International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Journal of New Materials for Electrochemical Systems
Vol.27, No.2, June 2024, pp. 107-134
Journal homepage: http://iieta.org/journals/jnmes

A Critical Review of the Techno-Economic Analysis of the Hydrogen Production from Water Electrolysers Using Multi-Criteria Decision Making (MCDM)

Solmaz Shanian and Oumarou Savadogo

Programmes of Energy Engineering, Laboratory of New Materials for Energy and Electrochemistry, Polytechnique-Montréal (QC) Canada

Corresponding Author Email: Solmaz.shanian@polymtl.ca

https://doi.org/10.14447/jnmes.v27i2.a04

Received: July 23, 2023
Accepted: May 5, 2024

Keywords:
Techno-economic analysis, Water electrolysers, Multi-Criteria Decision Making (MCDM), Cost optimization, Hydrogen production, green hydrogen, Sustainable, energy future.

ABSTRACT

Hydrogen is a potential energy vector and storage medium for achieving net-zero emissions on a large scale. Among the various methods of producing low- carbon hydrogen, water electrolysis is the most appropriate and promising. Despite the commercial implementation of technical and industrial hydrogen production via electrolysis, conducting a comprehensive economic analysis of its production using grid or micro grid renewable energy systems presents challenges. Accordingly, it's important to review the approaches in the literature on the performance and costs of water electrolysis systems. This critical review aims to identify key performance parameters of the main commercial water electrolysers. In particular, the review will highlight advances in materials and challenges of Alkaline and Polymer Electrolyte Membrane commercial water electrolysis technologies. A techno-economic analysis using Multi-Criteria Decision Making (MCDM) will be performed on these technologies. The review will present various MCDM analysis methods used for these analyses. Results obtained from these methods will be compared and discussed, including their technological issues and the cost of hydrogen prospects, will be shown. Additionally, the potential of using Multi-Criteria Decision Making (MCDM) as a tool for supporting appropriate decision-making in hydrogen production and identifying research and development gaps in water electrolysis will be presented. Also, the limitations and performance of commercial electrolysers while suggesting possible solutions for achieving cost-effective hydrogen production will be described. The goal of this critical review is to propose innovative ideas and solutions for driving cost-effective green hydrogen production for commercial applications. The manuscript clearly states its objective to provide a comprehensive review of the fundamental principles and challenges associated with Proton Exchange Membrane (PEM) and Alkaline Water Electrolysis (AWE). It aims to identify current trends in water electrolysis technology and evaluate the techno-economic feasibility of hydrogen production using Multi-Criteria Decision Making (MCDM) tools. This objective is directly aligned with the need for practical solutions in green hydrogen production, emphasizing the study's contribution towards promoting the adoption of green hydrogen as a critical technology for a low-carbon economy. The introduction discusses the significant challenges in adopting electrolysis technologies, such as high capital costs and the need for innovation in materials and design. It mentions ongoing research to find affordable alternatives to expensive materials like platinum, aiming to reduce the overall cost of electrolysis.

1. INTRODUCTION

Table 1 shows the prevision of the energy demand for 2035 for the various significant regions worldwide and their respective share of the net global energy demand growth in 2035 relative to 2011 (IEA, 2013). The most important demand is from China (31%)

Followed by India (18%), South East Asia (11%), Middle East (10%) and Africa (8%). It would be possible that the real values in 2035 will be higher than the estimated ones in the cases of India and Africa. In particular with more than hundred of millions of persons who do not have access to electricity and to appropriate cooking systems, its seem to be fundamental to get access to sustainable clean. Until 2022, at least 80% of our primary energy utilised worldwide is based on fossils(Dincer). The challenges to replace the fossil fuels (natural gas, crude oil, coal), based economy to a sustainable clean energy economy through an energy transition vehicle are the most important we are facing. Hydrogen can play an important role in this energy transition because it can be in a lot of industrials activities (transportation, metallurgy, fertilisers, ammonia synthesis, energy storage, electricity production through Fuel Cells.

Table 1. A Comparative Study of Major Global Regions and Their Contribution to Net Global Energy Demand Growth

	Africa	**Unites states of America**	**Brasil**	**South EAST ASIA**	**China**	**European Union**	**EuroAsia**	**India**	**Japan**	**Middle East**
Energy demand in MTOE In 2035	1080	2240	480	1000	4060	1540	1170	1540	480	1050
% of the net global energy demand growth 2011-2035 Primary energy demand in 2035 relative to 2011	8%	1%	5%	11%	31%	0%	5%	18%	0%	10%

Its global production which is very extensive comes from the fossil resources of natural gas, crude oil, coal, and electrolysis which contribution is 49, 29, 18, and 4%, respectively. Its annual output is 70 million tonnes, mainly consumed by the petroleum recovery and refining industry and ammonia production ((IEA), 2019). However, in addition to its current industrial applications, electrochemically produced hydrogen is gaining traction as a promising solution as an energy vector for electricity storage and a clean energy carrier for the transportation sector. It is an efficient way to store excess electricity or renewable energies as photovoltaic or wind energy systems in the form of green hydrogen generated from renewable sources until it is needed to generate electricity again using fuel cells or thermal engine ((IEA), 2019). Furthermore, compared to traditional gasoline-powered vehicles, hydrogen fuel cell vehicles emit only water vapour, making them a zero-emission alternative. According to the International Energy Agency((IEA), 2019), around 70 million tons of hydrogen were produced globally, and about 4% of that production came from water electrolysis. This represents around 2.8 million tons of hydrogen produced by water electrolysis globally .Hydrogen can also be used in fuel cells to generate heat and power for homes, buildings, and industrial applications, and as more hydrogen refuelling stations are built, fuel cell vehicles have the potential to revolutionize the transportation sector(IRENA, 2019).

The use of electrolysers to produce green hydrogen is gaining momentum as a clean and sustainable alternative to traditional hydrogen production methods (Commission, 2021). While the initial capital cost of electrolysers can be high, they offer the advantage of decentralized operation, making them suitable for a wide range of applications. However, the cost of materials used in electrolyser construction, such as platinum, is a significant challenge. These materials are expensive and can significantly increase the overall cost of production (DOE, 2021).To overcome this challenge, research is ongoing to find more affordable alternatives to the materials used in electrolyser construction. One promising alternative is the use of non-precious metal catalysts, such as cobalt, nickel, and iron. These materials are abundant and inexpensive compared to platinum, and their use can significantly reduce the overall cost of electrolysis. Another challenge facing the widespread adoption of electrolysers is the development of efficient and cost-effective electrolysers that can operate at scale. There is a need for further innovation in the design and manufacturing of electrolysers to improve their efficiency and reduce their overall cost. (Jang, Kim, Kim, Han, & Kang, 2022). A more fundamental cost decline is needed to make a real impact on the growth of green hydrogen. According to a report by the International Renewable Energy Agency (IRENA), the cost of green hydrogen needs to drop by at least 50% by 2030 to become competitive with fossil-fuel-based hydrogen in many applications, and by up to 85% to compete in energy-intensive industries like steel and ammonia production. Several factors contribute to the high cost of green hydrogen production. First, the cost of renewable electricity, the main input for electrolysis, needs to continue to decrease. Second, the cost of electrolysers themselves needs to decline through technological improvements, scaling up production, and increasing competition among suppliers. Third, the cost of producing and transporting the water used in electrolysis needs to be reduced (IRENA, 2020). To achieve these cost reductions, various policy measures are being considered or implemented by governments around the world. These include feed-in tariffs or other incentives to promote renewable energy deployment, public investment in research and development of electrolysis technologies, and support for the deployment of electrolysers at scale through public-private partnerships (Economics, 2020). Industry is also taking steps to reduce the cost of green hydrogen production. For example, several large companies, including Siemens, Air Liquide, and Linde, have formed the Green Hydrogen Catapult initiative, which aims to drive down the cost of green hydrogen to $2 per kilogram by 2026 through scaling up production and implementing best practices. Industry is also taking steps to reduce the cost of green hydrogen production. Despite these challenges, the production of green hydrogen using electrolysers is considered a promising solution for achieving a sustainable and low-carbon energy system. The objective of this study is to provide a comprehensive review of the fundamental principles and challenges associated with Proton Exchange Membrane (PEM) and Alkaline Water Electrolysis (AWE), and to identify the current trends in water electrolysis science and technology. Additionally, The study aims to demonstrate the potential of MCDM tools in the evaluation of various electrolysis technologies and their economic feasibility. By analyzing the current state of the art in electrolysis technology and evaluating the techno-economic feasibility of hydrogen production, this study can inform policymakers, industry, and researchers on the best strategies for promoting the adoption of green hydrogen as a key technology in the transition to a low-carbon economy.

2. WATER-ELECTROLYSIS ELECTROLYSIS TECHNOLOGIES-A SUMMARY

2.1 Introduction to water electrolysers technologies

A water electrolyser is an electrochemical device that uses electricity to split water into hydrogen and oxygen through an electrochemical reaction. It consists of an electrolyte, two electrodes (an anode and a cathode), and a power source. The anode oxidizes water molecules to form oxygen gas and positively charged hydrogen ions, while the cathode reduces hydrogen ions and electrons to form hydrogen gas(Millet, 2011),(Savadogo, 2000),(Mazloomi & Gomes, 2012).

The principal equation related to mole reaction of water is:

H_2O + Useful electric Energy (237.22 $kJ.mole^{-1}$) => Heat (48,62 $kJ.mole^{-1}$) + H_2 +$1/2O_2$ (1)

Thermodynamic and kinetic parameters define, respectively, the energy conditions of the electrolysis and the quantity of hydrogen we can get depending of the electric power applied to the electrolyser (2).

From the thermodynamic aspect, the electrolyser is defined by two parameters: The total theoretical energy (enthalpy (ΔH)) needed for water splitting. At the standard conditions, this change of enthalpy related to the water splitting is ΔH = 285.84 kJ.mole. From this energy a minimum required or thermos-neutral voltage (V_{Tn}) for the water electrolysis is obtained from the classical relation:

$$\Delta H = -nFV_{Tn} \tag{2}$$

Where n=2 is the number of electrons involved;
F = 96500 $Coulons.mole^{-1}$ is the Faraday constant;
V_{Tn} is the minimum required voltage in Volts.

This thermo-neutral voltage or the minimum practical voltage required for water splitting is calculated from relation (2) in the following equation (3):

$$V_{Tn} = -\frac{\Delta H}{nF} = 1.48 \text{ Volt} \tag{3}$$

The water splitting create heat or change in entropy(ΔS) and the real useful energy (without waste) for water splitting is the free Gibbs energy (ΔG). Similar to the relation between ΔH, and V_{Tn} an electrochemical reversible voltage (V_{rev}) is related to ΔG and can be calculated by the following equation (4):

$$V_{rev} = -\frac{\Delta G}{nF} = -\left(\frac{\Delta G}{nF} - \frac{T\Delta S}{nF}\right) = 1.23 \text{ Volt} \tag{4}$$

WhereT = temperature in Kelvin

The basic reactions of water electrolysis using alkaline and acidic electrolytes are respectively shown in Figure 1 and Figure 2.

Pure water is a poor ionic conductor, and consequently an ionic conductive water electrolyte (acid or alkaline) and good electro catalytic materials must be used for industrial electrolysers. This helps to make the splitting at a technical lower voltage. The hydrogen production cost from industrial electrolysers is also very dependant of the variation of the applied potential to the cells. The overvoltage (η) which which is the difference between the working voltage(V_{app}) or applied voltage of the electrolyser and its equilibrium potential (V_{eq}). The overvoltage related to the kinetics of the reactions at the electrodes surfaces is related to their respective current density(i) and their respective exchange current density (i_o) by the simple Tafel relation (5) (Savadogo, 2000):

$$\eta = V_{app} - V_{eq} = b\ln\left(\frac{i}{io}\right) \tag{5}$$

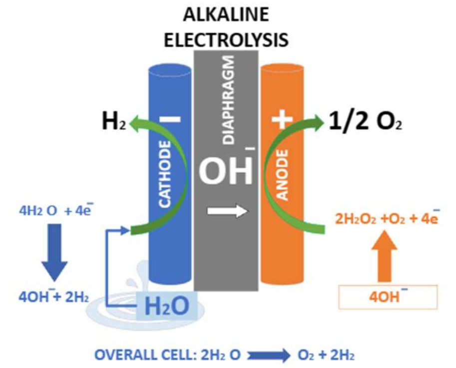

Figure 1. Schematic principle of Alkaline water splitting (Shiva Kumar & Himabindu, 2019)

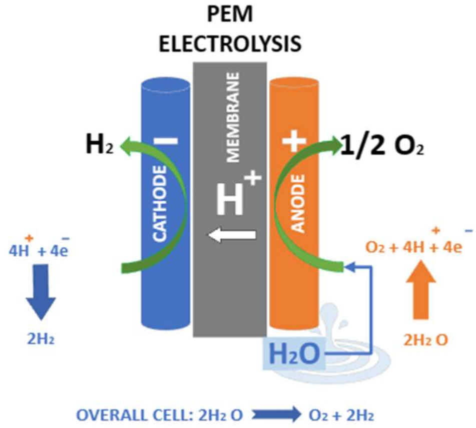

Figure 2. Schematic principle of PEM water splitting (Shiva Kumar & Himabindu, 2019)

Where $b = \frac{RT}{\beta nF}$ with R (8.31447 J mol^{-1} K^{-1}) is the ideal gas constant, T the operating temperature, β the charge transfer coefficient, n the number of electrons involved in the reaction. The overvoltage increases with the Tafel slope. It is better to decrease the Tafel slope value through the optimized choice of electrode materials or their modification for the hydrogen evolution reaction (HER) or the Oxygen Evolution Reaction (OER) during water splitting. In commercial PEM electrolysers, iridium oxide (IrO2) electrodes are used at the anode for the OER and platinum (Pt) based electrodes are at the cathode for the HER. In both cases the Tafel slopes are low as 30 millivolts per decade of current (30 mV/dec.). The low over voltages are also obtained for exchange high densities for both reactions. This is achieved with an exchange current as low as 10^{-3} $A.cm^{-2}$ on Pt for the HER and on IrO2 for the OER.

An applied voltage to an electrolytic cell to give a current density corresponding to a rate of hydrogen production depends on this over voltage according to the relation (6):

$$V_{app} = V_{eq} + \eta_a + |\eta_c| + \eta_\Omega \tag{6}$$

Where V_{eq} is the minimum value of the water decomposition voltage or the thermodynamic voltage of the cell, η_a and $|\eta_c|$ are the is given in relation (5).

η_Ω is the ohmic drop due to the total resistance R of: the electrolyte or/and the membrane which is between the anode and the cathode, the electrode/electrolyte interfaces, the electrode structure and the connecting circuit, and others.

η_Ω = IR where I is the total current of the electrolysis cell and R is defined above.

The overvoltages and the ohmic drop are the cost of voltage you may pay to drive the process at an industrial rate.

(Figure 3)shows the relative representation of the variation of the various overvoltage with the operating current. At the operating current density of the electrolysers (1A.cm^{-2}for PEM electrolysers), the anodic overvoltage and the ohmic drops are the most important losses of the cell.

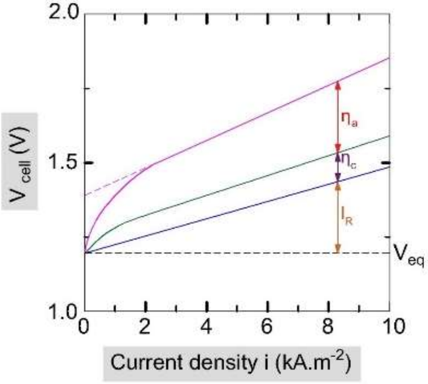

Figure 3. Variation of the different contributions of the cell voltage of a water electrolysis cell(Savadogo, 2000)

Therefore, at the first approximation, the cost of energy of processing hydrogen production is proportional to the overvoltage (η) (Savadogo, 2000):

$$\mathrm{CE} = \mathrm{aq}\eta\ (\mathrm{Veq} + \eta\mathrm{a} + |\eta\mathrm{c}| + \eta\Omega) \qquad (7.a)$$

or

$$C_E = aq\eta = aq(\ b_a \ln\left(\frac{i}{io}\right)\ ) + b_c \ln\left(\frac{i}{io}\right) + IR) \qquad (7)$$

Where a is in $ per kilowatt hours, q the electrical charge needed

$b_a(b_c)$ is the anodic(cathodic) Tafel slope. The other parameters are define above..

The conventional typical industrial alkaline electrolysers operate between 1.4 to 3 volts with a current density range of 0.2 to 0.8 A.cm^{-2}and the industrial PEM electrolysers operate between 1.4 and 2.5 Volts using a current density range of 1 to 2 A.cm^{-2}.

The hydrogen production rate is (f_{H2}) given by:

$$f\mathrm{H2} = \boldsymbol{\eta_F}\ \frac{\mathbf{I_{cell}\ N_{cell}}}{\boldsymbol{ZF}}\ \frac{\mathbf{22.41}}{\mathbf{1000}}\ 3600$$

Ncell = number of electrolysis cell

Icc is the current of a cell, 22,4 liters(l) is the volume occupied by 1 mole of gaz.

(η_F is the Faradaic efficiency of the stack, z is the number of electrons on the reactions and F is the Faraday constant (96 500 C/mole).

3600s/h and 1000 l/m^3

In comparison to the alkaline electrolyser, the PEM electrolyser operates at high current density and low potential. (Table 2). Indicates the overview of the Technical Features of the five Common Water Electrolysis Technologies. The Alkaline electrolysers exhibited the operating voltage (1 to 3 Volts) and the lowest operating current density with lowest operating current densities (0.2 to 0.8 A.cm^{-2}) whereas the PEM electrolysers exhibit low operating potential range (1.4 to 2.4 Volts) and high current density (1 to 2 A.cm^{21}). The features of the AEM electrolysers close to those of the PEM electrolyser. The microbial electrolyser cell operates with the lowest operating voltage range (1 to 1.5 Volt. This related to the positive effect of the microbes which involvement in the process contributes to lower the energy of transformation. (Table 3) shows the 2050 Targets technical parameters and comments of the technical advantages, disadvantages including on materials and economics considerations for four main Water Electrolysis technologies. All technical parameters are expected to increase significantly. In particular the PEM technology which operating current density will increase from 2 to 6 A.cm^{-2} and the SOE will exhibit the lowest specific energy (35 kWh/kg of hydrogen produced).

2.2 A brief history of water electrolysis technology

The history of water electrolysis dates to the late 18th century when Italian physicist Alessandro Volta first discovered the chemical reaction between metals and electrolytes in 1800. He developed the first battery, known as the "Voltaic Pile," which generated an electric current by immersing two different metals in an electrolyte solution. This ground breaking discovery set the foundation for further research in the field of electrochemistry and electrochemical cells. In 1801, English chemist and physicist William Nicholson and Swedish chemist Johann Wilhelm Ritter independently discovered the process of water electrolysis, which involves the splitting of water molecules into hydrogen and oxygen gases using an electric current. They used the Voltaic Pile to produce electrolysis and observed the formation of hydrogen and oxygen gases in separate vessels. In the early 19th century, Michael Faraday, an English chemist, and physicist, further advanced the study of electrolysis.

Faraday discovered the laws of electrolysis, which state that the amount of chemical reaction during electrolysis is proportional to the amount of electrical charge passed through the electrolyte solution. He also introduced the concept of electrode potential and laid the foundation for the study of electrochemistry.

In 1866, French chemist Auguste De la Rive and Swiss chemist George S. De la Rive invented the first commercial water electrolyser, which produced hydrogen and oxygen gases by electrolyzing sulfuric acid. This invention marked a significant milestone in the history of water electrolysis, as it opened new opportunities for industrial-scale hydrogen production. In the 20th century, significant developments in electrolysis technology led to the widespread adoption of water electrolysis for various applications. In the 1930s, German chemist Alwin Mittasch developed the alkaline electrolysis process, which is still widely used today for the production of hydrogen gas. In the 1960s, NASA used water electrolysis to generate oxygen for astronauts aboard spacecraft, which further highlighted the importance of this technology(Scott, 2019).

Table 2. Overview of Technical Features of Common Water Electrolysis Technologies(Anwar, Khan, Zhang, & Djire, 2021),((NREL), 2021),(IRENA, 2020)

	Alkaline	**AEM**	**PEM**	**Solid Oxide**	**MEC**
Anode reaction	2OH− → H2O + 12 O2 + 2e−	2OH− → H2O + 12 O2 + 2e−	H2O → 2H+ + 12 O2 + 2e−	O2− → 12 O2 + 2e−	Oxidation of organic matter by electroactive bacteria (e.g., Acetate → 2HCO3- + 4H+ + 4e-)
Cathode Reaction	H2O + 2e− → H2+ 2OH−	H2O + 2e−→ H2+ 2OH−	2H+ + 2e−→ H2	H2O + 2e− → H2 + O2−	2H+ + 2e- → H2
Overall cell	H2O → H2 + 21 O2	H2O → H2 + 21 O2	2H2O → H2 + 12 O2	H2O → H2 + 12 O2	Conversion of organic matter to hydrogen and bicarbonate
Electrolyte	KOH/NaOH (5M)	DVB polymer support with 1 KOH/NaOH	Solid polymer electrolyte (PFSA)	Yttria stabilized Zirconia (YSZ)	Typically, a buffer solution or wastewater
Separator	Asbestos/Zirfon/Ni	Fumatech,	® Nafion	Solid electrolyte YSZ	Often a Proton Exchange Membrane (PEM) or Anion Exchange Membrane (AEM)
Electrode/Catalyst (Hydrogen side)	Nickel coated perforated stainless steel	Nickel	Iridium oxide	Ni/YSZ	Various materials, often a form of catalyst-coated carbon
Electrode/Catalyst (Oxygen side)	Nickel coated perforated stainless steel	Nickel or NiFeCo alloys	Platinum carbon	Perovskites (LSCF, LSM) (La,Sr,Co,FE) (La,Sr,Mn)	Not applicable in most MECs (as these typically do not involve an oxygen reaction)
Gas Diffusion layer	Nickel mesh	Nickel foam/carbon cloth	Titanium mesh/carbon cloth	Nickel mesh/foam	Not typically used in MECs
Bipolar Plates	Stainless steel/Nickel coated stainless steel	Stainless steel/Nickel coated stainless steel	Platinum/Gold-coated Titanium or Titanium	Cobalt coated stainless steel	Not typically used in MECs
Nominal current density	0.2–0.8 A/cm2	0.2–2 A/cm2	1–2 A/cm2	0.3–1 A/cm2	0.1 - 1 A/m2
Voltage range (limits)	1.4–3 V	1.4–2.0 V	1.4–2.5 V	1.0–1.5 V	0.2 - 1 V
Operating temperature	70–90 ◦C	40–60 ◦C	50–80 ◦C	700–850 ◦C	Room temperature to slightly above (e.g., 20 - 40 °C)
Cell pressure	<30 bar	<35 bar	<70 bar	bar	Ambient
H2 purity	99.5–99.9998%	99.9–99.9999%	99.9–99.9999%	99.9%	Varies depending on system, generally requires further purification
Efficiency	50%–78%	57%–59%	50%–83%	89% (laboratory)	Varies widely depending on the specific system design
Voltage Efficiency (LHV)	50%-68%	52%-67%	50%-68%	75%-85%	Varies based on system design
Electrical Efficiency (stack)	47-66 kWh/Kg H2	51.5-66 kWh/Kg H2	47-66 kWh/Kg H2	35-50 kWh/Kg H2	Varies based on system design
Electrical Efficiency (system)	50-78 kWh/Kg H2	57-69 kWh/Kg H2	50-83 kWh/Kg H2	40-50 kWh/Kg H2	Varies based on system design
Lifetime (stack)	80 000 hours	> 5 000 hours	80 000-100 000 hours	< 20 000 hours	Not well defined, as this technology is largely in the research and development stage
Development status	Mature	R & D	Commercialized	R & D	Primarily at the research and development stage
Electrode area	000–30 000 cm2	<300 cm2	cm2	cm2	Varies based on system design
Cold Start (to nominal load)	< 50 minutes	< 20 minutes	< 15 minutes	> 600 minutes	Varies based on system design
Capital Costs (stack)	USD 270/kW	Unknown	USD 400/kW	> USD 2,000/kW	Varies based on system design

Capital costs (stack) minimum 1 MW	USD 270/kW	Unknown	USD 400/kW	>USD 2000/kW	Not well defined, as this technology is largely in the research and development stage
Capital costs (stack) minimum 10 MW	USD 500–1000/kW	Unknown	USD 700–1400/kW	Unknown	Oxidation of organic matter by electroactive bacteria (e.g., Acetate → 2HCO3- + 4H+ + 4e-)

Table 3. 2050 Targets technical parameters and comments of the technical advantages, disadvantages and on materials and economics considerations for 4 Water Electrolysis technologies.

Parameters (Future Target 2050)	**PEM**	**Alkaline**	**AEM**	**Solid Oxide**
Nominal current density	4-6 A/cm2	> 2 A/cm2	> 2 A/cm2	> 2 A/cm2
Voltage range (limits)	< 1.7 V	< 1.7 V	< 2 V	< 1.48 V
Operating temperature	80°C	> 90°C	80°C	< 600°C
Cell pressure	> 70 bar	> 70 bar	> 70 bar	> 20 bar
Load range	5%-300%	5%-300%	5%-200%	0%-200%
H2 purity	Same as 2020	> 99.9999%	> 99.9999%	> 99.9999%
Voltage efficiency (LHV)	>80%	> 70%	> 75%	> 85%
Electrical efficiency (stack)	< 42 kWh/Kg H2	< 42 kWh/Kg H2	< 42 kWh/Kg H2	< 35 kWh/Kg H2
Electrical efficiency (system)	< 45 kWh/Kg H2	< 45 kWh/Kg H2	< 45 kWh/Kg H2	< 40 kWh/Kg H2
Lifetime (stack)	100 000-120 000 hours	100 000 hours	100 000 hours	80 000 hours
Stack unit size	10 MW	10 MW	2 MW	200 kW
Electrode area	> 10 000 cm2	30 000 cm2	1 000 cm2	500 cm2
Cold start (to nominal load)	< 5 minutes	< 30 minutes	< 5 minutes	< 300 minutes
Capital costs (stack)	< USD 100/kW	< USD 100/kW	< USD 100/kW	< USD 200/kW
Capital costs (system)	< 200 USD/kW	< USD 200/kW	< USD 200/kW	< USD 300/kW
Advantages	Higher efficiency, Faster start-up time, Flexible operation at varying loads, Compact size and low weight	Lower capital cost, Longer lifespan, High durability, Low sensitivity to impurities in water or feedstock, Lower operating temperature and pressure requirements	High efficiency, Resistant to CO_2 and other impurities, Lower capital costs compared to PEM, Operates well in a wide range of temperatures	High electrical efficiency, High fuel flexibility (can use a range of fuel types), Good heat utilization (useful for cogeneration)
Disadvantages	Higher capital cost, Sensitive to impurities in water or feedstock, Lower durability and shorter lifespan, Higher operating temperature and pressure requirements	Sensitive to CO_2 impurities, Lower efficiency, Slower start-up time, Limited flexibility in varying loads	Slower start-up time compared to PEM, Lower durability and shorter lifespan compared to Alkaline	High operating temperatures, Slow start-up and shutdown, Less durable and shorter lifespan due to high-temperature operation
Material Considerations	Require noble metal catalysts and proton exchange membranes, Corrosion-resistant materials required for electrodes and bipolar plates	Can use cheaper and more readily available electrode materials such as nickel, iron, and steel, Corrosion-resistant materials still required for electrodes and bipolar plates	Requires development of stable anion exchange membranes and catalysts, Corrosion-resistant materials required for electrodes and bipolar plates	Requires high-temperature stable materials such as ceramics

Economic Considerations	Lower operating costs due to high efficiency and low maintenance, Can be integrated with renewable energy sources for lower energy costs	Higher operating costs due to lower efficiency and higher maintenance, Can be cost-effective for large-scale hydrogen production	Lower capital costs than PEM but higher operating costs due to less durability, Potentially cost-effective for certain niche applications	High capital costs due to use of exotic materials, Lower operating costs due to high electrical efficiency and good heat utilization
References	((NREL), 2021), (Anwar et al., 2021), (K. Hu et al., 2022),(IRENA, 2020)	(Anwar et al., 2021), ((NREL), 2021), (K. Hu et al., 2022),(IRENA, 2020)	((NREL), 2021), (Anwar et al., 2021), (K. Hu et al., 2022),(IRENA, 2020)	((NREL), 2021), (Anwar et al., 2021), (K. Hu et al., 2022),

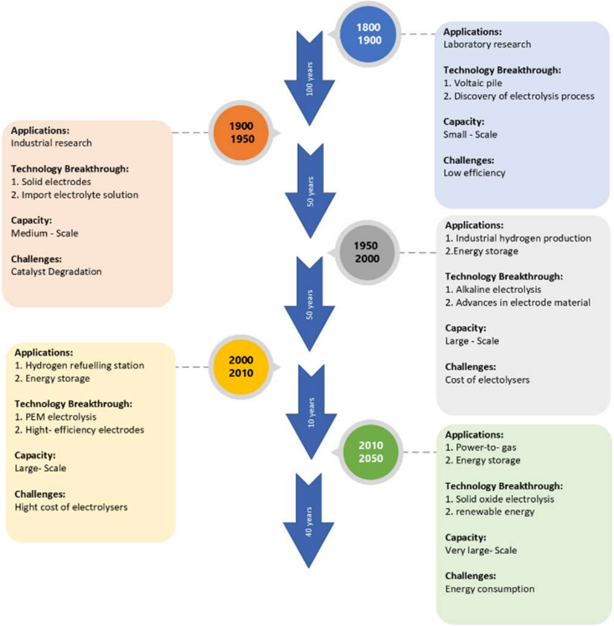

Figure 4. Challenge, application and technology of different generation of electrolysers(Shiva Kumar & Lim, 2022)

Commercial electrolysers which are mass-produced include Liquid Alkaline Electrolysers (AE) and Acidic Solid Polymer Electrolyte Membrane Electrolysers (PEM-electrolyser). Advanced technologies in development are based on Solid Anion Exchange Membranes (AEM) and Solid Oxide Electrolysers (SOE). Another type of electrolyser under development at the laboratory scale is Hydrogen production by Microbial Electrolysis Cell (MEC) technology. This is based on the utilization of organic matter, including renewable biomass and wastewater. This technology is closely related to Microbial Fuel Cells (MFCs) but operates on a reverse principle(Martin, Tartakovsky, & Savadogo, 2011),(H. Liu, Grot, & Logan, 2005),(Kadier et al., 2016)

Each type of electrolyser utilized appropriate membranes and different materials and operating conditions to optimize their efficiency and performance. Accordingly, the process of water electrolysis is influenced by factors such as electrode materials, electrolyte type, and operating conditions. The electrolyte plays a crucial role in facilitating the movement of charged ions, while the choice of electrode materials is essential for achieving high efficiency and performance in the electrochemical reaction. The choice of electrolyte material depends on the type of electrolyser and the desired operating conditions.(Vidas & Castro, 2021).

In 2021, the world's largest water electrolyser was installed in Canada, specifically in the province of Quebec. The project leverages the 20 MW power capacity of PEM technology provided by Hydrogenics, a Canadian company at the time. The project was developed by Air Liquide and can produce up to 8.2 tons of hydrogen per day. This quantity is equivalent to approximately 20,000 kilometres of zero-emission driving. However, it's worth noting that this record may change as larger-scale water electrolysis projects continue to develop globally. (Congress, 2021)

In 2020, 176 MW power of commercial alkaline electrolysers were installed worldwide and those of the PEM electrolysers technologies where 89 MW (IEA, 2021). Furthermore, a 175 GW of electrolyzer capacity has been projected until 2030 and 40% of this capacity or 70 GW is expected to be with PEM electrolyser capacity (Heraeus, 2023). The alkaline technology is the most mature technology because alkaline water electrolysis was used in the chlorine or fertilizer industries since the 1920's. This technology is supposed to have minimal capital expenses because its components involve less cost materials. From the same energy, the PEM technology has the potential to produce at least two times more hydrogen than the alkaline technology.

2.3 Descriptions of Alkaline electrolysers

Alkaline electrolysis is a well-established technology for producing hydrogen gas from water. This process involves the use of two microporous electrodes made of nickel or nickel-based steel, which are immersed in an electrolyte solution containing potassium hydroxide (KOH)(Brauns & Turek, 2020). The electrolyte serves as a conductive medium for the transfer of ions between the electrodes, while the microporous structure of the electrodes allows for efficient gas diffusion. The cathode electrode releases hydrogen gas and hydroxide ions (HO-) through the process of water reduction, while the anode electrode produces oxygen gas and water through the oxidation of hydroxide ions. This electrochemical process is driven by an external source of electrical energy, typically from renewable sources such as wind or solar power(Naqvi, Taner, Ozkaymak, & Ali, 2023). Recent advancements in electrode design and materials have led to improvements in the performance of alkaline electrolysis. One of the most significant developments is the zero-gap system (Figure 5), which eliminates the need for a diaphragm to separate the anode and cathode. This system employs a unique electrode configuration, where the anode and cathode are sandwiched together with a thin layer of electrolyte, allowing for better ion transport, and minimizing ohmic losses(Yu et al., 2021).

(

Figure 6) shows the diagram of operation of the alkaline electrolysis process (Bessarabov & Millet, 2018). For a classic liquid alkaline electrolyser technology which is more developed and commercialized, an ion exchanger diagram or ion membrane embedded in alkaline solution (KOH) separates the anode and the cathode. In the case where the electrolyte is a specific solid polymer electrolyte known as Anionic Exchange Membrane (AEM) without liquid which separates the anode and the cathode, the technology is the AEM electrolyser which is in development. The use of composite materials for the diaphragm has also improved the efficiency of alkaline electrolysis. These materials offer superior chemical stability and better resistance to mechanical degradation compared to traditional asbestos diaphragms. The electro-catalyst is another critical component in improving the efficiency of water splitting in alkaline electrolysis. The electro-catalyst is responsible for lowering the activation energy required for the reaction to occur, thus increasing the reaction rate. Platinum-group metals (PGMs) such as platinum, palladium, and iridium are commonly used as electro-catalysts due to their high catalytic activity and stability(Anwar et al., 2021). However, these metals are expensive and rare, which limits the scalability of alkaline electrolysis. Recent research has focused on developing alternative non-PGM electro-catalysts such as metal oxides, metal sulfides, and carbon-based materials. These materials offer lower cost and better abundance, making them more suitable for large-scale hydrogen production(Ganci et al., 2021). Temperature control is another important aspect of alkaline electrolysis. The electrolyte's temperature affects the reaction rate and the electrolysis efficiency. Most alkaline water electrolysis systems provide temperature control for the electrolyte to maintain an optimal temperature range. The optimal temperature range is typically between 60 and 80°C, as this range maximizes the reaction rate while minimizing energy losses due to excessive heating. However, operating at higher temperatures can lead to faster electrode degradation, which can negatively impact system performance and lifespan(Qi et al., 2023).

Alkaline electrolyser is a promising technology for large-scale hydrogen production, with recent advancements in electrode design, materials, and electro-catalysts leading to improved efficiency and cost-effectiveness and significant role in a sustainable hydrogen economy(Ehlers, Feidenhans'l, Therkildsen, & Larrazábal, 2023). While the basic components of an electrolyser include an anode, a cathode, an electrolyte solution, and an electrical power supply, additional components are required for optimal operation (Figure 7). The primary function of power electronics in an electrolyser is to regulate the voltage and current that flows into the cell, which ensures that the cell operates at optimal efficiency and avoids any potential damage. Overvoltage or under-voltage can lead to unwanted chemical reactions or instability, which can cause damage to the cell and reduce its performance(Guo et al., 2021).

Silicon, gallium nitride, and silicon carbide are commonly used materials in power electronics for electrolysers. Silicon is widely used because of its low cost, availability, and compatibility with other electronic components. However, it has some limitations in terms of efficiency, temperature tolerance, and switching speed. Gallium nitride (GaN) and silicon carbide (SiC) are newer materials that offer improved performance and efficiency compared to silicon. GaN and SiC are capable of handling higher power densities and switching frequencies, which makes them suitable for high-speed and high-power applications such as electrolysers. They also have superior thermal properties and can operate at higher temperatures without loss of performance(Renforth, 2019). In addition to selecting the appropriate material for the power electronics, other factors such as the design of the power converter and the control algorithms used to regulate the voltage and current also play an important role in optimizing the performance and efficiency of the electrolyser(F. Hu, Xie, Zhang, Hu, & An, 2020). In an alkaline electrolyser, the gas-exit pipe is a critical component for the efficient removal of hydrogen and oxygen gases produced during the electrolysis process. The pipe must be designed with a streamlined shape to minimize pressure drops and reduce resistance to gas flow, which helps to ensure that the gases are efficiently removed from the cell. Additionally, the pipe must be made of materials that are resistant to corrosion, as exposure to the highly alkaline electrolyte can cause rapid degradation of certain materials (Naqvi et al., 2023).Stainless steel is a popular material for the gas-exit pipe due to its excellent corrosion resistance, mechanical strength, and durability. Other materials such as nickel alloys and titanium are also used in some electrolyser designs. These materials are chosen for their high resistance to corrosion and ability to withstand the harsh conditions within the cell. The selection of the appropriate material and design of the gas-exit pipe are critical for ensuring the long-term performance and reliability of the electrolyser (Brauns & Turek, 2020). An alkaline electrolyser requires effective cooling systems to maintain the operating temperature of the cell and remove excess heat generated during electrolysis. The cooling systems can be either air or water-cooled and passive or active. The choice of a cooling system depends on various factors such as cell size, operating temperature, and ambient temperature (Sanchez, Amores, Abad, Rodriguez, & Clemente-Jul, 2020). Heat exchangers made of copper or aluminum are commonly used due to their high thermal conductivity and ease of manufacturing. Drying hydrogen and oxygen gases is also essential to maintain the quality of the gases and avoid damage to downstream equipment. Various materials such as activated carbon or molecular sieves are used for drying, but the selection of drying systems depends on the application requirements and purity levels (David, Ocampo-Martínez, & Sánchez-Peña, 2019). However, drying hydrogen and oxygen gases can be challenging and affect the efficiency and cost of the electrolysis process. All these components are shown on (Figure 7) of the schematic block of alkaline electrolyser system(IRENA, 2020).

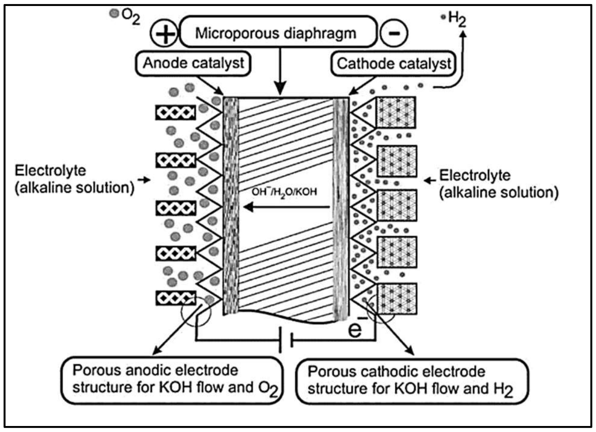

Figure 5. Schematic diagram representing the design of the zero-gap cell with a microporous separator. (Bessarabov & Millet, 2018)

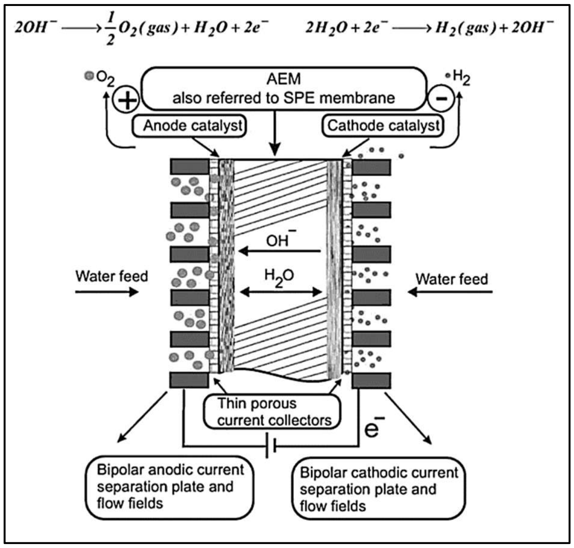

Figure 6. Diagram showing the operation of the calssical liquid (with diaphragm or ion membrane) alkaline electrolyser or Anion Exchange Membrane (AEM) electrolyser if the electrolyte is a anion exange solid polymer electrolyte membranes (Bessarabov & Millet, 2018)

2.4 Descriptions of PEM electrolysers

A proton exchange membrane (PEM) electrolysis stack is a key component in producing hydrogen by splitting water into hydrogen and oxygen using electricity. The stack comprises several repeating units, called cells, that are electrically connected in series, while reactant water/product gases are connected in parallel. The end plates are made of thick metal plates that hold these cells inside the stack(Bessarabov & Millet, 2018)(Figure 8).

The heart of each module is a polymer membrane coated with catalyst layers on both sides of the membrane to form what is called catalyst-coated membrane (CCM). The catalyst layers are typically made of platinum or other noble metals that facilitate the water splitting reaction(Bessarabov, Wang, Li, & Zhao, 2015). The porous transport layer (PTL) is a layer that enhances water diffusion and the water splitting reaction on the surface of the membrane in the electrolysis cells. Bipolar plates are another important component of PEM electrolysis stacks. As the name suggests, these plates have a cathodic side and an anodic side. The cathodic and anodic sides are separated by channels that allow the gas to flow through the stack.

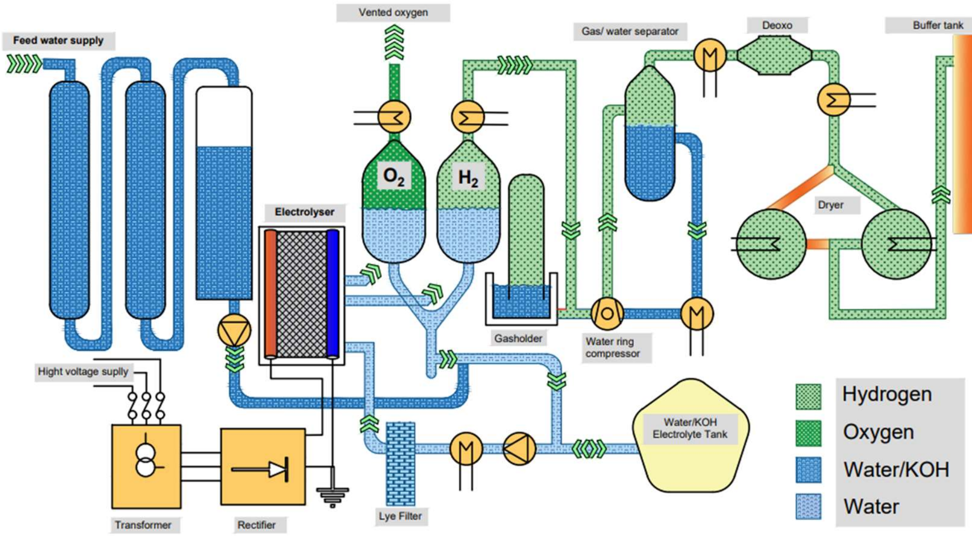

Figure 7. Schematic block of the Alkaline electrolysis system (IRENA, 2020)

Table 4. The advantages and disadvantages of PEM and Alkaline Electrolyze(Sun et al., 2018)

	Advantages	Disadvantages	Material Considerations	Economic Considerations	References
PEM	- Higher efficiency- Faster start-up time- Flexible operation at varying loads- Compact size and low weight	- Higher capital cost, Sensitive to impurities in water or feedstock, Lower durability and shorter lifespan, Higher operating temperature and pressure requirements	- Require noble metal catalysts and proton exchange membranes, Corrosion-resistant materials required for electrodes and bipolar plates	- Lower operating costs due to high efficiency and low maintenance, Can be integrated with renewable energy sources for lower energy costs	((NREL), 2021), (Anwar et al., 2021) (K. Hu et al., 2022)
ALKALINE	- Lower capital cost- Longer lifespan- High durability, Low sensitivity to impurities in water or feedstock- Lower operating temperature and pressure requirements	- Lower efficiency, Slower start-up time, Limited flexibility in varying loads	- Can use cheaper and more readily available electrode materials such as nickel, iron, and steel, Corrosion-resistant materials still required for electrodes and bipolar plates	- Higher operating costs due to lower efficiency and higher maintenance, Can be cost-effective for large-scale hydrogen production	(Anwar et al., 2021) ((NREL), 2021) (K. Hu et al., 2022)

The bipolar plates are also responsible for distributing the reactant water/product gases uniformly across the surface of the catalyst-coated membrane (Mayyas, Ruth, Pivovar, Bender, & Wipke, 2019). Proton exchange membrane (PEM) electrolysers require a balance-of-plant (BOP) subsystem that supports their operation by providing power, water, cooling, and other necessary functions. The BOP consists of several subsystems, including the power supply, deionized water circulation system, hydrogen processing, cooling, and miscellaneous (Figure 9).

The power supply subsystem converts incoming alternating current (AC) power to direct current (DC) power using an AC/DC rectifier. However, the rectifier can generate harmonics, which can cause issues such as reduced efficiency and increased equipment wear. A challenge for this subsystem is to reduce these harmonics and improve the overall efficiency of the system (Hernández-Gómez, Ramirez, Guilbert, & Saldivar, 2020). The deionized water circulation system supplies the electrolyser with deionized water to produce hydrogen and oxygen through the electrolysis reaction. One of the challenges in this subsystem is to ensure that the water supply is of high purity and free from any dissolved oxygen, which can damage the electrolyser. Additionally, the system needs to maintain the correct flow and pressure of the water supply to ensure the proper operation of the electrolyser (Chen et al., 2022). The hydrogen processing subsystem is responsible for removing any moisture and impurities from the hydrogen gas produced by the electrolyser. A challenge for this subsystem is to achieve high-purity hydrogen production while minimizing energy consumption and system complexity (Du et al., 2021). The cooling subsystem removes the excess heat generated by the electrolyser using a plate heat exchanger and a dry cooler. One of the challenges for this subsystem is to minimize the amount of water required for cooling while maintaining the safe and efficient operation of the electrolyser (Z. Wang et al., 2021). The miscellaneous subsystem includes the compressed air valve, ventilation, and safety requirements such as a combustible gas detector and exhaust ventilation. The challenge for this subsystem is to ensure the safety of the operators and prevent the buildup of potentially explosive gases(Colozza & Jakupca, 2019). Effective policies, regulations, and market mechanisms are required to promote the deployment of PEM electrolysers and hydrogen infrastructure at scale.

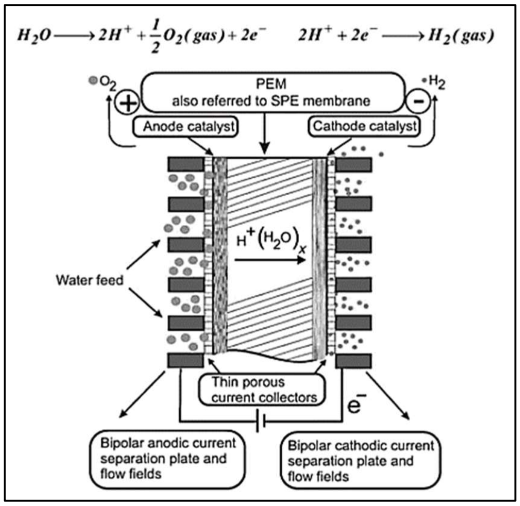

Figure 8. Schematic representing the operation of the PEMEC electrolysis process (Bessarabov & Millet, 2018).

2.5 Status of the Trends and Challenges for Alkaline and PEM electrolysers technologies

This section provides empirical evidence and concrete examples regarding the challenges and trends in alkaline and PEM electrolysis technologies. It discusses the evolution of alkaline electrolysers, the shift towards larger systems for economies of scale, and the integration of advanced materials to improve efficiency and reduce costs.

2.5.1. Alkaline electrolysers challenges and trends

A review of challenges and trends in water electrolysis provides valuable information for conducting techno-economic analyses and evaluating the economic feasibility of water electrolysis as a technology for producing green hydrogen(Brauns & Turek, 2020).

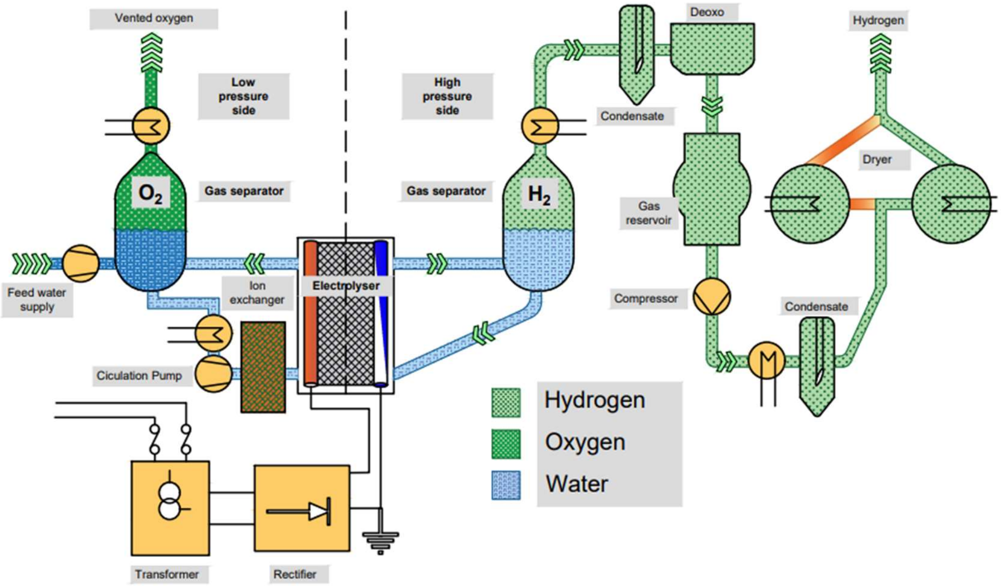

Figure 9. Block diagram of industrial hydrogen production with PEM technology (IRENA, 2020)

Alkaline electrolysers have been around for over a century and have undergone significant changes and improvements over time. The first-generation alkaline electrolysers were developed in the early 1900s and used asbestos diaphragms to separate the anode and cathode compartments. These electrolysers operated at low current densities, which limited their efficiency and production capacity(David et al., 2019). Additionally, the asbestos diaphragms posed health and safety risks due to the release of harmful fibers during operation. second-generation alkaline electrolysers were developed, which replaced the asbestos diaphragms with ion-exchange membranes. These membranes provided better separation of the anode and cathode compartments, resulting in higher current densities and improved efficiency(IRENA, 2020). However, the ion-exchange membranes were expensive and prone to degradation, limiting the lifespan of the electrolyser. the electrodes in first-generation alkaline electrolysers were typically made of nickel and iron, which had low efficiency and durability. Second-generation electrolysers used platinum-coated electrodes, which improved efficiency but were expensive. Third-generation alkaline electrolysers use advanced materials, such as nickel-iron-cobalt alloys, which offer high efficiency and durability at a lower cost than platinum. there has been a significant trend in the alkaline electrolyser industry towards larger, centralized systems(Brian D. James, Jennie Huya-Kouadio, Yaset Acevedo, & Kevin McNamara, 2021). This trend is driven by the growing demand for hydrogen for various industrial applications, including fuel cells, ammonia production, and refineries(Grigoriev, Fateev, Bessarabov, & Millet, 2020).

The shift towards larger systems is beneficial because it allows for economies of scale, resulting in lower production costs per unit of hydrogen produced(Kuleshov et al., 2019). This trend is evident in the size of alkaline electrolyser installations, which have been steadily increasing over the years. Large-scale alkaline electrolysers have the advantage of higher efficiency and reduced cost per unit of hydrogen produced, making them an attractive option for industries(Vidas & Castro, 2021). However, in this case, high energy consumption is required to produce Hydrogen. As indicated in section 1, this energy consumption is determined by the thermodynamic potential required to overcome the activation energy barrier of the reaction, which is influenced by several factors such as the electrode materials, temperature, and pressure(THOMAS, 18 June 2018,) advanced materials such as nickel-iron-cobalt alloys have shown promise in increasing the efficiency of the electrolysis process. Additionally,(Vidas & Castro, 2021) innovative reactor designs, such as those that use gas diffusion electrodes and bipolar plates, can improve mass and heat transfer, thereby increasing the overall efficiency of the system. the stability of the catalysts used in the electrodes. The catalysts, typically made of platinum group metals, can degrade over time due to the harsh chemical environment, leading to reduced performance and increased costs. Researchers are exploring alternative catalyst materials, such as non-noble metal catalysts, to improve stability and reduce costs(Zhigang, Baolian, & Ming, 1999).

The ion-exchange membrane used in liquid alkaline electrolysis systems must be durable and stable over long periods of time. The membrane must resist degradation and maintain its ionic conductivity to ensure efficient electrolysis(Sanchez et al., 2020). Researchers are exploring new materials and designs for membranes, including reinforced and composite membranes, to improve durability and stability. The electrodes in alkaline electrolysers degrade over time, reducing their efficiency and lifespan. To overcome these challenges, researchers are exploring new materials and coatings for the electrodes. One approach is to use more durable materials, such as titanium or coated steel, that are resistant to corrosion and degradation(Henning G. Langås, 2015). Another approach is to apply coatings to the electrodes that can improve their resistance to corrosion and impurities. For example, a thin layer of platinum can be applied to the surface of the electrode to enhance its catalytic activity and protect it from degradation(Linge et al., 2023).

Improving the durability and lifespan of the electrodes in alkaline electrolysis systems is critical for increasing the efficiency and reducing the cost of hydrogen production(Brauns & Turek, 2020). By using more durable materials and coatings, researchers hope to extend the lifespan of the electrodes and reduce the frequency of maintenance and replacement. This will make alkaline electrolysis a more viable and cost-effective technology to produce hydrogen gas(Grigoriev et al., 2020). Researchers at the Fraunhofer Institute for Solar Energy Systems in Germany have developed a system that combines alkaline electrolysis with a redox flow battery to store excess energy generated by renewable sources. The system allows for the efficient storage of excess energy, which can then be used to power the electrolysis process when renewable energy sources are not available(K. Hu et al., 2022).

This integration of alkaline electrolysis with energy storage systems is expected to increase the efficiency and economic viability of alkaline electrolysis technology, making it a more viable and sustainable option for hydrogen production(Sanchez et al., 2020). As the demand for hydrogen production increases, the integration of alkaline electrolysis with energy storage systems will need to be scaled up to meet the demand. This will require the development of larger and more sophisticated systems that can efficiently and effectively store and use excess renewable energy.

Additionally, the cost of integrating alkaline electrolysis with energy storage systems can be a challenge(THOMAS, 18 June 2018,).

The cost of energy storage systems, such as redox flow batteries, can be expensive, and the cost of integrating the systems with alkaline electrolysis technology can add to the overall cost of hydrogen production. Researchers at the University of Manchester in the UK have developed a graphene-based catalyst that can significantly increase the efficiency of alkaline electrolysis(Commission, 2021). The catalyst is made by depositing nickel nanoparticles onto a graphene support, which increases the surface area and enhances the catalytic activity of the nickel. The graphene-based catalyst has been shown to be highly efficient and durable, reducing the cost of hydrogen production by up to 20%(Thengane, Hoadley, Bhattacharya, Mitra, & Bandyopadhyay, 2014). These recent advancements demonstrate the continued progress being made in the techno-economics of alkaline electrolysis, which is helping to make hydrogen production a more economically viable and sustainable option.

Table 5. Alternative and Advanced Features of liquid Alkaline Electrolysis (Brian D James, Jennie Huya-Kouadio, Yaset Acevedo, & Kevin McNamara, 2021)

Component/Aspect	Possible Modifications/Alternatives
Diaphragm	Thinner diaphragm thickness, alternative materials (e.g. PBI), IMET,alternative to Zirfon Perl UTP 500 (polysulphone with ZrOx)
Elastic Elements	Eliminate entirely, use only on one electrode, alternate materials, alternate coiling/construction
Frames	Alternate metals, resins (e.g. vinyl chloride, PE, PP, PPS, PSF, Epoxy),

	injection mouldable materials (e.g. PPS-40GF, PEEK)
Seals	Teflon, EPDM, PEN
PTL/Current Distributors	Ni Foam, Ni Mesh, expanded metal (e.g. Thyssenkrupp Chlor-A), plastic mesh (coated)
Catalysts	Baseline: Ni-Mo and Ni-Fe(OH)2, Pt/Ru/Rare-Earths, RuO2, no noble metals, no catalyst on anode/OER side
Electrodes (Supports)	Eliminate via application. directly to membrane (CCM) or PTL, alternatives to fine woven Ni mesh (e.g., foams, possibly with graded porosity, micro fibrous/nanowire felts, Ni-coated steel, porous carbon paper, catalyst-coated perforated Ni sheet)
Bipolar-Plate/Separate-Plate	Ti, Ni, SS/Mild-Steel with Ni coating, flow fields or no flow fields
Other Ideas	Plastic Stack (use of plastic-framed cartridges, melt-welded to form a sealed stack)

2.5.2. PEM Electrolysers challenges and trends

Similar to the alkaline electrolysers section, this part of the manuscript elaborates on the developments in PEM electrolysis technology, including first-generation systems' reliance on simple materials and the advancements in materials and designs to improve performance and reduce costs.

(Figure 10) shows the diagram of the PEM challenges and trends in different generations of the technology(Jourdani, Mounir, & Marjani, 2017). The first-generation PEM electrolysis systems used simple materials such as polytetrafluoroethylene for the PEM stack, precious platinum based metals for the electrodes, and a basic DC power supply(Bessarabov & Millet, 2018).The Second-generation systems developed in the 1990s and 2000s used more advanced PEM materials like perfluoro sulfonic acid and perfluoro carboxylic acid polymers, and introduced new catalysts like nickel and cobalt-based catalysts the cathodes that were more cost-effective(Bessarabov et al., 2015). For most of industrial applications, still Pt based materials are used at the cathodes and iridium based oxide at the anodes. They also included advanced DC-DC converters for better efficiency and control over the applied current and voltage, resulting in significantly improved performance and durability. The PEM stack was the heart of the electrolysis system, and the focus was on improving its performance and durability(Alexander Buttler, 2018). The development efforts to improve the key components of the PEM stack in electrolysis systems for better membrane materials, as well as improving the catalyst coatings and electrode structures(IRENA, 2020). One of the trends in the development of PEM materials is the exploration of new polymer structures and compositions, including new classes of polymers such as ionomers, block copolymers, and composite materials(Mayyas et al., 2019). Ionomers are a class of polymers that contain both ionizable and non-ionizable regions within their molecular structure. These materials have the potential to offer high proton conductivity, good mechanical stability, and improved resistance to chemical degradation. Block copolymers, on the other hand, are composed of two or more types of polymers that are chemically linked together. By carefully controlling the composition and structure of the blocks, it is possible to design materials with specific properties, such as high proton conductivity, low gas permeability, and improved mechanical strength(Paidar, Fateev, & Bouzek, 2016).

Composite materials, which are composed of two or more different materials combined at the molecular or nanoscale level, have also been explored as a means of improving the properties of PEM materials. For example, incorporating inorganic materials such as silica or metal oxides into the polymer matrix can enhance the mechanical and thermal stability of the membrane, while still maintaining high proton conductivity(OLUFJENSEN, Chatzichristodoulou, Christensen, Bjerrum, & Li, 2019). Similarly, adding carbon-based materials such as graphene or carbon nanotubes can improve the electrical conductivity of the electrode materials, leading to higher efficiency and performance.

Despite the potential benefits of these new materials, there are also significant challenges associated with their development and implementation. For example, many of these materials are difficult and expensive to produce at scale, which can limit their commercial viability. One of the main challenges is maintaining the efficiency and performance of the small-scale systems at larger scales(Henning G. Langås, 2015). The internal resistance within the PEM stack increases with the size of the stack, leading to greater energy losses and a decrease in overall efficiency. This can be mitigated by optimizing the design of the stack, including the geometry, electrode spacing, and flow patterns. Recent advances in stack design have focused on improving the water management within the stack to ensure uniform and adequate hydration of the membrane and electrodes(ITM, 2021). This is essential for maintaining high proton conductivity and preventing dry-out of the membrane. Innovative approaches, such as the use of microfluidics and advanced flow channel designs, have been developed to improve the water distribution and flow within the stack.

Advanced control and monitoring systems can be used to optimize the operation of PEM stacks in real-time, adjusting parameters such as temperature, pressure, and flow rate to maximize efficiency and minimize energy losses. Before the development of advanced control and monitoring systems, PEM stacks were typically operated using simple control methods such as fixed voltage or current control, which were not able to adjust to changing operating conditions or respond to variations in load or environmental factors(ITM, 2021). One notable development in this area is the use of model-based control strategies, which involve creating a mathematical model of the PEM stack and using it to predict the optimal operating conditions for the system in real time. This allows the control system to make more precise and accurate adjustments to the operating parameters, resulting in improved efficiency and reduced energy losses(Abdel-Basset, Gamal, Chakrabortty, & Ryan, 2021).

Another development is the use of advanced monitoring techniques such as electrochemical impedance spectroscopy (EIS), which can provide detailed information on the performance of the stack and the state of its components(Ainscough, Peterson, & Miller, 2014). This information can be used to optimize the stack's operation and to identify potential issues before they become significant problems. One notable development in this area is the use of model-based control strategies, which involve creating a mathematical model of the PEM stack and using it to predict the optimal operating conditions for the system in real time. This allows the control system to make more precise and accurate adjustments to the operating parameters, resulting in improved efficiency and reduced energy losses. However, Advanced monitoring techniques for PEM stacks face several challenges, including the need for accurate and reliable sensors, careful placement of sensors, effective data processing algorithms, standardization of monitoring systems, and the need for real-time response to changes in the stack's performance. Overcoming these challenges is critical to realizing the full potential of PEM stacks in improving efficiency and reducing energy losses(Aminov & Bairamov, 2017).

Optimizing the structure of electrodes in PEM electrolysers, such as increasing the surface area or using porous materials, can improve mass transport and reduce resistance during electrochemical reactions. This can lead to higher efficiency and better performance(Anwar et al., 2021). However, challenges still exist, such as ensuring the durability of electrode materials and coatings under harsh conditions, like high temperature, pressure, and exposure to corrosive environments(E.ON, 2021).

Another development involves the use of carbon-based materials like graphene or carbon nanotubes, which have shown promise in enhancing the electrical conductivity of electrode materials, further improving efficiency and performance.

Despite these advancements, there are still challenges related to the scalability of these materials for large-scale applications and their long-term stability under operational conditions(Mackenzie, 2019).

The development of specialized coatings for electrodes can help reduce catalyst degradation and improve durability, contributing to the suitability of the system for large-scale hydrogen production. However, the cost of electrode materials, particularly when using costly catalysts like platinum, remains a challenge(Mayyas et al., 2019) . There are methods for enhancing the efficiency of Electrolysis, which could potentially result in breakthroughs and significant short-term advancements. For example, Centrifugal force application in PEM electrolysis, one key contributor to centrifugal electrochemical methods is Ernest O. Lawrence, who invented the cyclotron in the early 1930s, a device that utilizes centrifugal force for accelerating charged particles. Centrifugal force involves rotating the cell at high speeds, which improves mass transport and overall efficiency(S. S. Kumar & Lim, 2022). However, it requires specialized equipment and can cause increased complexity, costs, and potential mechanical stress on components, potentially reducing the electrolysers' durability and reliability. Moreover, The gravitational field approach in PEM electrolysis utilizes gravity to facilitate gas bubble separation from the electrode surface, improving mass transport and efficiency(Kuleshov et al., 2019). However, limitations include dependency on electrolyser orientation, potentially modest efficiency gains, and ineffectiveness in microgravity or zero-gravity environments like space applications. In addition, Ultrasound technology dates to the early 20th century. Paul Langevin, a French physicist, was a pioneer in the field, developing a method to detect submarines using underwater sound waves during World War I. The use of ultrasonic technology has since expanded to various applications, including the enhancement of chemical and physical processes. Ultrasound-assisted electrolysis, for example, has been explored by researchers since the latter half of the 20th century(S. S. Kumar & Lim, 2022). It uses high-frequency sound waves to improve mass transfer, remove gas bubbles, and increase efficiency(Marubeni, 2022). However, it may cause mechanical fatigue and wear on components due to vibrations, and the efficiency gains might not outweigh the added energy consumption and complexity of integrating the technology. Also, Magnetic field influence on PEM electrolysis involves using external magnetic fields to

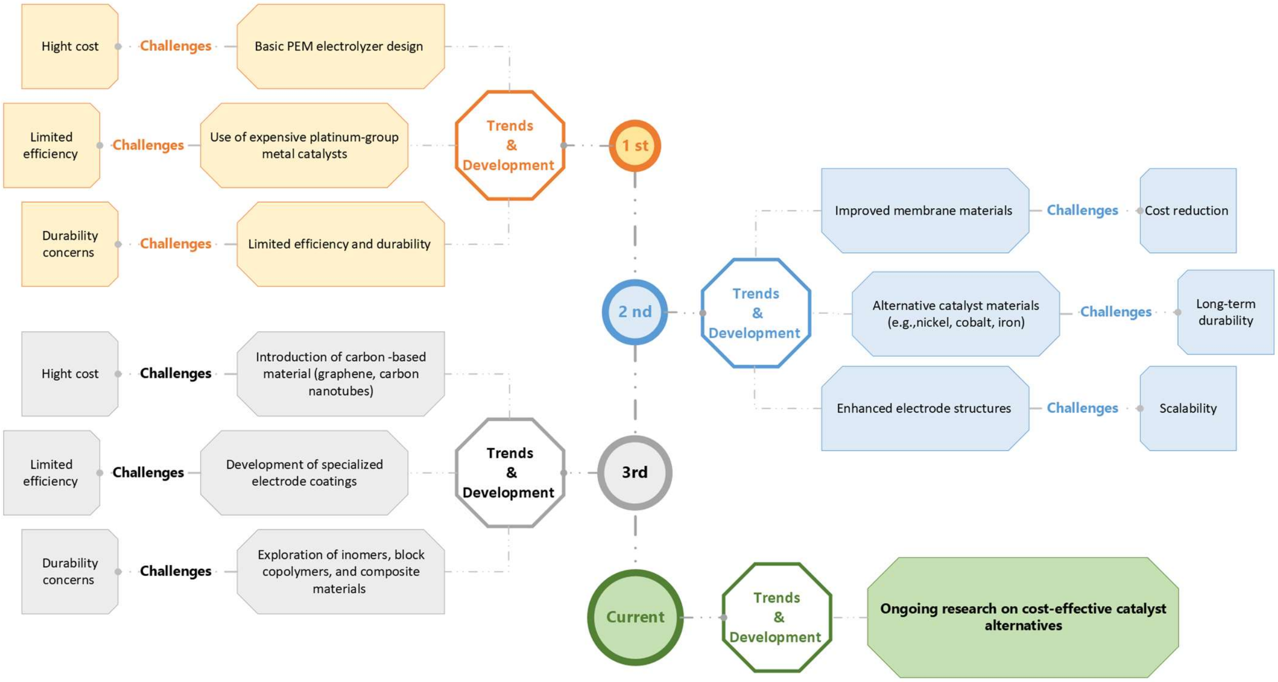

Figure 10. Diagram of the PEM challenges and trends in different generations of the technology (Jourdani et al., 2017)

potentially improve mass transport, bubble detachment, and overall efficiency. However, limitations include the need for extra equipment, increased complexity and cost, and a lack of full understanding of the magnetic field effects on electrolysis, necessitating further research(Aminov & Bairamov, 2017). The challenges and trends for techno-economic analysis of PEM water electrolysers highlight the potential and importance of this technology in the transition towards a sustainable and green energy future. As the demand for hydrogen production grows, advancements in PEM electrolysers promise to address the key challenges of cost reduction, efficiency improvement, and scalability(David Parra, 2016).

2.6 Cost-Cutting Measures and Markets for large scale plants

This section touches on how economies of scale, improvements in technology, and access to low-cost electricity can drive down the cost of hydrogen production through water electrolysis. It provides concrete examples, such as the increase in the size of electrolysis projects and the reduction in costs associated with larger plant sizes.

Several factors can drive down the cost of producing hydrogen through water electrolysis, including economies of scale, improvements in technology, access to low-cost electricity, recycling and reuse of materials, and government incentives and funding. These drivers of cost reduction can help to make hydrogen production through water electrolysis a more cost-effective option for a range of applications, by reducing capital costs, improving efficiency and productivity, and offsetting the cost of inputs such as electricity and water. By leveraging these factors, it may be possible to produce hydrogen from water electrolysis at a competitive cost, making it a promising technology for a low-carbon energy future (Chatenet et al., 2022).

One of the key drivers of cost reduction in water electrolysis systems is the impact of increasing plant size(Chatenet et al., 2022). As the size of the plant increases, the cost per unit of hydrogen produced tends to decrease due to economies of scale. This means that larger plants may be able to produce hydrogen more cost-effectively than smaller plants. The cost reductions that result from increasing plant size come from several factors, including the ability to spread fixed costs over a larger production volume, lower energy costs per unit of hydrogen produced, and increased efficiency in the use of materials and labor. As a result, many companies are investing in larger water electrolysis plants, with some facilities having a capacity of over 10 megawatts. By leveraging economies of scale, it may be possible to reduce the overall cost of producing hydrogen through water electrolysis, making it a more viable option for a range of applications(Tsiaka, Sinanoglou, & Zoumpoulakis, 2017). The increase in size of water electrolysis projects between 2000 and 2023. The average size of alkaline and proton exchange membrane water electrolysis systems have increased from around 10 kW and 1 kW to over 2 MW and 5 MW respectively. The growth in size is driven by the need to produce clean hydrogen at a larger scale to meet decarbonization targets and decreasing costs of renewable energy sources. Additionally, the number of water electrolysis projects has rapidly increased from around 300 projects worldwide in 2010 to over 3,000 projects in 2021. This trend is expected to continue, with the size of water electrolysis projects projected to increase further, reaching an average size of 50 MW by 2030 (Canton, 2021).

Design improvements can result in significant changes in current density or voltage efficiency for both PEM (Proton Exchange Membrane) and Alkaline fuel cells. For example, in PEM fuel cells, reducing the thickness of the membrane from 50 μm to 25 μm can increase the current density by 40%(Pikalova, Osinkin, & Kalinina, 2022). Increasing the platinum loading on the cathode of a PEM fuel cell from 0.1 to 0.4 mg/cm² can also result in a 38% increase in current density(Osmieri & Meyer, 2022). In Alkaline fuel cells, increasing the surface area of the cathode by four times can lead to a 3-fold increase in current density(Linge et al., 2023). Using nickel-iron (Ni-Fe) nanoparticles as the catalyst in an Alkaline fuel cell can result in a 58% increase in current density compared to using platinum(Radinović et al., 2022). By implementing these design improvements, fuel cell developers can enhance the efficiency and performance of both PEM and Alkaline fuel cells and bring us closer to achieving widespread use of these clean energy technologies. Increasing economies of scale in the production of PEM and Alkaline fuel cells can lead to cost reductions through increased automation, reduced labor costs, bulk purchasing of raw materials, and increased production efficiency. As production volumes increase, learning rates also increase, leading to further cost reductions through improvements in manufacturing processes, design, and the use of lower-cost materials. Some studies have shown that increasing economies of scale and learning rates have resulted in significant performance improvements and cost reductions for fuel cell technologies(Chatenet et al., 2022). As electrolysis is a key production method, By 2020, the global cumulative installed capacity for hydrogen electrolysis was around 200 MW(E. IRENA, 2020).

Notable projects and milestones include Germany's Hydrogen Strategy (€9 billion investment, 5 GW by 2030, additional 5 GW by 2040), the European Union's Hydrogen Strategy (6 GW by 2024, 40 GW by 2030, 10 million tonnes of renewable hydrogen by 2030), Nel Hydrogen Electrolyser's 2 GW factory in Norway by 2023, Japan's Basic Hydrogen Strategy (300,000 fuel cell vehicles, 900 hydrogen refueling stations by 2030), South Korea's Hydrogen Economy Roadmap (15 GW fuel cell capacity, 6.2 million fuel cell vehicles by 2040), Australia's National Hydrogen Strategy, the Asian Renewable Energy Hub, the Green Hydrogen Catapult Initiative (25 GW by 2026, green hydrogen below $2/kg), and the United States' Department of Energy's H2@Scale initiative (DOE, 2021). During 2022, countries like the US, Denmark, Egypt, Canada, and Portugal announced over 111.9 million tonnes per annum (mtpa) of low-carbon hydrogen production capacity. . In Canada, Green Hydrogen International (GHI) unveiled two major green hydrogen initiatives as the exclusive participant, with each project boasting a capacity of 43 million tonnes per annum. These projects are expected to start producing hydrogen by 2030 (GlobalData, 2023).

These various developments were made possible due to the continue support in research and development of a large-scale water electrolysis technologies which aim to develop efficient and cost-effective industrial methods for producing hydrogen fuel from water. As a clean and renewable energy source, hydrogen has gained importance in the face of increasing pressure to reduce greenhouse gas emissions. The potential of hydrogen to decrease carbon based gas emissions is why this research is becoming increasingly significant. Accordingly, worldwide significant development of electrolytic hydrogen production has increased significantly. Hydrogen Roadmap has been produced for more than 12 countries and the European Union at the year of in 2020. The hydrogen strategy of countries is summarized in (Figure 11) and (**Erreur ! Source du renvoi introuvable.**) **. European union plans to install 40 GW of renewable hydrogen electrolysers by 2030(IEA, 2013).

The variety of contexts and sectorial diversities from a country to another make difficult to get the same view in the green hydrogen economy.

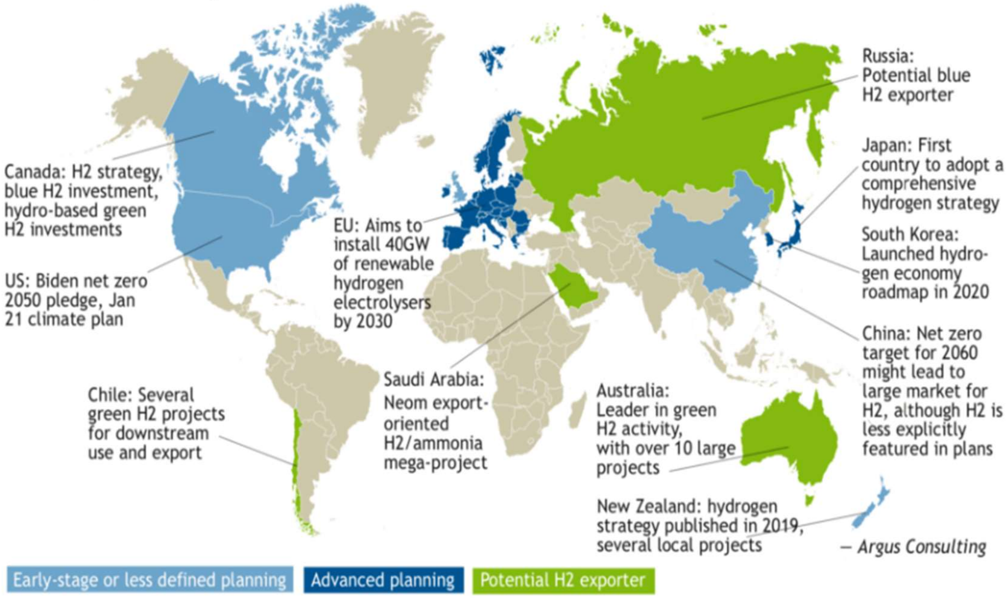

Figure 11. Hydrogen strategy for various regions and countries worldwid (IEA, 2013)

Table 6. Different Approaches to Hydrogen Energy Implementation Across Global Countries(IEA, 2013)

Country	**Hydrogen Strategy**
Russia	Potential blue H2 exporter
Japan	First country to adopt a comprehensive hydrogen strategy
South Korea	Launched hydrogen economy roadmap in 2020
China	Net zero target for 2060 might lead to large market for H2, though less explicitly featured in plans
New Zealand	Published hydrogen strategy in 2019, several local projects underway
Australia	Leader in green H2 activity with over 10 large projects
Saudi Arabia	Undertaking a Neom export oriented H2/ammonia mega-project in advanced planning stages
European Union	Aims to install 40GW of renewable hydrogen electrolysers by 2030
Canada	Comprehensive H2 strategy, blue H2 investment, hydrobased green H2 investments
United States	Committed to net zero emissions by 2050, climate plan unveiled in January 2021
Chile	Several green H2 projects for downstream use and export

For example, in the hydrogen roadmap of Canada published in 2020, the vision for 2050 is to have more than 5 million hydrogen fuel cell vehicles, to produce 20 Mt of hydrogen per year and 30% of Canada energy system. To support the strategy some emerging technologies must n=be also developed. As an example, a large-scale hydrogen production facility that utilizes water electrolysis and biomass gasification to produce hydrogen has been introduced. The project is led by a consortium of Canadian companies(Frangoul, 2021) and research institutions and is receiving funding from the Natural Sciences and Engineering Research Council of Canada. The results and the outcomes of these projects will play an important role in the development of large-scale hydrogen production using water electrolysis, making it more accessible, efficient, and cost-effective.

The Quebec province of Canada, there have been several studies and assessments conducted on the feasibility of using water electrolysis to produce hydrogen at a centralized facility(Neisiani.M., 2020),(Savadogo, Fradette, Chaouki, Neisiani, & Tanguy, 2020)

These studies have generally shown that the mass production of hydrogen by water electrolysis in Quebec is technically feasible. Hydro-Québec has announced plans to construct an electrolyser facility with a capacity of approximately 90 MW, making it one of the most powerful electrolysers in the world (Quebec, 2020). To develop technical skills in the electrolytic hydrogen production using PEM technology, the 6 MW PEM electrolysis project "Energiepark Mainz" in Germany has been established at the "Energiepark Mainz" facility to analyze the technical proficiency and efficiency of the Power-to-Gas process and evaluate its potential for grid balancing (M.Kopp, 2017).

There are several technology demonstration projects for electrolysis using renewable energy to produce hydrogen worldwide. These projects typically have a capacity range from 150 kW to 2 MW. Some recent demonstration projects include the HyBalance project in Denmark with a capacity of 2 MW, the H2 Future project in Austria with a capacity of 1.25 MW, the HyDeal project in Germany with a capacity of 1 MW, the H2@Scale project in the Netherlands with a capacity of 1 MW, and the HyBalance project in Finland with a capacity of 0.5 MW. These projects are located in Denmark, Austria, Germany, Netherlands and Finland (THOMAS, 18 June 2018,), respectively. The potential for reducing the cost of hydrogen production(THOMAS, 18 June 2018,) through electrolysis can be achieved by choosing an optimal location for the electrolyser and implementing intelligent methods of operation that adjust the production levels based on the cost of electricity. Increasing the rating of an electrolyser leads to an enhancement of the technical and economic benefits it provides. In the study of(David Parra, 2016) these benefits are more pronounced in systems that operate on a kilowatt scale, as opposed to those on a megawatt scale. Moreover, an analysis was conducted on the techno-economic performance of water electrolysis plants in the Swiss wholesale electricity market. The plants considered in the study ranged from 25 kW to 1 GW in capacity It's also crucial to mention that Proton Exchange Membrane (PEM) electrolysers require a higher capacity factor of around 11% to decrease their levelized costs when compared to alkaline electrolysers. These pilot plan projects indicate that alkaline and PEM electrolysers technologies are the two major technologies which are considered for mass industrial production of electrolytic hydrogen. Even the PEM technology is less mature than the alkaline technology, its rate of implementation is growing fast and its hydrogen production cost is decreasing more rapidly than the alkaline technology (IRENA, 2020).

Moreover The ISPT HydroHub project(Cooper, Horend, Röben, Bardow, & Shah, 2022) is an initiative in the Netherlands that aims to develop an electrolyser powered by a 1 GW offshore wind farm. The project aims to produce hydrogen through water electrolysis, using electricity generated by the wind farm. The hydrogen produced can be used for various applications, including as a fuel for transportation and as a source of clean energy for industrial processes. The goal of the project is to demonstrate the feasibility of large-scale hydrogen production using renewable energy sources and to pave the way for the wider adoption of this technology in the future.

the "Green Hydrogen Catapult" project in the UK(ITM, 2021) . The project aims to develop a 10 MW electrolyser powered by renewable energy, with the goal of producing hydrogen at a cost competitive with fossil fuels. The project is being led by ITM Power, a UK-based hydrogen energy company, and is receiving funding from the UK government's Department for Business, Energy and Industrial Strategy.

The "HyBalance" project in Denmark(HyBalance, 2020). The project aims to develop a high-temperature electrolysis technology (Solid Oxide Electrolyser) to produce hydrogen from renewable energy sources. The goal of the project is to produce hydrogen at a cost of less than 3$ US per kg, which would make it competitive with hydrogen produced from fossil fuels. The project is being led by a consortium of Danish companies and research institutions and is receiving funding from the European Union's Horizon 2020 research program.

Germany plans to implement the H_2 Future project(Krull, 2020) which aims to build a 100 MW PEM electrolysis plant to produce hydrogen from renewable energy sources. The project is a collaboration between Siemens Energy and the industrial gases company Air Liquide and is expected to be completed by 2023. The aims of these various projects are to demonstrate the economical feasibility of hydrogen electrolytic production using renewable energy plants such as wind or photovoltaic power plants. This will support, for example, the European Union plan to install 40 GW of hydrogen electrolysers power plants by 2030 based on renewable energy power.

3. Multi-criteria decision making (MCDM)

3.1 Introduction

The manuscript discusses conducting a techno-economic analysis of hydrogen production from water electrolysers using MCDM. This approach inherently combines theoretical frameworks (e.g., economic models and decision-making theories) with empirical research (e.g., data on cost, efficiency, and performance of electrolysis technologies. .

It explains how MCDM combines theoretical frameworks with empirical research, incorporating data on cost efficiency and performance of electrolysis technologies. The methodological detail covers the mathematical models of MCDM tools that support decision-making processes involving multiple criteria, highlighting their ability to handle complexity and incorporate multiple perspectives.

Table 7. Comparison of 20 Large-Scale Water Electrolyzers by Manufacturing Location, ModelSeries,Thermodynamic Characteristics(S. S. Kumar & Lim, 2022).

Model	Manufacturing Location	Series	Maximum Power Input	Cell Voltage	Electrolysis Efficiency
ITM Power Gigastack	UK	-	10 MW	< 1.9 V	> 80%
Nel Hydrogen Alkaline	Norway	A Series	5 MW	< 2.0 V	> 80%
McPhy 2 MW	France	-	2 MW	< 1.8 V	> 70%
Siemens 5 MW	Germany	-	5 MW	< 1.9 V	> 80%
Green Hydrogen Systems 5 MW	Denmark	GHS A-Series	5 MW	< 2.0 V	> 80%
Tianjin Mainland Hydrogen Equipment 500 kW	China	-	500 kW	< 2.2 V	> 70%
Nel Hydrogen PEM	Norway	N Series	2 MW	< 1.9 V	> 80%
Enapter 1 MW	Italy	-	1 MW	< 2.0 V	> 80%
Cummins PEM (Hydrogenics)	USA	H-Series	5MW	< 1.9 V	> 80%
Thyssenkrupp 1 MW	Germany	-	1 MW	< 2.0 V	> 80%
Giner ELX 1 MW	USA	-	1 MW	< 2.0 V	> 80%
Air Liquide Alkaline	France	-	1 MW	< 2.0 V	> 80%
AREVA H2Gen Alkaline	France	-	1 MW	< 2.0 V	> 80%
Hy9 PEM	USA	-	200 kW	< 1.8 V	> 80%
Sunfire SOEC	Germany	-	100 kW	< 1.6 V	> 80%
H-Tec PEM	Germany	-	60 kW	< 1.8 V	> 80%
Enertrag PEM	Germany	-	60 kW	< 1.8 V	> 80%
ITM Power PEM	UK	-	30 kW	< 1.8 V	> 80%
McPhy Alkaline	France	-	30 kW	< 2.5 V	> 70%
Green Hydrogen Systems PEM	Denmark	GHS S-Series	20 kW	< 1.8 V	> 80%

Note: This is not an exhaustive list, and the thermodynamic characteristics may vary depending on various factors such as operating conditions, materials used, and design features.

Multi-criteria decision-making (MCDM) tools are mathematical models used to support decision-making processes involving multiple criteria or objectives. These tools enable decision-makers to consider several factors simultaneously and make informed decisions based on multiple criteria (Zopounidis & Pardalos, 2010). The advantages include the ability to handle complexity, flexibility, a structured and transparent process for decision-making, and the ability to incorporate multiple perspectives. However, MCDM methods also have some disadvantages such as high data requirements, complexity, subjectivity, and the need for consensus among stakeholders, which can be time-consuming and resource intensive. Multi-Criteria Decision Making (MCDM) models can be broadly categorized into the following groups(Pohekar & Ramachandran, 2004):

a. Value-based methods: These methods are based on the aggregation of values or utilities assigned to the criteria. Some common value based MCDM models include:
   - Simple Additive Weighting (SAW)
   - Weighted Product Model (WPM)
   - Analytic Hierarchy Process (AHP)
   - Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)
   - Elimination and Choice Expressing Reality (ELECTRE)
   - Multi-Attribute Utility Theory (MAUT)
   - Multi-Attribute Value Theory (MAVT)

b. Outranking methods: These methods involve comparing and ranking alternatives based on pairwise relationships. Examples of outranking MCDM models include:
   - ELECTRE (a model that is both value-based and outranking)
   - Promethee (Preference Ranking Organization Method for Enrichment Evaluations)

c. Fuzzy methods: These methods incorporate fuzzy set theory to handle uncertainty and vagueness in decision-making. Some common fuzzy MCDM models are:
   - Fuzzy AHP
   - Fuzzy TOPSIS
   - Fuzzy ELECTRE
   - Fuzzy Promethee

d. Goal programming methods: These methods focus on minimizing deviations from predefined goals or targets for each criterion. Goal programming techniques commonly used in MCDM include:
   - Goal Programming (GP): This is the basic form of goal programming where deviations from goals are minimized, without any priority or preference given to specific goals.
   - Weighted Goal Programming (WGP): In this approach, each goal is assigned a weight reflecting its relative importance, and the objective is to minimize the weighted sum of deviations from the goals.
   - Lexicographic Goal Programming (LGP): This method involves prioritizing the goals and minimizing deviations in a lexicographic order. Higher priority goals are satisfied before lower priority goals.
   - Fuzzy Goal Programming (FGP): Fuzzy goal programming extends the basic goal programming approach by incorporating fuzzy sets to represent the

goals and their priorities. This allows for handling uncertainty and vagueness in goal formulation.

- Multi-Objective Goal Programming (MOGP): This approach combines multiple conflicting objectives in a decision-making process and aims to find a compromise solution that satisfies all objectives as much as possible.

e. Hybrid methods: These MCDM techniques integrate two or more of the methods to address complex decision-making problems. Hybrid methods can offer improved performance and better results by leveraging the strengths of different MCDM approaches. Some examples of hybrid MCDM methods include:

- AHP-TOPSIS: This hybrid method combines the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). AHP is used to determine the weights of criteria, while TOPSIS is employed to rank the alternatives based on their proximity to the ideal solution.
- AHP-PROMETHEE: This approach combines AHP and Promethee (Preference Ranking Organization Method for Enrichment Evaluations). AHP is used to determine the criteria weights, and Promethee is applied to rank the alternatives based on pairwise preference relations.
- Fuzzy AHP-TOPSIS: This method integrates Fuzzy AHP and Fuzzy TOPSIS, utilizing fuzzy set theory to handle uncertainty in both the weighting and ranking processes.
- Fuzzy AHP-PROMETHEE: This hybrid approach incorporates fuzzy set theory into both AHP and Promethee, allowing for the management of uncertainty in the criteria weighting and alternative ranking processes.
- ELECTRE-GP: This method combines the Elimination and Choice Expressing Reality (ELECTRE) method with Goal Programming (GP) to find a compromise solution that is both outranking and satisfies predefined goals.

The choice of an MCDM method or a hybrid method depends on the specific decision-making problem, the nature of the criteria, and the preferences.

The manuscript categorizes MCDM models into value-based methods, outranking methods, fuzzy methods, goal programming methods, and hybrid methods. Hybrid methods are particularly relevant to your interest, as they integrate two or more of the mentioned methods to address complex decision-making problems. For example, AHP-TOPSIS and AHP-PROMETHEE are hybrid methods combining the strengths of different MCDM approaches for improved performance and better results. These hybrid approaches are discussed, explaining how they offer a nuanced way to evaluate and select among various options by leveraging both theoretical frameworks and empirical data.

The detailed explanation of hybrid MCDM techniques underlines the manuscript's engagement with combining theory and empirical research. This approach allows for a more comprehensive evaluation and selection process in the context of green hydrogen production and water electrolysis technologies, providing a richer, data-informed perspective that bridges theoretical models with practical, real-world considerations.

In previous study, our group used multiple criteria decision analysis as a methodology concept for the selection of materials(Shanian & Savadogo, 2006a) including highly sensitive components(Shanian & Savadogo, 2009) It has been shown that ELECTRE can be used successfully in selecting a suitable material for the particular application of a loaded thermal conductor. For the selection of materials for sensitive components for aero space applications, TOPSIS, ELECTRE IV and VIKOR methods were used and compared. The ELECTRE IV method demonstrates a reasonable ability when the material designer is not able to define a set of weighting factors. It was concluded that using these methods as complements can be considered as an efficient tool for optimal design. A multi-criteria decision method based on a non-compensatory solution using the ELECTRE IV method has been applied for material selection of the bipolar plate for polymer electrolyte fuel cells. It was shown that The ELECTRE IV lists candidate materials from best to worst, taking into account all the material selection criteria. This was in agreement with experimental data obtained from these materials(Shanian & Savadogo, 2006b). It was shown that if a material selection decision matrix and a criteria sensitivity analysis are produced, the ELECTRE I can be applied to perform a reasonable material selection for a particular application, including a logical ranking of considered materials(Shanian & Savadogo, 2006a) TOPSIS Multiple-criteria support model based on a user-defined code in Mathematica has been developed to facilitate the

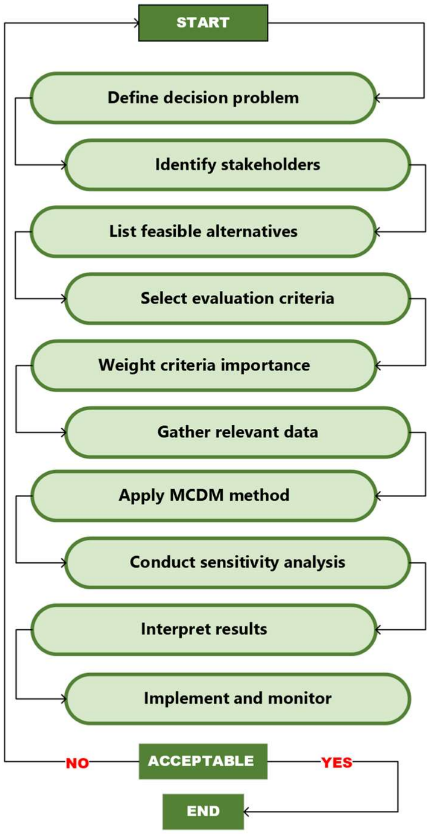

Figure 12. Common procedure for MCDM analysis(Zopounidis & Pardalos, 2010)

implementation of the method for materials selection for PEFC bipolar plates applications.

It was shown that the optimum value of each criterion is independent of other criteria values (i.e., no interaction is allowed). This allowed a good ranking of The proposed approach may be applied to other problems of material selection of fuel cell components (Shanian & Savadogo, 2006c) The ELECTRE III method (Elimination and Choice Translating Reality III) with Fuzzy outranking methods have been used for materials section of bipolar plates for polymer electrolyte fuel cell applications. A list of all possible choices from the best to the worst is then obtained using this method by taking into account all materials selection criteria, including the cost criterion(Shanian & Savadogo, 2006b) .In all cases, it was found good agreement between the results of the methods being used and available experimental data and the Cambridge Engineering Selector (CES) databases. These results indicate the high potential of using MCDM methods for material selection and other components for electrochemical processes.

- This segment elaborates on the use of MCDM for conducting a techno-economic analysis of hydrogen production from water electrolysers. It discusses how MCDM integrates theoretical frameworks with empirical research, incorporating data on cost efficiency and performance of electrolysis technologies. However, it primarily focuses on explaining the methodology and mathematical models of MCDM tools without directly referencing empirical case studies or data analysis that validate these concepts in real-world applications.
- Gaps in the body of knowledge. Although this part identifies gaps in the literature, such as the lack of standardized MCDM methods and limited case studies, it implicitly acknowledges the manuscript's reliance on theoretical overviews and a review of existing literature rather than presenting new empirical findings or in-depth case study analyses.)

3.2 MCDM for sustainable energy planning implementation

In the context of energy and water electrolyser cost, MCDM tools can be used to evaluate the costs associated with various energy and water electrolysis technologies. In the renewable energy sector, MCDM models serve as a key method for addressing complex decision-making, incorporating direct or indirect strategies based on stakeholder input or past experiences. These models, require both engineering and managerial assessments due to various factors, including technical, institutional, social, and economic aspects. However, MCDM processes can be contentious as changing priorities may lead to different solutions depending on the decision-makers involved.(A. Kumar et al., 2017)

MCDM tools can help decision-makers evaluate the various factors that impact the cost of energy and water electrolysis, such as the efficiency of the process, the availability of water and energy, and the cost of inputs such as electricity and water. By considering multiple criteria, MCDM tools can help identify the most cost-effective and efficient technology for producing hydrogen (A. Kumar et al., 2017).

The following are examples of how each category of MCDM models as explained in the last section can be applied(J.-J. Wang, Jing, Zhang, & Zhao, 2009): Value-based methods can be used to evaluate and select renewable energy technologies based on multiple criteria such as cost, efficiency, and environmental impact. These methods can also help with optimal site selection for renewable energy installations, considering factors such as land use, resource availability, and grid connectivity. Additionally, value-based methods can prioritize energy efficiency measures for buildings or industrial processes, which can help to reduce energy consumption and increase cost savings.

Outranking methods can be used to compare and rank different energy policies or strategies based on their alignment with sustainability goals, economic development, and social acceptability. These methods can also be used to assess the feasibility of different energy storage systems for integration with renewable energy sources. Additionally, outranking methods can evaluate the environmental impact of various energy generation technologies, which can help to identify the most sustainable and socially acceptable options.

Fuzzy methods can be used to analyze uncertainties in energy demand forecasting, considering fluctuations in economic growth, population, and technology maturity, reliability and adoption. These methods can also be used to estimate the potential of renewable energy resources in a region with imprecise data or uncertain conditions. Additionally, fuzzy methods can evaluate the resilience of energy systems under varying climate conditions or potential disruptions, which can help to identify potential vulnerabilities and develop effective contingency plans.

Group decision-making methods can be used to facilitate stakeholder engagement and consensus-building in energy policy development, including public, private, and community perspectives. These methods can also be used to determine the optimal mix of energy sources for a region or country, considering diverse stakeholder priorities and objectives. Additionally, group decision-making methods can evaluate the social acceptability and impact of energy projects on local communities, which can help to identify potential social conflicts and develop effective mitigation strategies.

Life cycle assessment (LCA) methods can be used to evaluate the environmental impact of energy technologies and systems throughout their entire life cycle, including raw material extraction, manufacturing, transportation, use, and disposal. LCA methods can help to identify the most sustainable and environmentally friendly options for energy production and consumption and can also inform policy decisions related to waste management and recycling. LCA methods are closely related to value-based and fuzzy methods, as they often involve multiple criteria and uncertainties(Ren, Li, Ding, & Dong, 2020).

Multi-criteria decision analysis (MCDA) methods can be used to evaluate and compare energy options based on multiple criteria, such as environmental impact, cost, reliability, and social acceptability. MCDA methods can help to identify trade-offs and synergies between different criteria and can also incorporate stakeholder preferences and values into decision-making processes. MCDA methods are closely related to outranking and group decision-making methods, as they involve the comparison and prioritization of different options based on multiple criteria and stakeholder perspectives(J.-J. Wang et al., 2009).

System dynamics modeling (SDM) methods can be used to simulate and analyze the behavior of complex energy systems over time, including interactions between different components, feedback loops, and uncertainties. SDM methods can help to identify potential bottlenecks and vulnerabilities in energy systems and can also inform policy decisions related to energy planning and management. SDM methods are closely related to fuzzy methods, as they often involve the analysis of uncertain and dynamic systems(Pohekar & Ramachandran, 2004).

Risk assessment and management (RAM) methods can be used to identify and evaluate potential risks associated with energy technologies and systems, such as safety hazards, security threats, and environmental risks. RAM methods can help to prioritize risk mitigation measures and develop contingency plans to minimize the likelihood and impact of potential incidents. RAM methods are closely related to value-based and group decision-making methods, as they often involve the consideration of multiple criteria and stakeholder perspectives(Pohekar & Ramachandran, 2004).

In addition, there are numerous MCDM models available, and there are some popular ones that can be applied to energy planning such as (Pohekar & Ramachandran, 2004). The Analytic Hierarchy Process (AHP) developed by Saaty since 1980 (Saaty, 1980) is a structured decision-making technique that enables decision-makers to prioritize alternatives based on multiple criteria. In the context of energy planning, AHP helps in identifying the optimal energy mix, considering factors such as cost, environmental impact, and energy security. By prioritizing different energy sources and technologies, AHP aids in developing robust and sustainable energy policies and strategies. The energy planning problem is broken down into a hierarchy, starting with the goal (optimal energy mix) at the top, followed by criteria (cost, environment, security), sub-criteria (if any), and energy alternatives (different sources and technologies) at the bottom. In addition, Decision-makers conduct pairwise comparisons of criteria, sub-criteria, and alternatives to determine their relative importance. These comparisons are typically done using a numerical scale (e.g., 1-9), with higher values indicating greater importance. finally Based on the pairwise comparisons, the priorities of the criteria, sub-criteria, and alternatives are calculated using mathematical techniques, such as the eigenvector method. This results in a set of weights that reflect the relative importance of each element in the hierarchy., Moreover, the priorities of the alternatives are combined with the priorities of the criteria and sub-criteria to calculate the overall priority of each energy alternative. The energy sources and technologies are then ranked according to their overall priorities, with the highest-ranked alternative being the most suitable choice for the optimal energy mix (J.-J. Wang et al., 2009).

The Analytic Network Process (ANP) is an advanced decision-making technique developed by Thomas L. Saaty in 1996 (Saaty, 1996)as an extension of the Analytic Hierarchy Process (AHP). ANP is particularly suitable for complex decision-making problems in energy planning where factors are interconnected and exhibit dependencies. By considering these interdependencies. It provides a more holistic and realistic approach to energy planning and helps assess and prioritize the incorporation of various renewable energy sources into the energy mix by considering technical, economic, environmental, and social factors(Linkov & Moberg, 2011).

Policymakers use ANP to compare and evaluate different energy policies based on their effects on energy security, sustainability, affordability, and environmental protection. It employed to optimize the planning and development of energy infrastructure projects(Zopounidis & Pardalos, 2010). The ANP framework involves problem structuring, Super matrix development, normalization and Limiting Super matrix creation, and synthesis and ranking. It structures energy planning problems into networks, representing relationships among nodes. The Super matrix captures interactions and influences among nodes. After normalizing and creating a Limiting Super matrix, the decision-maker can rank alternatives and determine the optimal energy mix (Triantaphyllou & Triantaphyllou, 2000).

(Roy, 1990)The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision-making method used to rank alternatives based on their similarity to the ideal solution. The method considers both the positive and negative aspects of each option and calculates the relative closeness of each alternative to the ideal solution.

In TOPSIS, the ideal solution is the alternative that has the highest values for the positive criteria and the lowest values for the negative criteria. The ranking of the alternatives is based on the Euclidean distance between each alternative and the ideal solution, with the alternative closest to the ideal solution receiving the highest rank.

TOPSIS is commonly used in various fields, including energy production, to evaluate and rank alternative energy sources or technologies based on criteria such as energy efficiency, cost, environmental impact, scalability, and reliability(Triantaphyllou & Triantaphyllou, 2000).

3.3 Multi-Criteria Decision Making (MCDM) as a Tool for Evaluating Hydrogen Production

Uncertainty plays a crucial role in applying Multi-Criteria Decision Making (MCDM) to green hydrogen production project selection. Factors such as input cost fluctuations, regulatory changes, and technological progress can impact the decision-making process. To make relevant decisions, it's vital to consider these uncertainties and their effects on project feasibility and viability. MCDM techniques use sensitivity and scenario analyses to evaluate decision-making robustness under various conditions. Thus, addressing and incorporating uncertainty is essential in MCDM for green hydrogen project selection, as it can significantly influence the evaluation and comparison of alternatives, potentially affecting the reliability and robustness of the decision-making process(H.-C. Liu & Liu, 2016).

Uncertainty in MCDM for green hydrogen production projects arises from various sources:

- Data Uncertainty: Inaccurate, incomplete, or unreliable data can lead to incorrect or misleading results, caused by limitations in data collection methods, outliers, or data errors.
- Model Uncertainty: Different decision models and criteria can yield varying rankings of alternatives, requiring decision-makers to choose the most suitable model and criteria based on their specific needs.
- Weighting Uncertainty: Subjective weighting of criteria depends on the decision-maker's preferences, which can vary, leading to different rankings of alternatives even when using the same data and criteria.
- Scalability Uncertainty: Predicting the scalability of a project is challenging due to uncertainties in

technological advancements, reliability, energy market conditions, and government policies, making it a critical factor in the project's long-term success.

Decision-makers must consider these sources of uncertainty to make informed decisions, as they can significantly affect the evaluation and comparison of alternatives(Ceran, 2020).

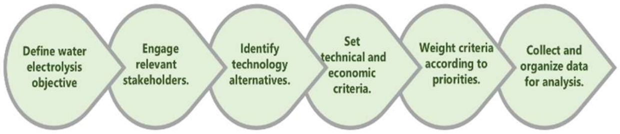

Figure 13. decision-making process for water electrolysers(A. Kumar et al., 2017).

3.4 Techno-economic Factors and MCDM Criteria

The selection of key indices or criteria for water electrolyser technoeconomic evaluation involves the consideration of multiple factors, including technical, economic, and environmental aspects. A comprehensive understanding of these factors is essential for designing and selecting the most suitable electrolyser technology for hydrogen production. By incorporating these factors into the decision-making process, stakeholders can make more informed decisions that contribute to a sustainable hydrogen economy(Ceran, 2020).

- **Technological Factors**:

Technological factors are crucial in the selection process, as they influence the efficiency, reliability, and longevity of water electrolysers. These factors include the fallowing aspects.

*Efficiency: Higher efficiency leads to reduced energy consumption and lower operational costs;

*Durability: Long-lasting electrolysers reduce maintenance and replacement costs, contributing to lower overall expenses.

*Response time: Fast response times allow electrolysers to adapt to fluctuating energy demands and operate more efficiently.

*Scalability: Scalable technologies enable cost-effective expansion of hydrogen production capacity;

*Technological maturity: Mature technologies have more extensive operational experience and reliable performance data(Linkov & Moberg, 2011). Assessing technology maturity and development potential allows stakeholders to understand market readiness, risks, and future advancements.

- **Economic Factors**: Economic factors play a vital role in determining the feasibility and attractiveness of water electrolyser technologies. These factors can be listed in the following.

*Capital cost: Lower capital costs make the technology more accessible and reduce the initial investment barrier.

*Operating cost: Operating costs directly impact the cost of hydrogen production, affecting the technology's competitiveness in the market;

*Levelized cost of hydrogen (LCOH): LCOH is a comprehensive metric that accounts for all costs associated with hydrogen production, allowing for direct comparisons between different technologies;

*Market potential: Market potential reflects the demand for hydrogen and the expected growth of the technology in the coming years(Linkov & Moberg, 2011).

- **Environmental Factors**: Environmental factors are increasingly important due to rising concerns about climate change and the need for sustainable hydrogen production methods. The environmental issues are the main reason of the development of green hydrogen as an energy vector These factors include the following aspects.

*Life cycle greenhouse gas (GHG) emissions: Lower GHG emissions contribute to mitigating climate change and promoting environmentally responsible hydrogen production.

*Water consumption: Minimizing water consumption is essential for sustainable resource management and reducing the environmental footprint of hydrogen production.

*Land use: Optimizing land use can reduce the environmental impact and facilitate the integration of electrolysers with other energy systems(Bhole & Deshmukh, 2018).

The criteria used can vary depending on the specific application, operating conditions, and other factors, but they typically encompass economic, social, technical, and environmental considerations. These indices and criteria provide a comprehensive evaluation of the potential hydrogen production system, allowing stakeholders to make relevant decisions about investment, operation, and future development.

- **Social impacts**

Social factors are important in the techno-economic analysis of water electrolysers as they ensure the technology aligns with societal needs and expectations, ultimately influencing its success and adoption. Here are the sub-criteria and their importance:

*Social acceptability: Gaining public support and acceptance is crucial for the successful deployment and adoption of water electrolyser technologies. Positive perception helps facilitate investment, regulatory approvals, and infrastructure development.

*Safeguard: Ensuring the safety of the technology, including the handling, storage, and use of hydrogen, is vital for public trust and acceptance. A strong safety record reduces potential barriers to adoption and minimizes risks to communities and the environment.

*Degree of government support: Government support, through policies, incentives, and funding, can significantly impact the development and adoption of water electrolyser technologies. Understanding the level of support helps evaluate the feasibility and potential for growth in the market;

- **Technical aspects**

It plays a crucial role in the techno-economic analysis of water electrolysers, as they enable performance optimization, cost assessment, and evaluation of system reliability and durability of the components. Taking these criteria into account provides a comprehensive understanding of the electrolyser components, promoting informed decision-making, system optimization, and the adoption of efficient and reliable hydrogen production technologies. Here are the sub-criteria in this study:

*Catalysts: Catalyst selection impacts the efficiency and durability of the electrolyser. Different catalyst materials and structures can influence the overall system performance and cost.

*Lifetime in hours: Assessing the expected lifetime of the components is crucial for determining its long-term reliability, maintenance costs, and return on investment.

*Bipolar plate in \$/m^2: Bipolar plates affect the cost, efficiency, and durability of the system. Comparing the costs of different materials and designs can help identify optima solutions.

*Electrolyte: The choice of electrolyte impacts the system's efficiency, safety, and operating conditions. Understanding the pros and cons of various electrolytes is vital for selecting the most suitable option.

*Electrode: Electrode materials and designs influence the system's efficiency, durability, and cost. Analyzing different electrode options helps optimize the electrolyser's performance.

*Porous transport layer (PTLS) (D6): PTLS facilitates gas and liquid transport within the cell, affecting efficiency, durability, and cost. Evaluating various PTLS options ensures optimal system performance.

*Diaphragm: The diaphragm separates the gas products and affects efficiency, durability, and cost. Different diaphragm materials and designs can significantly impact the electrolyser's performance.

Gaps in the body of knowledge

The literature review of the techno-economic evaluation of water electrolysis using Multi-Criteria Decision Making (MCDM) methods reveals several gaps in the body of knowledge. These gaps include. This part identifies specific gaps in the existing literature regarding the techno-economic evaluation of water electrolysis using MCDM methods. It mentions the lack of standardized MCDM methods, limited case studies, incomplete evaluation of uncertainty, limited consideration of environmental impact, and lack of interdisciplinary approaches.

1. Lack of standardized MCDM methods - There is a lack of standardization in the MCDM methods used to evaluate the techno-economic feasibility of water electrolysis, with different studies using different methods, making it difficult to compare results and identify trends. A standardized MCDM method would provide a consistent and transparent approach to the evaluation of water electrolysis, allowing for the comparison of results across different case studies.
2. Limited case studies - There is a limited number of case studies on the use of MCDM methods for the evaluation of water electrolysis, making it difficult to identify best practices and develop a comprehensive understanding of the subject. Expanding the number of case studies would provide a deeper understanding of the potential and limitations of MCDM methods for the evaluation of water electrolysis.
3. Incomplete evaluation of uncertainty - Most MCDM studies have only partially considered the impact of uncertainty on the results of the analysis, with few studies incorporating sensitivity analysis and scenario analysis to assess the robustness of the decision-making process under different conditions. A more comprehensive evaluation of uncertainty would provide a better understanding of the potential risks and benefits associated with water electrolysis as a green hydrogen production process.
4. Limited consideration of environmental impact - Many MCDM studies have only partially considered the environmental impact of water electrolysis, with few studies providing a comprehensive evaluation of the environmental impact of the process. A more comprehensive evaluation of the environmental impact of water electrolysis would provide a more complete picture of the sustainability of the process.
5. Lack of interdisciplinary approach - Most MCDM studies have been limited to a single discipline, such as economics or engineering, with few studies incorporating interdisciplinary approaches that consider multiple factors and perspectives in the analysis. An interdisciplinary approach would provide a more complete understanding of the techno-economic feasibility of water electrolysis, taking into account factors such as cost, environmental impact, and technological maturity.

4. DISCUSSION

Water electrolyser projects harness cutting-edge technologies to produce clean and sustainable hydrogen energy. Utilizing renewable resources, these projects can reduce greenhouse gas emissions and fossil fuel dependence. Investing in water electrolyser projects stimulates economic growth, job creation, and technology advancements, while enhancing energy resilience and promoting sustainability. However, addressing scalability, cost optimization, and efficient distribution networks is crucial.

Economic factors are, of course, vital in water electrolyser projects for countries transitioning to cleaner energy sources. Initial capital investment, operational and maintenance expenses, and renewable electricity affordability impact hydrogen production feasibility. Governments and private entities must collaborate to develop supportive policies, financial incentives, and subsidies. This fosters a conducive economic environment for green hydrogen adoption, stimulates job creation, promotes innovation, and supports sustainable growth while achieving energy transition goals.

Table 7. Criteria for water electrolyser technoeconomic evaluation(Gu, Wang, Chen, & Tang, 2022)

Category	Subcategory	Key Indices or Criteria	Description
Economic	Capital Cost	Initial Investment	The cost of acquiring, installing and commissioning the electrolyser system
Economic	Operating Cost	Energy Consumption	The cost of energy needed to run the electrolyser
Economic	Operating Cost	Maintenance	The cost of maintenance and repairs for the electrolyser
Economic	Operating Cost	Labor	The cost of labor required for the operation of the electrolyser
Social	Availability	Operational Time	The amount of time the electrolyser is operational and able to produce hydrogen
Technical	Efficiency	Electrical Efficiency	The percentage of electrical energy input that is converted into hydrogen output
Technical	Scalability	Production Capacity	The ability of the electrolyser system to accommodate increasing production demands
Technical	Durability	Lifespan	The expected lifespan of the electrolyser system and its components
Technical	Reliability	Performance Consistency	The consistency and predictability of the electrolyser's performance over time
Environmental	Safety	Operational Safety	The measures in place to ensure the safe operation of the electrolyser system
Environmental	Environmental Impact	Emissions	The impact of the electrolyser's operation on the environment in terms of emissions
Environmental	Environmental Impact	Waste Generation	The impact of the electrolyser's operation on the environment in terms of waste generated

There isn't a universally superior MCDM model, their effectiveness varies based on applications and objectives. But to foster a cleaner and more sustainable energy future(A. Kumar et al., 2017),we may consider more and more hybrid techniques which are emerging to tackle these challenges. MCDM captures planning objectives but is typically limited to larger geographical scales. Enhancing water electrolyser projects requires a comprehensive framework that considers multiple scenarios and focuses on local resources. This approach will assist countries in developing sustainable hydrogen production strategies, taking into account a range of scenarios and criteria. These include technical, economic, and technological aspects, as well as environmental considerations and societal impacts that could influence the success of the project. Consequently, this will allow for accurate determination of the Levelized Cost of Hydrogen (LCOH), enabling countries to more effectively implement their hydrogen production plans.

5. CONCLUSION

The conclusion highlights the critical review of the principal aspects (technical, technological, economical, environmental, and social impacts) of green hydrogen production from water electrolysis. It reiterates the importance of using MCDM techniques for the techno-economic analysis of water electrolysis projects, aiming to advance the green hydrogen industry development.

Critical review on principal aspects such as: technical, technological, economical, environmental and social impacts aspects of green hydrogen production from water electrolysis was achieved. Basic of water electrolysis reactions, the balance of energy, the type of materials and components and the techno economical issues were addressed. The role of Multi-Criteria Decision Making (MCDM) in reducing the cost of water electrolyser projects is significant in the global pursuit of clean energy. By evaluating various aspects of a project, such as capital investment, operational and maintenance expenses, and technology choices, MCDM enables stakeholders to make appropriate decisions that optimize costs and enhance efficiency. This comprehensive approach helps identify the most promising solutions and investment strategies. As countries around the world strive to transition to cleaner energy sources and meet their sustainability targets, MCDM's ability to systematically analyze and prioritize cost-effective water electrolyser solutions becomes increasingly essential. The application of MCDM for water electrolyser projects not only supports the global adoption of green hydrogen but also contributes to the overall goal of reducing greenhouse gas emissions and fostering a sustainable energy future.

The objective of this work is to investigate the use, in the literature, of Multi-Criteria Decision Making (MCDM) techniques for the electrolytic hydrogen production. The literature review shows that les number of criteria than the 5 main aspects or criteria such as economical, technical. Technological, environmental, and social impacts where mostly used in MCDM, until now, for the studies or in the assessments of real projects. We think that at least these 5 criteria must be considered for MCDM approach in the analysis of the feasibility and viability of a project. We will further use these 5 main criteria and to build a new MCDM approach which will contribute to the advancement of the green hydrogen industry development. This will support the growth sustainable energy solutions by providing decision-makers with a comprehensive evaluation of the techno-economic potential of water electrolysis as a green hydrogen production process.

REFERENCES

[1] (IEA), I. E. A. (2019). Hydrogen: A Clean Energy Carrier. Retrieved from https://www.iea.org/reports/hydrogen-a-clean-energy-carrier

[2] (NREL). (2021). Electrolysis for Hydrogen Production. Retrieved from https://www.nrel.gov/hydrogen/proton-exchange-membrane-electrolysis.htm

[3] Abdel-Basset, M., Gamal, A., Chakrabortty, R. K., & Ryan, M. J. (2021). Evaluation of sustainable hydrogen production options using an advanced hybrid MCDM approach: A case study. International Journal of Hydrogen Energy, 46(5), 4567-4591. doi:https://doi.org/10.1016/j.ijhydene.2020.10.232

[4] Ainscough, C., Peterson, D., & Miller, E. (2014). Hydrogen production cost from PEM electrolysis. DOE hydrogen and fuel cells program record, 14004.

[5] Alexander Buttler, H. S. (2018). Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. Renewable and Sustainable Energy Reviews. doi:https://doi.org/10.1016/j.rser.2017.09.003

[6] Aminov, R., & Bairamov, A. (2017). Performance evaluation of hydrogen production based on off-peak electric energy of the nuclear power plant. International Journal of Hydrogen Energy, 42(34), 21617-21625. doi:https://doi.org/10.1016/j.ijhydene.2017.07.132

[7] Anwar, S., Khan, F., Zhang, Y., & Djire, A. (2021). Recent development in electrocatalysts for hydrogen production through water electrolysis. International Journal of Hydrogen Energy, 46(63), 32284-32317. doi:https://doi.org/10.1016/j.ijhydene.2021.06.191

[8] Bessarabov, D., & Millet, P. (2018). PEM water electrolysis (Vol. 1): Academic Press.

[9] Bessarabov, D., Wang, H., Li, H., & Zhao, N. (2015). PEM electrolysis for hydrogen production: principles and applications: CRC press.

[10] Bhole, G. P., & Deshmukh, T. (2018). Multi-criteria decision making (MCDM) methods and its applications. International Journal for Research in Applied Science & Engineering Technology (IJRASET), 6(5), 899-915. doi:http://doi.org/10.22214/ijraset.2018.5145

[11] Brauns, J., & Turek, T. (2020). Alkaline water electrolysis powered by renewable energy: A review. Processes, 8(2), 248. doi: https://doi.org/10.3390/pr8020248

[12] Canton, H. (2021). International energy agency—iea. In The Europa Directory of International Organizations 2021 (pp. 684-686): Routledge

[13] Ceran, B. (2020). Multi-Criteria comparative analysis of clean hydrogen production scenarios. Energies, 13(16), 4180. doi:10.3390/en13164180

[14] Chatenet, M., Pollet, B. G., Dekel, D. R., Dionigi, F., Deseure, J., Millet, P., . . . Staffell, I. (2022). Water electrolysis: from textbook knowledge to the latest scientific strategies and industrial developments. Chemical Society Reviews. doi:10.1039/D0CS01079K

[15] Chen, X., Yang, C., Sun, Y., Liu, Q., Wan, Z., Kong, X., . . . Wang, X. (2022). Water management and structure optimization study of nickel metal foam as flow distributors in proton exchange membrane fuel cell. Applied Energy, 309, 118448. doi:https://doi.org/10.1016/j.apenergy.2021.118448

[16] Colozza, A. J., & Jakupca, I. J. (2019). Thermal System Sizing Comparison of a PEM and Solid Oxide Fuel Cell Systems on Mars. Retrieved from

[17] Commission, E. (2021). Green hydrogen from electrolysis: What is it and how can it help decarbonise the EU energy system? Retrieved from https://ec.europa.eu/energy/topics/renewable-energy/hydrogen_en

[18] Congress, G. C. (2021). World's largest hydrogen electrolysis plant in Canada now operational. Retrieved from https://www.greencarcongress.com/2020/12/20201221-airliquide.html

[19] Cooper, N., Horend, C., Röben, F., Bardow, A., & Shah, N. (2022). A framework for the design & operation of a large-scale wind-powered hydrogen electrolyzer hub. International Journal of Hydrogen Energy, 47(14), 8671-8686. doi:https://doi.org/10.1016/j.ijhydene.2021.12.225

[20] David, M., Ocampo-Martínez, C., & Sánchez-Peña, R. (2019). Advances in alkaline water electrolyzers: A review. Journal of Energy Storage, 23, 392-403. doi:https://doi.org/10.1016/j.est.2019.03.001

[21] David Parra, M. K. P. (2016). Techno-economic implications of the electrolyser technology and size for power-to-gas systems. International Journal of Hydrogen Energy. doi:https://doi.org/10.1016/j.ijhydene.2015.12.160

[22] Dincer, I. Energy Solutions to Combat Global Warming: Springer.

[23] DOE. (2021). Hydrogen Fuel Cell Vehicles. doi:https://doi.org/10.1016/j.jpowsour.2021.229450

[24] Du, Z., Liu, C., Zhai, J., Guo, X., Xiong, Y., Su, W., & He, G. (2021). A review of hydrogen purification technologies for fuel cell vehicles. Catalysts, 11(3), 393. doi: https://doi.org/10.3390/catal11030393

[25] E.ON. (2021). green hydrogen production facility in Germany. Retrieved from https://www.eon.com/en.html

[26] Economics, S. E. (2020). Hydrogen Strategy for a Climate-Neutral Europe. Brussels.

[27] Ehlers, J. C., Feidenhans'l, A. A., Therkildsen, K. T., & Larrazábal, G. O. (2023). Affordable Green Hydrogen from Alkaline Water Electrolysis: Key Research Needs from an Industrial Perspective. ACS Energy Letters, 8, 1502-1509. doi:https://doi.org/10.1021/acsenergylett.2c02897

[28] Frangoul, A. (2021). biggest green hydrogen plants. Retrieved from https://www.cnbc.com/2021/01/19/canada-is-set-to-have-one-the-worlds-biggest-green-hydrogen-plants.html

[29] Ganci, F., Patella, B., Cannata, E., Cusumano, V., Aiello, G., Sunseri, C., . . . Inguanta, R. (2021). Ni alloy nanowires as high efficiency electrode materials for alkaline electrolysers. International Journal of Hydrogen Energy, 46(72), 35777-35789. doi:https://doi.org/10.1016/j.ijhydene.2020.11.208

[30] GlobalData. (2023). Hydrogen market growth to surge in 2023 despite slowing global economy, says GlobalData. Retrieved from https://www.globaldata.com/media/oil-gas/hydrogen-market-growth-surge-2023-despite-slowing-global-economy-says-globaldata/

[31] Grigoriev, S., Fateev, V., Bessarabov, D., & Millet, P. (2020). Current status, research trends, and challenges in water electrolysis science and technology. International Journal of Hydrogen Energy, 45(49), 26036-26058. doi:https://doi.org/10.1016/j.ijhydene.2020.03.109

[32] Gu, Y., Wang, D., Chen, Q., & Tang, Z. (2022). Techno-economic analysis of green methanol plant with optimal design of renewable hydrogen production: A case study in China. International Journal of Hydrogen Energy, 47(8), 5085-5100. doi:https://doi.org/10.1016/j.ijhydene.2021.11.148

[33] Guo, X., Wei, Y., Wan, Y., Zhou, Y., Kong, L., Zhang, Z., . . . Malinowski, M. (2021). Review on power electronic converters for producing hydrogen from renewable energy sources. Dianli Xitong Zidonghua/Automation of Electric Power Systems, 45(20), 185-199. doi:https://doi.org/10.7500/AEPS20201101004

[34] Henning G. Langås, N. H. (2015). LARGE SCALE HYDROGEN PRODUCTION. Retrieved from https://www.sintef.no/contentassets/9b9c7b67d0dc4fbf9442143f1c52393c/9-hydrogen-production-in-large-scale-henning-g.-langas-nel-hydrogen.pdf

[35] Hernández-Gómez, Á., Ramirez, V., Guilbert, D., & Saldivar, B. (2020). Development of an adaptive static-dynamic electrical model based on input electrical energy for PEM water electrolysis. International Journal of Hydrogen Energy, 45(38), 18817-18830. doi:https://doi.org/10.1016/j.ijhydene.2020.04.182

[36] Heraeus, PEM Electrolysis: Iridium Catalysts for Electrodes Heraeus

[37] Hu, F., Xie, Z.-P., Zhang, J., Hu, Z.-L., & An, D. (2020). Promising high-thermal-conductivity substrate material for high-power electronic device: silicon nitride ceramics. Rare Metals, 39, 463-478. doi:https://doi.org/10.1007/s12598-020-01376-7

[38] Hu, K., Fang, J., Ai, X., Huang, D., Zhong, Z., Yang, X., & Wang, L. (2022). Comparative study of alkaline water electrolysis, proton exchange membrane water electrolysis and solid oxide electrolysis through multiphysics modeling. Applied Energy, 312, 118788. doi:https://doi.org/10.1016/j.apenergy.2022.118788

[39] HyBalance. (2020). a project that demonstrates the use of hydrogen in energy systems. Retrieved from https://hybalance.eu/#:~:text=HyBalance%20is%20a%20project%20that,and%20in%20the%20industrial%20sector.

[40] IEA. (2013). World Energy Outlook Analysis. Retrieved from https://www.iea.org/report s/world-energy-outlook-2013

[41] IEA. (2021). Global installed electrolysis capacity by technology,Global Hydrogen Review. Retrieved from https://www.iea.org/data-and-statistics/charts/global-installed-electrolysis-capacity-by-technology-2015-2020

[42] IRENA. (2019). The Potential of Hydrogen. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Jan/IRENA_The_potential_of_hydrogen_2019.pdf

[43] IRENA. (2020). Green hydrogen cost reduction: Scaling up electrolyzers to meet the challenge. Abu Dhabi. Retrieved from https://www.irena.org/

[44] IRENA, E. (2020). Green hydrogen cost reduction: scaling up electrolysers to meet the 1.5 C climate goal. In /Publications/2020/dec/green-hydrogen-cost-reduction (pp. 105).

[45] ITM. (2021). Green Hydrogen, produced by PEM electrolysers. Retrieved from https://itm-power.com/

[46] James, B. D., Huya-Kouadio, J., Acevedo, Y., & McNamara, K. (2021). Liquid Alkaline Electrolysis Techno-Economic Review.

[47] James, B. D., Huya-Kouadio, J., Acevedo, Y., & McNamara, K. (2021). Liquid Alkaline Electrolysis Techno-Economic Review. Retrieved from https://www.energy.gov/sites/default/files/2022-02/7-TEA-Liquid%20Alkaline%20Workshop.pdf

[48] Jang, D., Kim, J., Kim, D., Han, W.-B., & Kang, S. (2022). Techno-economic analysis and Monte Carlo simulation of green hydrogen production technology through various water electrolysis technologies. Energy conversion and management, 258, 115499. doi:https://doi.org/10.1016/j.enconman.2022.115499

[49] Jourdani, M., Mounir, H., & Marjani, A. E. (2017). Latest trends and challenges InProton Exchange Membrane Fuel Cell (PEMFC). The Open Fuels & Energy Science Journal, 10. doi:10.2174/1876973X01710010096

[50] Kadier, A., Simayi, Y., Abdeshahian, P., Azman, N. F., Chandrasekhar, K., & Kalil, M. S. (2016). A comprehensive review of microbial electrolysis cells (MEC) reactor designs and configurations for sustainable hydrogen gas production. Alexandria Engineering Journal, 55(1), 427-443. doi:https://doi.org/10.1016/j.aej.2015.10.008

[51] Krull, F. (2020). the H2FUTURE research project. Retrieved from https://www.siemens-energy.com/global/en/news/magazine/2020/h2future-voestalpine-linz.html

[52] Kuleshov, N., Kuleshov, V., Dovbysh, S., Grigoriev, S., Kurochkin, S., & Millet, P. (2019). Development and performances of a 0.5 kW high-pressure alkaline water electrolyser. International Journal of Hydrogen Energy, 44(56), 29441-29449. doi:https://doi.org/10.1016/j.ijhydene.2019.05.044

[53] Kumar, A., Sah, B., Singh, A. R., Deng, Y., He, X., Kumar, P., & Bansal, R. (2017). A review of multi criteria decision making (MCDM) towards sustainable renewable energy development. Renewable and Sustainable Energy Reviews, 69, 596-609. doi:https://doi.org/10.1016/j.rser.2016.11.191

[54] Kumar, S. S., & Lim, H. (2022). An overview of water electrolysis technologies for green hydrogen production. Energy Reports, 8, 13793-13813. doi:https://doi.org/10.1016/j.egyr.2022.10.127

[55] Linge, J. M., Erikson, H., Mooste, M., Piirsoo, H.-M., Kaljuvee, T., Kikas, A., . . . Kannan, A. M. (2023). Ag nanoparticles on mesoporous carbon support as cathode catalyst for anion exchange membrane fuel cell. International Journal of Hydrogen Energy. doi:https://doi.org/10.1016/j.ijhydene.2022.12.138

[56] Linkov, I., & Moberg, E. (2011). Multi-criteria decision analysis: environmental applications and case studies: CRC Press.

[57] Liu, H.-C., & Liu, H.-C. (2016). FMEA using uncertainty theories and MCDM methods: Springer.

Liu, H., Grot, S., & Logan, B. E. (2005). Electrochemically assisted microbial production of hydrogen from acetate. Environmental science & technology, 39(11), 4317-4320. doi:https://doi.org/10.1021/es050244p

[58] M.Kopp, D. C., C.Stiller, K.Scheffer, J.Aichinger, B.Scheppat. (2017). Energiepark Mainz: Technical and economic analysis of the worldwide largest Power-to-Gas plant with PEM electrolysis. International Journal of

Hydrogen Energy. doi:https://doi.org/10.1016/j.ijhydene.2016.12.145

[59] Mackenzie, W. (2019). Green hydrogen production: Landscape, projects and costs. Edinburgh: Wood Mackenzie. Martin, E., Tartakovsky, B., & Savadogo, O. (2011). Cathode materials evaluation in microbial fuel cells: A comparison of carbon, Mn2O3, Fe2O3 and platinum materials. Electrochimica acta, 58, 58-66. doi:https://doi.org/10.1016/j.electacta.2011.08.078

[60] Marubeni. (2022). The Renewable Hydrogen Project. Retrieved from https://www.marubeni.com/en/

[61] Mayyas, A. T., Ruth, M. F., Pivovar, B. S., Bender, G., & Wipke, K. B. (2019). Manufacturing cost analysis for proton exchange membrane water electrolyzers. Retrieved from

[62] Mazloomi, K., & Gomes, C. (2012). Hydrogen as an energy carrier: Prospects and challenges. Renewable and Sustainable Energy Reviews, 16(5), 3024-3033. doi:https://doi.org/10.1016/j.rser.2012.02.028

[63] Millet, P. (2011). Water Electrolysis for Hydrogen Generation. In Electrochemical Technologies for Energy Storage and Conversion (pp. 383-423).

[64] Naqvi, S. A. H., Taner, T., Ozkaymak, M., & Ali, H. M. (2023). Hydrogen Production through Alkaline Electrolyzers: A Techno-Economic and Enviro-Economic Analysis. Chemical Engineering & Technology, 46(3), 474-481. doi: https://doi.org/10.1002/ceat.202200234

[65] Neisiani.M., S., O., Chaouki, J ., Fradette, L., & Tanguy, A. Philippe. (2020). Volet B: Revue de littérature technico-éonomique de l'hydrogène: de la production a l'utilisation. Gouvernement du Quebec, Transition enérgétique. . Retrieved from https://transitionenergetique.gouv.qc.ca/fileadmin/medias/pdf/expertises/Etude_hydrogene_Volet_B.pdf

[66] OLUFJENSEN, J., Chatzichristodoulou, C., Christensen, E., Bjerrum, N. J., & Li, Q. (2019). Intermediate temperature electrolysers. Electrochemical Methods for Hydrogen Production, 25, 253. doi:https://doi.org/10.1039/9781788016049

[67] Osmieri, L., & Meyer, Q. (2022). Recent advances in integrating platinum group metal-free catalysts in proton exchange membrane fuel cells. Current Opinion in Electrochemistry, 31, 100847. doi:https://doi.org/10.1016/j.coelec.2021.100847

[68] Paidar, M., Fateev, V., & Bouzek, K. (2016). Membrane electrolysis—History, current status and perspective. Electrochimica acta, 209, 737-756. doi:https://doi.org/10.1016/j.electacta.2016.05.209

[69] Pikalova, E., Osinkin, D., & Kalinina, E. (2022). Direct electrophoretic deposition and characterization of thin-film membranes based on doped BaCeO3 and CeO2 for anode-supported solid oxide fuel cells. Membranes, 12(7), 682. doi: https://doi.org/10.3390/membranes12070682

[70] Pohekar, S. D., & Ramachandran, M. (2004). Application of multi-criteria decision making to sustainable energy planning—A review. Renewable and Sustainable Energy Reviews, 8(4), 365-381. doi:https://doi.org/10.1016/j.rser.2003.12.007

[71] Qi, R., Li, J., Lin, J., Song, Y., Wang, J., Cui, Q., . . . Wang, J. (2023). Design of the PID temperature controller for an alkaline electrolysis system with time delays. International Journal of Hydrogen Energy. doi:https://doi.org/10.1016/j.ijhydene.2023.01.356

[72] Quebec, H. (2020). Hydro-Québec to operate one of the world's most powerful electrolyzers to produce green hydrogen. Retrieved from http://news.hydroquebec.com/en/press-releases/1667/hydro-quebec-to-operate-one-of-the-worlds-most-powerful-electrolyzers-to-produce-green-hydrogen/

[73] Radinović, K., Mladenović, D., Milikić, J., Alsaiari, M., Harraz, F. A., Santos, D. M., & Šljukić, B. (2022). Tuning Electrocatalytic Activity of Gold Silver Nanoparticles on Reduced Graphene Oxide for Oxygen Reduction Reaction. Journal of The Electrochemical Society, 169(5), 054501. doi: 10.1149/1945-7111/ac67b7

[74] Ren, X., Li, W., Ding, S., & Dong, L. (2020). Sustainability assessment and decision making of hydrogen production technologies: A novel two-stage multi-criteria decision making method. International Journal of Hydrogen Energy, 45(59), 34371-34384. doi:https://doi.org/10.1016/j.ijhydene.2019.12.134

[75] Renforth, P. (2019). The negative emission potential of alkaline materials. Nature communications, 10(1), 1401. doi:https://doi.org/10.1038/s41467-019-09475-5

[76] Roy, B. (1990). Decision-aid and decision-making. European Journal of Operational Research, 45(2-3), 324-331. doi:https://doi.org/10.1016/0377-2217(90)90196-I

[77] Saaty, T. L. (1980). TheAnalyticHierarchyProcess. McGrawhill, Juc. New York.

[78] Saaty, T. L. (1996). Decision making with dependence and feedback: The analytic network process (Vol. 4922): RWS publications Pittsburgh.

[79] Sanchez, M., Amores, E., Abad, D., Rodriguez, L., & Clemente-Jul, C. (2020). Aspen Plus model of an alkaline electrolysis system for hydrogen production. International Journal of Hydrogen Energy, 45(7), 3916-3929. doi:https://doi.org/10.1016/j.ijhydene.2019.12.02

[80] Savadogo, O. (2000). Water electrolysis in acid medium. Hemijska industrija, 54(3), 95-101.

[81] Savadogo, O., Fradette, L., Chaouki, J., Neisiani, M., & Tanguy, P. A. (2020). Étude sur le potentiel technico-économique du développement de la filière de l'hydrogène au Québec et son potentiel pour la transition énergétique–Volet A: Portrait régional, canadien et international actuel de l'économie de l'hydrogène. Rapport préparé pour Transition énergétique Québec. Polytechnique Montréal.

[82] Scott, K. (2019). Electrochemical methods for hydrogen production: Royal Society of Chemistry.

[83] Shanian, A., & Savadogo, O. (2006a). ELECTRE I decision support model for material selection of bipolar plates for Polymer Electrolyte Fuel Cells applications. Journal of New Materials for Electrochemical Systems, 9(3), 191.

[84] Shanian, A., & Savadogo, O. (2006a). A material selection model based on the concept of multiple attribute decision making. Materials & Design, 27(4), 329-337. doi:https://doi.org/10.1016/j.matdes.2004.10.027

[85] Shanian, A., & Savadogo, O. (2006b). A non-compensatory compromised solution for material selection of bipolar plates for polymer electrolyte membrane fuel cell (PEMFC) using ELECTRE IV. Electrochimica acta, 51(25), 5307-5315. doi:https://doi.org/10.1016/j.electacta.2006.01.055

[86] Shanian, A., & Savadogo, O. (2006c). TOPSIS multiple-criteria decision support analysis for material selection of metallic bipolar plates for polymer electrolyte fuel

cell. Journal of Power Sources, 159(2), 1095-1104. doi:https://doi.org/10.1016/j.jpowsour.2005.12.092

[87] Shanian, A., & Savadogo, O. (2006b). Using multi-pseudocriteria and fuzzy outranking relation analysis for material selection of bipolar plates for PEFCs. Journal of The Electrochemical Society, 153(5), A887. doi: 10.1149/1.2181437

[88] Shanian, A., & Savadogo, O. (2009). A methodological concept for material selection of highly sensitive components based on multiple criteria decision analysis. Expert Systems with Applications, 36(2, Part 1), 1362-1370. doi:https://doi.org/10.1016/j.eswa.2007.11.052

[89] Shiva Kumar, S., & Himabindu, V. (2019). Hydrogen production by PEM water electrolysis – A review. Materials Science for Energy Technologies, 2(3), 442-454. doi:https://doi.org/10.1016/j.mset.2019.03.002

[90] Shiva Kumar, S., & Lim, H. (2022). An overview of water electrolysis technologies for green hydrogen production. Energy Reports, 8, 13793-13813. doi:https://doi.org/10.1016/j.egyr.2022.10.127

[91] Sun, X., Xu, K., Fleischer, C., Liu, X., Grandcolas, M., Strandbakke, R., . . . Chatzitakis, A. (2018). Earth-abundant electrocatalysts in proton exchange membrane electrolyzers. Catalysts, 8(12), 657. doi:10.3390/catal8120657

[92] Thengane, S. K., Hoadley, A., Bhattacharya, S., Mitra, S., & Bandyopadhyay, S. (2014). Cost-benefit analysis of different hydrogen production technologies using AHP and Fuzzy AHP. International Journal of Hydrogen Energy, 39(28), 15293-15306. doi:https://doi.org/10.1016/j.ijhydene.2014.07.107

[93] THOMAS, D. (18 June 2018,). COST REDUCTION POTENTIAL

[94] FOR ELECTROLYSER TECHNOLOGY. Retrieved from https://www.humsterlandenergie.nl/resources/LInks-duurzaam/Linkpagina/20180619_Hydrogenics_EU-P2G-Platform_for-distribution.pdf

[95] Triantaphyllou, E., & Triantaphyllou, E. (2000). Multi-criteria decision making methods: Springer.

[96] Tsiaka, T., Sinanoglou, V. J., & Zoumpoulakis, P. (2017). Extracting bioactive compounds from natural sources using green high-energy approaches: trends and opportunities in lab-and large-scale applications. In Ingredients extraction by physicochemical methods in food (pp. 307-365): Elsevier.

[97] Vidas, L., & Castro, R. (2021). Recent Developments on Hydrogen Production Technologies: State-of-the-Art Review with a Focus on Green-Electrolysis. Applied Sciences, 11(23), 11363. doi:https://doi.org/10.3390/app112311363

[98] Wang, J.-J., Jing, Y.-Y., Zhang, C.-F., & Zhao, J.-H. (2009). Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renewable and Sustainable Energy Reviews, 13(9), 2263-2278. doi:https://doi.org/10.1016/j.rser.2009.06.021

[99] Wang, Z., Wang, X., Chen, Z., Liao, Z., Xu, C., & Du, X. (2021). Energy and exergy analysis of a proton exchange membrane water electrolysis system without additional internal cooling. Renewable Energy, 180, 1333-1343. doi:https://doi.org/10.1016/j.renene.2021.09.037

[100] Yu, Z. Y., Duan, Y., Feng, X. Y., Yu, X., Gao, M. R., & Yu, S. H. (2021). Clean and affordable hydrogen fuel from alkaline water splitting: past, recent progress, and future prospects. Advanced Materials, 33(31), 2007100. doi: https://doi.org/10.1002/adma.202007100

[101] Zhigang, S., Baolian, Y., & Ming, H. (1999). Bifunctional electrodes with a thin catalyst layer forunitized'proton exchange membrane regenerative fuel cell. Journal of Power Sources, 79(1), 82-85. doi:https://doi.org/10.1016/S0378-7753(99)00047-6

[102] Zopounidis, C., & Pardalos, P. M. (2010). Handbook of multicriteria analysis (Vol. 103): Springer Science & Business Media.