

From electrolysers to fuel cells

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Summary. — The following article presents two key technologies that will play a critical role in decarbonising the energy sector and combat climate change. The first technology is water electrolysis which has the ability to use renewable energy to split the water into hydrogen and oxygen. The second technology is fuel cells that can use hydrogen produced from renewable electricity and oxygen from the atmosphere to produce electricity and heat. The types of water electrolysis and fuel cells technologies are outlined in detail together with their applications. Their key challenges that have prevented these technologies from being used at scale are briefly described including the current research focus to face these challenges.

1. – Introduction

Hydrogen is considered an attractive energy vector due to its high energy-to-mass ratio (120 MJ/kg) that can easily replace fossil fuel consumption, meeting global energy demands. Its name comes from the Greek word “hydro” and “genes” that means water forming. Currently, 96% of the industrial production of hydrogen comes from fossil fuels,

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also known as “grey” hydrogen. The remaining 4% is produced from renewable energy in conjunction with water electrolysis, which is known as “green” hydrogen.

Water electrolysis is based on two half-reactions: i) the hydrogen evolution reaction (HER) at the cathode: $2\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2\text{OH}^-$, and ii) the oxygen evolution reaction (OER) at the anode: $4\text{OH}^- \rightarrow 2\text{H}_2\text{O} + \text{O}_2 + 4\text{e}^-$. Theoretically, the standard thermodynamic potential of -1.23 V (*vs.* reversible hydrogen electrode, RHE) is required to split the water into H_2 and O_2 regardless of the electrolyte media. This additional energy requirement, also known as overpotential, is the main challenge associated with the production of green hydrogen, which has compromised its commercial viability to date.

On the other hand, when hydrogen is combined with oxygen in an electrochemical cell, also known as a fuel cell, a spontaneous redox reaction takes place producing a current that can do work in addition to heat. The two half-reactions that take place in a fuel cell are very similar to the ones in a water electrolysis cell, also known as an electrolyser. The only differences are in the sign of the electrochemical values and the directions of each reaction. In detail, in a fuel cell we have: i) the hydrogen oxidation reaction (HOR) at the anode: $\text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^-$, and ii) the oxygen reduction reaction (ORR) at the cathode: $\text{O}_2 + 4\text{e}^- + 4\text{H}^+ \rightarrow 2\text{H}_2\text{O}$. The theoretical standard thermodynamic potential is $+1.23\text{ V}$ (*vs.* reversible hydrogen electrode, RHE) required to combine H_2 and O_2 to produce water.

2. – Types of water electrolysers

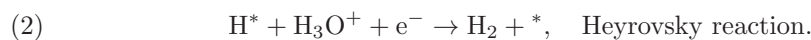
There are four types of water electrolysers: i) the proton exchange membrane water electrolyser (PEMWE), ii) the high-temperature water electrolyser, iii) the alkaline water electrolyser (AWE), and iv) the anion exchange membrane water electrolyser (AEMWE) [1]. The type of water electrolyser is defined by the nature of the electrolyte used. In simple terms, the pH of the electrolyte defines the electrochemical mechanisms of the HER and OER, and as a result of that the type of the electrolyser. Hence, we have water electrolysers that operate at acidic conditions ($\text{pH} < 7$) like the proton exchange membrane water electrolyser, others that operate at neutral conditions ($\text{pH} = 7$) as the high-temperature water electrolysers, and last the ones that operate at alkaline conditions ($\text{pH} > 7$) like the alkaline water electrolysers and the anion exchange water electrolysers. The detailed reaction mechanisms of the HER at various pHs are as follows.

In acidic conditions ($\text{pH} < 7$), the HER proceeds according to the following steps [2,3]:

1) A proton from the hydronium cation (H_3O^+) and an electron combine on the catalysts surface, resulting in an adsorbed hydrogen intermediate (H^*)



2) The adsorbed hydrogen atom combines with a proton and an electron, producing a hydrogen molecule



3) Two adsorbed hydrogen atoms couple, producing a hydrogen molecule



In these reactions, * stands for the catalyst surface, and H^* is the adsorbed hydrogen intermediate.

In neutral conditions ($\text{pH} = 7$), the HER mechanism is more complicated compared to acidic or alkaline conditions, since both H_2O molecules and hydronium cation H_3O^+ ions take part in the mechanism, following a two-step reduction process [4]:

4) At low cathodic overpotentials reaching the equilibrium potential (*i.e.*, 0 V *vs.* reversible hydrogen electrode (RHE)), H_3O^+ ions are the dominant reactant species

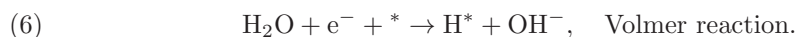


5) At high cathodic overpotentials, the dominant reactant species switch from H_3O^+ ions to H_2O molecules

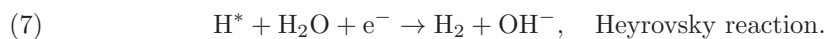


In alkaline conditions ($\text{pH} > 7$), due to the low concentration of protons, the HER mechanism is different to the one in acidic conditions, and proceeds according to the following steps [2, 3]:

1) Molecular H_2O , instead of H_3O^+ , couples with an electron, resulting in an adsorbed hydrogen intermediate on the catalyst



2) The adsorbed hydrogen intermediate combines with molecular H_2O and an electron to produce a hydrogen molecule



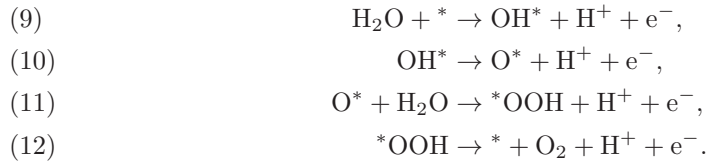
3) The same as in acidic conditions, two adsorbed hydrogen atoms couple to produce a hydrogen molecule



On the other hand, the detailed reaction mechanisms for the OER at various pH values are outlined below.

In acidic conditions ($\text{pH} < 7$), the OER mechanism proceeds according to the following steps [2-4]:

1) A multistep four electron transfer process takes place to produce oxygen molecules based on the adsorbed OH^* , O^* and $^*\text{OOH}$ intermediate species present on the catalyst surface:

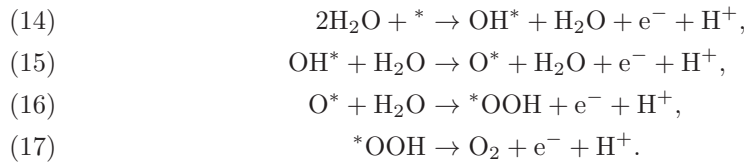


2) Two adsorbed oxygen atoms couple to produce an oxygen molecule:



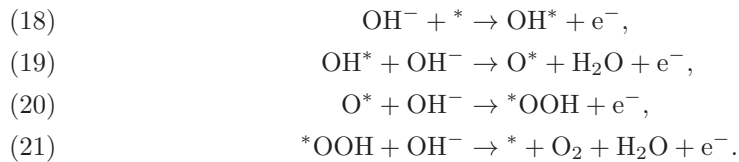
In these reactions, $*$ stands for the catalyst surface, and OH^* , O^* and $^*\text{OOH}$ are the adsorbed oxygen intermediates.

In neutral conditions ($\text{pH} = 7$), the OER mechanism proceeds according to the following steps [4]:



In alkaline conditions ($\text{pH} > 7$), the OER mechanism proceeds according to the following steps [2, 3]:

1) An essential elementary step takes place for the formation of OH^* , and then subsequent steps involve the formation of O^* and $^*\text{OOH}$ intermediate species on the catalyst surface



2) The same as in acidic conditions, two adsorbed oxygen atoms couple to produce an oxygen molecule



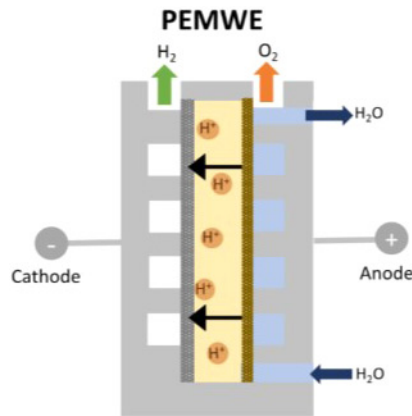


Fig. 1. – Schematic representation of proton exchange membrane water electrolyser (PEMWE).
Source: <https://doi.org/10.1038/s41560-020-0550-8>.

2'1. Proton exchange membrane water electrolyser (PEMWE), pH < 7. Acidic electrolyte. – A proton exchange membrane water electrolyser (fig. 1) comprises of a solid acid electrolyte polymer sandwiched between the anode and the cathode. Water is only fed to the anode, where it is oxidised to form O₂ and H⁺. The protons (H⁺) then travel through the PEM to the cathode to be reduced to H₂. The catalyst materials used for the fabrication of the anode are iridium or ruthenium oxide. Whereas for the fabrication of the cathode, platinum is used as the catalyst material. The cell temperature of this type of water electrolyser is between 50 and 80 °C, with a stack pressure below 30 bar. Its current density can range between 0.6 and 10 A/cm² with a cell voltage of 1.75 to 2.20 V, and a power density to 4.4 W/cm². The cell voltage efficiency of this electrolyser can vary from 57 to 80%, and can produce hydrogen with a rate equal to 30 Nm³/h. Its lifetime stack is maximum 20 000 h, with an overall system lifetime of 10 to 20 years. Its degradation rate can be determined to < 14 μV/h.

2'2. High-temperature water electrolyser, pH = 7. Neutral electrolyte. – In a high-temperature water electrolyser (fig. 2), water evaporates and transports to the cathode as steam to produce H₂ while a solid oxide or ceramic membrane transports O²⁻ to the anode. The catalysts material used for the fabrication of the anode are Sr-based and Co-based perovskites, such as (La, Sr)(Co, Fe)O₃ and La_{0.8}Sr_{0.2}MnO_{3-δ}. On the other hand, Ni-cermets are used for the cathode. The operating temperature of the cell is between 700 and 1000 °C with a stack pressure of 10 to 60 bar. The current density and the cell voltage of this type of electrolyser is 1 A/cm² and 1.3–1.5 V, respectively, with an overall efficiency above 90%.

2'3. Alkaline water electrolyser (AWE), pH > 7. Alkaline electrolyte. – The alkaline water electrolyser (fig. 3) operates as a 2-compartment cell where a liquid alkaline electrolyte (20–30% KOH) is circulated around both sides and a porous diaphragm allows

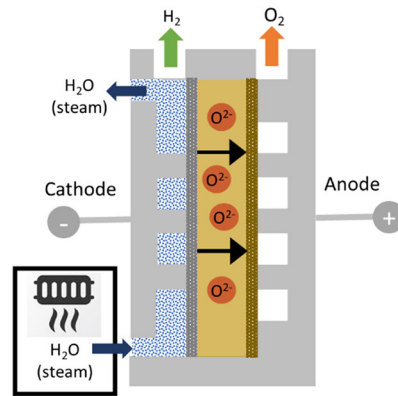


Fig. 2. – Schematic representation of a high-temperature water electrolyser. Source: <https://doi.org/10.1038/s41560-020-0550-8>.

hydroxyl ions (OH^-) to migrate preventing gas crossover. The anode and the cathode are most often fabricated by Ni/Co/Fe and Ni/C-Pt, respectively. The cell temperature can range between 60 and 80 °C, whereas its stack pressure is below 30 bar. The current density in this type of electrolyser is 0.2 to 0.4 A/cm² with a cell voltage between 1.8 and 2.4 V. The efficiency of an AWE is 52–80%, and can produce hydrogen with a 760 Nm³/h. Its lifetime stack can be evaluated just under 90 000 h with a degradation rate of 3 μV/h and under, with an overall system lifetime of 20 to 30 years.

2.4. Anion exchange membrane water electrolyser (AEMWE), pH > 7. Alkaline electrolyte. – In an anion exchange membrane water electrolyser (fig. 4), an OH^- transporting membrane is placed between the anode and cathode. Water is supplied to the cathode,

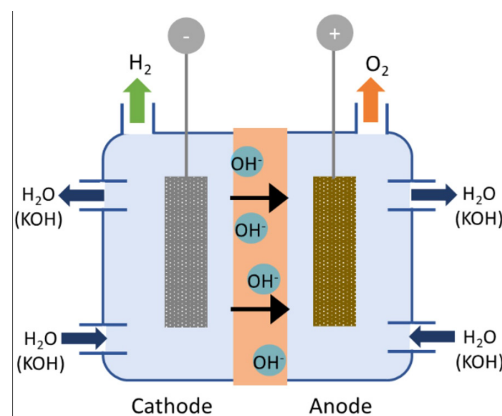


Fig. 3. – Schematic representation of an alkaline water electrolyser (AWE). Source <https://doi.org/10.1038/s41560-020-0550-8>.

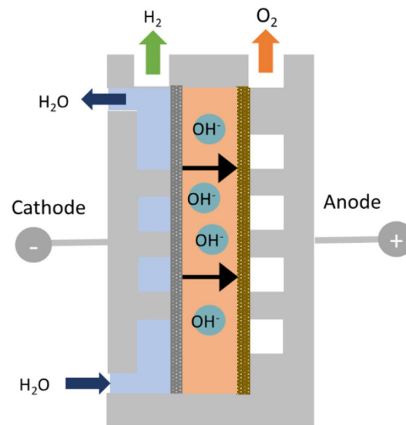


Fig. 4. – Schematic representation of an anion exchange membrane water electrolyser (AEMWE).
Source: <https://doi.org/10.1038/s41560-020-0550-8>.

as shown in fig. 4, but it is also possible to supply water to the anode or even to both sides if desired. The catalyst material used for the anode and cathode are Ni, Fe, Co, Mn and Cu. The operating cell temperature is below $60\text{ }^{\circ}\text{C}$ with a stack pressure between 15 and 30 bar. Its current density is 1 A/cm^2 with a cell voltage of 1.57 to 1.8 V, and an overall efficiency of 75%.

3. – Where can we find water electrolyzers?

Water electrolyzers can be either scaled up or down according to the end application (fig. 5). We can find water electrolyzers coupled with renewable energy power plants on site for the mass production of green hydrogen; or we can even see them in smaller scale, mainly installed at industrial premises for the production of hydrogen used for ammonia production for fertilizers and fuel for fuel cell applications such as buses, trucks and trains. Most likely in the near future we are anticipating in seeing smaller scale of water electrolyzers installed at residential or commercial premises for heating or cooling; perhaps even coupled with a fuel cell for the on-site production of electricity.

4. – The problems of current water electrolyzers

The problems associated with current water electrolysis technologies are: i) the manufacturing cost of electrolyzers, ii) the cost of running them, and iii) their low overall efficiencies. Even though the cost of renewable electricity is decreasing every day, the manufacturing cost of electrolyzers still remains high. This cost is directly linked to the high price of the catalyst raw materials used for the fabrication of the anode and cathode. On the other hand, the overall efficiency of current commercial electrolyzers is between 70 and 80%. This number needs to keep increasing in order to compete with fossil fuels.

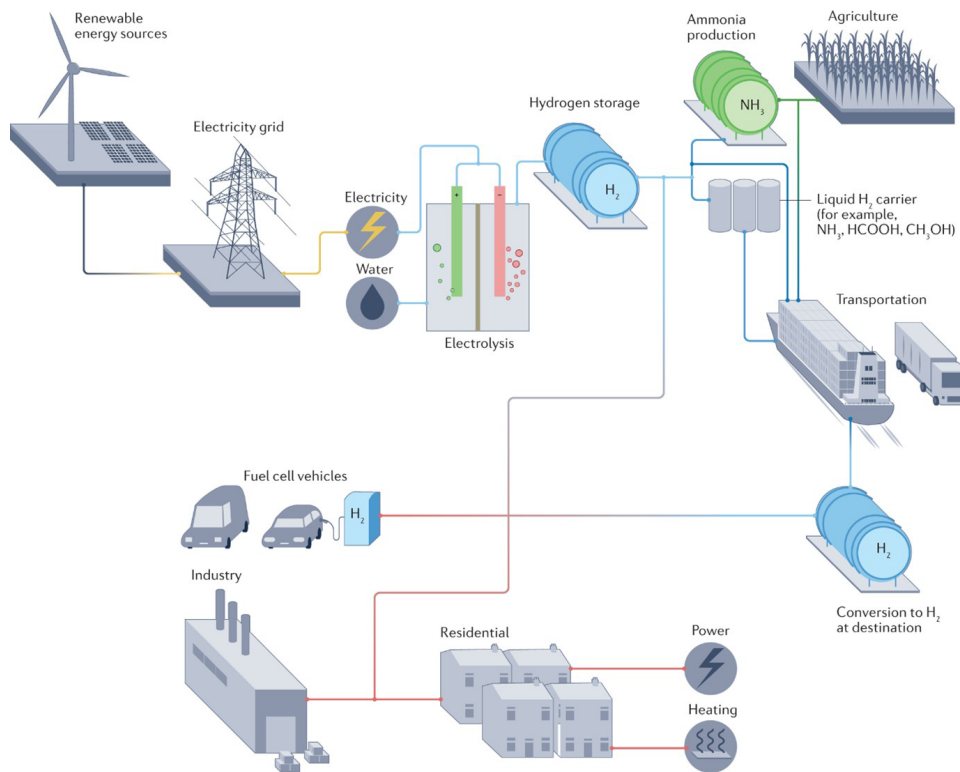


Fig. 5. – Hydrogen produced from renewable water electrolysis can be utilized as a CO₂-neutral source in the agricultural, transportation, industrial and residential sectors. Source: <https://doi.org/10.1038/s43586-022-00164-0>.

5. – Current research focus on water electrolyzers

Research efforts have focused on two categories with the aim of making water electrolysis technologies competitive and to gradually become the dominant technology of producing hydrogen. The first focus is to develop new catalyst material for the fabrication of the anode and cathode that are cost-effective and efficient. Whereas, the second focus is to design new electrochemical cell architectures that can facilitate better the needs dictated by water electrolysis. If we can accomplish these two research aims, it is anticipated that the efficiency of electrolyzers will dramatically increase, whereas their overall manufacturing cost will decrease, making water electrolysis competitive and an attractive option of replacing fossil fuel consumption.

6. – Types of fuel cells

Unlike water electrolyzers, fuel cells are categorized into six different types according to their operating temperature and are classified as low-, medium- or high-temperature fuel cells [5]. In detail, these six types are: i) the alkaline fuel cell (AFC), ii) the proton-

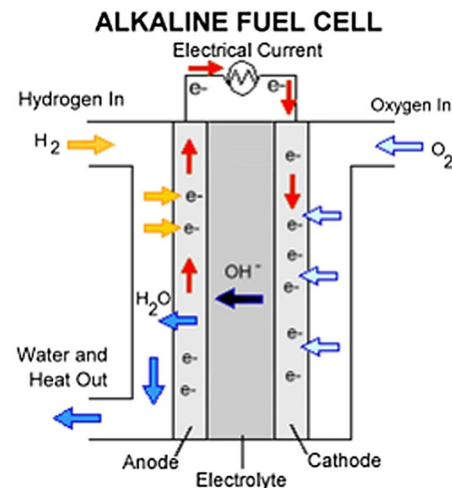


Fig. 6. – Schematic representation of an alkaline fuel cell. Source: <https://doi.org/10.1186/2043-7129-1-16>.

exchange membrane fuel cell (PEMFC), iii) the direct methanol fuel cell (DMFC), iv) the phosphoric acid fuel cell (PAFC), v) the molten carbonate fuel cell (MCFC), and vi) the solid oxide fuel cell (SOFC).

6.1. Alkaline fuel cell (AFC), low temperature. – The alkaline fuel cell (fig. 6) was the first fuel cell technology to be developed, and also to be widely used in the U.S. space program for producing electricity and water on-board spacecrafts. The catalyst materials used for the fabrication of the electrodes in AFCs are platinum based, but also silver and nickel have also been used in some cases but require higher operating temperatures since these materials are less efficient in comparison to platinum. The anode gas in an AFC is hydrogen, whereas the cathode gas is oxygen. The electrolyte used in this type of fuel cell is a potassium hydroxide solution (KOH). Its operating temperature is between 20 and 90 °C, with a performance range up to 100 kW and a cell efficiency of 60 to 70%. The electrochemical half-reaction that takes place at the anode is: $\text{H}_2 + 2\text{OH}^- \rightarrow 2\text{H}_2\text{O} + 2\text{e}^-$ Whereas, at the cathode is: $\frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2\text{e}^- \rightarrow 2\text{OH}^-$. The overall electrochemical reactions is as follows: $\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$.

6.2. Proton-exchange membrane fuel cell (PEMFC), low temperature. – The proton-exchange membrane fuel cell (fig. 7), also known as polymer electrolyte membrane (PEM) fuel cell, was mainly developed for transport applications, stationary fuel-cell applications and portable fuel-cell applications. This type of fuel cell generates electricity on the basis of the exact opposite operating principles of a PEMWE, where it consumes electricity. Apparently, it is the most prominent candidate to replace the aging alkaline fuel-cell technology, which was used by NASA in the U.S. Space Shuttle. In this type of fuel cells hydrogen is used as the anode gas, and oxygen from the air is used as the cathode

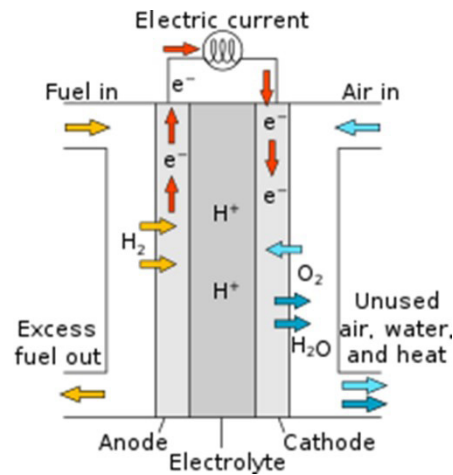


Fig. 7. – Schematic representation of a proton-exchange membrane fuel cell. Source: <https://doi.org/10.1186/2043-7129-1-16>.

gas. The electrolyte between the anode and the cathode is a polymer membrane. Its operating temperature is 20 to 80 °C, with a up to 500 kW performance range, and a cell efficiency ranging between 50 and 70%. The electrochemical half-reaction at the anode is: $\text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^-$, and the cathode is: $\frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2\text{O}$. The overall reaction is $\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$.

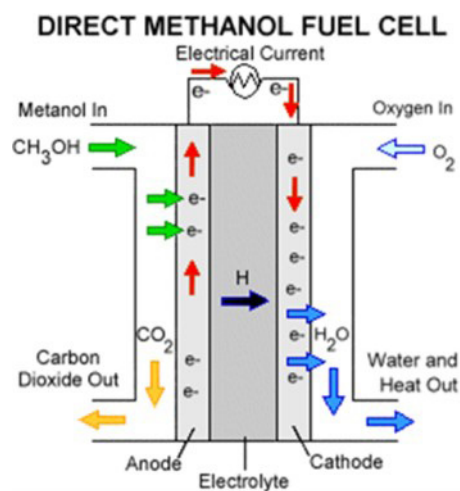


Fig. 8. – Schematic representation of a direct methanol fuel cell. Source: <http://derekcarrsavvy-chemist.blogspot.com/2017/03/redoxii-fuel-cells.html>.

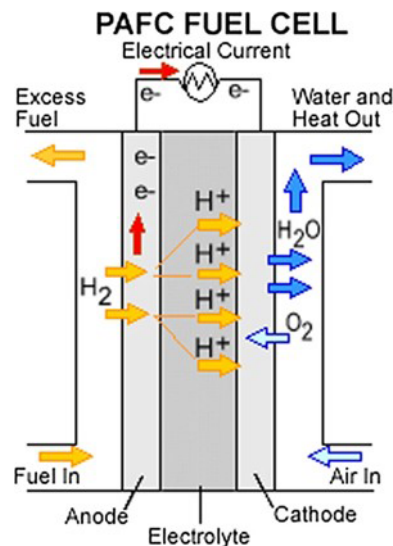


Fig. 9. – Schematic representation of a phosphoric acid fuel cell. Source: <https://sustainablechemicalprocesses.springeropen.com/articles/10.1186/2043-7129-1-16/figures/4>.

6.3. Direct-methanol fuel cell (DMFC), low temperature. – The direct-methanol fuel cell (fig. 8), is a subcategory of a proton-exchange membrane fuel cell, where methanol is used as the fuel. Their main advantage of this fuel cell technology is the fact that methanol is easier to transfer than hydrogen, since it is an energy-dense and reasonably stable liquid at all environmental conditions. The anode gas used in these types of fuel cells, as mentioned above, is methanol. Whereas, the cathode gas is oxygen from the air. A polymer membrane is used as an electrolyte, as in the PEMFCs. Its operating temperature range though is slightly higher than the one observed in the PEMFCs, which is between 20 and 130 °C. Its performance range is up to 100 kW with a cell efficiency between 20 and 30%. At the anode we observe the following electrochemical half-reaction: $\text{CH}_3\text{OH} + \text{H}_2\text{O} \rightarrow 6\text{H}^+ + 6\text{e}^- + \text{CO}_2$. At the cathode the reaction is as follows: $3/2\text{O}_2 + 6\text{H}^+ + 6\text{e}^- \rightarrow 3\text{H}_2\text{O}$. The overall cell reaction is: $\text{CH}_3\text{OH} + 3/2\text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{CO}_2$.

6.4. Phosphoric acid fuel cell (PAFC), medium temperature. – The phosphoric acid fuel cell (fig. 9) is a type of fuel cell that uses liquid phosphoric acid as the electrolyte, and it was the first one to be commercialized. It was first developed in the mid-1960s and has been field-tested since the 1970s. Over the years, the PAFCs have improved significantly in stability, performance, and cost. Having such superb characteristics, the PAFCs have become a good candidate for early stationary applications. The electrodes in a PAFC are made of gold, tantalum, titanium and carbon, whereas only platinum can be used as the catalysts. The anode gas can be hydrogen, natural gas or biogas,

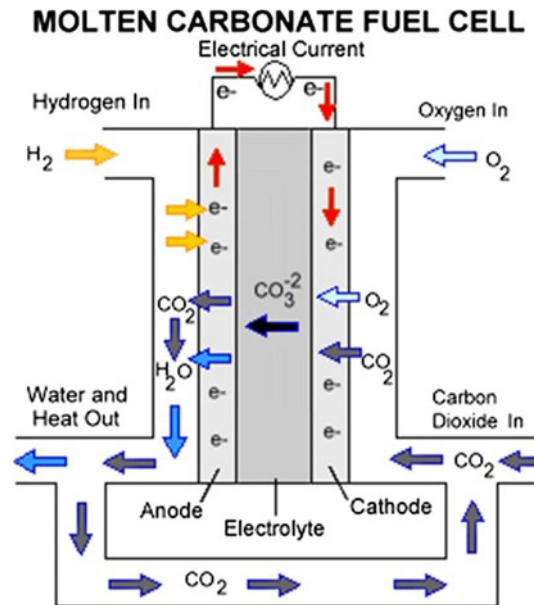


Fig. 10. – Schematic representation of a molten carbonate fuel cell (MCFC). Source: <https://sustainablechemicalprocesses.springeropen.com/articles/10.1186/2043-7129-1-16/figures/3>.

and the cathode gas is oxygen from the air. The electrolyte as previously mentioned is phosphoric acid. The operating temperature range of this type of fuel cell is between 160 and 220 °C, and has a performance range up to 10 MW, and a cell efficiency of 55%. The reaction at the anode is: $\text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^-$, and the cathode is: $\frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2\text{O}$, with the overall reaction being: $\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$.

6.5. Molten carbonate fuel cell (MCFC), high temperature. – The molten carbonate fuel cell (fig. 10) was developed for natural gas, biogas (produced as a result of anaerobic digestion or biomass gasification), and coal-based power plants for electrical utility, industrial, and military applications. It is a high-temperature fuel cell, with an operating temperature between 620 and 660 °C, that uses an electrolyte composed of a molten mixture of potassium and lithium carbonate. As previously mentioned, the gas at the cathode in this type of fuel cells is natural gas, coal gas and biogas, whereas at the cathode is oxygen from the air. The performance range reported for the MCFCs is up to 100 MW, with a cell efficiency of 65%. The half electrochemical reaction at the anode is: $\text{H}_2 + \text{CO}_3^{2-} \rightarrow \text{CO}_2 + \text{H}_2\text{O} + 2\text{e}^-$, and at the cathode is: $\frac{1}{2}\text{O}_2 + \text{CO}_2 + 2\text{e}^- \rightarrow \text{CO}_3^{2-}$. The overall electrochemical reaction being: $\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$.

6.6. Solid oxide fuel cell (SOFC), high temperature. – The solid oxide fuel cell (fig. 11) is a type of a fuel cell that is constructed entirely from solid-state materials. Yttrium-stabilised zirconium oxide, which is a solid oxide material, is used as the electrolyte

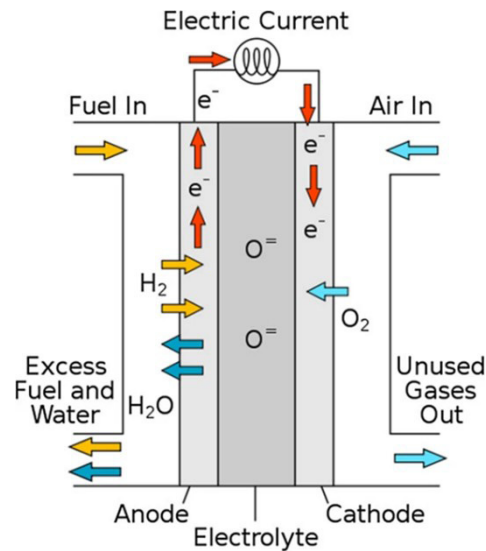


Fig. 11. – Schematic representation of a solid oxide fuel cell. Source: <https://sustainablechemicalprocesses.springeropen.com/articles/10.1186/2043-7129-1-16#Fig4>.

to conduct negative oxygen ions from the cathode to the anode. The electrochemical oxidation of the hydrogen, carbon monoxide or other organic intermediates by oxygen ions occurs on the anode side. An electronically conducting nickel/yttria-stabilised zirconia cermet (Ni/YSZ) is used as the catalyst material for the construction of the anode. On the other hand, the cathode is constructed by a mixed conducting perovskite like lanthanum manganate (LaMnO_3). Its working temperature is between 800 and 1000 °C, with a performance range up to 100 mV and a cell efficiency of 60–65%. The reactions at the anode can be described as: $\text{H}_2 + \text{O}_2^- \rightarrow \text{H}_2\text{O} + 2\text{e}^-$ and $\text{CO} + \text{O}_2^- \rightarrow \text{CO}_2 + 2\text{e}^-$, and at cathode is: $\text{O}_2 + 4\text{e}^- \rightarrow 2\text{O}^{2-}$, with an overall electrochemical reaction: $\text{H}_2 + \text{O}_2 + \text{CO} \rightarrow \text{H}_2\text{O} + \text{CO}_2$.

6.7. Reversible fuel cells. – Reversible fuel cells (fig. 12), are also known as “unitized regenerative fuel cells”, operate like batteries [6]. Hence, they have the potential to be one solution to the problem of storing electricity generated by renewable energy resources. Reversible fuel cells (RFCs) can produce fuel using the surplus renewable electricity and reconvert it back to electricity using the same device. For example, when there is surplus energy during periods of high solar radiation in summer, an RFC system can, in electrolysis mode, produce hydrogen and oxygen, which are then stored in tanks. When there is a lack of energy, the unit is fed with the stored gases operating in fuel cell mode to produce electricity. To date, there are three types of reversible fuel cells that are categorised according to their operating temperature. These three types are: i) the reversible alkaline fuel cell (RAFC), ii) the reversible polymer electrolyte fuel cell (RPEFC), and iii) the reversible solid oxide fuel cell (RSOFC).

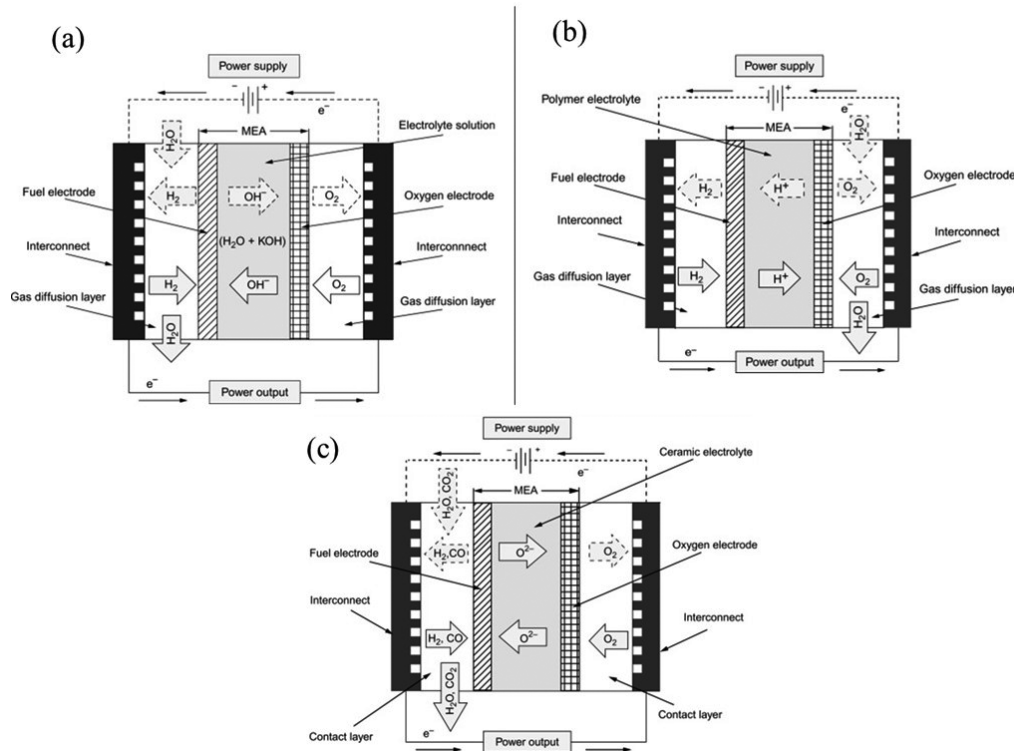


Fig. 12. – Schematic representations of (a) reversible alkaline fuel cell (RAFC), (b) reversible polymer electrolyte fuel cell (RPEFC), and (c) reversible solid oxide fuel cell (RSOFC). Source: <https://doi.org/10.1016/B978-1-78242-363-8.00005-0>.

The reversible alkaline fuel cell (fig. 12a), uses an aqueous solution of potassium hydroxide (KOH) as the electrolyte. The catalysts material used in this type of fuel cell bath for the manufacturing of the anode and cathode is platinum based. Its operating temperature when it is in a fuel cell mode is of 60–120 °C. The two half-reactions that take place when the device is in electrolysis mode are: $2\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2\text{OH}^-$ at the cathode, and $2\text{OH}^- \rightarrow \frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2\text{e}^-$ at the anode. On the other hand, when the device is in fuel cell mode the two half-reactions can be described as follows: $\text{H}_2 + 2\text{OH}^- \rightarrow 2\text{H}_2\text{O} + 2\text{e}^-$ at the anode, and $\frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2\text{e}^- \rightarrow 2\text{OH}^-$ at the cathode.

The reversible polymer electrolyte fuel cell (fig. 12b) consist of two porous electrodes separated by a polymer electrolyte membrane. The most commonly used polymer electrolyte membrane used in this type of fuel cells is a perfluorosulfonic acid polymer. The two half electrochemical reactions that take place while the device is in electrolysis mode are: $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$ at the cathode, and $\text{H}_2\text{O} \rightarrow \frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2\text{e}^-$ at the anode. When the device is in fuel cell mode the reactions are: $\text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^-$ at the anode, and $\frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2\text{O}$ at the cathode.

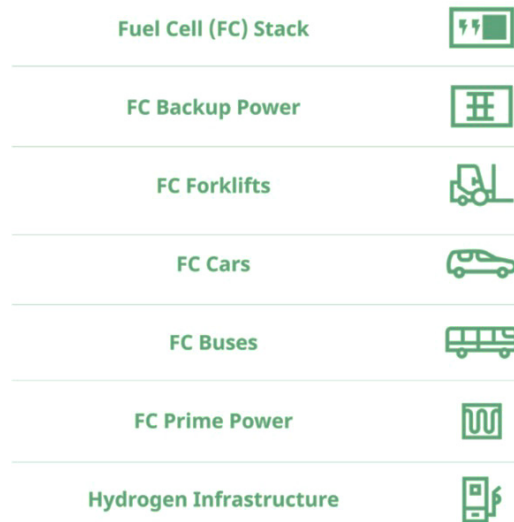


Fig. 13. – Applications of fuel cells. Source: <https://www.plugpower.com/fuel-cell-applications-101-where-are-fuel-cells-used-today/>.

The reversible solid oxide fuel cell (fig. 12c) is assembled by two porous electrodes, separated by a dense, oxide ion-conducting electrolyte. The electrolyte in this type of fuel cell is most frequently doped zirconia, which is a fluorite-structured oxide like yttria-stabilized zirconia (8YSZ = 8 mol.% Y_2O_3 -stabilized ZrO_2) or scandia-stabilized zirconia (ScSZ). The catalysts material used for the production of the anode are composites of zirconia and Ni-metal catalyst (Ni/YSZ), while perovskites are used for the cathode. When the device is in electrolysis mode, the half electrochemical reaction that takes place at the cathode is: $H_2O + 2e^- \rightarrow H_2 + O_2^-$, and at the anode is: $O_2^- \rightarrow \frac{1}{2}O_2 + 2e^-$. While in fuel cell mode, the reaction that takes place at the anode is: $H_2 + O_2^- \rightarrow H_2O + 2e^-$, and at the cathode is: $\frac{1}{2}O_2 + 2e^- \rightarrow O_2^-$.

7. – Where can we find fuel cells?

Fuel cells have a vast area of applications that range from stationary to mobility (fig. 13). As previously mentioned, fuel cells can be used as batteries to counteract the intermittency of renewable energy sources and support renewable energy production 24/7. Therefore, stacks of fuel cells can be found in renewable energy power plants that have the ability to either convert the excess of renewable energy to hydrogen and oxygen and recombined these gases to produce electricity when energy demand is high (reversible fuel cell) or to directly use hydrogen produced on site by an electrolyser with oxygen from the air to produce the necessary electricity for supporting the grid (fuel cell). In the mobility space, fuel cells can be found in forklifts, cars, buses, and trucks. In this space, fuel cells combine hydrogen and oxygen gas to produce electricity to run a motor. Last, fuel cells are still extensively used in space for powering space crafts.

8. – The problems of current fuel cells

The problems of current fuel cells are very similar in nature to the ones of electrolyzers. The first main problem is the high cost that is associated with the production of the fuel cells, and particularly the one associated with the production of the anode and cathode. The other problem is that current fuel cells have very low efficiencies that do not exceed 70%. These low efficiencies are due to the various side reactions that take place during their operation that compromise the overall efficiency.

9. – Current research focus on fuel cells

The research focus to date on fuel cells can be split into two categories. The first being the development of new cost-effective and high-performing catalytic materials that can be used as the anode and cathode. The second being focused on the design of new and improved electrochemical cells that better facilitate the needs dictated by the various electrochemical reactions that take place in a fuel cell.

10. – Conclusion

Climate change is a reality and fossil fuel consumption for the production of energy is one of its key drivers. Decarbonising our energy sector will be crucial if we want to combat climate change. This can be easily achieved by widely utilising green energy technologies such as electrolyzers and fuel cells. Electrolyzers have the ability to split water into hydrogen and oxygen by using renewable energy, whereas fuel cells can use this green hydrogen to recombine it with oxygen obtained from the atmosphere to produce electricity. Both electrolyser and fuel cell technologies have the advantage of scalability. They can be easily scaled up or down according to the end use. Hence, big stacks of electrolyzers and fuel cells can be found in renewable energy power plants where are used to support the grid 24/7. Whereas, smaller stacks can be found in industrial, commercial or residential areas. Last fuel cells are widely utilised in spacecrafts for producing electricity and water, but also in cars, forklifts, trucks and busses. The two main drawbacks of these green technologies that has prevented their mass utilisation in the energy sector is: i) their high manufacturing cost since expensive raw materials are used for the production of the electrodes, and ii) their low efficiencies which are not beyond 80% for the electrolyzers and 70% for the fuel cells.

* * *

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