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Electrolyser Technology Advancements For Green Hydrogen Production:A Review

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Abstract:

The urgent need for sustainable energy solutions has led to advances in electrolyser technology, particularly in green hydrogen production. This review provides an overview of recent developments in electrolyser systems, including alkaline electrolysis, proton exchange membrane (PEM), and electronic oxide materials. We analyse their performance, durability, and power, as well as accessories and electronics that increase performance and reduce costs. We also discuss the integration of renewable energy and the impact of energy efficiency on technology and energy solutions. This article aims to present the status of electrolyser technology and its important role in supporting the transition to a hydrogen economy by combining the latest research results and technological developments. Future research and development directions are also important in terms of innovation potential that could advance the potential of green hydrogen as a clean energy source.

Keywords:

Proton exchange membrane electrolysis cell (PEMEC), Solid oxide electrolysis, Hydrogen, Renewable energy, Electrolysis, Alkaline electrolysis

Introduction:

The world's search for sustainable energy solutions continues due to concerns about climate change and the need to decarbonize various sectors. Green hydrogen, produced by electrolysis of water using renewable energy, is a favourite of clean energy consumers in a variety of applications including transportation, industry, and energy storage, as well as many food products. Advances in electrolysers are vital to improving the quality, efficiency, and potency of green hydrogen products as the country strives to meet its security goals. The process of producing hydrogen involves an electric current that drives a reaction that splits water into hydrogen and oxygen [1]. The efficiency of the electrolyser directly affects the economic efficiency of green hydrogen production, so the continued development of the technology is important. There are three main types of electrolysers – alkaline electrolysers, proton exchange membrane (PEM), and solid oxide electrolysers (SOEC) – each with specific characteristics that affect their application and development. Alkaline electrolysers have become the most important electrolysers.

However, they often face problems with efficiency and response time, especially when combined with renewable energy sources such as wind and solar. Recent developments in alkaline technology include the development of high-quality electronic devices and improved operating strategies to increase their performance and flexibility. products, especially for applications requiring rapid response to changing input power. Their high performance and design make them suitable for integration with renewable energy systems. However, proton exchange membrane technology often requires higher material costs, mainly due to the use of low-quality metals. Continuous research is aimed at improving the efficiency and durability and performance of PEM systems. competence.

SOEC can save significant amounts of energy compared to electrolysis processes by using heat to drive endothermic reactions. However, the technology is still in the early stages of commercialization and faces challenges related to hardware stability and integration. Advances in catalyst development, especially precious metal discovery and advanced techniques, have the potential to reduce costs associated with electrolyser installation. In addition, the integration of AI and machine learning in electrolyser design and operation is promising for efficient and effective operation [2].

By combining existing research results, technological developments, and new models, we aim to achieve success in improving the performance, durability, and cost-effectiveness of electrolysers. We will also discuss the implications of these advances for the broader hydrogen industry, including their role in achieving global security goals and transitioning to a powerful future. Understanding the latest developments in electrolyser technology is important for stakeholders across the energy spectrum, from policymakers to industry leaders. This review not only provides an overview of the current state of electrolyser progress, but also highlights the importance of continued research and development to unlock the full potential of green hydrogen as a sustainable energy source.

1. Electrolysis Process:

Hydrogen is produced in electrolyser via electrochemical conversion of water to hydrogen and oxygen. The reaction can be expressed as:

$$H_2O_{(l)} + 237.2\left(\frac{kJ}{mol}\right)_{electricity} + 48.6\left(\frac{kJ}{mol}\right)_{heat} \rightarrow H_2 + 0.5O_2$$

The operation of an electrolyser is different from that of a fuel cell. In a fuel cell, oxygen and hydrogen react to produce electricity and water, while in an electrolyser, electricity is used to split water into oxygen and hydrogen. In general, electrolysers can be divided into three groups: proton exchange membrane electrolysers (PEM), alkaline electrolysers, and solid oxide electrolysers (SOEC). This classification depends on their electrolyte. Each of these electrolysers is briefly described below [3].

2. PEM Electrolysers:

The PEM electrolyser was first developed by Russel et al. in the 1960s. Like a fuel cell, a PEM electrolyser has two electrodes and an electrolyte. Water is transported to the anode where it is broken down into oxygen and carbon dioxide. The protons produced are then transferred through the membrane to the cathode where electrons are gained and hydrogen is produced. Since oxygen and hydrogen are produced by different electrodes, a separate room is not needed, making the system more convenient. The reaction between the anode and cathode can be written as [3]:

Anode $H_2O \rightarrow 2H^+ + 0.5O_2 + e^-$

Cathode $2H^+ + 2e^- \rightarrow H_2$

2.1 Operation and Characteristics:

As mentioned in the introduction, the three main electrolyser technologies reported so far are alkaline electrolysers, proton exchange membrane electrolysers, and sulphur dioxide electrolysers. However, only alkaline and proton exchange membrane technologies are currently available in the market; So, technology is still in the research and development stage. Of the two existing technologies, alkaline technology is mature and widespread, and has been operating on the same principles since its introduction more than 100 years ago. Therefore, many alkaline hydropower plants have been built to date. On the other hand, the advantages of this technology include low energy consumption (e.g. cobalt, nickel, iron), high operating life, and fuel purity. On the other hand, the technology's low current speed hinders its development in emerging markets with great potential. In addition, alkaline technology is not suitable for the post operational load that needs to be connected to the RES in terms of flexibility. To overcome the above problems of alkaline technology, PEM technology has been developed since 1960 [1]. In fact, this technology can operate at high current and is particularly suitable for mixing with RES due to its fast response time. Therefore, since RES is considered a very high energy source, the energy generated during the conversion process can be absorbed by the PEM electrolyser, thus increasing energy efficiency.

However, compared with alkaline electrolysers, PEM electrolysers use expensive catalysts such as platinum (cathode side) and iridium (anode side), thus increasing the global cost of electrolysers.

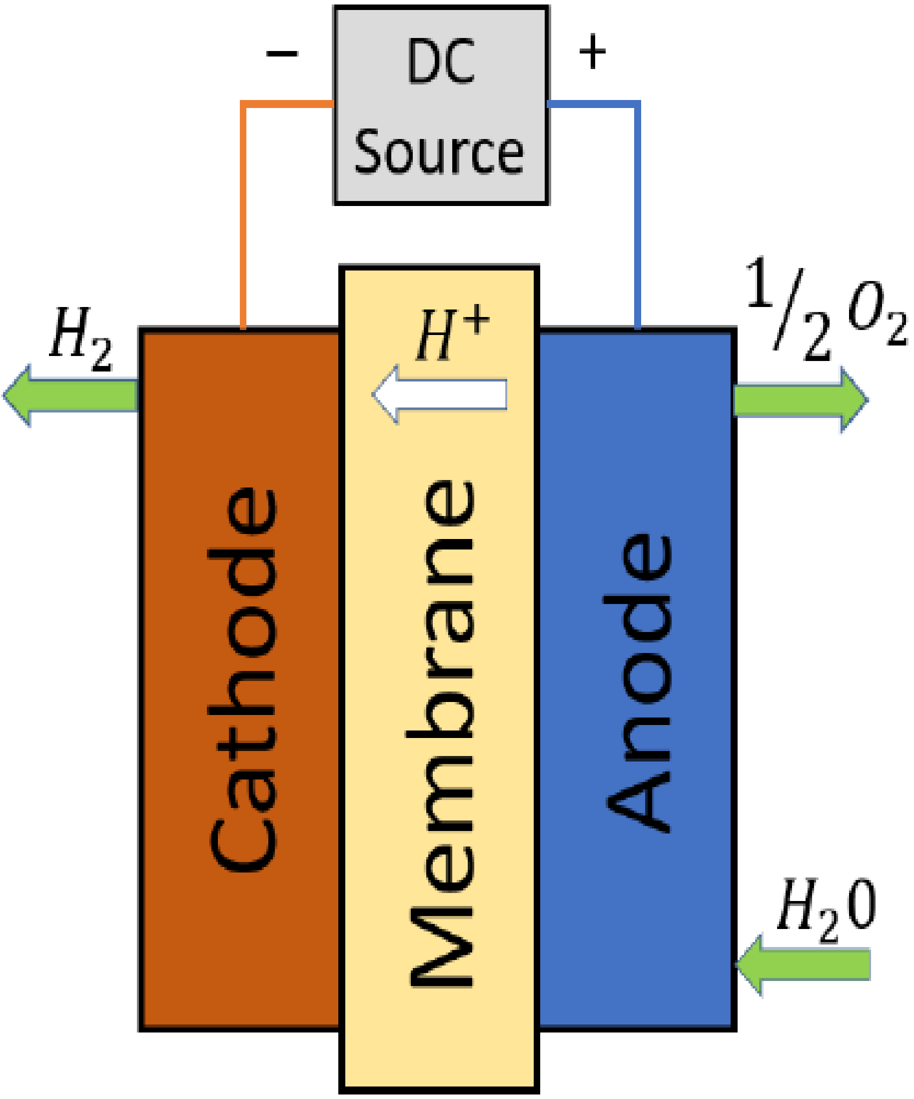

Figure 1: Schematic illustration of a basic water PEM electrolysis system [1].

2.2 Dynamic Issues:

In the past few years, many contributions have been published in the literature on the development of static models based on semiempirical and empirical equations. However, the kinetic model is often overlooked because very little work has been done on it. Like fuel cells, electrolysers are electronic devices whose response time to reach steady state can be slow or fast depending on the task. We recently performed the first study of the PEM electrolyser field based on the current distribution. It turned out that the answer depends on the operating conditions, so the model of the dynamics is very important to make the model reliable and accurate. The PEM electrolyser was removed. The technical specifications of the investigated PEM electrolyser can be found here. The first experiment was done using current steps from 0 to 10 A; this is one of the most important things to have when electrolysers are combined with RES because they are a powerful source and their operation is largely dependent on the weather. The current response is followed by a slow voltage increase or decrease before the electrolyser reaches a steady state. This slow reaction is related to the kinetics of the anodic and cathodic reactions as shown [1]. Also, since the change can be slower or faster depending on the energy input, it is important to establish accurate and reliable models based on the change parameters.

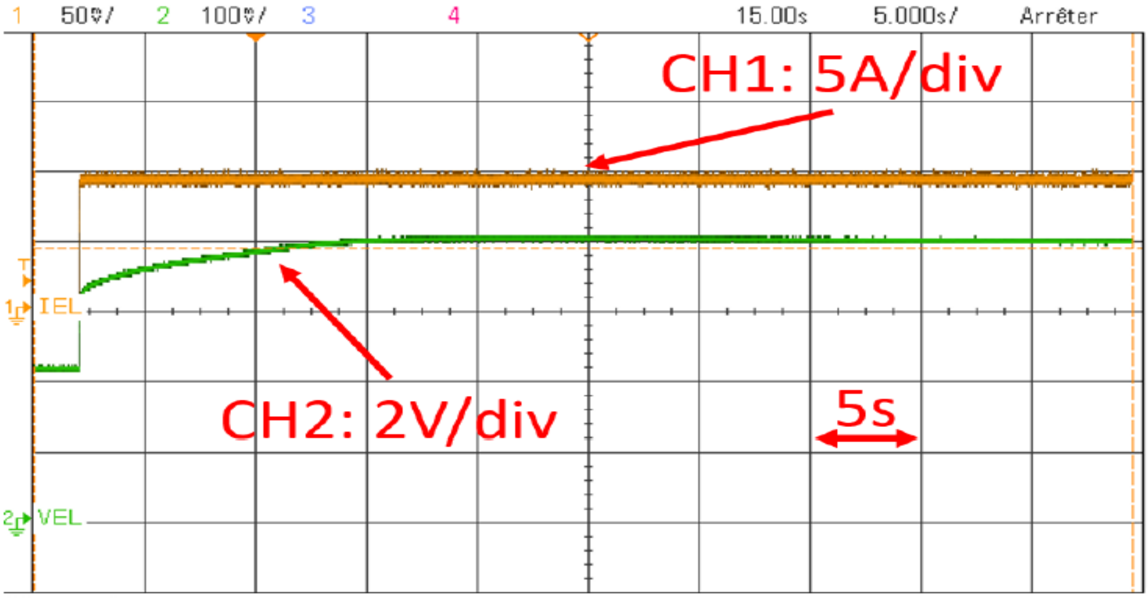

Figure 2: Response of the electrolyser because of a rising electrical current from 0 to 10 A [1].

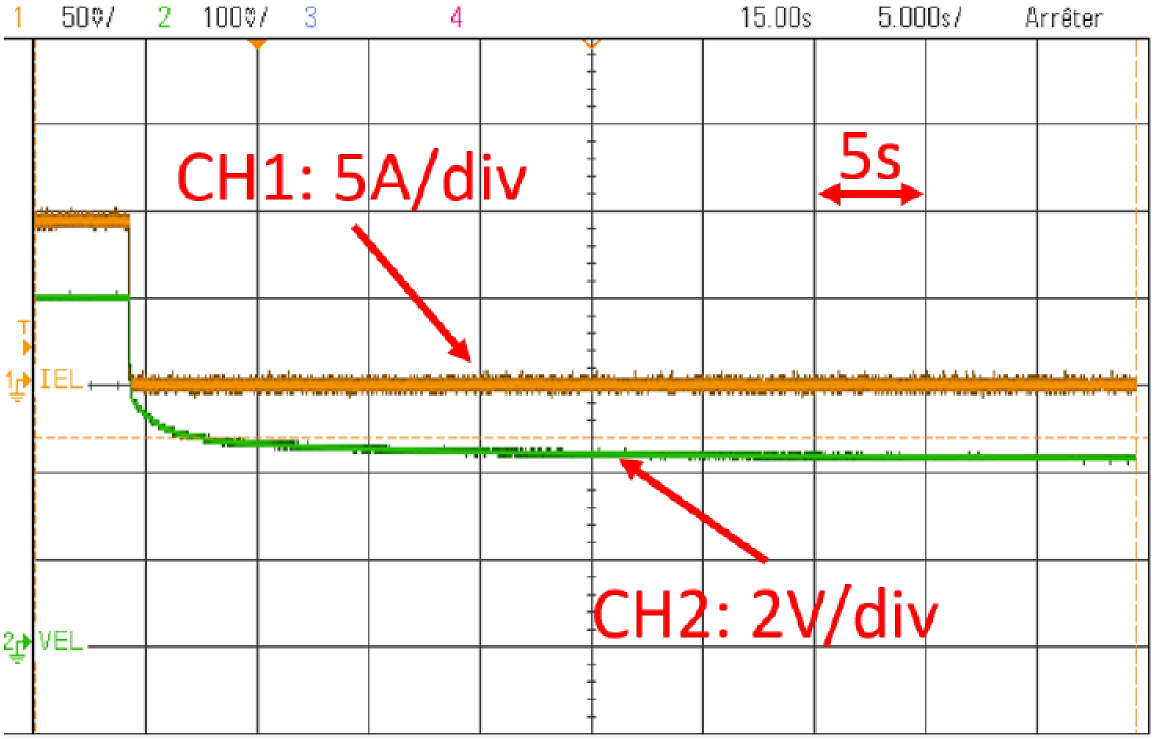

Figure 3: Response of the electrolyser because of a falling electrical current from 10 to 0 A [1].

2.3 Modelling Concept:

The voltage used by the electrolyser is equal to the difference in voltage loss due to the reversible and irreversible processes that occur when the electrolyser is turned on. Best of all, water electrolysis is a reversible process. This means that with some energy, water molecules can be split into oxygen and hydrogen (the electrolyser operation) and the oxygen and hydrogen can be recombined, water and energy. The difference will be created when mixed (the working gas cell). Therefore, the amount of voltage used by the water splitting reaction is usually called the reversible voltage. The amount of electricity is used by irreversible processes such as [4]:

i) initiating the electrochemical reaction by removing electrons from the current,

ii) overcoming the problems that prevent the movement of electrons through many current objects. and at the same time preventing the positive flow of hydrogen protons across the membrane, and

iii) preventing the mass of reactants (water) and products (oxygen and hydrogen) across the membrane. This is more pronounced at high temperatures.

These irreversible actions lead to a loss known as overvoltage, ohmic overvoltage, concentration, or diffusion overvoltage. In the literature, these are often called over voltages or overpotentials. Therefore, the total energy required to initiate and maintain the electrochemical reaction of electrolysis is the result of the energy required to complete the reversible and irreversible process in an acidic environment. We can say this in the following words: Total energy consumed =Energy consumed by the reversible action + Energy consumed by the irreversible action.

2.4 Modelling Procedure:

In this section, the models will be implemented as parts of an electrical circuit to emulate the behaviour of an electrolyser be reviewed and discussed. Electrical models can still be divided according to the methodology of their development, dynamic scale behaviour and modelling to analytical or empirical models, static or dynamic and cells or reservoirs.

electric equal circuit fashions (EEC) are the models which use electric additives (e.g., electric voltage and/or current assets, and passive factors: resistors, inductors, capacitors) to assemble an electrical circuit that may emulate the behaviour brand new a normal machine or device.

For developing an EEC for the PEM electrolyser, tries are made to broaden such an electrical illustration which could emulate the special voltage drops that arise while the electrolyser is became on. thus, the EEC estimations found inside the literature are specially based on experimental outcomes in the shape contemporary polarization curves which might be used to broaden empirical equations that may carefully describe those curves. the general equation brand new the electrolyser cellular voltage is expressed as [4]:

$$E_{cell} = E_{rev} + E_{ohm} + E_{act} + E_{\frac{conc}{diff}}$$

Based on this equation, a general representation, as shown in Figure 3, can be constructed, and used to model PEM electrolysers. Any electrical term in this representation of the circuit can be used by the circuit process; this term can be approximated or can represent the real process or the work results resulting from the fall.

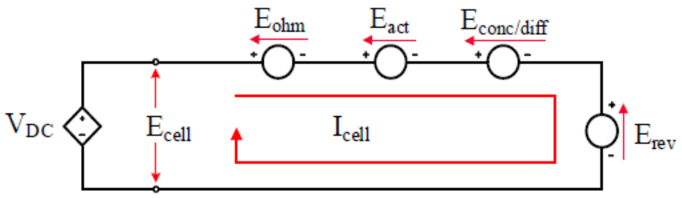

Figure 4: General electrical representation of the PEM electrolyser cell [4].

Different models of the circuit can be constructed from this representation of the circuit, depending on the opinion or decision taken. However, in this paper only the representations in the Circuit Court mentioned in this document are discussed and examined, since the purpose of this paper is to correct and evaluate the data available in the PEM electrolyser prototype model. Understanding the strengths and problems of existing electrolyser models will help develop new ways to improve the overall performance and accuracy of these models in simulating the behaviour of PEM electrolysers. In addition to the reverse and ohmic voltage drops that can be clearly seen in the polarization curve, other issues such as charge matching on both sides of the membrane must be considered during electrical modelling of PEM electrolysers. This effect is called the double-layer capacitance effect and its effect depends on the overvoltage value and the concentration overvoltage value.

3. Alkaline Electrolyser:

The alkaline electrolyser was the first type of electrolyser created by Troostwijk in 1789. It has continued to be used since then and is currently the most widely used and developed electrolyser. It also has the lowest cost of any of the various types of electrolysers. Unlike PEM electrolysers, water is fed to the cathode in alkaline cells. The water, which receives energy from an external source, is separated into hydrogen gas and OH^-. The anode delivers the electrolyte to the anode where oxygen and water are formed. The reaction between the anode and cathode is as follows [3]:

Anode $4OH^- \rightarrow O_2 + 2H_2O + 4e^-$

Cathode $2H_2O + 2e^- \rightarrow 2OH^- + H_2$

Some problems in alkaline electrolysers are usually related to aqueous electrolytes. First, the liquid state of the electrolyte can cause leakage problems. Second, it has a lower ohmic shock than the current obtained. Finally, its performance is reduced under part load Performance. This is due to the reduced efficiency of the anode and cathode during part load operation, resulting in lower hydrogen and oxygen production. On the other hand, the hydrogen permeability in the electrolyte remains unchanged. In this case, the hydrogen concentration on the anode side increases, which reduces the performance of the battery.

3.1 Classification:

Several different electrolytic cell regions have been introduced. When it comes to fuel cells, the distribution system is full of new materials. Electrolytic cells were previously divided into three types. Alkaline electrolytic cells use a liquid electrolyte such as sodium hydroxide or potassium hydroxide. Acid electrolytic cells are usually equipped with a proton-based polymer electrolyte membrane. The third option is a battery with a strong oxide electrolyte that electrolytically converts water vapor at low temperatures. As new designs and new materials are developed, electrolysis machines can now be classified in many ways [5].

3.1.1 Classification by Operation Condition:

Different electrolysis systems require different functions, which will have different effects on electricity. Temperature and pressure must be adjusted for each type of battery. It can distinguish between low temperature (70-80°C), medium temperature (150-200°C) and high temperature (700-1000°; C) batteries, as well as low and electricity of generators [5].

3.1.2 Classification by Substrate:

Electrolytic cells typically use water, but other substrates can be used. The use of ammonia, methanol, urea, and even black alcohol, a byproduct of the paper industry, are possible and require intensive research [5].

3.1.3 Classification by Electrolyte:

Electrolyte is one of the most common materials used to describe electrolytic cells. It can vary depending on the pH of the electrolyte (alkaline vs. acidic) or the state of the electrolyte (liquid electrolyte, polymer electrolyte, or solid oxide electrolyte). Polymer electrolyte membranes used to function solely as acid polymers, but with the rise of anion exchange membranes (AEM) in recent years, the membranes have moved beyond being proton exchange membranes (PEM) [5].

3.2 Mathematical Model of Alkaline Electrolyser:

The purpose of developing the model is to predict the purity of fuel produced by an alkaline water electrolyser as a function of current density, electrolyte flow rate, temperature and concentration, and electrolyte circulation. They can be divided into "mixed type" and "separated", in which the anolyte and catholyte are continuously mixed to compensate for the electrolyte concentration difference caused by the half-cell protection, and "separation" formed by two circles. Separation interaction, Prevent oil explosion and pollution of other people's petroleum products. The whole concept of the structure is based on the suction body gas-liquid reactor model, as shown in Figure 5.

The electrolytic cell is divided into two continuous tank reactors (CSTR) j, connected to a separator that allows dissolved species i (e.g. hydrogen and oxygen) to pass $N_{cross,i}$. Each half of the cell is fed with free gas via the electrolyte solution V_L^j, and the gas exits the electrodes at the molar flow rate $n_{R,i}^j$ caused by the electrochemical reaction. In order to estimate the gas partial pressure $p_{out,i}^j$ and the liquid concentration $c_{out,i}^j$ at the anode and cathode outlets of the electrolytic cell, it is necessary to follow the two-phase heterogeneous model that determines the phase change $N_{phys,i}^j$ according to the type of physical absorption and desorption [6].

In practice, the two-phase flow is represented by V_L^j and V_G^j, leaving the electrolytic cell and entering the gas liquid separator, as shown in Figure 6, which shows the flow pattern of the electrical image from the meter. In this model, it is assumed that no other changes occur in the separator, since the transfer area is good and the coefficient is less than in the electrolytic cell. This is due to the merging of the bubbles in the pipe after the cell exit and the almost stagnant liquid in the separator. It is assumed that the separator behaves perfectly, so that only dissolved gases are recycled to the electrolytic cell when the air bubbles are completely removed. In "mixed mode" the two electrolyte circuits in the anode and cathode compartments are combined before being fed back into the electrolytic cell. In Figure 6 this electrolyte is shown in green (in the web version), while the "separation" is shown with a purple line.

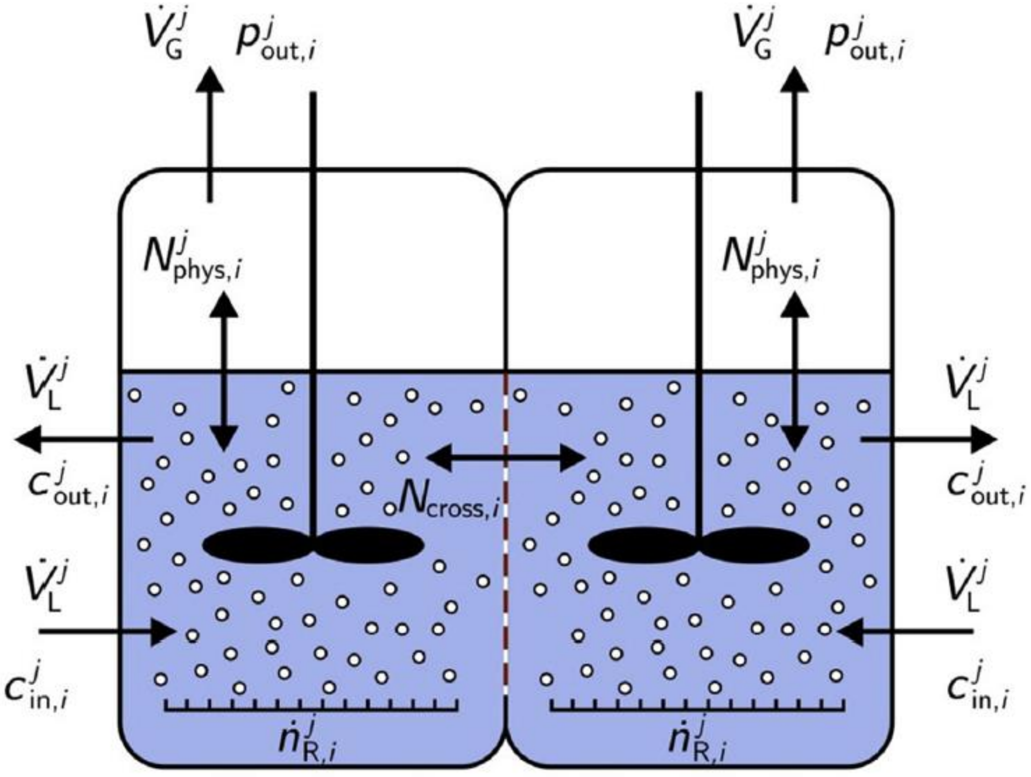

Figure 5: Basic CSTR model concept of the electrolysis cell with occurring fluxes. Compartment j = anodic, cathodic; species $i = H_2 + O_2 + H_2O$ [6]

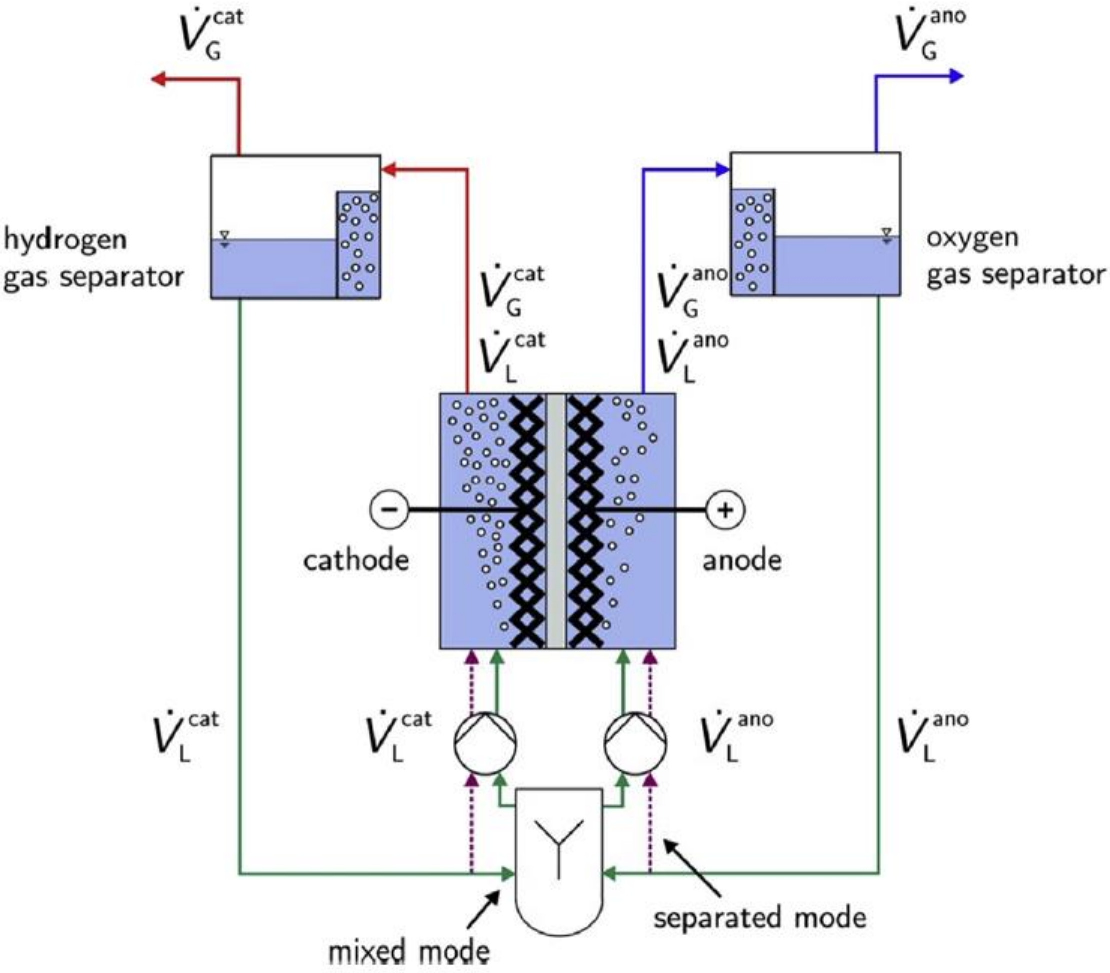

Figure 6: Model flowsheet derived from lab-scale electrolyser [6].

Other assumptions and simplifications have been made, including:

- stationary process
- ideal CSTR behaviour with constant temperature and concentration
- water saturated product gases
- film model for the mass transfer
- neglect of the recombination reaction and assumption of 100% faradaic efficiency
- monodisperse bubble size distribution
- no mass transfer in pipes and gas separators
- ideal mixer

The gaseous solution is considered as hydrogen, oxygen, and water, while the liquid phase equation is considered as hydrogen and oxygen only. Since the solid phase of the Zirfon separator used has been shown to be gas impermeable, it is expected that the passage through the separator will only occur in the liquid phase. Due to the very strong electrolyte used in the experimental setup and the continuous changes in water, any change in the OH^- concentration was assumed to be negligible [6].

3.3 Alkaline Electrolyser Performance:

Next, we tested the performance of each membrane in an alkaline water electrolyser using a $NiFe_2O_4$ anode catalyst and a NiFeCo catalyst. In all cases, the cells were operated at 60 C with both anode and cathode injection 1 M KOH. Figure 7 compares the linear sweep voltammograms obtained after 15–30 min of operation for each membrane. At a potential of 1.9 V, the Sustainion® 37-50 membrane shows approximately 1 A/cm^2, the Fumatech FAS-50 approximately 0.5 A/cm^2, the FAPQ 0.16 A/cm^2, the AMI -7001 0.11 A/$cm^2$2, Nafion 0.1 A/cm^2, and the PBI 0.05 A/cm^2. Measurements were then made by holding the cell current at 1 A/cm^2 and measuring the change in voltage over time. The results are shown in figure 8. We were able to maintain 1 A/cm^2 using only Sustainion® 37-50 membrane and FAS-50 membrane. Sustainion® membrane can maintain 1 A/cm^2 voltage [7].

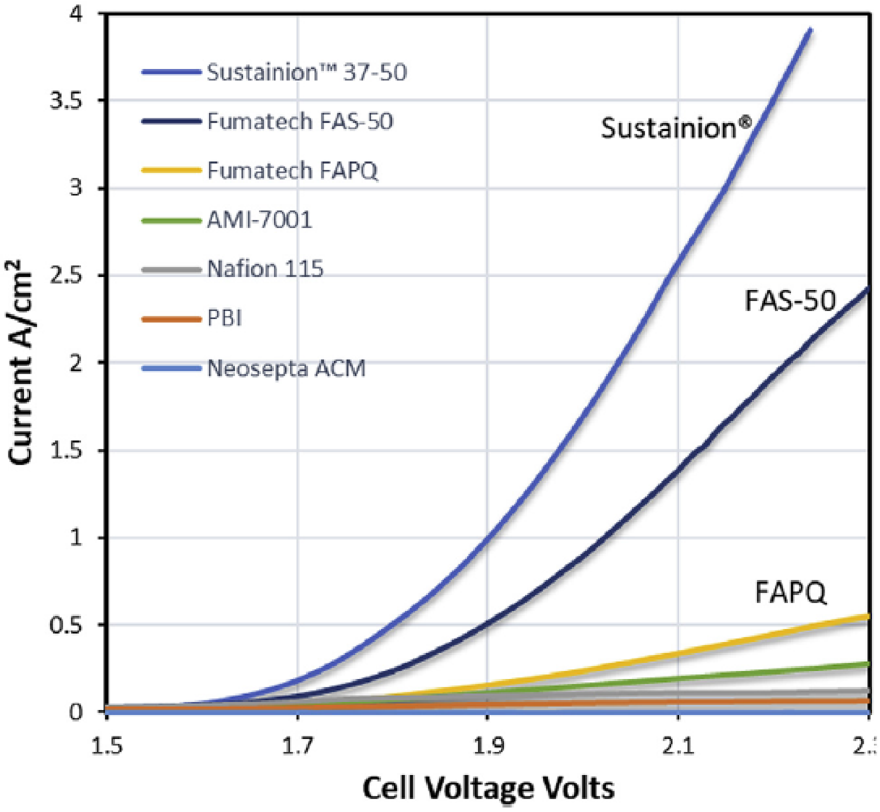

Figure 7: A comparison of the current produced in the cell as a function of voltage for each of the membranes considered here measured via linear sweep voltammography at 60 C with 1 M KOH. In all cases the cell had $NiFe_2O_4$ anode catalysts and NiFeCo cathode catalysts at loadings of 2mg/cm^2. [7]

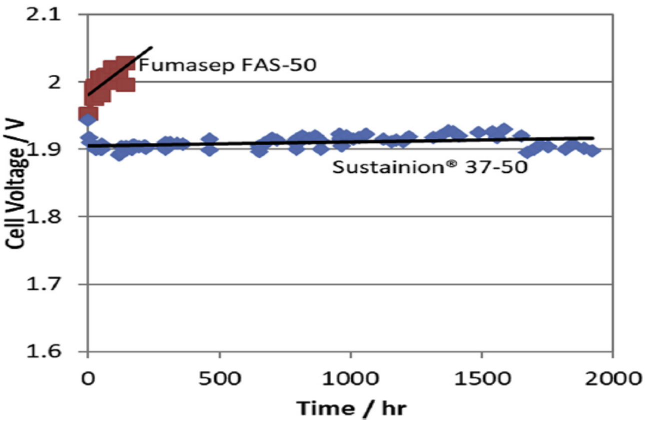

Figure 8: The steady state voltage to maintain 1 A/cm^2 current with the Sustainion® 37-50 membrane and the FAS-50 membrane at 60 C with 1 M KOH. In all cases the cell had $NiFe_2O_4$ anode catalysts and NiFeCo cathode catalysts with catalyst loadings of 2 mg/cm^2. [7]

Preliminary data show an average increase of approximately 400 µV/h, but the level loss reaches approximately 200 µV/h after 180 hours. We tested the leakage current of the cells with FAS-50 film for 200 h. The cell showed a leakage current of 1.23 V of 0.2 A/cm^2, indicating membrane failure, so we stopped the test. We also tested the current flow of the cells with the Sustainion® anion membrane. We did not observe any serious water leakage at any stage of operation. More detailed information shown in the supplementary material shows that cells with Sustainion® 37-50 membranes have lower leakage current 1 A/cm^2 at 60°C operating hours. We have seen many carbons streams age and start leaking. When we replace the carbon stream with nickel stream, everything is stable. One of the studies showed a control voltage 1 A/cm^2 of 20 µV/h. Another show increases of 0.8, 3, 5 and 10 µV/h [7].

3.4 Available AWEs:

Alkaline water electrolysis has been developed for a long time. Many different AWs are available for sale and use worldwide. Table 1 lists the highlights of some examples. Although asbestos has been banned throughout the EU since 1999, it was reported that asbestos was still used as a separator in some cells, except for electrolysers, until 2015. Nickel foam or stainless steel is usually used as electrode material. This compares to using a lot of energy to produce electricity or renewable energy in the same situation, as shown in Table 2, which is half the cost of alkaline electrolysers in the group, because their products are large and heavy and mass production has not yet been established. Still, we have reduced all costs. Prices are expected to fall to about 66% of current prices by 2030 [5].

Table 1: Basic Parameters of Commercially Available Alkaline Electrolysers

Company	Type	Electrolyte	Working Temp. (∘C)	Postulated Performance	Capacity	Service Life	References
NEL Hydrogen	NEL A 150–485	25% KOH	80	3.8–4.4 kWh $Nm^{-3}H_2$	50–485 Nm^3H_2/h	30–40 years	Ref [8]
Hydrog(e)nics	HySTAT 10–60	30% KOH	70a	4.9–5.4	4–60 Nm^3H_2/h	50.000 h	Ref [9]

				kWh Nm^{-3} at full load			
Uralhimmash	FV-180–500	NA	85–90	NA	172–536 $m^3 H_2$/h	25.000 h/ 10 yearsb	Ref [10]
Teledyne	Titan HMXT 50–200	NA	NA	NA	2.8–11.2 $Nm^3 H_2$/h	25+years	Ref [11]
	Titan EC 500–750	NA	NA	NA	20–40 $Nm^3 H_2$/h	25+years	
	Titan EL 1000–1400	NA	NA	NA	56–80 $Nm^3 H_2$/h	NA	
McPhy	Baby McPhy	NA	NA	2.8 kW max. consumption	400 Nlt/h	NA	Ref [12]
	McLyzer 3–30 bar	NA	NA	7.4–63 kW max. consumption	3–60 $Nm^3 H_2$/h	NA	
IHT	Type 20-S-556	NA	NA	4.3–4.6 kWH $Nm^{-3} H_2$	27–760 NmH_2/h	10–15 years	Ref [13]

Table 2: Hydrogen Prices, Germany 2012

	Alkaline (€/kg)	PEM (€/kg)
Mainstream grid (100% load)	3.2	4.1
Mainstream grid (balancing service)	2.7	3.5
Renewable energy sources (off-grid)	5.0	7.6

Table 3 shows the current technoeconomic characteristics and future successes of PEMEC and ALK electrolysers. Modern PEMEC electrolysers are more flexible and faster than the ALK systems used today. The higher operating efficiency and faster response time of PEMEC technology provide great benefits in the adjustment process to bring more revenue to the electricity market.

Table 3: Techno-economic features of PEMEC and ALK electrolysers between 2017 and 2025.

Methods	PEMEC		ALK	
	2017	2025	2017	2025
Efficiency (kWh electricity per kg of hydrogen)	58	52	51	49
Lifespan stack (working hours)	40,000	50,000	80,000	90,000
Low Heating Value Efficiency (%)	57	64	65	68
OPEX (Initial CAPEX % per yr)	2	2	2	2
CAPEX -overall cost of the system (both costs of installation/power supply) in EUR per kW	1200	700	750	480
Lifespan of the system (yrs)	20 years	-	20 years	-
Output pressure (Bar)	30	60	atmospheric	15
CAPEX – replacement of stack (EUR per kW)	420	210	340	215

4. Solid Oxide Electrolyser:

Solid oxide electrolysers (SOECs) are a new type of electrolyser introduced by Donitz and Erdle in 1980. In a SOEC cell, water is transported to the cathode side where it takes electrons and produces hydrogen and oxygen ions. The anions are transported through the electrolyte to the anode where they are converted to oxygen. The anodic and cathodic reactions are shown in the equation: [18b]

Anode $O^{2-} \rightarrow 0.5O_2 + 2e^-$

Cathode $H_2O + 2e^- \rightarrow O^{2-} + H_2$

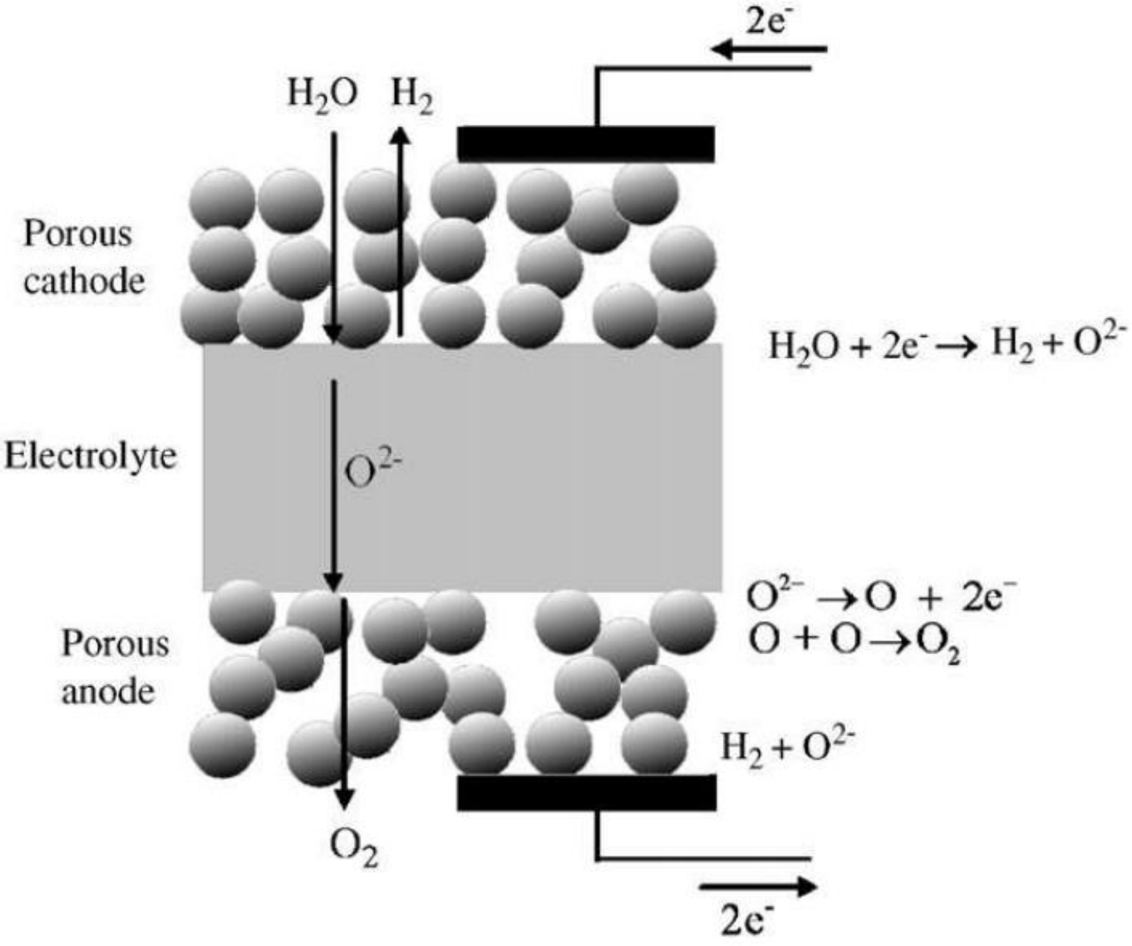

Figure 9: Schematics of SOEC hydrogen production [3].

Unlike PEM and alkaline electrolysers, the operating temperature of SOEC is very high (900-950°C). This high temperature reduces the amount of electricity required for the electrolysis process [3].

$$\Delta G = \Delta H - T\Delta S$$

In the model above, ΔG is the minimum electrical requirement and it is seen that it decreases as the temperature increases. In the high temperature oxide electrolytic cell, the total energy, electrical energy, and thermal energy required for the electrolysis process change with temperature as seen in Figure 10. Electrical and thermal energy depend on temperature. When the operating temperature of the battery increases, the electric current decreases, and the heating power increases. This behaviour is very beneficial because generating electricity is more expensive than producing it. Therefore, by increasing the battery temperature, less electricity is needed and more thermal energy is needed to perform the electrolysis process [3].

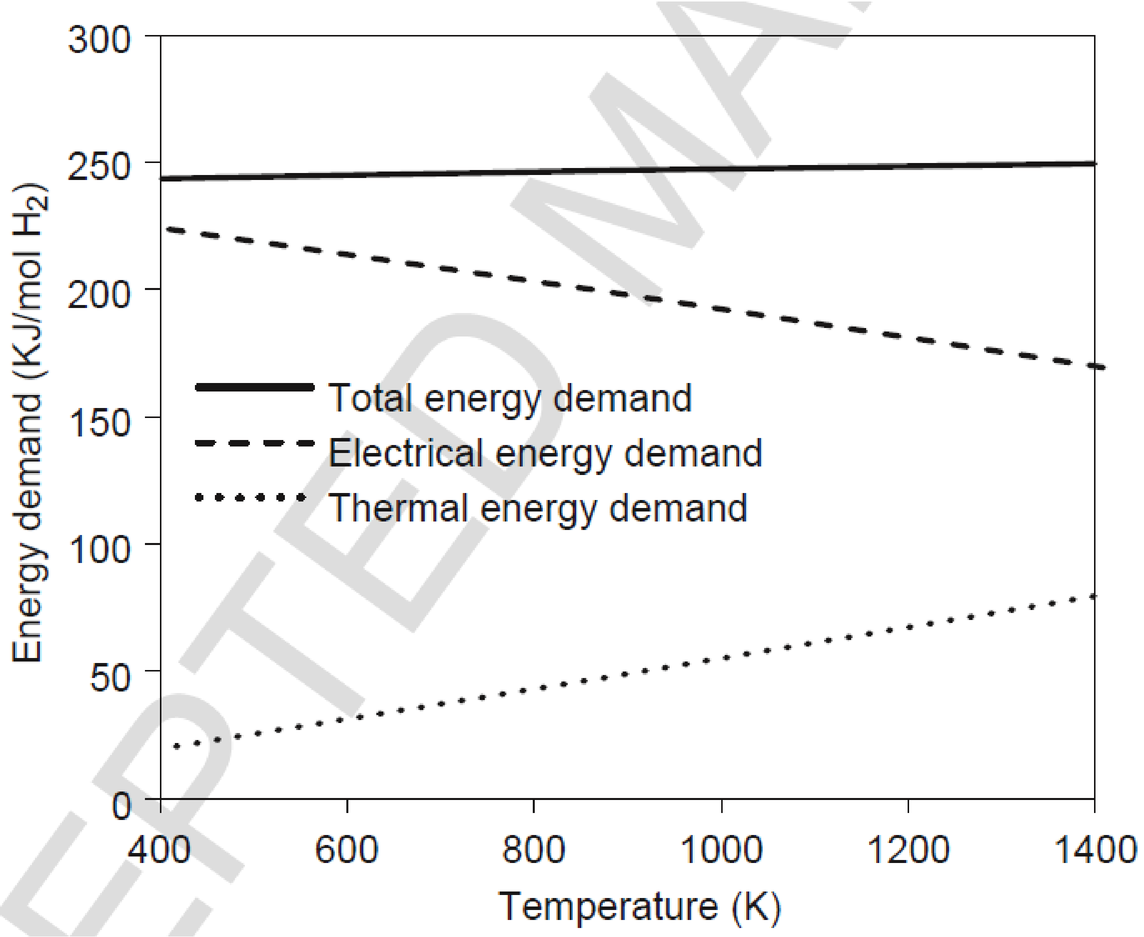

Figure 10: Total energy, electrical energy and thermal energy required for electrolysis process in high temperature solid oxide electrolysers [9]

It should be noted that the increase in cell temperature means that expensive materials and ceramics must be used in the battery, which increases the investment cost of the system. It should also have a heat source that will provide the necessary heat. Another advantage of SOEC is that it uses an electrolyte material. So, leakage is not a problem. It also causes a higher accumulation, thus reducing the ohmic loss in the cell.

4.1 SOEC Component Requirement:

SOEC components operate at low temperatures and must meet certain requirements for efficient and cost-effective hydrogen production, including [9]:

- Electrolytes must be chemically stable, must have good electrical performance, will reduce the ionic conductivity of the electrolyte value and current cell efficiency.
- The dense electrolyte must be gastight to eliminate any possibility of recombination of H_2 and O_2 , but it should be as thin as possible to minimize the ohmic overpotential.
- Both electrodes should be chemically stable in the highly reducing/oxidizing environments and have good electronic conductivity.
- Both electrodes should have suitable porosity and pore size to:
- support gas transportation between the electrode surface and the electrode–electrolyte interface and
- provide sufficient electrolyte–electrode–gas triple phase boundary (reaction sites).
- The thermal expansion coefficients of both electrodes should be close to that of the electrolyte to prevent material failure of the electrolyte due to exceedingly high mechanical stress induced by thermal expansion mismatch.

- Interconnect materials are needed in large-scale hydrogen production plant. The interconnect materials must be chemically stable in the reducing/oxidizing environments as they are exposed to the hydrogen/steam and oxygen simultaneously.
- The cost of the raw materials and the manufacturing cost should be as low as possible.

4.2 Electrolyte materials:

4.2.1 Stabilized zirconia:

Electrolytes are an important part of SOEC. The most common electronic material used in SOEC is yttria-stabilized zirconia (YSZ), which has high oxygen ion conductivity and good overall durability. Zirconium dioxide has a high melting point of about 2973K, but it can cause large, destructive volume changes during the phase transition from monoclinic phase to tetragonal phase around 1373K and cubic fluorite phase at 2643K. Adverse changes can be prevented by adding some alkaline earth metals or rare earth oxides. Increase oxygen ion conductivity. Table 4 shows some experimental data on the ionic conductivity of doped ZrO_2. It is observed that the electrolyte has higher conductivity when doped with Y_2O_3, Yb_2O_3, and Sc_2O_3,. In comparison, the conductivity of the electrolytes doped with MgO, La_2O_3, and CaO is low [9].

Table 4: Reported ionic conductivity of different doped zirconia materials at typical temperatures

Material	Conductivity (S/cm)	Temperature (K)	Remarks	Reference
8YSZ	0.13	1273	Prepared by spay drying of nitrate precursor solution	Ref [15]
10.5YSZ	0.034	1073	Thin film prepared by aerosol-assisted metal-organic chemical vapour deposition (AAMOCVD)	Ref [16]
10YSZ	4.52×10^{-6}	673	300 nm-thick film was prepared by atomic laser deposition (ALD)	Ref [17]
9.5YSZ	0.057	1173	Fifteen to 25 mm-thick film prepared by magnetic pulse compaction of tapes cast of nanopowders	Ref [18]
8YSZ	0.083	1173	Spark Plasma Sintering at 1573K and at pressure 70Mpa	Ref [19]
CaO–ZrO_2 with 12.5mol% CaO	0.055	1273	NIL	Ref [20]
La_2O_3–$ZrO_2$with 5 mol% La_2O_3	0.0044	1273	NIL	Ref [20]

MgO–$ZrO_2$with 13.7mol% MgO	0.098	1273	Prepared by conventional ceramic processing involving wet mixing, pressing, sintering, and machining	Ref [21]
Sc_2O_3–$ZrO_2$with 9–11mol% Sc_2O_3	0.28-0.34	1273	Prepared by sintering of coprecipitated powders	Ref [22]
Sc_2O_3–$ZrO_2$with 6 mol% Sc_2O_3	0.18	1273	The sintered film was treated by hot isostatic pressing (HIP) to improve the mechanical strength	Ref [23]

4.2.2 Doped $LaGaO_3$:

Despite the high resistance and ionic conductivity, temperature limits the connectivity of the devices and poses a problem for the long-term stability of SOEC assemblies. temperature, between 673 and 1073 K. Early studies on $LaGaO_3$-based electrolytes were conducted by Ishihara et al. They found that Sr doping in La medium could increase the conductivity of $LaGaO_3$ (Figure 11(a)) and the conductivity can be further improved by doping Mg into the Ga region (Figure11(b)). $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_3$ has higher conductivity than normal YSZ and ScSZ [9].

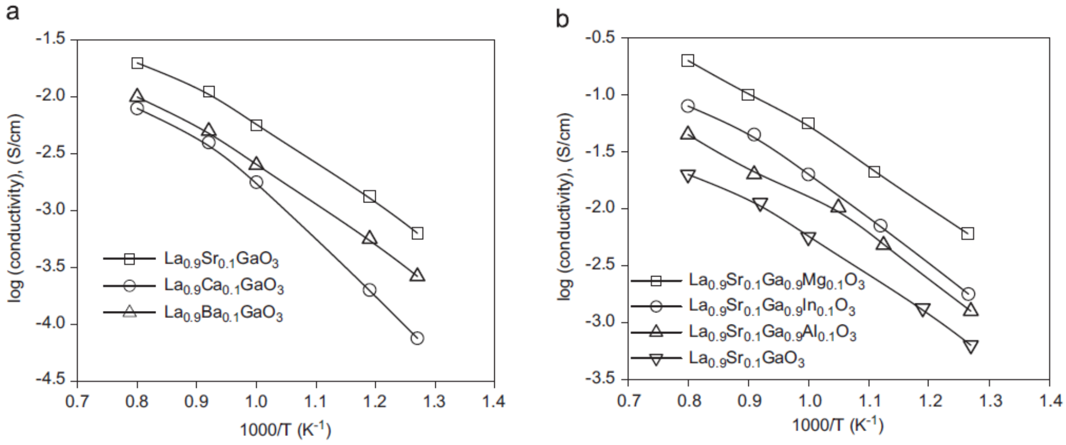

Figure 11: Oxygen ionic conductivity of doped $LaGaO_3$ - (a) Sr doped $LaGaO_3$and (b) Sr and Mg co-doped $LaGaO_3$ [9]

4.3 Solid Oxide Electrolyser Cell models:

A solid oxide electrolyser (SOEC) or solid oxide vapor electrolyser (SOSE) (Figure 12) is an electric power conversion device that converts the electric current of an electrical conductor into an electric current of an oil. The SOEC can produce carbon monoxide, hydrogen, and a mixture of the two through electrochemical reactions. It will continue to deliver fuel if gas and/or carbon dioxide and electricity are supplied [9].

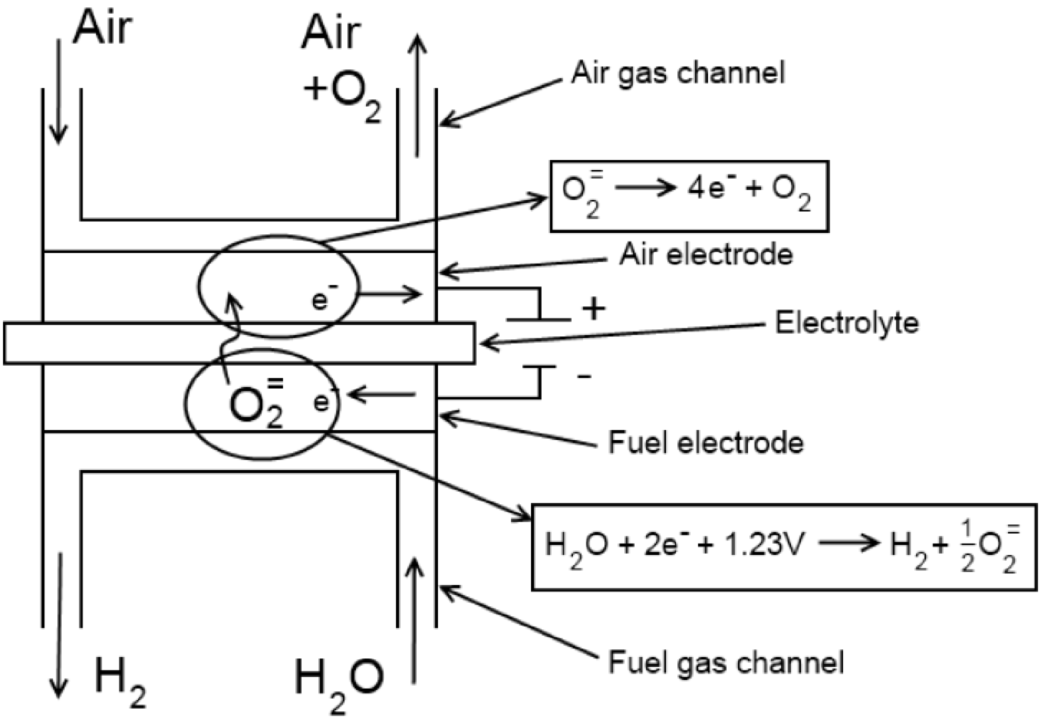

Figure 12: Schematic of a Solid Oxide Electrolyser cell in a planar configuration, with air as a sweep gas and steam as a reactant. The basic reactions on the electrodes and the component nomenclature are given [9]

In fact, the life of the cell is limited by the degradation of its constituent parts. A typical SOEC is based on a pure ionic conductor in the form of a solid electrolyte. The most used is yttrium-stabilized zirconia (YSZ), which transports oxygen ions when polarized by an electric field. There are other less common types of SOECs, such as co-ion cells and proton conduction cells, where oxygen and hydrogen ions, or hydrogen ions alone, are transported through the membrane. This study was limited to cells that produce oxygen ions (not necessarily YSZ). An electrolyte material is sandwiched between two electrodes connected by porous electrodes, forming a closed circuit. In addition to the positive-electrolyte-negative electrode (PEN) arrangement, each cell contains an interface and a gas [9].

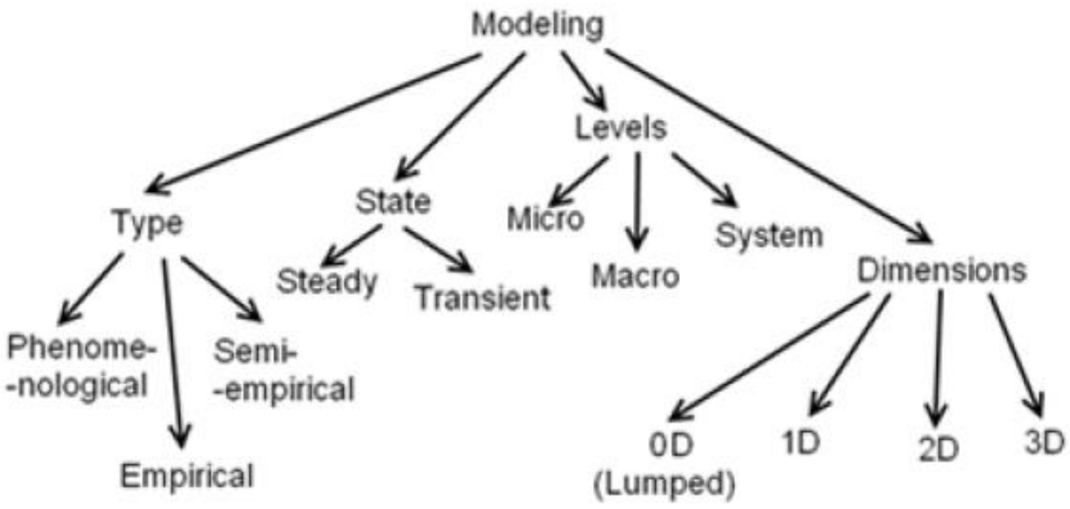

Figure 13: Categories of models of physical phenomena [9]

4.4 Microstructural changes in Ni/YSZ fuel electrodes:

The microstructural changes (i.e. Ni migration) during SOEC operation can be viewed as several different events. The normal nickel migration phenomena associated with the degradation process are as follows, as shown in Fig. 14 [11].

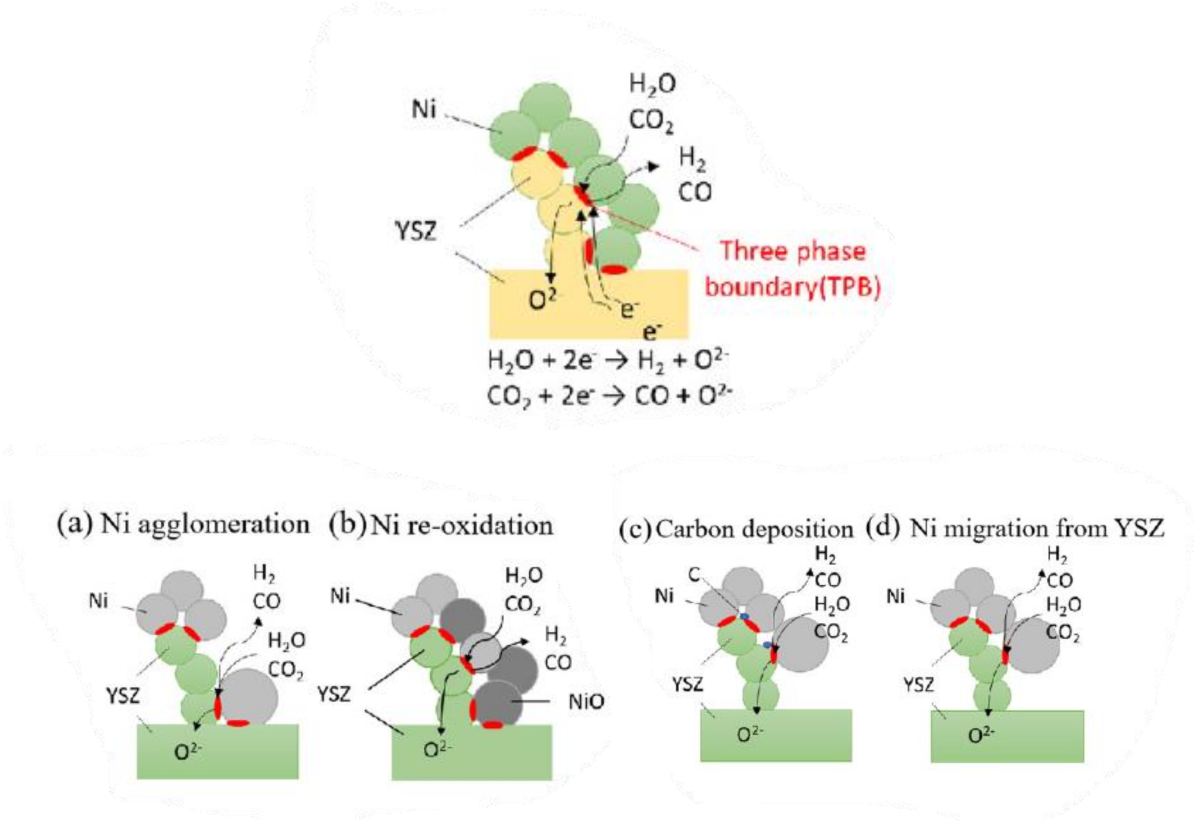

Figure 14: Typical microstructural changes observed for Ni/YSZ electrodes: (a) Ni agglomeration, (b) Ni re-oxidation, (c) Carbon deposition and (d) Ni migration from YSZ [11].

1. Ni agglomeration is one of the most common degradation phenomena in Ni/YSZ. The number of metal particles increases and decreases as shown in Fig. 14(a). Initially, Ni is equal to the gas electrode. During electrolysis, Ni agglomeration leads to the loss of contact between Ni atoms, thus reducing the electron conduction path through the Ni network and increasing the polarization resistance. Ni agglomeration occurs in high-temperature air regardless of the operating conditions (SOEC and SOFC); however, nickel migration appears to be stronger in the electrolytic mode.
2. When high water vapor and high current or voltage are used in the electrolysis process, reoxidation of Ni to NiO occurs easily. This leads to the deterioration of the oil electrode, which is manifested by high polarization resistance.
3. Carbon deposition is mainly achieved by using CO_2 as fuel for co-electrolysis. Recently, co-electrolysis SOEC systems have attracted much attention for the separation and recovery of CO_2, for example, in the production of H_2/CO_2 (syngas), ammonia, methanol and methane. However, using carbon dioxide in fuel can cause carbon deposition, which can cause serious damage to the fuel electrode.
4. Ni migration from electrolyte is also a degradation phenomenon that occurs in Ni/YSZ in SOEC and SOFC types, but different types show different phenomena. In SOFC type, high temperature (e.g. 1223 K) causes Ni (OH)x to migrate out of the electrolyte in the gas phase along the H_2O gradient. At low temperatures, nickel will migrate into the electrolyte. One theory is that nickel near the electrolyte loses its electrochemical connection first due to coarsening. Since the water vapor partial pressure is the highest in the new TPB, the Ni (OH)x concentration is the highest here, causing a difference in the electrolyte. In SOEC mode, it manifests itself as depletion of only one side of the electrolyte, resulting in poor coupling between the electrode and the electrolyte, resulting in strong polarization and ohmic resistance.

5. Advantages and Disadvantages of different types of electrolysis technologies.

Table 5: Pros and Cons

	PEMEC	AKL	SOE
Pros	High-purity H2. Significant load gradient with excellent dynamic properties: ideal for fluctuating RES. Cold start takes just 15 min.	Plants with a significant nominal throughput (greater than 100 MW) Proven technology. Does not necessitate the use of essential raw materials Most minimal costs of investment (€1000/kW) and a long lifespan.	Most significant efficiency (80%) Appropriate for co-electrolysis: direct synthesis gas production
Cons	Costlier investments (2000 euros per kW). The use of precious metal electrodes.	Comparatively lengthy cold start time (50 min). Sensitivity to product gas contaminants	Highest cold start duration (a few hours). Currently, the process is ongoing. Investments with the highest costs (2500 euros per kW)

Conclusion:

The global search for sustainable energy solutions is increasingly important as concerns about climate change and the need for decarbonisation grow. Green hydrogen, generated by the electrolysis of water using renewable energy, stands out as a versatile and promising option for various applications, including transportation, industry, and energy storage. The efficiency and economic viability of green hydrogen production is largely dependent on advances in electrolyser technology, which are necessary to improve the quality and performance of hydrogen products. Of the three primary types of electrolysers- alkaline electrolysers, proton exchange electrolysers (PEMs), and solid oxide electrolysers (SOECs) each offers unique advantages and faces different challenges. Alkaline electrolysers currently lead the market, but require improvements in efficiency and response, especially when integrated with variable renewable energy sources.

PEM technology, while efficient, faces high material costs, requiring continuous research to increase its durability and performance. SOEC, although promising in terms of energy savings, is still in the early stages of commercialization and must overcome stability and integration issues. The potential for integrating artificial intelligence and machine learning into electrolyser design represents an exciting frontier for optimizing operations and reducing costs. Continued collaboration between researchers, industry stakeholders and policy makers are critical to fostering innovation and addressing the challenges associated with electrolyser technologies.

Ultimately, understanding and advancing electrolyser technology will be critical to harnessing the full potential of green hydrogen as a sustainable energy source. This commitment to research and development not only supports the growth of the hydrogen industry, but also plays a key role in achieving global energy security and facilitating the transition to a cleaner and more sustainable energy future.

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