Annex 1 HySkills Module Exemplar

Module Operation & Maintenance of Electrolysers & Fuel Cells

Content

OUTCOME 1 - Describe the basic principles of electrolyser & fuel cell technology systems

Electrolyser

What is an electrolyser

An electrolyser is a device capable of splitting water molecules into their constituent oxygen and hydrogen atoms**.** The bonds between the two elements are very stable and electrical energy is needed for this splitting to take place in a process called electrolysis. Efficient electrolysers will be key to the penetration of hydrogen in industries and the adoption of hydrogen fuel cells.

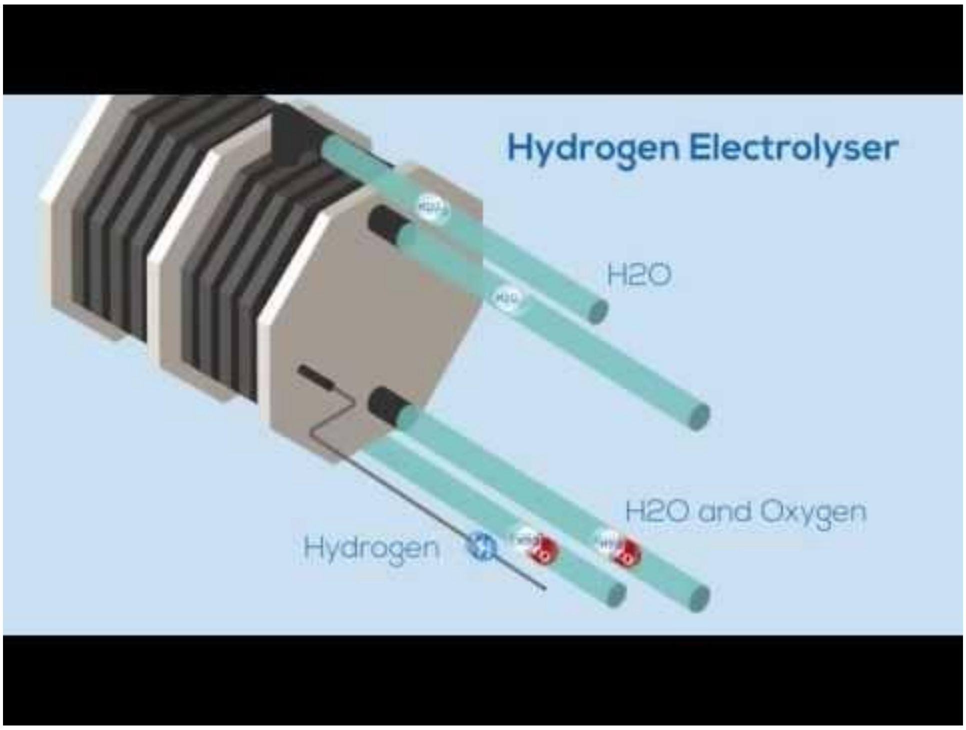
Hydrogen fuel cells use hydrogen as a fuel in an electrochemical process that combines hydrogen and oxygen to produce electrical energy and water. The reverse process of electrolysis, which produces hydrogen and oxygen from water, can use e. g. a range of renewable energy resources such as wind, wave or solar to produce hydrogen as a fuel for renewable power generation. There is also growing interest in hydrogen power as a uniquely clean energy source that can produce heat and whose only by-products are water.

One of the world's largest electrolysers is located in Fukushima, Japan, at the site of the well-known nuclear disaster, symbolising a paradigm shift in energy production as it is powered by solar panels. Most recently, in January 2021, the Japanese electrolyser was far surpassed by the one in Bécancour, Canada, which consists of a polymer membrane device with an output of 8.2 tonnes per day.

How an electrolyser works

An electrolyser consists of a conductive electrode stack separated by a membrane to which a high voltage and current is applied. This causes an electric current in the water which causes it to break down into its components: hydrogen and oxygen. The complete system also includes pumps, power electronics, gas separator and other auxiliary components such as storage tanks. Electrolysis was first discovered in 1800. After the invention of the electric battery by Alessandro Volta in the same year, other chemists tried connecting their poles in a container of water. They discovered that the current flowed through the water and that hydrogen and oxygen were separated at the electrodes.

The oxygen generated in parallel is released into the atmosphere or can be stored for later use as a medical or industrial gas in some cases. The hydrogen is stored as a compressed gas or liquefied for use in industry or in hydrogen fuel cells, which can power transport vehicles such as trains, ships and even aircraft.



Uses for fuel cells

Hydrogen is a clean fuel that, when consumed in a fuel cell, produces only water, electricity, and heat. Hydrogen and fuel cells can play an important role in our national energy strategy, with the potential for use in a broad range of applications, across virtually all sectors—transportation, commercial, industrial, residential, and portable. Hydrogen and fuel cells can provide energy for use in diverse applications, including distributed or combined-heat-and-power; backup power; systems for storing and enabling renewable energy; portable power; auxiliary power for trucks, aircraft, rail, and ships; specialty vehicles such as forklifts; and passenger and freight vehicles including cars, trucks, and buses.

Due to their high efficiency and zero-or near zero-emissions operation, hydrogen and fuel cells have the potential to reduce greenhouse gas emission in many applications. Research has shown that hydrogen and fuel cells have the potential to achieve the following reductions in emissions:

- Light-duty highway vehicles: more than 50% to more than 90% reduction in emissions over today's gasoline vehicles.
- Specialty vehicles: more than 35% reduction in emissions over current diesel and battery-powered lift trucks.

- Transit buses: demonstrated fuel economies of approximately 1.5 times greater than diesel internal combustion engine (ICE) buses and approximately 2 times higher than natural gas ICE buses.
- Auxiliary power units (APUs): more than 60% reduction in emissions compared to truck engine idling.
- Combined heat and power (CHP) systems: 35% to more than 50% reduction in emissions over conventional heat and power sources (with much greater reductions—more than 80%—if biogas or hydrogen from low- or zero-carbon sources is used in the fuel cell)

The greatest challenge for hydrogen production, particularly from renewable resources, is providing hydrogen at lower cost. For transportation fuel cells, hydrogen must be cost-competitive with conventional fuels and technologies. To reduce overall hydrogen cost, research is focused on improving the efficiency and lifetime of hydrogen production technologies as well as reducing the cost of capital equipment, operations, and maintenance.

How are electrolysers commercialized based hydrogen production?

There are four main ways that electrolysers can be commercialized:

Power to mobility: Hydrogen can be used as fuel at refuelling stations for fuel-cell electric vehicles such as buses, trains, and car.

Power to Fuel: Be used in refineries to remove sulphur from fossil fuels.

Power to Industry: Be used directly as an industrial gas in the steel industry, flat glass plants, semi-conductor industry, etc. It can also be injected directly into the natural gas grids for lower carbon heating and other natural gas applications.

Power to Gas: Be used in the production of green chemicals such as methanol, fertilizers (ammonia) and any other liquid fuel, even jet fuel!

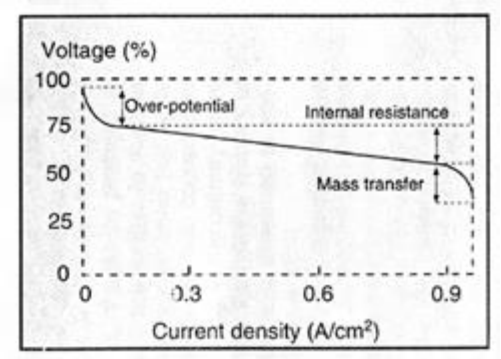
Fuel cell

A hydrogen fuel cell is an electrochemical cell that uses a spontaneous redox reaction to produce current that can do work. The net reaction is exothermic. Combining the 2 half-cell potentials for the electrochemical reaction gives a positive cell potential.

$$H_2 + 1/2\ O_2 \longrightarrow H_2O \qquad \Delta G_f = -229\ \text{kJ/mol}$$

$$H_2 \longrightarrow 2\ H^+ + 2\ e^- \qquad E^0 = 0.00\ \text{V}$$

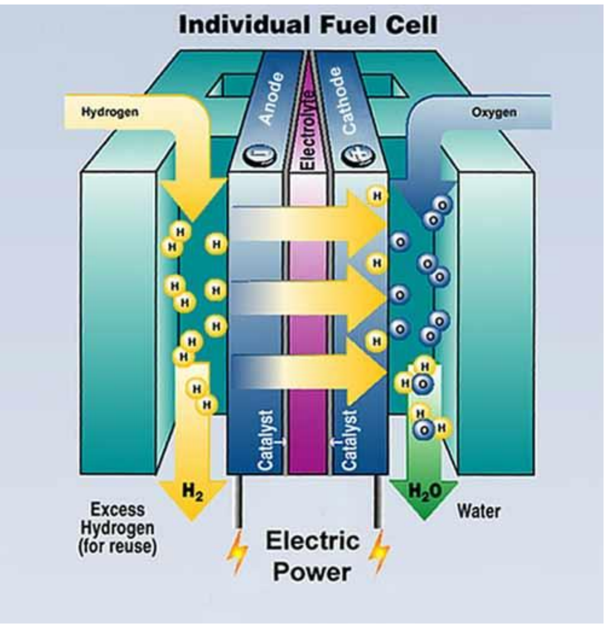
$$O_2 + 4\ e^- + 4\ H^+ \longrightarrow 2\ H_2O \qquad E^0 = 1.23\ \text{V}$$



The theoretical voltage for a hydrogen fuel cell should be 1.23 V, however typical potentials are 0.6 to 0.7 and actually drop as the current flows. Why?

- An overpotential is required to make the cathode reaction proceed at a fast enough rate.
- Charge carriers lose energy as heat (resistance) as they flow through the media.
- Mass transfer to the electrodes is slow.

Fuel cell principle



The hydrogen flows to a platinum catalyst connected to the anode. Molecular hydrogen is dissociated to atomic hydrogen on the metal surface and the atomic hydrogen is oxidized. The protons travel through a solid electrolyte, the polymer electrolyte membrane or PEM, and the electrons travel through the external circuit. Molecular oxygen is reduced at the cathode and combined with protons to form water.

A major problem with hydrogen fuel cells is the source of the hydrogen. The quantity of H2 in the atmosphere is very low so it must be produced. Currently, most hydrogen is made from natural gas and petroleum. It can also be produced from coal in the water gas and water gas shift reactions. All of these use the energy stored in fossil fuels and generate CO2. Electricity generated from other means (nuclear power, hydro power, or solar energy) can produce hydrogen through electrolysis. This is the reverse of the hydrogen fuel cell reaction. It is clear that H2 is an energy transfer medium rather than a fuel.

Fuel cell stack and electric

The achievable voltage of a fuel cell can be calculated with the help of the standard potential. For the reaction of hydrogen with oxygen, this is about 1.23 V. However, real fuel cells rarely achieve a no-load voltage greater than 1.0 V. This is caused by the internal resistance or an inadequate supply of hydrogen to the electrodes. The voltage is independent of the size of the fuel cell, as it depends only on the hydrogen used as a fuel. However, the size of the fuel cell is decisive for the amount of current, i.e., the number of electrons that can be produced per unit of time. If higher voltages are needed, then it is recommended to connect several fuel cells together.

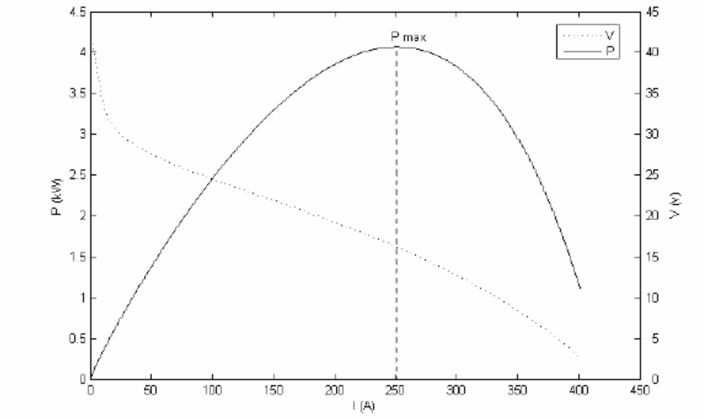


Figure 1 Fuel cell stack output voltage and power vs. its current curves - https://www.researchgate.net/figure/Fuel-cell-stack-output-voltage-and-power-vs-its-current-curves_fig1_267262048

With the fuel cell stack used here, parallel and series connections can be tried out. Characteristic curves will be recorded in the investigation. The characteristic curve of voltage indicates the voltage that the fuel cell can maintain when a defined amount of current is drawn. The defined current will be set using variable resistors. These convert the current into heat. The characteristic curve of power is also current-dependent. Here, the power of the fuel cell, which is the product of voltage and current, is plotted against the current.

A fuel cell should be operated at close to its maximum power, if possible. To achieve this, the current drawn is regulated. It is necessary to have a sufficient amount of hydrogen available when recording characteristic curves. Very little hydrogen is consumed at low current levels. The higher the current drawn, the more hydrogen is needed. At very high current levels it can happen that the voltage will fall owing insufficient hydrogen reaching the electrodes; the reaction is "starved". This would falsify the results of the characteristic curves.

An individual fuel cell typically delivers low voltages and high currents. Typical voltage and current ranges are from 0.4 to 0.9 V and from 0.5 to 1 A/cm2 respectively. For example, the fuel cell is reported to produce about 0.7 V (after losses) and 0.6 A/cm2. In order to achieve a higher power

output, the fuel cells need to be stacked together as shown in the Figure below. Depending on the power output and the applications, fuel cells come in various shapes and sizes.

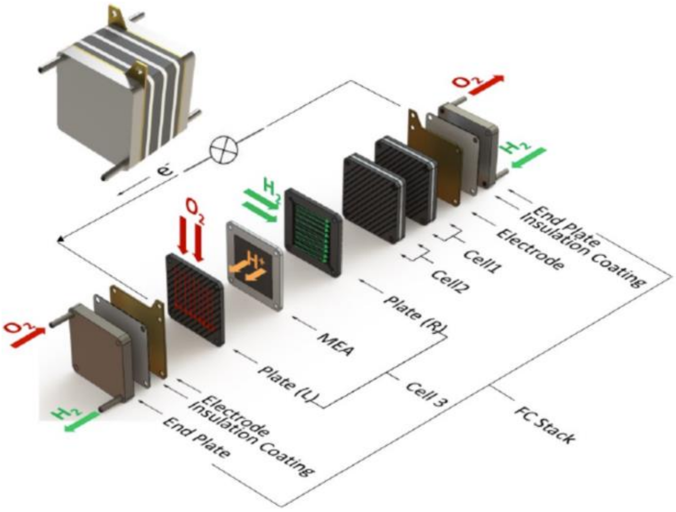


Figure 2 Schematics of a fuel cell stack operation and component - https://www.researchgate.net/publication/309898224_A_review_on_prognostics_and_health_monitoring_of_proton_exchange_membrane_fuel_cell

Use of fuel cells

Stationary fuel cells generate electricity through an electrochemical reaction, not combustion, providing clean, efficient, and reliable off-grid power to homes, businesses, telecommunications networks, utilities, and others. Stationary fuel cells are quiet and have very low emissions, so they can be to be installed nearly anywhere. These systems provide power on-site directly to customers, without the efficiency losses of long-range grid transmission.

Power generation

Stationary fuel cell systems also take up much less space in proportion to other clean energy technologies. For instance, a 10 MW fuel cell installation can be sited in a about an acre of land. This is compared to about 10 acres required per MW of solar power and about 50 acres per MW of wind. Most stationary fuel cells connect directly to our nation’s natural gas infrastructure, generating resilient power to critical facilities, even when grid power is unavailable.

Fuel cells are highly efficient, typically reaching fuel to electricity efficiency of 60 percent, nearly double the efficiency of today’s electric grid. Fuel cells also generate heat which, if captured, can increase overall energy efficiency to more than 90 percent. The heat produced by fuel cells can generate additional electricity through a turbine, provide heating directly to nearby buildings or facilities, and even cooling with the addition of an absorption chiller.

Unlike combustion-based power generation, stationary fuel cells provide virtually emission-free power. Fuel cells do not produce particulate pollutants, unburned hydrocarbons, or the gases that produce acid rain. They emit less carbon dioxide than other, less efficient technologies, and when using fuel generated from renewable sources such as biomass, fuel cells are completely carbon neutral.

Transportation

Imagine a car, SUV, or truck that performs like a conventional vehicle, a fuel tank that can be filled up in three - five minutes and emits zero emissions except for water vapor – that's today's fuel cell electric vehicle (FCEV). Fuel cells utilize hydrogen to produce electricity onboard the vehicle through a chemical process, without combustion.

Fuel Cell Electric Vehicle (FCEVs)

Capable of traveling 300-400 miles on a tank of hydrogen and refuelling in three-five minutes, FCEVs combine the emissions-free driving of an electric vehicle with the range and convenience of a traditional internal combustion engine. FCEVs are up to three times more energy efficient than conventional vehicles. Having no internal moving parts, FCEVs also are quiet and highly reliable.

FCEVs are zero-emission vehicles – they produce no tailpipe pollution except water vapor. In addition, compared to internal combustion vehicles, FCEVs greatly reduce greenhouse gas carbon emissions even when accounting for the full hydrogen fuel life cycle. When using hydrogen generated from solar or wind electrolysis, total life cycle CO2 emissions eliminated completely.

Fuel Cell Buses

Several dozen fuel cell buses are operating in cities, providing clean and reliable transportation alternatives for commuters. Producing no emissions, fuel cell buses are attractive options for urban areas, operating quietly and reducing maintenance costs. Fuel cell buses also demonstrate advantages operating in extreme temperatures, especially over battery-powered alternatives.

Heavy-Duty Trucks

Similarly, to fuel cell buses, heavy duty trucks can utilize fuel cells to reduce emissions and provide reliable vehicles for a variety of purposes. Several prototypes have been deployed at port facilities in Southern California, where they serve in short range drayage operations. Future applications for fuel cell heavy duty trucks include long haul trucking cross-country as well. Check out our *In Transitions* blog post on Fuel Cell-Powered Port Vehicles for more information.

Medium-Duty Trucks

Fuel cell vehicles are being deployed within larger fleets of delivery vehicles, providing clean and reliable transportation for local networks. Whether the sole power for the vehicle or in combination with batteries, fuel cells operate reliably and extend the range of the vehicle over solely battery-powered vehicles.

Material Handling

If you work in a warehouse, you might already be driving a fuel cell vehicle today. Forklifts and other material handling devices have proven to be an ideal market for early adopters of fuel cell powered vehicles. Many major companies are finding that fleets of fuel cell forklifts increase productivity and save money at their warehouses and distribution centres. Check out our Material Handling Fact Sheet for more information.

Unmanned Aerial and Underwater Vehicles

Several models of unmanned aerial vehicles (UAVs), or “drones”, currently utilize fuel cells for power. These provide the drones with longer flight times and quick refuelling, compared to traditional battery-operated drones. While only fuel cell-powered UAVs are currently commercially available, additional research and development is being put towards underwater fuel cell drones as well.

Rail Transportation

Fuel cell trains are now operational in Germany, with travellers benefiting from the reduction in noise and air pollution from conventional diesel-powered trains. Outside of Germany, deployments of fuel cell trains are scheduled for Japan and South Korea in the future. Along with line electrification, fuel cell trains are beneficial options to reduce emissions from the transportation sector and meet growing challenges.

Marine Transportation

Marine vessels of varying sizes are currently testing fuel cells in new capacities on the water. Several ferries around the world have begun hydrogen operations, while larger fuel cell models are being prototypes and examined for container shipping vessels. Vessels from large to small are looking to fuel cells to meet emissions targets and keep people and cargo moving.

OUTCOME 2 - Describe the basic characteristics of fuel cells as well as electrolysers and the function of their component parts

Types of electrolysers

At present, there are different types of electrolysers depending on their size and function. The most commonly used are described below.[i]

Alkaline electrolyser

Alkaline electrolysers use a liquid electrolyte solution, such as potassium hydroxide or sodium hydroxide, and water. Hydrogen is produced in a cell consisting of an anode, a cathode and a membrane. The cells are usually assembled in series to produce more hydrogen and oxygen at the same time. When current is applied to the electrolysis cell stack, hydroxide ions move through the electrolyte from the cathode to the anode of each cell, generating bubbles of hydrogen gas on the cathode side of the electrolyser and oxygen gas at the anode. They have been in use for more than 100 years and do not require noble metals as a catalyst; however, they are bulky equipment that obtains medium purity hydrogen and are not very flexible in operation.

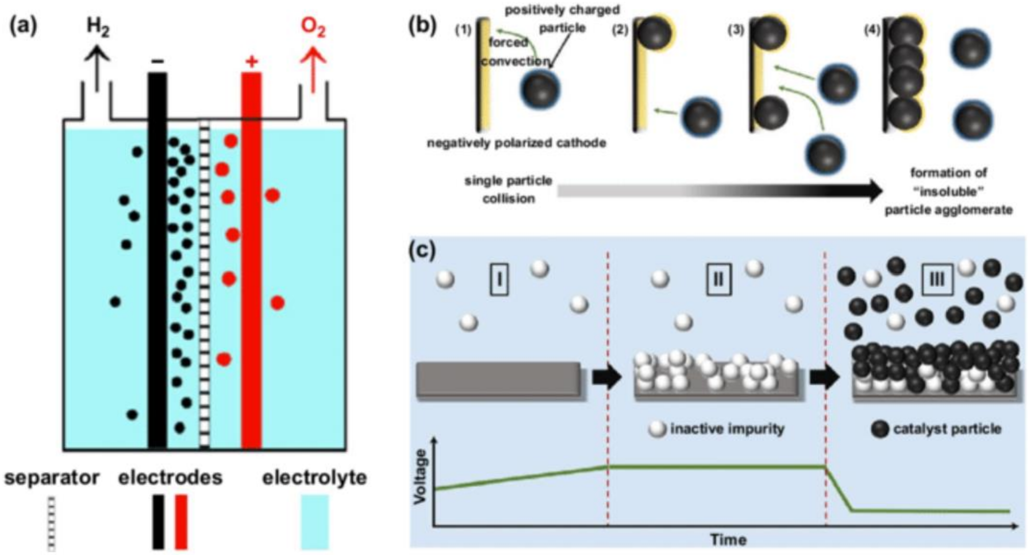
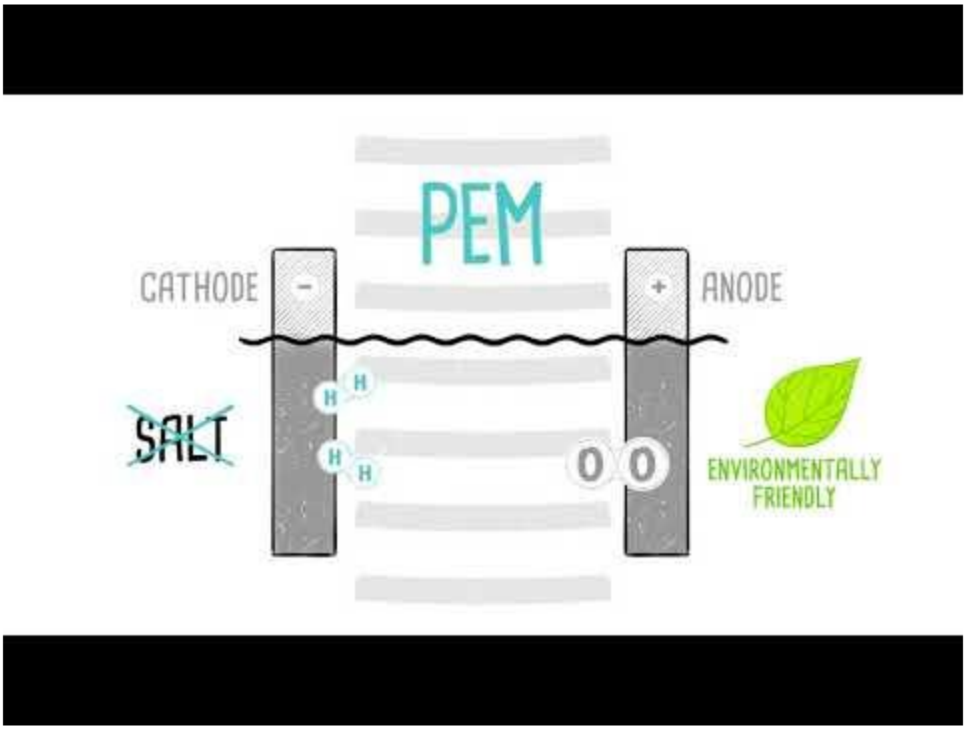


Figure 3 Schematic diagram of conventional alkaline electrolyser - Copyright 2012 Elsevier Inc

Proton exchange membrane electrolyser

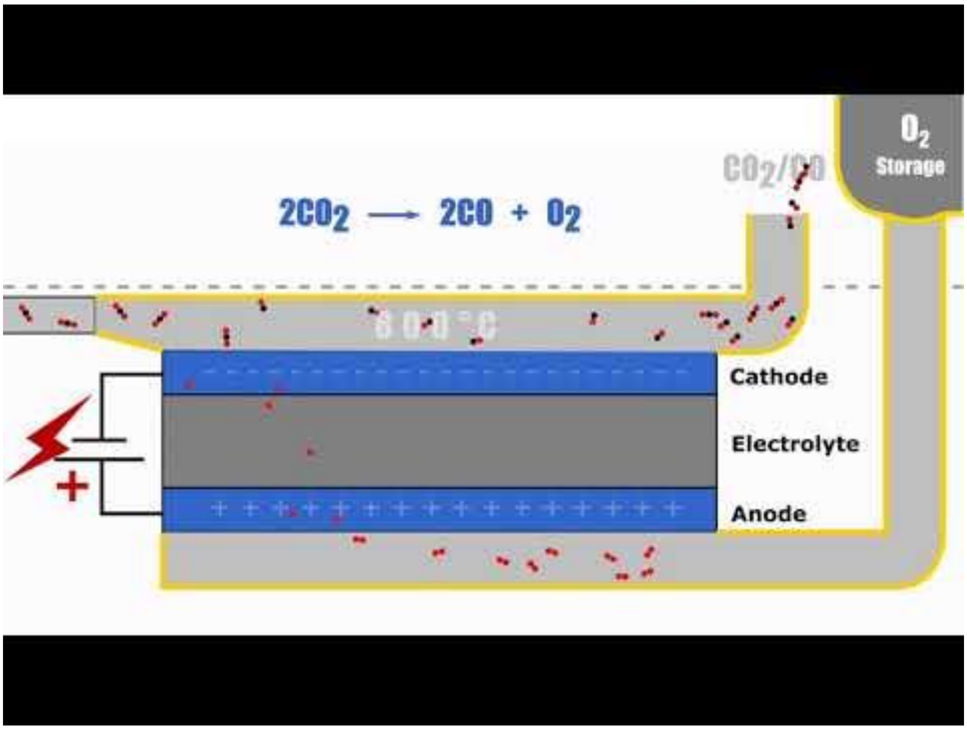
PEM electrolysers use a proton exchange membrane and a solid polymer electrolyte. When current is applied to the battery, water splits into hydrogen and oxygen and the hydrogen protons pass through the membrane to form hydrogen gas on the cathode side. They are the most popular because they produce high-purity hydrogen and are easy to cool**.** They are best suited to match the variability of renewable energies, are compact and produce high-purity hydrogen. On the other hand, they are somewhat more expensive because they use precious metals as catalysts.



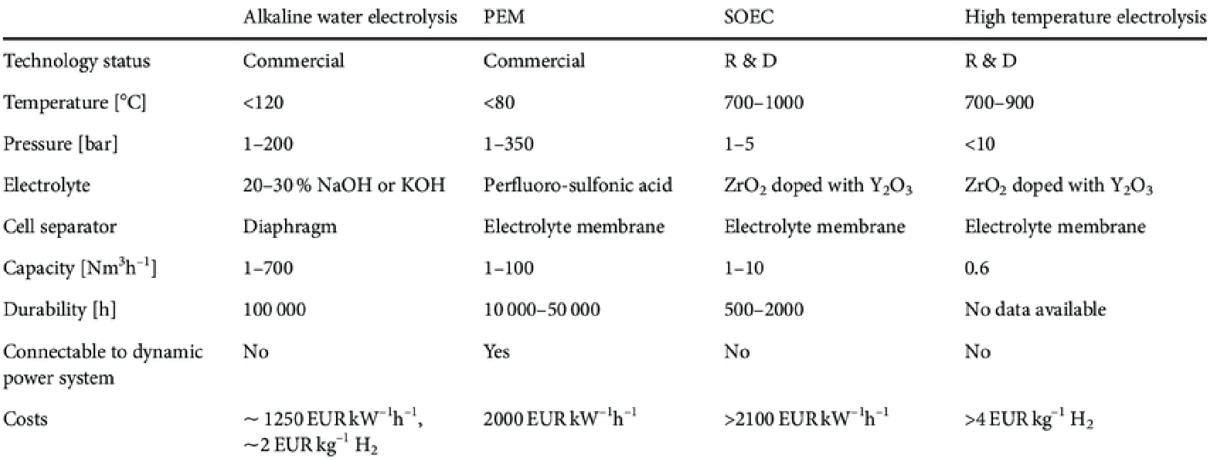
Solid oxide electrolysis cell (SOEC)

SOECs operate at a higher temperature (between 500 and 850 ºC) and have the potential to be much more efficient than PEMs and alkaline electrolysers. The process is called high-temperature electrolysis (HTE) or steam electrolysis and uses a solid ceramic material as the electrolyte. Electrons from the external circuit combine with water at the cathode to form hydrogen gas and negatively charged ions. Oxygen then passes through the sliding ceramic membrane and reacts at the anode to form oxygen gas and generate electrons for the external circuit.

There are other types of electrolysers that are not yet as efficient or cost-effective as the above but have a lot of potential for development. One example is photo electrolysis, which uses only sunlight to separate water molecules without the need for electricity. However, this device requires semiconductors that have not yet been sufficiently developed.



Comparison and summary of different water electrolysis technologies



	Alkaline water electrolysis	PEM	SOEC	High temperature electrolysis
Technology status	Commercial	Commercial	R & D	R & D
Temperature [°C]	<120	<80	700–1000	700–900
Pressure [bar]	1–200	1–350	1–5	<10
Electrolyte	20–30 % NaOH or KOH	Perfluoro-sulfonic acid	ZrO_2 doped with Y_2O_3	ZrO_2 doped with Y_2O_3
Cell separator	Diaphragm	Electrolyte membrane	Electrolyte membrane	Electrolyte membrane
Capacity [Nm^3h^{-1}]	1–700	1–100	1–10	0.6
Durability [h]	100 000	10 000–50 000	500–2000	No data available
Connectable to dynamic power system	No	Yes	No	No
Costs	~ 1250 EUR $kW^{-1}h^{-1}$, ~2 EUR kg^{-1} H_2	2000 EUR $kW^{-1}h^{-1}$	>2100 EUR $kW^{-1}h^{-1}$	>4 EUR kg^{-1} H_2

Figure 4 https://www.researchgate.net/figure/Comparison-of-different-water-electrolysis-technologies-79-93-133-134-138_tbl4_337716604

Fuel cell

A fuel cell is needed to convert hydrogen (H2) into electricity; strictly speaking, this is a hydrogen-oxygen fuel cell. It is also often referred to simply as a "hydrogen fuel cell". In the following, "fuel cell" and "hydrogen fuel cell" are used synonymously. In hydrogen fuel cells, hydrogen serves as the fuel and oxygen (O2) as the oxidant. By converting chemical energy directly into electrical energy and heat, hydrogen fuel cells have significantly higher efficiencies than conventional power plants.

In combination with a fuel storage system and hydrogen recycling, fuel cell systems enable pollution-free energy generation. The power spectrum of hydrogen fuel cells ranges from the sub-kW range of individual cells to the MW range in the form of virtual power plants.

The field of application of hydrogen fuel cells ranges from heat and power supply in buildings to off-grid applications and the propulsion of vehicles, aeroplanes and ships. Fuel cells have increasingly come into focus, especially due to the discussions about the role of hydrogen in e-mobility. cell consists of a network of several cells that are separated by separators and arranged in a stack. The structure of a fuel cell is planar in layers or, in the case of solid oxide fuel cells, tubular as a tube system.

Components of fuel cells

Electrolysis plays a decisive role in the functioning of fuel cells: the core of an individual fuel cell is formed by a liquid or solid electrolyte, which is enclosed on both sides by bipolar electrode plates (anode and cathode).

These plates have a porous diffusion layer (GDL - gas diffusion layer), which guides the reaction gases over a precious metal-coated catalyst surface (low and medium temperature range) or over a catalyst made of nickel, ceramic or steel (high temperature range). This is how, in most fuel cell types, the hydrogen is split on the anode side and the electrons are discharged to the electrical consumer. The hydrogen protons migrate through the electrolyte to the cathode side, where they combine with the added oxygen to form water (H2O)

Fuel cells are classified primarily by the kind of electrolyte they employ. This classification determines the kind of electro-chemical reactions that take place in the cell, the kind of catalysts required, the temperature range in which the cell operates, the fuel required, and other factors. These characteristics, in turn, affect the applications for which these cells are most suitable. There are several types of fuel cells currently under development, each with its own advantages, limitations, and potential applications.

Catalyst Layers

A layer of catalyst is added on both sides of the membrane—the anode layer on one side and the cathode layer on the other. Conventional catalyst layers include nanometre-sized particles of platinum dispersed on a high-surface-area carbon support. This supported platinum catalyst is mixed with an ion-conducting polymer (ionomer) and sandwiched between the membrane and the GDLs. On the anode side, the platinum catalyst enables hydrogen molecules to be split into protons and electrons. On the cathode side, the platinum catalyst enables oxygen reduction by reacting with the protons generated by the anode, producing water. The ionomer mixed into the catalyst layers allows the protons to travel through these layers.

Gas Diffusion Layers

The GDLs sit outside the catalyst layers and facilitate transport of reactants into the catalyst layer, as well as removal of product water. Each GDL is typically composed of a sheet of carbon paper in which the carbon fibres are partially coated with polytetrafluoroethylene (PTFE). Gases diffuse rapidly through the pores in the GDL. These pores are kept open by the hydrophobic PTFE, which prevents excessive water build-up. In many cases, the inner surface of the GDL is coated with a thin layer of high-surface-area carbon mixed with PTFE, called the microporous layer. The microporous layer can help adjust the balance between water retention (needed to maintain membrane conductivity) and water release (needed to keep the pores open so hydrogen and oxygen can diffuse into the electrodes).

Hardware

The Membrane Electrode Assembly MEA is the part of the fuel cell where power is produced, but hardware components are required to enable effective MEA operation.

Bipolar Plates

Each individual MEA produces less than 1 V under typical operating conditions, but most applications require higher voltages. Therefore, multiple MEAs are usually connected in series by stacking them on top of each other to provide a usable output voltage. Each cell in the stack is sandwiched between two bipolar plates to separate it from neighbouring cells. These plates, which may be made of metal, carbon, or composites, provide electrical conduction between cells, as well as providing physical strength to the stack. The surfaces of the plates typically contain a “flow field,” which is a set of channels machined or stamped into the plate to allow gases to flow over the MEA. Additional channels inside each plate may be used to circulate a liquid coolant.

Gaskets

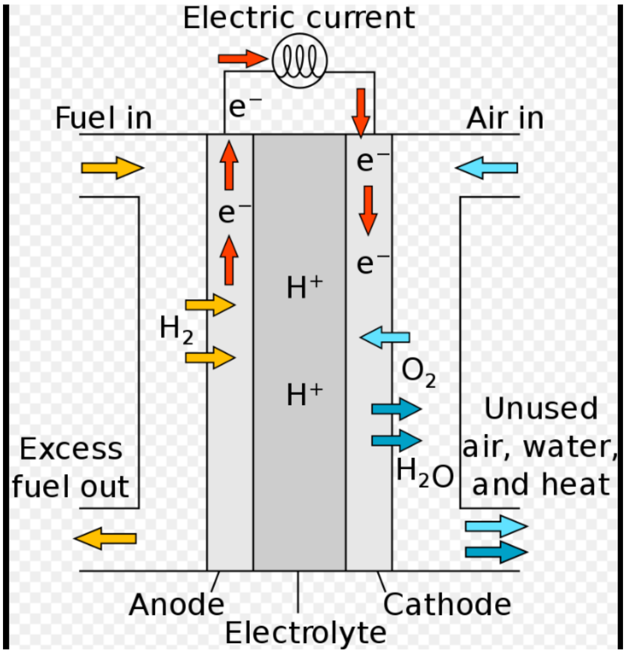
Each MEA in a fuel cell stack is sandwiched between two bipolar plates, but gaskets must be added around the edges of the MEA to make a gas-tight seal. These gaskets are usually made of a rubbery polymer

Types of fuel cells

Polymer electrolyte membrane fuel cells

Polymer electrolyte membrane (PEM) fuel cells—also called proton exchange membrane fuel cells—deliver high power density and offer the advantages of low weight and volume compared with other fuel cells. PEM fuel cells use a solid polymer as an electrolyte and porous carbon electrodes containing a platinum or platinum alloy catalyst. They need only hydrogen, oxygen from the air, and water to operate. They are typically fuelled with pure hydrogen supplied from storage tanks or reformers.

PEM fuel cells operate at relatively low temperatures, around 80°C (176°F). Low-temperature operation allows them to start quickly (less warm-up time) and results in less wear on system components, resulting in better durability. However, it requires that a noble-metal catalyst (typically platinum) be used to separate the hydrogen's electrons and protons, adding to system cost. The platinum catalyst is also extremely sensitive to carbon monoxide poisoning, making it necessary to employ an additional reactor to reduce carbon monoxide in the fuel gas if the hydrogen is derived from a hydrocarbon fuel. This reactor also adds cost. PEM fuel cells are used primarily for transportation applications and some stationary applications. PEM fuel cells are particularly suitable for use in vehicle applications, such as cars, buses, and heavy-duty trucks.



Direct methanol fuel cell

Most fuel cells are powered by hydrogen, which can be fed to the fuel cell system directly or can be generated within the fuel cell system by reforming hydrogen-rich fuels such as methanol, ethanol, and hydrocarbon fuels. Direct methanol fuel cells (DMFCs), however, are powered by pure methanol, which is usually mixed with water and fed directly to the fuel cell anode.

Direct methanol fuel cells do not have many of the fuel storage problems typical of some fuel cell systems because methanol has a higher energy density than hydrogen—though less than gasoline or diesel fuel. Methanol is also easier to transport and supply to the public using our current infrastructure because it is a liquid, like gasoline. DMFCs are often used to provide power for portable fuel cell applications such as cell phones or laptop computers.

Alkaline fuel cell

Alkaline fuel cells (AFCs) were one of the first fuel cell technologies developed, and they were the first type widely used in the U.S. space program to produce electrical energy and water on-board spacecraft. These fuel cells use a solution of potassium hydroxide in water as the electrolyte and can use a variety of non-precious metals as a catalyst at the anode and cathode. In recent years, novel AFCs that use a polymer membrane as the electrolyte have been developed. These fuel cells are closely related to conventional PEM fuel cells, except that they use an alkaline membrane instead of an acid membrane. The high performance of AFCs is due to the rate at which electro-chemical reactions take place in the cell. They have also demonstrated efficiencies above 60% in space applications.

A key challenge for this fuel cell type is that it is susceptible to poisoning by carbon dioxide (CO2). In fact, even the small amount of CO2 in the air can dramatically affect cell performance and durability due to carbonate formation. Alkaline cells with liquid electrolytes can be run in a recirculating mode, which allows for electrolyte regeneration to help reduce the effects of carbonate formation in the electrolyte, but the recirculating mode introduces issues with shunt currents. The liquid electrolyte systems also suffer from additional concerns including wettability, increased corrosion, and difficulties handling differential pressures. Alkaline membrane fuel cells (AMFCs) address these concerns and have lower susceptibility to CO2 poisoning than liquid-electrolyte AFCs do. However, CO2 still affects performance, and performance and durability of the AMFCs still lag that of PEMFCs. AMFCs are being considered for applications in the W to kW scale. Challenges for AMFCs include tolerance to carbon dioxide, membrane conductivity and durability, higher temperature operation, water management, power density, and anode electrocatalysis.

Phosphoric acid fuel cells

Phosphoric acid fuel cells (PAFCs) use liquid phosphoric acid as an electrolyte—the acid is contained in a Teflon-bonded silicon carbide matrix—and porous carbon electrodes containing a platinum catalyst. The PAFC is considered the "first generation" of modern fuel cells. It is one of the most mature cell types and the first to be used commercially. This type of fuel cell is typically used for stationary power generation, but some PAFCs have been used to power large vehicles such as city buses.

PAFCs are more tolerant of impurities in fossil fuels that have been reformed into hydrogen than PEM cells, which are easily "poisoned" by carbon monoxide because carbon monoxide binds to the platinum catalyst at the anode, decreasing the fuel cell's efficiency. PAFCs are more than 85% efficient when used for the co-generation of electricity and heat but they are less efficient at generating electricity alone (37%–42%). PAFC efficiency is only slightly more than that of combustion-based power plants, which typically operate at around 33% efficiency. PAFCs are also less powerful than other fuel cells, given the same weight and volume. As a result, these fuel cells are typically large and heavy. PAFCs are also expensive. They require much higher loadings of expensive platinum catalyst than other types of fuel cells do, which raises the cost.

Molten carbonate fuel cells

Molten carbonate fuel cells (MCFCs) are currently being developed for natural gas and coal-based power plants for electrical utility, industrial, and military applications. MCFCs are high-temperature fuel cells that use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminium oxide matrix. Because they operate at high temperatures of 650°C (roughly 1,200°F), non-precious metals can be used as catalysts at the anode and cathode, reducing costs.

Improved efficiency is another reason MCFCs offer significant cost reductions over phosphoric acid fuel cells. Molten carbonate fuel cells, when coupled with a turbine, can reach efficiencies approaching 65%, considerably higher than the 37%–42% efficiencies of a phosphoric acid fuel cell plant. When the waste heat is captured and used, overall fuel efficiencies can be over 85%.

Unlike alkaline, phosphoric acid, and PEM fuel cells, MCFCs do not require an external reformer to convert fuels such as natural gas and biogas to hydrogen. At the high temperatures at which MCFCs operate, methane and other light hydrocarbons in these fuels are converted to hydrogen within the fuel cell itself by a process called internal reforming, which also reduces cost.

The primary disadvantage of current MCFC technology is durability. The high temperatures at which these cells operate, and the corrosive electrolyte used accelerate component breakdown and corrosion, decreasing cell life. Scientists are currently exploring corrosion-resistant materials for components as well as fuel cell designs that double cell life from the current 40,000 hours (~5 years) without decreasing performance.

Solid oxide fuel cells

Solid oxide fuel cells (SOFCs) use a hard, non-porous ceramic compound as the electrolyte. SOFCs are around 60% efficient at converting fuel to electricity. In applications designed to capture and utilize the system's waste heat (co-generation), overall fuel use efficiencies could top 85%.

SOFCs operate at very high temperatures—as high as 1,000°C (1,830°F). High-temperature operation removes the need for precious-metal catalyst, thereby reducing cost. It also allows SOFCs to reform fuels internally, which enables the use of a variety of fuels and reduces the cost associated with adding a reformer to the system.

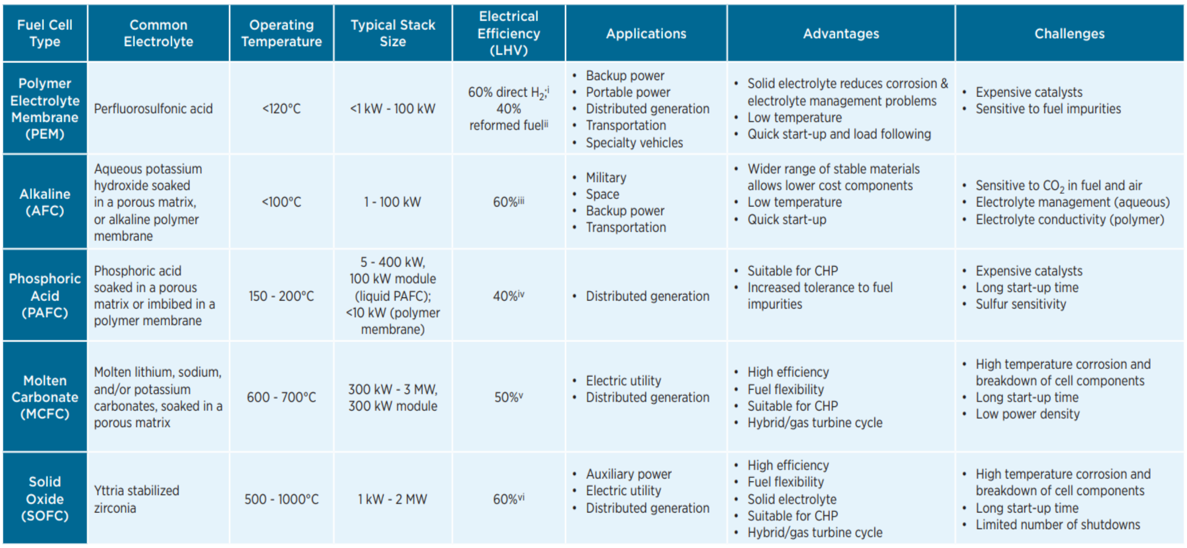
SOFCs are also the most sulphur-resistant fuel cell type; they can tolerate several orders of magnitude more Sulphur than other cell types can. In addition, they are not poisoned by carbon monoxide, which can even be used as fuel. This property allows SOFCs to use natural gas, biogas, and gases made from coal. High-temperature operation has disadvantages. It results in a slow start up and requires significant thermal shielding to retain heat and protect personnel, which may be acceptable for utility applications but not for transportation. The high operating temperatures also place stringent durability requirements on materials. The development of low-cost materials with high durability at cell operating temperatures is the key technical challenge facing this technology.

Scientists are currently exploring the potential for developing lower-temperature SOFCs operating at or below 700°C that have fewer durability problems and cost less. Lower-temperature SOFCs have not yet matched the performance of the higher temperature systems, however, and stack materials that will function in this lower temperature range are still under development.

Reversible fuel cells

Reversible fuel cells produce electricity from hydrogen and oxygen and generate heat and water as by-products, just like other fuel cells. However, reversible fuel cell systems can also use electricity from solar power, wind power, or other sources to split water into oxygen and hydrogen fuel through a process called electrolysis. Reversible fuel cells can provide power when needed, but during times of high-power production from other technologies (such as when high winds lead to an excess of available wind power), reversible fuel cells can store the excess energy in the form of hydrogen. This energy storage capability could be a key enabler for intermittent renewable energy technologies.

Comparison and summary of the different fuel cells



Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Electrical Efficiency (LHV)	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)	Perfluorosulfonic acid	<120°C	<1 kW - 100 kW	60% direct H_2;[i] 40% reformed fuel[ii]	• Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up and load following	• Expensive catalysts • Sensitive to fuel impurities
Alkaline (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100°C	1 - 100 kW	60%[iii]	• Military • Space • Backup power • Transportation	• Wider range of stable materials allows lower cost components • Low temperature • Quick start-up	• Sensitive to CO_2 in fuel and air • Electrolyte management (aqueous) • Electrolyte conductivity (polymer)
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	150 - 200°C	5 - 400 kW, 100 kW module (liquid PAFC); <10 kW (polymer membrane)	40%[iv]	• Distributed generation	• Suitable for CHP • Increased tolerance to fuel impurities	• Expensive catalysts • Long start-up time • Sulfur sensitivity
Molten Carbonate (MCFC)	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	600 - 700°C	300 kW - 3 MW, 300 kW module	50%[v]	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	500 - 1000°C	1 kW - 2 MW	60%[vi]	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Solid electrolyte • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Limited number of shutdowns

Figure 5 http://energy.asu.edu.jo/index.php/2016-08-28-08-51-21/hydrogen-fuel-cells

Advantages and disadvantages of electrolyser and fuel cells

Green hydrogen produced from electrolysis (a high energy process) and renewable energy sources is a high-cost option, which only accounts for around 5% of total H2 production. Currently, the vast majority of global hydrogen production derives from fossil fuel sources (methane gas reforming) and will continue to do so for several decades. However, as manufacturing capacity for more efficient and cost-effective electrolysers grows, it is expected that costs of production will fall markedly alongside roll-out of maturing renewable power generation technologies and capacity.

In order to produce a secure, resilient and decarbonised energy system, production and bulk storage of hydrogen will play an important role in balancing intermittent supply of energy from renewable energy sources with end-user demands (i.e., for grid electricity, domestic and industrial heating and fuel for transportation).

Debates continue regarding hydrogen fuel cells advantages and disadvantages, but despite current limitations, hydrogen is still an environmentally friendly alternative to fossil fuels and can be used to provide flexible and high-density power and propulsion for a wide range of industrial plant and modes of transportation using hydrogen fuel cell technology.

What are the main advantages

Hydrogen fuel cell and electrolyser technology presents several advantages over other power sources including:

1. Renewable and Readily Available

Hydrogen is the most abundant element in the Universe and despite the challenges associated with its extraction from water, is a uniquely abundant and renewable source of energy, perfect for our future zero-carbon needs for power supplies.

2. Hydrogen is a Clean and Flexible Energy to support Zero-Carbon Energy Strategies

Hydrogen fuel cells provide an inherently clean source of energy, with no adverse environmental impact during operation as the by-products are simply heat and water. Unlike biofuel or hydropower, hydrogen doesn’t require large areas of land to produce. In fact, NASA have even been working on using hydrogen as a resource with the water produced as a by-product being used as drinking water for astronauts. This shows that hydrogen fuel cells are a non-toxic fuel source and therefore superior in this way to coal, natural gas and nuclear power which are all either potentially dangerous or hard to obtain. Production, storage and use of hydrogen will play an important role in driving further development of renewable energy, by balancing their intermittent supply modalities with the challenging end-user demands, avoiding the need for significant early investment to upgrade grid infrastructure.

3. More Powerful and Energy Efficient than Fossil Fuels

Hydrogen fuel cell technology provides a high-density source of energy with good energy efficiency. Hydrogen has the highest energy content of any common fuel by weight. High pressure gaseous and liquid hydrogen have around three times the gravimetric energy density (around 120MJ/kg) of diesel and LNG and a similar volumetric energy density to natural gas. These

4. Highly Efficient when Compared to Other Energy Sources

Hydrogen fuel cells are more efficient than many other energy sources, including many green energy solutions. This fuel efficiency allows for the production of more energy per pound of fuel. For example, a conventional combustion-based power plant generates electricity at 33-35% efficiency compared to up to 65% for hydrogen fuel cells. The same goes for vehicles, where hydrogen fuel cells use 40-60% of the fuel’s energy while also offering a 50% reduction in fuel consumption.

5. Almost Zero Emissions

Hydrogen fuel cells do not generate greenhouse gas emissions as for fossil fuel sources, thus reducing pollution and improving air quality as a result.

6. Reduces Carbon Footprints

With almost no emissions, hydrogen fuel cells do not release greenhouse gases, which means they do not have a carbon footprint while in use.

7. Fast Charging Times

The charge time for hydrogen fuel cell power units is extremely rapid, similar to that for conventional internal combustion engine (ICE) vehicles and markedly quicker in comparison to battery-powered electric vehicles. Where electric vehicles require between 30 minutes and several hours to charge, hydrogen fuel cells can be recharged in under five minutes. This fast-charging time means that hydrogen powered vehicles provide the same flexibility as conventional cars.

8. No Noise Pollution

Hydrogen fuel cells do not produce noise pollution like other sources of renewable energy, such as wind power. This also means that, much like electric cars, hydrogen powered vehicles are much quieter than those that use conventional internal combustion engines.

9. No Visual Pollution

Some low-carbon energy sources, including wind energy and biofuel power plants can be an eyesore, however, hydrogen fuel cells do not have the same space requirements, meaning that there is less visual pollution too.

10. Long Usage Times

Hydrogen fuel cells offer greater efficiencies with regard to usage times. A hydrogen vehicle has the same range as those that use fossil fuels (around 300 miles). This is superior to that currently offered by electric vehicles (EVs), which are increasingly being developed with fuel cell power units as ‘range-extenders’. Hydrogen fuel cells are also not significantly impacted by the outside temperature and do not deteriorate in cold weather, unlike EVs. This advantage is increased further when coupled with the short charging times.

11. Ideal for Use in Remote Areas

Where local conditions allow, the availability of hydrogen through local generation and storage could prove to be an alternative to diesel-based power and heating in remote areas. Not only will this reduce the need to transport fuels but will also improve the lives of those living in distant regions by offering a non-polluting fuel obtain from a readily available natural resource.

12. Versatility of Use

As the technology advances, hydrogen fuel cells will be able to provide energy for a range stationary and mobile applications. Hydrogen powered vehicles are just one example, but it could also be used in smaller applications such as domestic products as well as larger scale heating systems. Similar to ICE powerplants, the functions of energy storage capacity (i.e., the fuel tank) and engine size are decoupled, in contrast to battery-based power (i.e., for which power scales linearly with mass), thus providing great flexibility in design.

13. Democratisation of Power Supply

Hydrogen fuel cells have the potential to reduce the dependency of a nation on fossil fuels, which will help democratise energy and power supplies around the world. This increased independence will prove a benefit for many countries who are currently reliant on fossil fuel supply. Of course, this will also avoid the problem of rising fossil fuel prices as stocks reduce.

What are the Disadvantages of Electrolyser and Hydrogen Fuel Cells?

For all the many advantages, there are still a few disadvantages and challenges to address:

1. Hydrogen Extraction

Despite being the most abundant element in the Universe, hydrogen does not exist on its own so needs to be extracted from water via electrolysis or separated from carbon fossil fuels. Both of these processes require a significant amount of energy to achieve. This energy can be more than that gained from the hydrogen itself as well as being expensive. In addition, this extraction typically requires the use of fossil fuels, which in the absence of CCS undermines the green credentials of hydrogen.

2. Investment is Required

Hydrogen fuel cells need investment to be developed to the point where they become a genuinely viable energy source. This will also require the political will to invest the time and money into development in order to improve and mature the technology. Put simply, the global challenge for development of widespread and sustainable hydrogen energy is how best to incrementally build the ‘supply and demand’ chain in the most cost-effective manner.

3. Cost of Raw Materials

Precious metals such as platinum and iridium are typically required as catalysts in fuel cells and some types of water electrolyser, which means that the initial cost of fuel cells (and electrolysers) can be high. This high cost has deterred some from investing in hydrogen fuel cell technology. Such costs need to be reduced in order to make hydrogen fuel cells a feasible fuel source for all.

4. Regulatory Issues

There are also barriers around regulatory issues concerning the framework that defines commercial deployment models. Without clear regulatory frameworks to allow commercial projects to understand their cost and revenue basis, commercial projects can struggle to reach a financial investment decision (FID).

5. Overall Cost

The cost for a unit of power from hydrogen fuel cells is currently greater than other energy sources, including solar panels. This may change as technology advances, but currently this cost is a barrier to widespread use of hydrogen even though it is more efficient once produced. This expense also impacts costs further down the line, such as with the price of hydrogen operated vehicles, making widespread adoption unlikely at the moment.

6. Hydrogen Storage

Storage and transportation of hydrogen is more complex than that required for fossil fuels. This implies additional costs to consider for hydrogen fuel cells as a source of energy.

7. Infrastructure

Because fossil fuels have been used for decades, the infrastructure for this power supply already exists. Large scale adoption of hydrogen fuel cell technology for automotive applications will require new refuelling infrastructure to support it, although for long-range applications such as those for HGVs and delivery truck is it likely the start-to-end refuelling will be used.

8. Highly Flammable

Hydrogen is a highly flammable fuel source, which brings understandable safety concerns. Hydrogen gas burns in air at concentrations ranging from 4 to 75%.

OUTCOME 3 - Standards and Regulations used for the design, installation, commissioning and maintenance of electrolyser &fuel cell technology systems

Principles for safety planning

As hydrogen and fuel cell technologies gain a greater commercial foothold, safe practices in the production, storage, distribution and use of hydrogen are essential for safe demonstrations, positive perception and widespread public acceptance and trust. A thorough and integrated approach to project safety planning, monitoring and reporting needs to address technical and organisational tiers and it must involve all concerned parties via appropriate communication and actions. For example, in the case of a system installation, the involved parties would include hydrogen/fuel cell/equipment suppliers, facility operators, maintenance/repair providers, authorities, potential customers, safety engineers and first responders. The following critical elements help ensure that safety is integrated into the annual and multi-annual programmes, projects, system demonstrations and other activities.

Detection of hydrogen [H_2]

Observation	Inference
1. Colourless gas	Cl_2 and NO_2 are not present
2. Odourless gas	Can be O_2, H_2, CO_2 or water vapours
3. Neutral towards litmus	Can be O_2 H_2 or water vapours
4. The burning wooden splint goes off and gas burns with pale blue flame producing pop sound	It is a combustible gas It burns explosively in air. Gas is hydrogen

* Click on each observation to know more

Early Identification of Safety Expertise

In many cases valuable specific safety experience might be available and therefore it is a straightforward and essential ingredient in safety planning to identify and use this expertise directly. Safety expertise should be consulted early in a programme or a project's life to ensure that safety engineering design features, practices and procedures are consistently applied as part of the project implementation. Work scope could include but not limited to:

- Reviewing planning documents ensuring that safety issues are addressed and budgeted to close the most important knowledge gaps and technological bottlenecks in respective projects, the forthcoming annual working plan (AWP) and in an update of the Multi-Annual Working Plan (MAWP).
- Reviewing designs with the intent of approving and/or assisting with the approval of a project.
- Inspecting and performing regular audits of the installation to ensure safe execution of the project.
- Investigating lessons learned and reporting for accidents, incidents and near-misses for applying the knowledge gained in corresponding updates of the safety plan.
- Developing further safety-related management issues.
- Formulating knowledge gaps and technological bottlenecks identified within a project scope to be addressed in similar projects in the future. The EHSP is committed to help in this regard and will provide expertise in case the project consortium does not have own safety expertise or wishes an independent view on the above aspects.

Compliance with Regulations, Codes and Standards Safety

Compliance with Regulations, Codes and Standards Safety planning must account for relevant regulations, codes and standards (RCS), including international, national and regional. Regulations establish minimum safety requirements and at least implicitly require complying with the state-of-the-art, which is defined not only via standards but also refers to best practice guidelines, industry codes, scientific publications, etc. So, the use of RCS still requires the developers and other stakeholders to use new knowledge not yet included into RCS but published elsewhere. For instance, best safety practices and lessons learned, incorporating a wealth of experience with new knowledge and insights gained, are important aspects of continuous and priority attention given to safety.

Compliance with applicable regulations and referred standards is essential for ensuring public confidence in hydrogen projects, particularly for those demonstrating or deploying new technologies. Where strict compliance for a specific design, installation, and/or operation cannot be achieved, and alternatives are proposed, a sound technical basis should be formally agreed upon by all the relevant parties, including stakeholders and authorities.

Project teams should consult local authorities early in the project. Early engagement will facilitate a greater understanding of the local requirements, which in some cases could be more restrictive than European or national regulation. On the other side, the early contact also helps informing the authorities about the new technologies and give them enough time for acquiring further independent information.

Potential hazards, failure mechanisms and incidents

Potential hazards, failure mechanisms, and related incidents associated with any work process or system should always be identified, analysed, reported (recorded in relevant knowledge databases, e.g., handbooks, papers, etc.) and eliminated or mitigated as part of sound safety planning and comprehensive hydrogen safety engineering, which extends beyond the recommendations of this document. All relevant objects or aspects that may be adversely affected by a failure should be considered, including low frequency high consequences events.

So, the general protection objective is to exclude or at least minimise potential hazards and associated risks to prevent impacts on the following:

- People

  Hazards that pose a risk of injury or loss of life to people must be identified and eliminated or mitigated. A complete safety assessment considers not only those personnel who are directly involved in the work, but also others who are at risk due to these hazards.

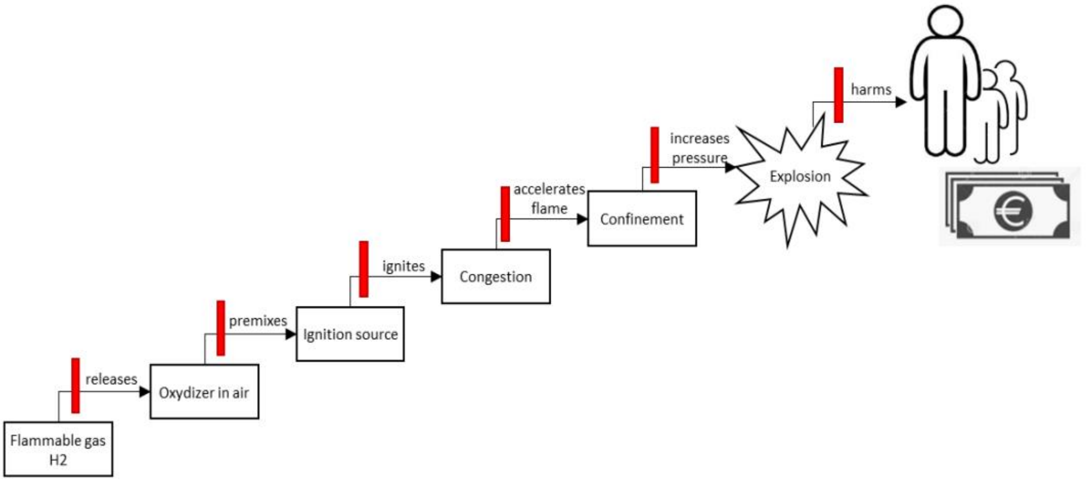
- Property.

  Damage to or loss of equipment or facilities must be prevented or minimised. Damage to equipment can be both the cause of incidents and the result of incidents. An equipment failure can result in collateral damage to nearby equipment and property, which can then trigger additional equipment failures or even lead to additional hazards and risks, e.g., through the domino effect. Effective safety planning, monitoring and reporting considers and minimises serious risk of equipment and property damage.

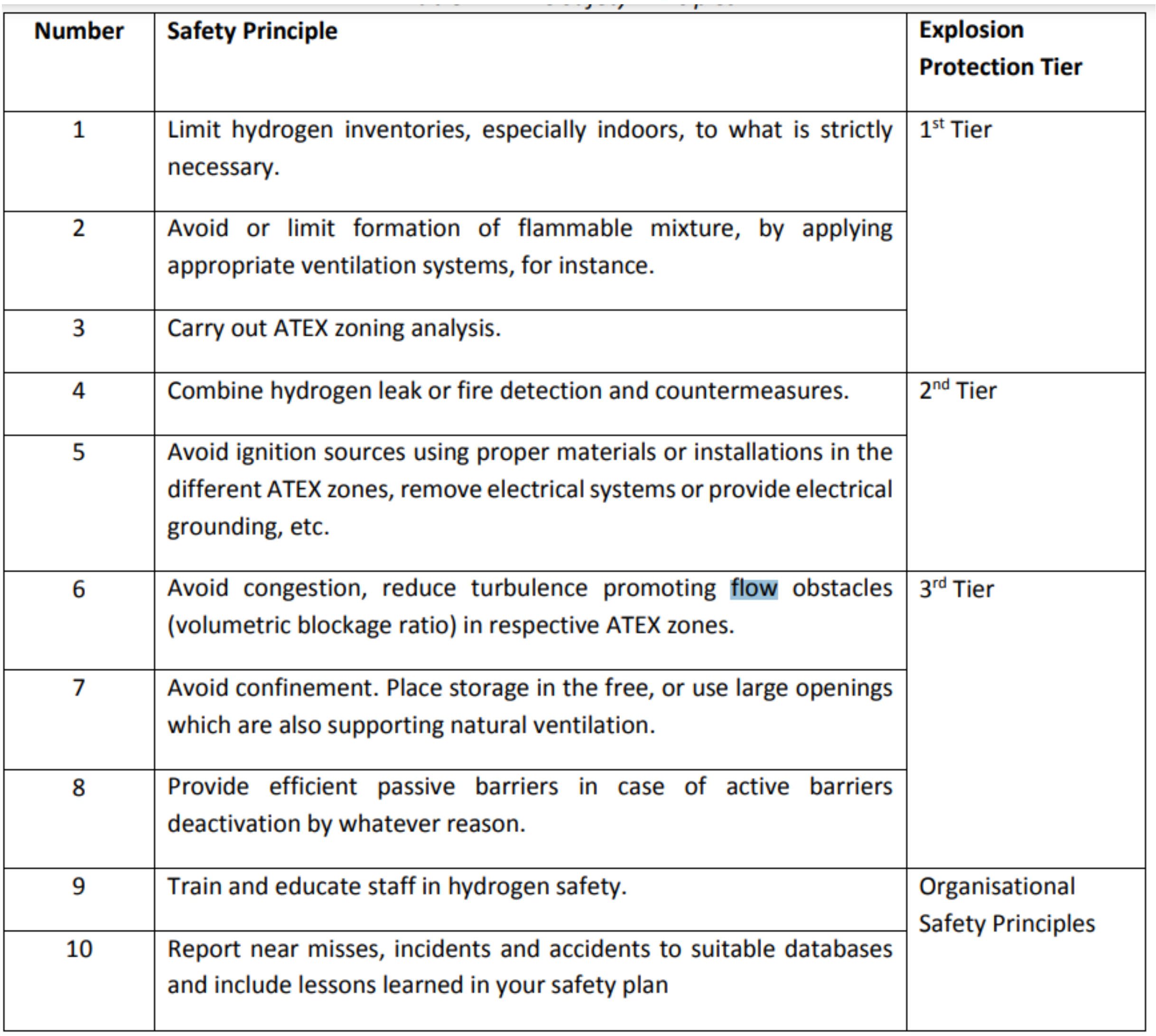
- Environment

  Damage to the environment must be prevented. Any aspect of a natural or the built environment, which can be harmed due to a hydrogen system or infrastructure failure, should be identified and analysed. A qualification of the failure modes resulting in environmental damage must be considered.

Best safety practices try either to remove or at least limit essential elements in this chain of events or introduce barriers at the transitional. Acting on a single block can reduce the hazards and associated risks, limit the consequences or even prevent an accident. However, the earlier the escalation path is interrupted, the more reliable and cost-effective are the mitigation or prevention measures



It should be noted that even if the escalation may be stopped successfully at an early stage, certain hazards still will exist. A small unignited release or a jet fire, for instance, won’t generate explosion loads, but will imply considerable physical hazards or thermal loads. The burst of a pressurised pipe or vessel will lead to serious blast loads even without a chemical reaction. In summary, the derived safety principles state simple objectives, being widely understandable and acting as preventive barriers or at least as risk reducing measures on the various elements of the chain of events.



Number	Safety Principle	Explosion Protection Tier
1	Limit hydrogen inventories, especially indoors, to what is strictly necessary.	1st Tier
2	Avoid or limit formation of flammable mixture, by applying appropriate ventilation systems, for instance.	
3	Carry out ATEX zoning analysis.	
4	Combine hydrogen leak or fire detection and countermeasures.	2nd Tier
5	Avoid ignition sources using proper materials or installations in the different ATEX zones, remove electrical systems or provide electrical grounding, etc.	
6	Avoid congestion, reduce turbulence promoting flow obstacles (volumetric blockage ratio) in respective ATEX zones.	3rd Tier
7	Avoid confinement. Place storage in the free, or use large openings which are also supporting natural ventilation.	
8	Provide efficient passive barriers in case of active barriers deactivation by whatever reason.	
9	Train and educate staff in hydrogen safety.	Organisational Safety Principles
10	Report near misses, incidents and accidents to suitable databases and include lessons learned in your safety plan	

These safety principles should be reflected in the safety plan, in any process of identifying safety vulnerabilities or hazards and in any risk assessment procedure. Any expert in charge of a safety review shall have those principles in mind. However, they do not replace neither legal requirements, comprehensive hydrogen safety engineering, nor detailed risk assessment eventually required by RCS. They allow stakeholders to take safety into account at different stages of the design, implementation and operation of a process using hydrogen in a very basic manner.

Safety plan

A safety plan addresses potential threats and impacts to people, to property and to the natural and built environment as well as the corresponding prevention, mitigation and protection measures. As an integral part of any project, hydrogen installation, and fuel cell system, a safety plan should reflect sound and thoughtful consideration for the identification and analysis of safety vulnerabilities, elimination or control of hazards, and mitigation measures to keep the risk at acceptable level.

Appropriate communication is equally important and should be described in the safety plan, including how the plan will be monitored and results of the activities reported as required. A special challenge for an appropriate communication exists in projects, where work typically is conducted by multiple organisations. Safety plans should be "living documents" that recognise the type of work being conducted, the factors of human error, the nature of equipment life, and consider the inevitable changes that occur in project development and execution. A safety plan should be prepared using a graded approach based on level of hazards, associated risks and complexity.

The plan should cover all work being conducted, including experimental/operational activities, with emphasis on the aspects involving hydrogen safety knowledge, hazardous materials, pressure equipment, hydrogen system peculiarities, etc. There may be cases when a preliminary safety plan is developed during the project application phase as requested by a call. In these cases, elements such as hazards, and associated risk analysis, prevention and mitigation techniques should be covered more generally with a focus on what hazards and risk analysis activities will be completed during the initial design phase after the project is awarded. The elements of a good safety plan are summarized as follows, though this should not be considered as an exhaustive and mandatory list of safety considerations for all projects.

Exhaustive and mandatory list of safety considerations for all projects:

- Description of Work
- Project Safety Planning
    a. Policies and available experience
    b. Safety reviews
    c. Mitigation plan
    d. Procedures
    e. Operating steps
    f. Sample handling and transport
    g. Equipment and mechanical Integrity
    h. Project safety documentation
- Operations Management
    a. Personnel training
    b. Safety review procedures
    c. Safety events and lessons learned
    d. Emergency response
    e. Self-audits

    f. Management of change procedures

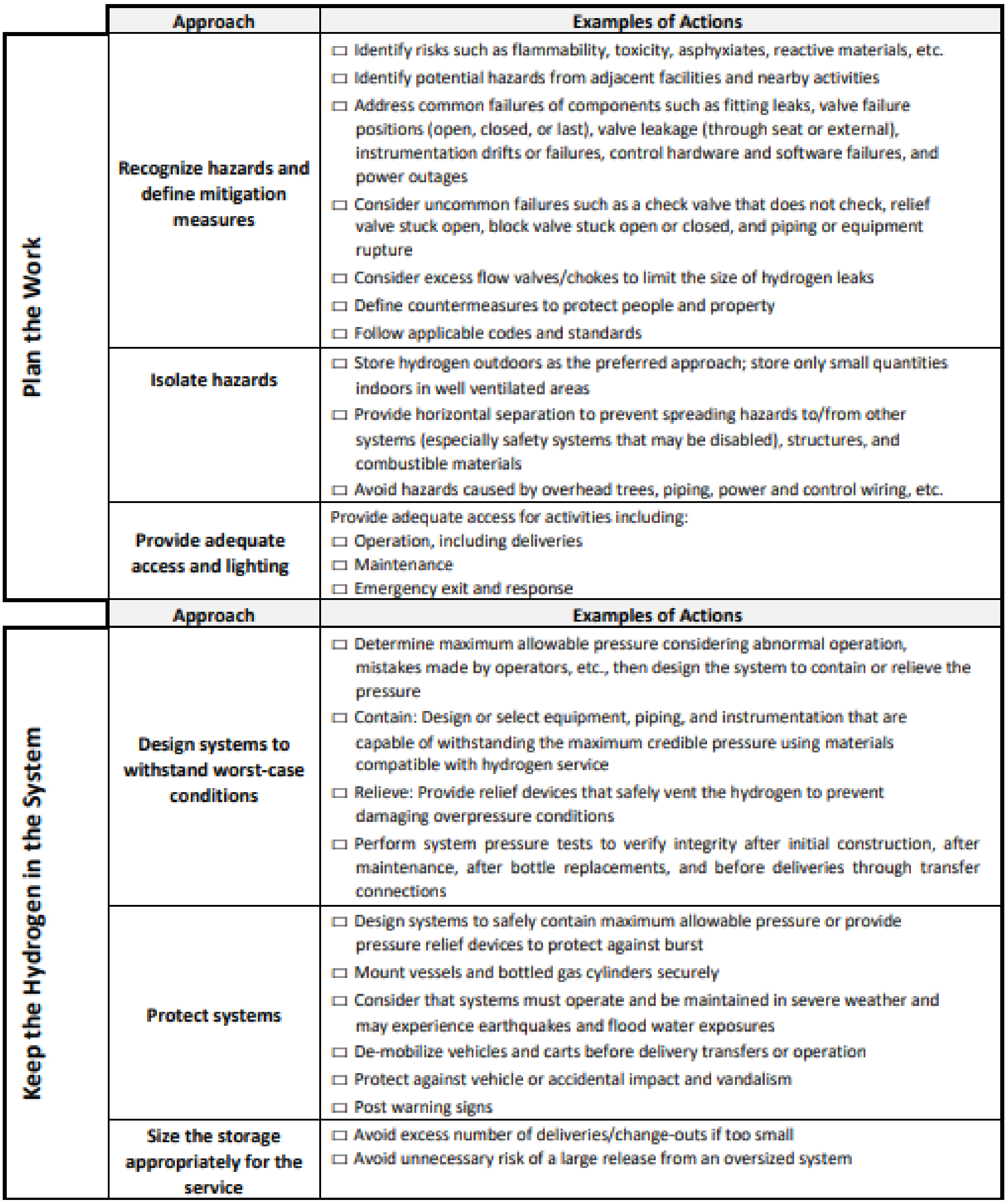
- Additional Documentation and Reporting
    a. Flow diagram showing equipment (e.g., PID) including functional description of each component
    b. Preliminary layout
    c. Extended discussion of RCS and in a case of detailed performance analysis to address the question, if regulations or standards allow for alternatives for simplified correlations or requirements, like tabular safety distance rules, etc. d. Other Comments or Concerns
    d. Details of safety planning, its monitoring and update

Installation and commissioning checklists

Project commissioning is the process of assuring that all systems and components of a building or industrial plant are designed, installed, tested, operated, and maintained according to the operational requirements of the owner or final client. A commissioning process may be applied not only to new projects but also to existing units and systems subject to expansion, renovation or revamping.

In practice, the commissioning process is the integrated application of a set of engineering techniques and procedures to check, inspect and test every operational component of the project: from individual functions (such as instruments and equipment) up to complex amalgamations (such as modules, subsystems and systems).

Maintenance and servicing plans



	Approach	Examples of Actions
Plan the Work	**Recognize hazards and define mitigation measures**	☐ Identify risks such as flammability, toxicity, asphyxiates, reactive materials, etc. ☐ Identify potential hazards from adjacent facilities and nearby activities ☐ Address common failures of components such as fitting leaks, valve failure positions (open, closed, or last), valve leakage (through seat or external), instrumentation drifts or failures, control hardware and software failures, and power outages ☐ Consider uncommon failures such as a check valve that does not check, relief valve stuck open, block valve stuck open or closed, and piping or equipment rupture ☐ Consider excess flow valves/chokes to limit the size of hydrogen leaks ☐ Define countermeasures to protect people and property ☐ Follow applicable codes and standards
	Isolate hazards	☐ Store hydrogen outdoors as the preferred approach; store only small quantities indoors in well ventilated areas ☐ Provide horizontal separation to prevent spreading hazards to/from other systems (especially safety systems that may be disabled), structures, and combustible materials ☐ Avoid hazards caused by overhead trees, piping, power and control wiring, etc.
	Provide adequate access and lighting	Provide adequate access for activities including: ☐ Operation, including deliveries ☐ Maintenance ☐ Emergency exit and response
	Approach	**Examples of Actions**
Keep the Hydrogen in the System	**Design systems to withstand worst-case conditions**	☐ Determine maximum allowable pressure considering abnormal operation, mistakes made by operators, etc., then design the system to contain or relieve the pressure ☐ Contain: Design or select equipment, piping, and instrumentation that are capable of withstanding the maximum credible pressure using materials compatible with hydrogen service ☐ Relieve: Provide relief devices that safely vent the hydrogen to prevent damaging overpressure conditions ☐ Perform system pressure tests to verify integrity after initial construction, after maintenance, after bottle replacements, and before deliveries through transfer connections
	Protect systems	☐ Design systems to safely contain maximum allowable pressure or provide pressure relief devices to protect against burst ☐ Mount vessels and bottled gas cylinders securely ☐ Consider that systems must operate and be maintained in severe weather and may experience earthquakes and flood water exposures ☐ De-mobilize vehicles and carts before delivery transfers or operation ☐ Protect against vehicle or accidental impact and vandalism ☐ Post warning signs
	Size the storage appropriately for the service	☐ Avoid excess number of deliveries/change-outs if too small ☐ Avoid unnecessary risk of a large release from an oversized system

	Approach	Examples of Actions
	Provide hydrogen shutoff(s) for isolation	☐ Locate automatic fail-closed shutoff valves at critical points in the system (such as storage exit, entry to buildings, inlets to test cells, etc.) to put the system in a safe state when a failure occurs ☐ Consider redundant or backup controls ☐ Install manual valves for maintenance and emergencies
	Prevent cross-contamination	☐ Prevent back-flow to other gas systems with check valves, pressure differential, etc.

	Approach	Examples of Actions
Manage Discharges	Safely discharge all process exhausts, relief valves, purges, and vents	☐ Discharge hydrogen outdoors through a vent stack or into a laboratory ventilation system that assures proper dilution ☐ Direct discharges away from personnel and other hazards ☐ Secure/restrain discharge piping
	Prevent build-up of combustible mixtures in enclosed spaces	☐ Do not locate equipment or piping joints/fittings in poorly ventilated rooms or enclosed spaces. Use only solid or welded tubing or piping in such areas ☐ Provide sufficient ventilation and/or space for dilution ☐ Avoid build-up of hydrogen under ceilings/roofs and other partly enclosed spaces
	Remove potential ignition sources from flammable spaces/zones	☐ Proper bonding and grounding of equipment ☐ No open flames ☐ No arcing/sparking devices, e.g., properly classified electrical equipment

	Approach	Examples of Actions
Detect and Mitigate	Leak detection and mitigation	☐ Provide detection and automatic shutdown/isolation if flammable mixtures are present, particularly in enclosed spaces ☐ Consider methods for manual or automatic in-process leak detection such as the ability for isolated systems to hold pressure ☐ Periodically check for leaks in the operating system
	Loss of forced ventilation indoors	☐ Automatically shut off the supply of hydrogen when ventilation is not working
	Monitor the process and protect against faults	☐ Provide alarms for actions required by people, e.g., evacuation ☐ Provide the capability to automatically detect and mitigate safety-critical situations ☐ Consider redundancy to detect and mitigate sensor or process control faults ☐ Provide the ability for the system to advance to a "safe state" if power failures or controller faults are experienced
	Fire detection and mitigation	☐ Appropriate fire protection (extinguishers, sprinklers, etc.) ☐ Listed hydrogen specific flame detection ☐ Automatic shutdown and isolation if fire is detected
Manage Operations	Establish and document procedures	☐ Responsibilities for each of the parties involved ☐ Operating procedures ☐ Emergency procedures ☐ Preventive maintenance schedules for equipment services, sensor calibrations, leak checks, etc. ☐ Safe work practices for maintenance such as lock-out/tag-out, hot work permits, and hydrogen line purging ☐ Review and approval of design and procedural changes

	Approach	Examples of Actions
	Train personnel	☐ MSDS awareness for hydrogen and other hazardous materials ☐ Applicable procedures and work instructions for bottle change-out, deliveries, operation, maintenance, emergencies, and safety work practices
	Monitor	☐ Track incidents and near-misses, and establish corrective actions ☐ Monitor compliance to all procedures and work instructions