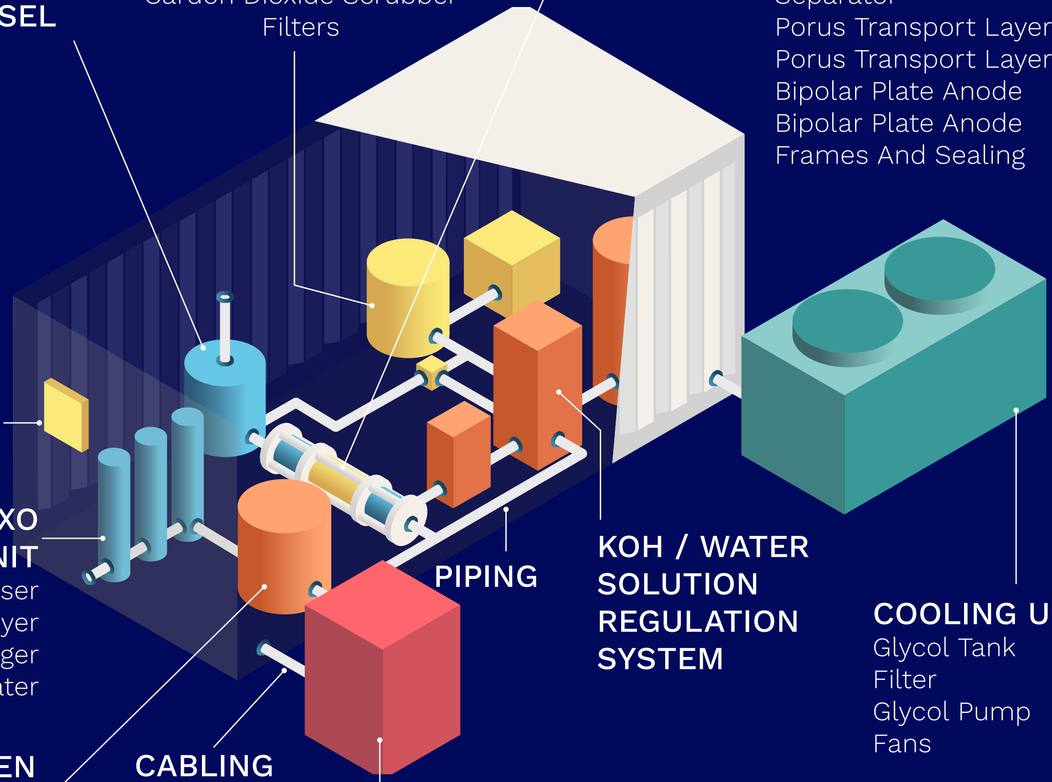
Alkaline Electrolyser

Overview

Alkaline electrolyser (AE) stacks consist of two electrodes. The electrolyte is in a liquid form and the electrodes and generated gas are physically separated via a porous inorganic diaphragm, also known as separator.

Alkaline electrolysers are the most mature technology, and their long-term stability allows them to be used in industry for the large-scale production of hydrogen for different end uses. Alkaline electrolysers present the simplest stack and system design, which translates to ease of manufacture and is ultimately the cheapest electrolysis technology.

A 3D diagram of an Alkaline electrolyser including all the auxiliary components associated with a complete system is shown here. As well as the electrolyser stack, the system includes key components required to supply the input water and mix it with the potassium hydroxide electrolyte, supply the input electricity, cool the system as required and purify the outputs from the stack.



Alkaline electrolysis componentry

Alkaline electrolysis stack

The electrolyser stack forms the heart of the overall electrolyser system and is where the hydrogen production takes place. The electrolyser stack consists of numerous electrolyser cells, which in turn comprise an electrolyte and two electrodes, namely the anode and cathode. Hydrogen is produced at the cathode, whilst oxygen gas is generated at the anode. Alkaline electrolysis uses a concentrated solution of potassium hydroxide (KOH) in water as the electrolyte, which is continuously recirculated through the cell. The two electrodes are typically separated by a microporous composite membrane, or diaphragm, which is soaked in the electrolyte solution to allow ionic transfer, whilst minimising crossover of hydrogen and oxygen gases to the other electrodes. Crossover or mixing of oxygen and hydrogen reduces cell efficiency but more importantly is a safety hazard and must be avoided. This is done through keeping current density at reduced levels, working at reduced gas pressures and by increasing diaphragm thickness. Multiple stacks can be combined to increase system size and hydrogen production capacity.

KOH electrolyte circulation

The lye solution is continuously pumped around the stack in a circulation loop. Flow is controlled through a pump and mass flow regulator.

Stack thermal management

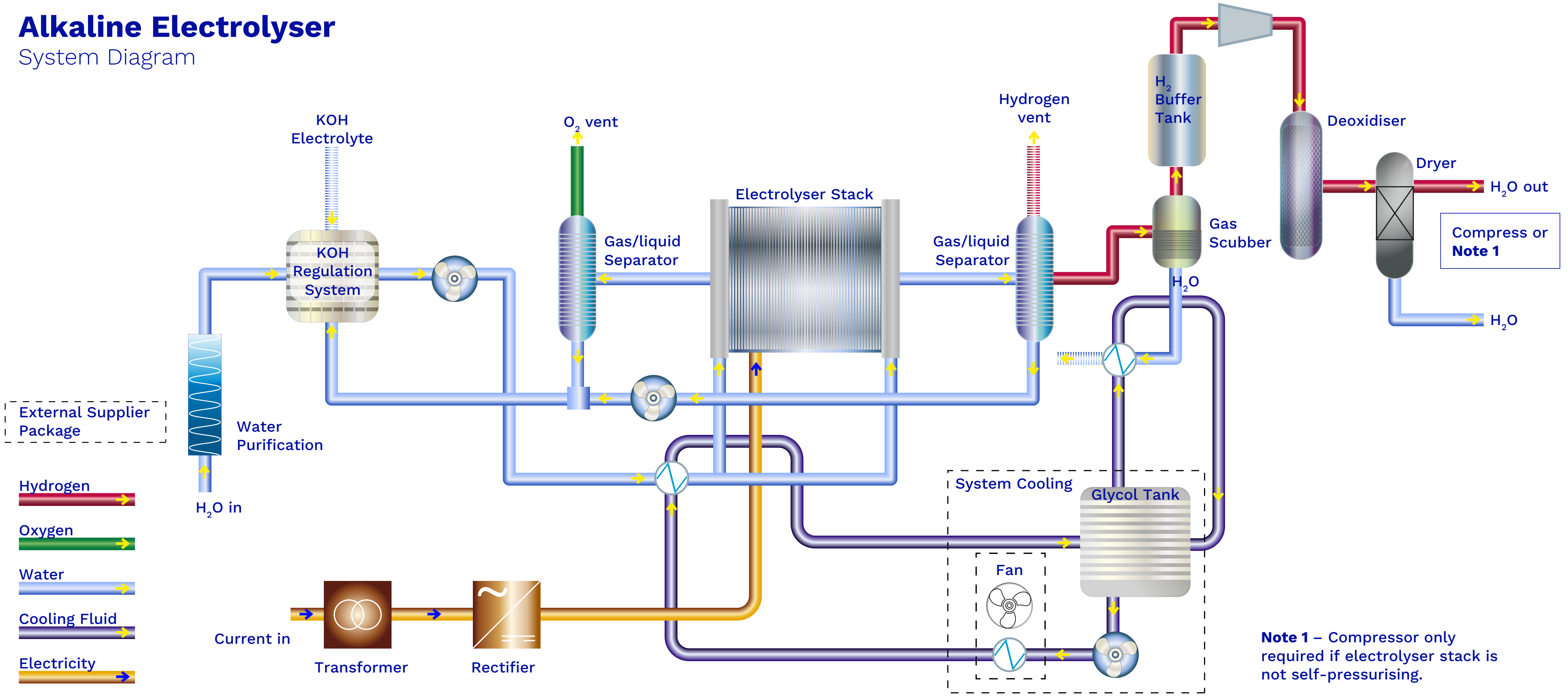
The electrolyser stack generates heat as well as hydrogen and oxygen gas. This heat must be managed through a thermal management system; in case of Alkaline Electrolysis this is typically managed by cooling the lye recycle stream in a fan assisted radiator heat exchanger. Liquid-liquid heat exchange coupled with heat rejection to ambient in an external loop can be used alternatively.

Product separation and purification

After the electrolysis process, the products require purification. Both oxygen and hydrogen streams are saturated in lye, which is separated in a gas-liquid flash separator. Additional removal of lye occurs in two sets of scrubbers for each gas. Lye from these two separation steps is returned to the KOH stack circulation loop. Oxygen is usually vented to atmosphere at this stage. If capturing is desirable, further purification may be required. Hydrogen is further purified in a de-oxo unit, where residual oxygen, which occurs due to slipover during electrolysis, is removed by catalytic reaction with hydrogen. Any final remaining water is removed through a combination of cooling/condensation and in a final drying step, typically through PSA or TSA.

Alkaline Electrolyser

System Diagram



Component list for an Alkaline Electrolyser (1/2)

Sub-component	Material(s)	Specs
Anode	Nickel coated perforated stainless steel	Stainless steel, typically 304 or 316. Modified with Ni, e.g. electrodeposition
Cathode	Nickel coated perforated stainless steel	Stainless steel, typically 304 or 316. Modified with Ni, e.g. electrodeposition
Electrolyte	Potassium hydroxide (KOH) 5-7 $molL^{-1}$	Water purity, typically < 5 uS/cm, although often more stringent ASTM Type II used
Separator	Zirfon - ZrO2 (zirconium dioxide) reinforced with PPS (polyphenylene sulphide) mesh	
Porous transport layer anode	Nickel mesh (not always present)	
Porous transport layer cathode	Nickel mesh	
Bipolar plate anode	Nickel-coated stainless steel	Stainless steel, typically 304 or 316. Modified with Ni, e.g. electrodeposition
Bipolar plate cathode	Nickel-coated stainless steel	Stainless steel, typically 304 or 316. Modified with Ni, e.g. electrodeposition
Frames and sealing	Polysulfone, polytetrafluoroethylene, ethylene propylene diene monomer	
Stack tensioning system (e.g. SS plates, nuts and bolts	Stainless steel	
Lye leak containment system	Concrete or stainless steel	
Electrical contacting terminals		

Component list for an Alkaline Electrolyser (2/2)

Sub-component	Material(s)	Specs
Gas and fluid manifolding	Stainless steel	
Lye pumps		
Lye coolers - typically air cooled, alternatively glycol-water based cooling. Piping, fan, radiator and control system		
Gas-liquid separators for lye and oxygen/ hydrogen	Polypropylene or stainless steel (e.g. 316)	
Scrubbers for removing trace lye from product gases		
Hydrogen de-oxo unit (catalytic combustion)	Typically Pt or Pd catalyst on Al_2O_3 support, Stainless (304 or 316) or carbon steel vessel	
Hydrogen drying unit (PSA / TSA) – see other fact sheets		
Heat exchange (cooling) for water condensation/separation - combined with power supply cooling	E.g. stainless steel, aluminium	
Oxygen and hydrogen venting stacks		

PEM Electrolyser

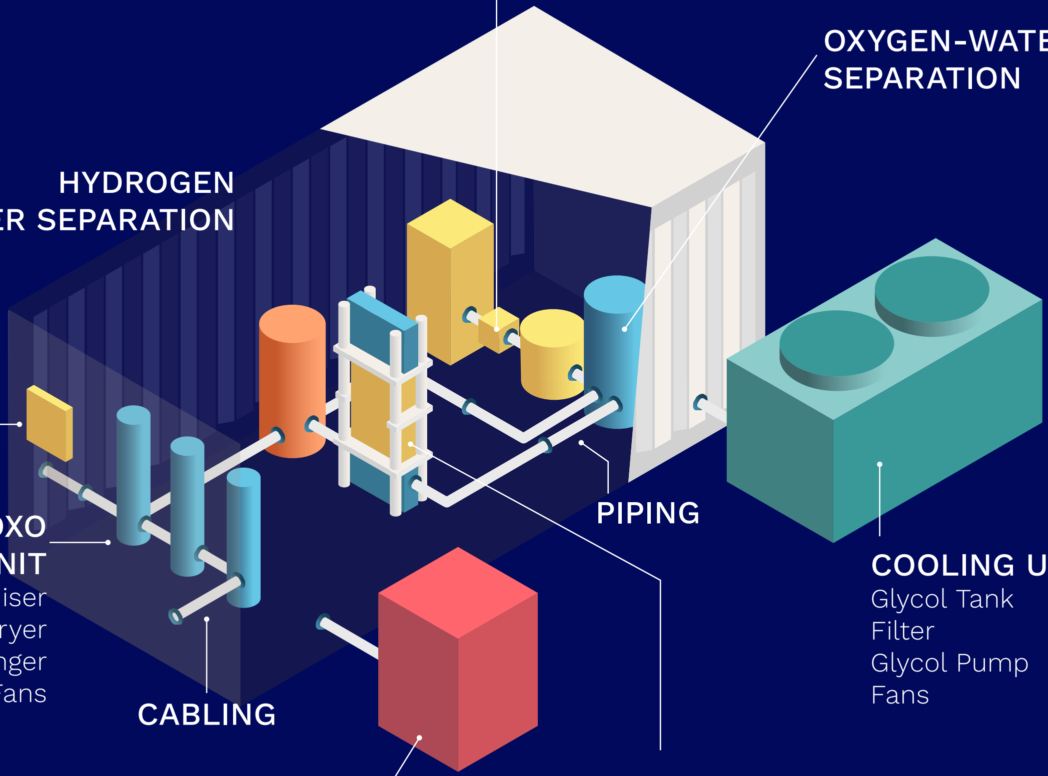
Overview

A 3D diagram of a Proton Exchange Membrane (PEM) electrolyser including all the auxiliary components associated with a complete system is shown here

Similar to Alkaline electrolysis, a PEM electrolyser stack consists of two electrodes, however, in this case they are separated by a solid polymer electrolyte, which is responsible for transporting ions from anode to cathode whilst physically separating the generated hydrogen and oxygen gas.

PEM electrolysers can ramp hydrogen production up and down to meet a variable demand. This flexible demand response makes the PEM electrolyser particularly suitable for intermittent renewable energy applications, including curtailed electricity consumption. For many hydrogen projects currently in development, PEM electrolysers are emerging as a favoured technology.

PEM electrolysers are more expensive than alkaline electrolysers at present, however their design is more compact.



PEM electrolysis componentry

PEM electrolysis stack

Conceptually, a PEM stack contains the same key components as seen in AE, namely numerous electrolyser cells connected in series, and cells comprising electrolyte and two electrodes. In PEM electrolysers however, the electrolyte is a thin, dense, and gastight, polymer layer, which conducts protons from cathode to anode. The protonic nature of this process, gives an acidic environment and this requires different electrocatalysts which need to be chemically stable in this environment. Currently, the only materials that are known to be both stable and active under these conditions are platinum group metals, which are rare and therefore expensive. To keep cost low, they are usually impregnated in low concentrations in a carbon-based porous membrane layer.

The electrolyte polymer membrane is prone to contamination with impurities, thus requiring higher purity feedwater than alkaline electrolysers. A major advantage of PEM technology is the gastight nature of the electrolyte polymer layer, reducing risk of gas crossover, thus allowing for operation at higher pressures and operating at higher current densities. Gas crossover can still occur in case of mechanical failure, such as a membrane puncture. Multiple stacks can be combined to increase system size and hydrogen production capacity.

Water circulation

Excess water leaving the anode is separated from oxygen and recycled to the stack inlet/feed supply. PEM stacks require humidification and water levels are continuously monitored to prevent the stack drying out.

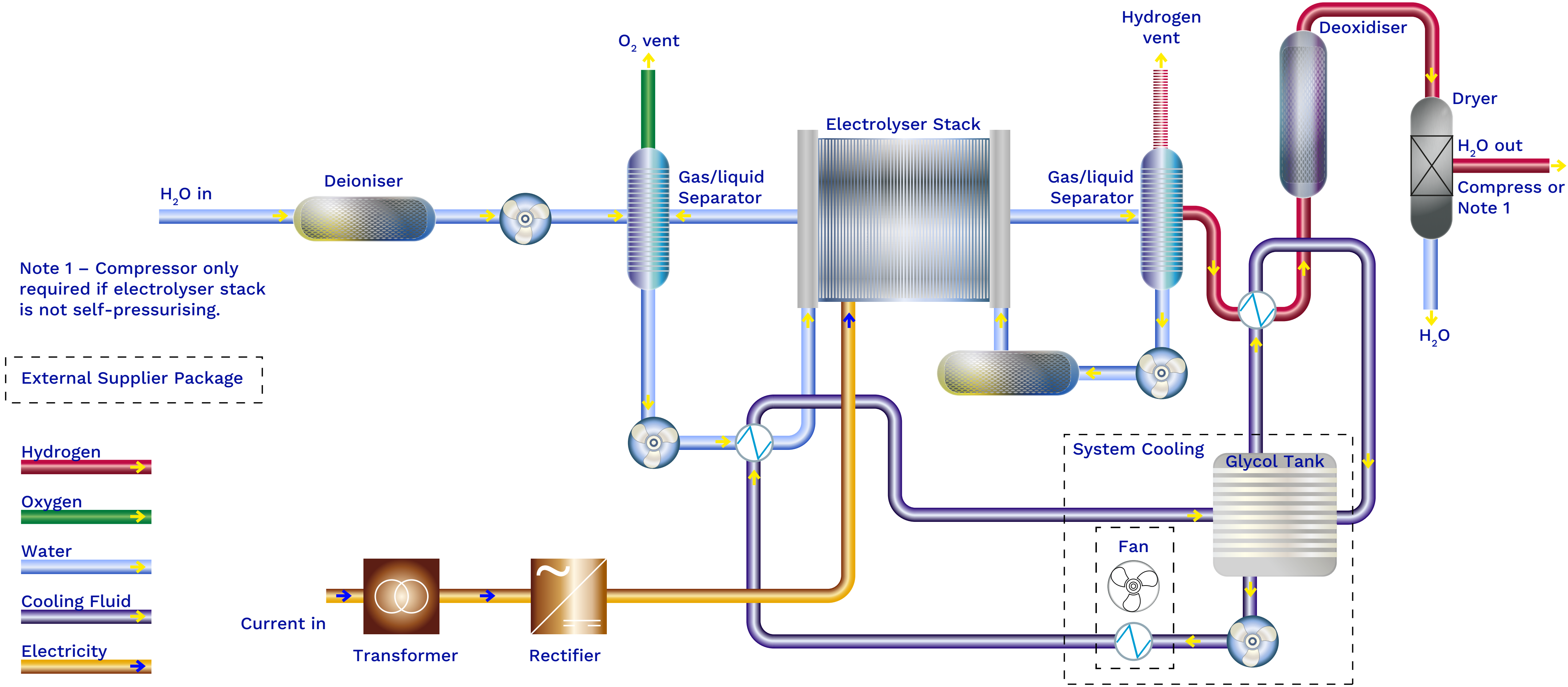
Stack thermal management

The electrolyser stack generates heat as well as hydrogen and oxygen gas. This heat must be managed through a thermal management system; in case of PEM Electrolysis this is typically managed by cooling the water (-oxygen mixture) leaving the anode in a liquid-liquid heat exchanger coupled with heat rejection to ambient in an external loop. Water inlet temperature to the stack can be controlled through controlling coolant flow rates and by adjusting electrolyser production rate.

Product separation and purification

After the electrolysis process, the products require purification. Both oxygen and hydrogen streams are saturated with water, which is separated in a gas-liquid flash separator, with water recycled to the stack and purified if necessary. As in AE, oxygen is usually vented to atmosphere at this stage. Hydrogen is further purified in a de-oxo unit, where residual oxygen is removed by catalytic reaction with hydrogen. Any final remaining water is removed through a combination of cooling/condensation and in a final drying step, typically through PSA or TSA.

PEM Electrolyser
System Diagram



Component list for a PEM Electrolyser (1/2)

Sub-component	Material(s)	Specs
Anode	Iridium and Iridium oxide	Finely dispersed or coated on titanium or alternative supports materials
Cathode	Platinum nanoparticles on carbon black	
Electrolyte	Perfluorosulfonic acid (PFSA) Membranes	
Separator	Perfluorosulfonic acid (PFSA) Membranes	
Porous transport layer anode	Platinum coated sintered porous titanium	Thin Pt coating on titanium felt, applied using advanced coating techniques, e.g. Physical Vapor Deposition (PVD)
Porous transport layer cathode	Sintered porous titanium or carbon cloth	
Bipolar plate anode	Platinum-coated titanium	
Bipolar plate cathode	Gold-coated titanium	
Frames and sealing	Polysulfone, polytetrafluoro-ethylene, ethylene propylene diene monomer	
Stack tensioning system (e.g. SS plates, nuts and bolts	Stainless steel	
Electrical contacting terminals		
Gas and fluid manifolding	Stainless steel	

Component list for a PEM Electrolyser (2/2)

Sub-component	Material(s)	Specs
Water pumps		
Stack humidity monitoring/control		
Stack water flow management system		
Cooling unit		Typically liquid-liquid heat exchanger, such as glycol-water based cooling. Piping, fan, radiator and control system (thermal sensing)
Gas-liquid separators for water and oxygen/hydrogen	Polypropylene or stainless steel (e.g 316) vessel	
Hydrogen de-oxo unit (catalytic combustion)	Typically platinum (Pt) or palladium (Pd) catalyst on Aluminium Oxide (Al_2O_3) support	Stainless steel (304 or 316) or carbon steel vessel
Hydrogen drying unit (PSA / TSA) – see other fact sheets		
Heat exchange (cooling) for water condensation/separation	E.g. stainless steel, aluminium	
Oxygen and hydrogen venting stacks		

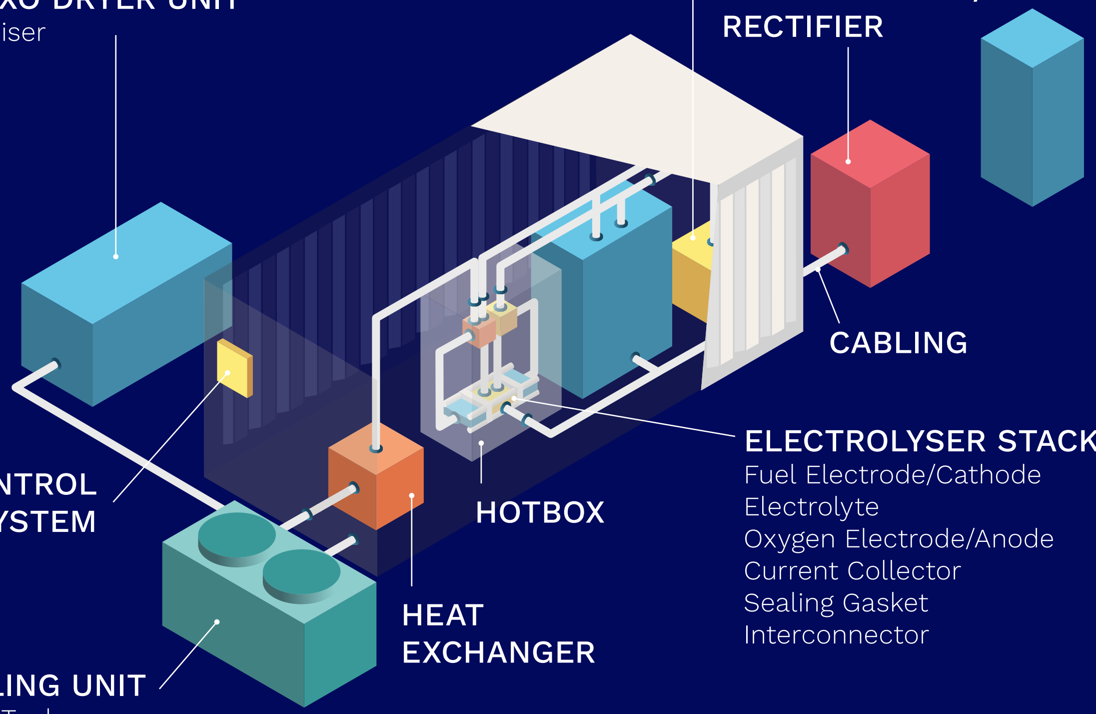
SO Electrolyser

Overview

Solid Oxide Electrolysers (SOEs) differ from PEM and Alkaline electrolysers as they utilise heat to make hydrogen from steam. SOE electrolyser stacks are made from a mix of ceramics and metal that can handle very high temperatures of >500°C.

SOEs are best placed where there is a waste heat source available (e.g. nuclear or industrial facilities) as it can utilise this heat to reduce the electrical requirement to produce hydrogen. The main advantage of SOEs is their high system efficiency of 80-90%, if waste heat can be used. There is also an opportunity to capture and use the excess heat from electrolysis to improve efficiency further. However, SOEs are not able to ramp up and down very quickly due to the high temperatures involved, therefore are better suited to base load requirements.

A 3D diagram of an SO electrolyser including all the auxiliary components associated with a complete system is shown here. As well as the electrolyser stack, the system includes key components required to supply the input water and mix it with the potassium hydroxide electrolyte, supply the input electricity, cool the system as required and purify the outputs from the stack.



SO electrolysis componentry

Solid Oxide Electrolysis stack

Due to the high temperature operation of SOE stacks, cell and stack components typically comprise ceramic and metallic materials. As in PEM, the electrolyte provides gastight separation of anode and cathode compartments and is typically a dense oxide ion conducting material, such as stabilised zirconia, although cells based on high temperature proton conducting materials are in research and development stage. The high temperature operating conditions allow for inexpensive electrocatalysts for the hydrogen evolution reaction, such as nickel; complex perovskite oxides are typically used on the anode side. Major challenges for SOE are the high temperature cell sealing and degradation of materials under the demanding conditions.

Like PEM and AE, most SOE stacks are based on planar cells, stacked in series. Other architectures are possible however, such as tubular cell designs, which can offer advantages in high temperature sealing. Multiple stacks can be combined to increase system size and hydrogen production capacity.

Stack thermal management

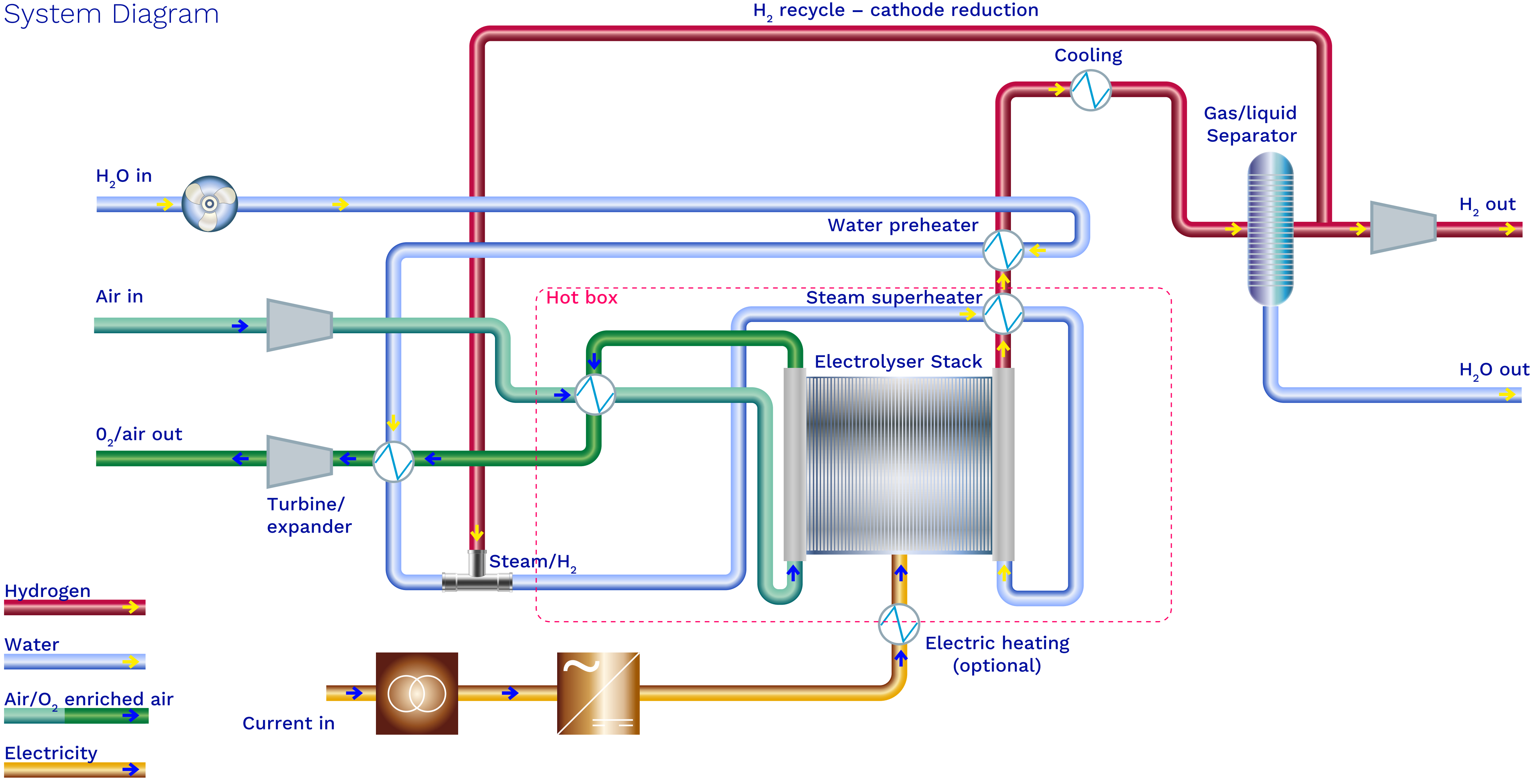
Thermal management is in many ways more straightforward in SOE than in low temperature electrolysis stacks. Heat generated through electrical resistance can be utilised to maintain the stack temperature and to preheat incoming steam and air, thereby lowering external heat demand and negating the requirement for external heat rejection. Remaining heat demand is typically met electrically with the stack assembly housed inside a high temperature furnace or hot box. Waste heat from other processes can be utilised in heat exchangers, heating inlet water/steam and air. Other componentry that requires operation at high temperature is all housed inside this well insulated hotbox. In case of pressurised operation, there is the potential for recovery of mechanical energy through turbine expanders

Product separation and purification

Product separation for high temperature electrolysis is somewhat simpler than for the low temperature technologies. Oxygen from SOE is generally not separated, as it is already diluted in air. Hydrogen leaving the stack is saturated with steam, which is removed by a combination of cooling, flash separation and further drying using PSA/TSA. A de-oxo unit, as used in AE and PEM, can normally be omitted as any oxygen crossing over in the stack will have reacted directly with hydrogen to form water at the high operating conditions.

SO Electrolyser

System Diagram



Component list for Solide Oxide Electrolysis (SOE, 1/2)

Sub-component	Material(s)	Specs
Fuel electrode/cathode	Nickel (Oxide) (Ni/NiO) + Yttria-Stabilised Zirconia (YSZ)	Typically submicron to several micron particle size. Minimum 40 vol% Nickel (Ni) for electronic percolation
Electrolyte	Yttria-Stabilised Zirconia (YSZ)	Typically submicron particle size powders or dense sintered substrates
Oxygen electrode/Anode	Perovskite materials, typically Lanthanum Strontium Cobalt Ferrite (LSCF) or Lanthanum Strontium Manganite (LSM)	Typically submicron particle size powders. Chemical composition can vary
Current collector	Silver (Ag)/gold (Au)/platinum (Pt)/nickel (Ni) mesh	
Sealing gasket	Mica/thermiculite/glass-ceramics	
Interconnector	Stainless steel, or specialist alloys, possibly with coatings to reduce chromium (Cr) evaporation	Examples: AISI430, AISI316, Crofer APU 22, Crofer 22H, Ducralloy, CFY, Chromium Iron Pentachromium (CrFe5), etc. Coatings typically manganese,cobalt (Mn,Co)-spinel based
Stack tensioning system (e.g. SS plates, nuts and bolts, high T springs)	Stainless steel or oxidation resistant alloys, e.g. Inconel 600	Highly dependent on stack architecture
Electrical contacting terminals	Platinum (Pt) silver (Ag), copper (Cu) or specialist alloy inside hotbox	Specification dependent on operating conditions. Conductivity and high temperature oxidation/corrosion resistance critical

Component list for Solide Oxide Electrolysis (SOE, 2/2)

Sub-component	Material(s)	Specs
Gas and fluid manifolding	Stainless steel, or high temperature alloys, e.g. Inconel 600 or 625	Dependent on operating conditions. Coatings may be applied for added oxidation resistance
Elecrtrical furnace and/or hot box	Furnace insulation (alumina-silicate based) and suitable heating elements, e.g. Silicon carbide (SiC), furnace/temperature control	
Heat exchangers	Plate-fin or tube-shell	Suitable for high temperature operating conditions, e.g. Inconel 625 or 718
Turbine expanders for mechanical energy recovery – optional		
Gas-liquid separators for steam/hydrogen mixture	Typically stainless steel (e.g. 316)	
Hydrogen drying unit (PSA / TSA) - see other fact sheets		
Heat exchange (cooling) for water condensation/separation and hydrogen drying steps -water or water-glycol cooling unit	Stainless steel, (e.g. 304 or 316), or aluminium (Al) if suitable under process conditions	
Oxygen enriched air and hydrogen venting stacks		

Balance of Plant componentry

(all electrolyser technologies 1/3)

Water supply

The electrolysis process requires a purified source of water, as contaminants in the water negatively impact on the process. Effects include parasitic production of unwanted side products as well as damage to the electrolyser stack components, reducing its lifetime. The overall process can take a variety of water sources, although installed purification systems are typically designed to process tap water. Other sources of water may be considered in future, such as fresh water, waste water treatment plant effluent, or sea water, but they may require additional levels of feedstock purification.

Water purification

Water purification systems usually combine a number of purification steps, including filtration steps (for solids and organics), a Reverse Osmosis (RO) unit and an Ion Exchange unit. Different levels of water purity are required for different electrolyser technologies, with PEM generally requiring water with highest purity. Water purities are often stated in terms of conductivity, see table. The equivalent reagent purity standard (ASTM D1193-06) is also listed.

High temperature operation

SOE requires a supply of steam. This is ideally achieved by using waste heat from other processes, but usually also requires some additional heat supply. Steam evaporators with pressure control are additional componentry.

Technology	Water conductivity (μS/cm)	Equivalent purity standard (ASTM D1193-06)
AE	<5	Type IV
PEM	<1	Type II
SOE	<5	Type IV

Water supply componentry
Water pumps
Water pressurisation module / pressure control
Steam evaporator (SOE only)
Heat exchangers (SOE) - Material suitable under process conditions, e.g. stainless steel
Mass flow control
Reverse Osmosis units
Deionising unit / ion exchange unit
Filtration / adsorption (e.g. activated carbon and Polypropylene or PVC meshes)
Tubing suitable for DI water – typically PP or PE. Passivated SS can be used alternatively (passivation according to AMS 2700 Type VI)

(all electrolyser technologies 2/3)

Electrical supply

Electrolyser systems are typically supplied by a 3 phase AC power supply at 380-415 V, which enters the system through a distribution box (including breakers/isolators) and feeds into a switchgear cabinet which contains a number of power electronics components, such as rectifiers and transformers. The switchgear cabinet, which is integral to the overall electrolyser system, subsequently supplies the various electrolyser components with the appropriate electrical power. The electrolyser stack requires a DC power supply to operate, and depending on stack size and electrical configuration, typically operates with currents of > 1,000 A and several 100s VDC. This DC power supply is typically generated from a rectifier unit which is part of the switchgear unit. The power electronics also supply a single phase 240V supply for any additional balance of plant components (e.g. water purification and gas purification), as well as several 24VDC control systems.

Keeping operating voltages below 1500 VDC means electrolysers are regulated by the Low Voltage

Electrical components
Power electronics, incl. Transformer, Rectifier, DC/DC converter
Distribution box
Isolators / emergency shutdown features
Earthing and bonding
Control systems
Wiring and contacting for different supply subsystems (stack DC, single phase AC and 24VDC)
Power supply cooling unit - ethylene or propylene glycol-water based cooling unit (pump, fan, radiator and piping plus control system)

(all electrolyser technologies 3/3)

This list of remaining componentry includes process control componentry, thermal management equipment, electrical switchgear and safety features. Alkaline electrolysers systems are typically deployed as containerised units on concrete foundations, mostly in 40ft shipping containers. Energy recovery and integration can enhance overall system efficiency and is of particular importance for SOE, which can utilise high grade waste heat from other processes, such as ammonia synthesis, refining or steel making, to lower electrical demand. Pressurised operation also offers opportunities to recover heat by passing product streams, such as enriched air, through turbine expanders and extracting mechanical work.

Additional safety features include pressure and temperature monitoring linked to pressure relief valves and overall process control allowing process shutdown. Absolute and differential pressure transducers can be used to indicate abnormal stack behaviour, such as excessive gas crossover in AE/PEM. Oxygen detection in hydrogen and vice versa are also deployed to keep product gas compositions within safe parameters. External gas monitoring equipment allows for leak detection and response incl. shutdown. Vent stacks are used for safe release of oxygen and excess hydrogen. Ventilation systems in enclosed spaces (containers) are essential to prevent build up of flammable atmospheres.

Generic BoP components

Heat exchangers, radiators and cooling fans	Electrical cabling, terminals, cable harnesses and cable storage/gutters
Liquid/water/lye pumps	Electrical signalling (control systems and sensors)
Pressure gauges	Electrical switchboard and electronics cabinets
Pressure transducers – absolute and differential	Electrical safety and interlocks
Back pressure regulators	Shipping containers and suitable coatings for protection against weather, typically C2
Temperature sensing e.g. thermocouples, and control (HX)	Acoustic shielding
Mass flow control	Stairways, handrails, safety barriers
Control valves – solenoid (actuated)	Concrete foundations and plinths
Multidirectional and non-return valves	Earthing and drainage
Ball valves	Gas detection – fixed location and handheld
Pressure relief valves	Lightning protection
Burst valves	Warning signage
Pipework - stainless steel ASTM 316/304	Ventilation / air circulation system linked to gas detection – incl. air filters and louvres installed in containers
Compression fittings or orbital welded	
Process control systems	
Turbine expanders for mechanical energy recovery	

Standards and codes of practice (1/3)

Organisation	Standard	Details	Date of Publication
Electrolyser Standards - Low Temperature Electrolysis (AE and PEM)			
International Organisation of Standardisation	ISO 22734 - Expected to be replaced by ISO/FDIS 22734-1 | ISO/AWI TS 22734-2	Hydrogen generators using water electrolysis - Industrial, commercial, and residential applications	Edition 1 Published 2019
Electrolyser Standards - High Temperature Electrolysis (SOE)			
International Electrotechnical Commission	IEC 62282	The collection of standards that establishes performance and safety requirements for fuel cell technologies	Between 2012 and 2025
Codes of Practice			
British Compressed Gases Association	Code of Practice 4	Gas supply and distribution systems (excluding acetylene)	Revision 5: 2020
	Code of Practice 34	The application of Pressure Equipment (Safety) Regulations to customer sites	Revision 2: 2024

Standards and codes of practice (2/3)

Organisation	Standard	Details	Date of Publication
Directives			
Health and Safety Executive	ATEX - 2014/34/EU	Two EU directives which describe the minium safety requiements for workplaces and equipment used in explosive atmoshperes - ATEX Workplace Directive and the ATEX Equipment Directive	Published in 2014 and applicable from 2016
Health and Safety Executive	Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR)	Require employers to control the risks to safety from fire, explosions and substances corrosive to metal	Published 2002
Health and Safety Executive	Pressure System Safety Regulations (PSSR)	The aim of these Regulations is to prevent serious injury from the hazard of stored energy as a result of the failure of a pressure system or one of its component parts.	Published 2000
European Commission	Pressure Equipment Directive (PED) 2014/68/EU	Applies to the design, manufacture and conformity assessment of stationary pressure equipment with a maximum allowable pressure greater than 0.5 bar.	Current consolidated version: 2014

Standards and codes of practice (3/3)

Organisation	Standard	Details	Date of Publication
Directives			
European Commission	Electromagnetic Compatibility 2014/30/EU	Limits electromagnetic emissions from equipment to ensure that, when used as intended, such equipment does not disturb radio and telecommunication, as well as other equipment. The directive also governs the immunity of such equipment to interference and seeks to ensure that this equipment is not disturbed by radio emissions, when used as intended.	Published March 2014
European Union	Low Voltage Directive 2014/35/EU	Ensures that electrical equipment within certain voltage limits provides a high level of protection for European citizens, and benefits fully from the single market. It has been applicable since 20 April 2016.	Applicable since April 2016
European Agency for Health and Safety at Work	Machinery Directive 2006/42/EC	Lays down health and safety requirements for the design and construction of machinery, placed on the European market	Last update June 2024

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