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**Techno-economic analysis of hydrogen production by water electrolysis using
multi-criteria decision methods (MCDM)**

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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Ce mémoire intitulé :

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présenté par **Solmaz SHANIAN**

en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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DEDICATION

To my dear brother, who guided and supported me throughout my master's journey, not only changing my life for the better but also making it brighter. I dedicate this achievement to you in recognition of your positive impact on my life.

To my dear husband, Mohammadali, a steady light, shining hope through life's storms.

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I wish to extend my sincerest gratitude to my research director, Prof. Omarou Savadogo, for providing me with the opportunity to work in this field. I am deeply grateful for his guidance, support, and encouragement during my studies. His passion for science and personal investment in my projects enabled me to overcome numerous challenging moments. I would not have achieved success without his unwavering care and attention.

I also express my heartfelt thanks to Professor Oumarou Savadogo for his invaluable advice and steadfast support throughout the entirety of the research project.

RÉSUMÉ

L'hydrogène est reconnu comme un vecteur d'énergie essentiel pour un avenir durable, avec un potentiel considérable pour décarboner divers secteurs de l'économie mondiale. Ces dernières années, la production d'hydrogène par électrolyse de l'eau a attiré l'attention des chercheurs et des acteurs industriels du monde entier, car elle offre une voie prometteuse vers la production d'énergie propre, durable et respectueuse de l'environnement. Ce procédé exploite les ressources abondantes en eau et l'électricité renouvelable pour produire de l'hydrogène sans émettre de gaz à effet de serre, ce qui en fait un élément clé dans la poursuite mondiale d'un avenir à faible teneur en carbone. Alors que des pays comme le Canada adoptent la demande croissante d'énergies propres, l'importance mondiale de la production d'hydrogène par électrolyse de l'eau ne peut être surestimée. Cependant, la compétitivité en termes de coûts de cette technologie reste un défi.

Dans cette thèse, nous présentons une évaluation technico-économique de la production d'hydrogène par électrolyse de l'eau, en utilisant la prise de décision multicritères (MCDM) pour évaluer et optimiser le coût et les performances des différentes technologies d'électrolyseurs. L'objectif principal de cette étude est de démontrer l'efficacité du MCDM pour identifier les critères les plus rentables et gérer l'incertitude associée aux multiples critères qui contribuent à l'efficacité globale du système.

En nous concentrant sur les électrolyseurs à membrane échangeuse de protons (PEM) et alcalins, nous avons développé un code pour déterminer leurs caractéristiques thermodynamiques, ce qui nous a permis de calculer le coût de production d'hydrogène. En comparant les coûts et les performances de ces types d'électrolyseurs, nous avons pu évaluer l'influence des différents critères sur la réduction des coûts entre les alternatives.

Cette recherche met en évidence l'importance de l'hydrogène dans la transition énergétique mondiale et démontre l'utilité du MCDM comme moyen de gérer les critères de réduction des coûts dans le contexte des technologies d'électrolyse de l'eau. Les résultats offrent des perspectives précieuses pour les décideurs de l'industrie de la production d'hydrogène et contribuent à l'optimisation des technologies d'électrolyse de l'eau pour une production durable d'hydrogène à l'échelle mondiale.

ABSTRACT

Hydrogen is recognized as a vital energy carrier for a sustainable future, with substantial potential to decarbonize various sectors of the global economy. In recent years, hydrogen production through water electrolysis has attracted significant attention from researchers and industry stakeholders worldwide, as it offers a promising path towards clean, sustainable, and environmentally friendly energy generation. This process harnesses abundant water resources and renewable electricity to produce hydrogen without producing greenhouse gas emissions, making it a key component in the global pursuit of a low-carbon future. As countries like Canada embrace the increasing demand for clean energy, the worldwide importance of hydrogen production through water electrolysis cannot be overstated. However, the cost competitiveness of this technology remains a challenge.

In this thesis, we present a techno-economic assessment of hydrogen production by water electrolysis, employing Multi-Criteria Decision Making (MCDM) to evaluate and optimize the cost and performance of different electrolyser technologies. The primary objective of this study is to demonstrate the effectiveness of MCDM in identifying the most cost-effective criteria and managing the uncertainty associated with multiple criteria that contribute to the overall system efficiency.

Focusing on Proton Exchange Membrane (PEM) and Alkaline electrolyzers, we developed a code to determine their thermodynamic characteristics, which allowed us to calculate the hydrogen production cost. By comparing the costs and performance of these electrolyser types, we were able to assess the influence of different criteria on cost reduction between alternatives.

This research highlights the importance of hydrogen in the global energy transition and demonstrates the utility of MCDM to manage criteria for cost reduction in the context of water electrolysis technologies. The results offer valuable insights for decision-makers in the hydrogen production industry and contribute to the optimization of water electrolysis technologies for sustainable hydrogen production worldwide.

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LISTE OF SYMBOLS AND ABBREVIATIONS

AEC	Alkaline Electrolysis Cell
BEV	Battery Electric Vehicle
BWM	Best Worst Method
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CHP	Combined Heat and Power
CSP	Concentrated Solar Power
DOE	Department of Energy
EOR	Enhanced Oil Recovery
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas Emissions
H ₂	Hydrogen
HOMER	Hybrid Optimization of Multiple Energy Resources
ICE	Internal Combustion Engine
IEA	International Energy Agency
LCA	Life Cycle Assessment
LCOH	Levelized Cost of Hydrogen
MCDM	Multi-Criteria Decision Making
NREL	National Renewable Energy Laboratory
OPEX	Operational Expenditure

PEM	Proton Exchange Membrane
PV	Photovoltaic
RES	Renewable Energy Sources
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
WASPAS	Weighted Aggregated Sum Product Assessment

CHAPTER 1 INTRODUCTION

1.1. Problem statement

Hydrogen is becoming increasingly important as an energy carrier due to its renewable and clean characteristics, high energy density, versatility, and potential to help achieve low-carbon economy goals. The decision to produce hydrogen using water electrolysis is driven by the growing need for cleaner and more sustainable energy sources, as traditional fossil fuels contribute to climate change and other environmental problems. In contrast, hydrogen produced through water electrolysis is considered a clean and renewable energy source that can help reduce greenhouse gas emissions and other harmful pollutants. Moreover, the availability of renewable energy sources such as wind and solar power has made water electrolysis an attractive option for producing hydrogen in Canada, as it can be powered sustainably.

The production of hydrogen through water electrolysis presents significant potential as a clean and renewable energy source. However, the high cost associated with this technology has limited its widespread adoption. To evaluate the feasibility of hydrogen production through water electrolysis from both technical and economic perspectives, a comprehensive technical-economic analysis is necessary. This analysis must consider various factors such as equipment capital cost, process energy efficiency, and electricity cost. Although the current cost of hydrogen production through water electrolysis is higher than conventional fossil fuel-based methods, there is a need to develop sustainable and efficient production methods that can compete with conventional methods. , such as for example, natural gas reforming. Multi-criteria decision analysis (MCDM) enables us to take a proper decision by choosing the best alternative among available alternatives or small set of good alternatives, or grouping alternatives into different preference sets. In other words MCDM solving enables to choose the efficient and not necessary the dominated alternatives. In the case of this work, MCDM techniques provide a powerful tool for evaluating the existing industrial technologies or alternatives for the hydrogen production through water electrolysis by considering multiple criteria and options or alternatives. This will enable us to a decision on which might be the efficient technology among the others for hydrogen production from water electrolysis. MCDM offers a framework for assessing complex problems and uses methods such as AHP,

TOPSIS, and MAUT. This approach can aid in decision-making by identifying the most appropriate hydrogen production technology based on criteria such as economic.

Considerations, technology aspects, technical parameters, social and environmental impacts.

For example, Accordingly, MCDM techniques can be used to conduct a comparative analysis of different hydrogen production technologies such as alkaline electrolysis, PEM electrolysis, and solid oxide electrolysis.

Although the high cost associated with hydrogen production through water electrolysis has hindered its development and use as a clean and renewable energy source, technico-economic analysis of hydrogen production through water electrolysis using MCDM techniques provides a comprehensive and integrated evaluation method that can determine the feasibility of this technology based on multiple criteria. This approach can enable effective decision-making and identify the most appropriate hydrogen production technology. To achieve a sustainable and efficient hydrogen production system, continuous research and development of advanced technologies and cost-effective solutions are necessary. By leveraging MCDM techniques to evaluate the feasibility of hydrogen production through water electrolysis, decision-makers can make informed choices that will expedite the adoption of hydrogen as a clean and renewable energy source.

1.2. Objectives

The main objective of this thesis is as follows:

- The main objective is to use multi criteria decision making (MCDM) methods to determine the techno-economic limiting parameters in the development of hydrogen production using water electrolysis.
- The success of the main objective is supported by the following sub-objectives:
- Conduct a comprehensive review of relevant literature on the techno-economic analysis of hydrogen production using water electrolysis.
- Utilize the Fuzzy best-worst method (FBWM) of MCDM to determine the weight of each criterion.

- Apply Interval TOPSIS, and WASPAS MCDM techniques to carry out a comprehensive techno-economic analysis of hydrogen production from water electrolysis.
- Determine the most appropriate MCDM method for the analysis and identify the limiting parameters for industrial hydrogen production from water electrolysis.
- Estimate the levelized cost of hydrogen for a 5 MW proton exchange membrane (PEM) and alkaline electrolysis system.

1.3. Thesis organization

There are seven chapters in this thesis. Chapter 2 examines the existing literature on water electrolysis science and technology, focusing on the challenges and trends. Additionally, we investigate the use of techno-economic and multi-criteria decision-making (MCDM) as tools for evaluating hydrogen production, with the aim of identifying any knowledge gaps.

Chapter 3 details the methodology employed to achieve the research objectives. Moving on to Chapter 4 and 5 presents the articles 1 and 2 submitted to scientific journals.

Finally, Chapter 6 and 7 and recommendation presents the overall conclusions drawn from the study.

In this dissertation, the articles present:

- A critical review of the techno-economic analysis of the hydrogen production from water electrolyzers using multi-criteria decision making (MCDM)
- Techno economic of Hydrogen by water Electrolysers using MCDM methods.

The first article begins with a review of the literature addressing the design, materials, and features that contribute to the cost of hydrogen production using water electrolyzers. This literature review offers a comprehensive overview of green hydrogen production technologies, with a particular emphasis on water electrolysis. The article summarizes two commercial water electrolysis technologies, discussing their technological and commercial prospects, hydrogen production costs, advances in materials, and challenges faced.

Moreover, the research investigates the potential of Multi-Criteria Decision Making (MCDM) as a tool to support informed decision-making in hydrogen production and to identify research and development gaps in the field of water electrolysis. It also describes the limitations and

performance of commercial electrolyzers, proposing possible solutions for achieving cost-effective hydrogen production.

The primary objective of the first study was to pinpoint the key factors affecting the reduction of hydrogen production costs using water electrolyzers. The findings from the first article laid the groundwork for the second study.

The second article commences with a techno-economic analysis of hydrogen production using Alkaline and Proton Exchange Membrane (PEM) electrolyzers. The performance of these electrolyzers is evaluated using Multi-Criteria Decision-Making (MCDM) techniques. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Weighted Aggregated Sum Product Assessment (WASPAS) interval methods are employed for comparison, while the Best Worst Method (BWM) with fuzzy logic is utilized to assign weights to evaluation criteria.

The evaluation framework encompasses five dimensions, including environmental, technical, technological, economic, and social factors, which are further divided into 30 sub-criteria. These insights provide a thorough understanding of the strengths and weaknesses of each electrolyser, enabling stakeholders to make well-informed decisions regarding cost reduction in hydrogen production technologies.

CHAPTER 2 LITERATURE REVIEW

2.1. Electrolysis

There are various definitions of electrolysis, (Millet, 2011) but one of them defines it as the process of passing an electric current through ionic matter, which can be either molten or dissolved in a suitable solvent, to initiate a nonspontaneous chemical reaction. In all electrolysis technologies, the fundamental components include an anode and a cathode (electrodes) and an electrolyte. When an electric current is applied, hydrogen is generated at the cathode, and oxygen is generated at the anode. (Buttler & Spliethoff, 2018). The electrolysis equation, taken from (Buttler & Spliethoff, 2018), can be seen in Equation (1).



Researchers have shown that electrolysis was first observed by the two scientists William Nicholson (1753-1815) and Anthony Carlisle (1768-1842) who used a voltaic pile to liberate hydrogen and oxygen from water. (Millet, 2011). One of the most notable figures in the history of electrolysis is Michael Faraday, who conducted extensive research on the subject in the early 19th century. Faraday's experiments helped to establish many of the fundamental principles of electrolysis and laid the foundation for the development of modern electrolysis technologies.

In the years following Faraday's work, electrolysis continued to be an important area of research, with many scientists and inventors working to improve and refine the technology.

The production of hydrogen through water electrolysis ranks as the second most prominent method, following methane reforming. However, water electrolysis is typically more costly than methane reforming due to the materials employed in these techniques. There are three primary types of electrolysis: (i) Alkaline electrolyzers, (ii) Polymer electrolyte membranes (PEM), and (iii) Solid oxide electrolyzers. (Buttler & Spliethoff, 2018).

Hydrogen production technologies currently used in water electrolysis among the industrialized methods are the production of hydrogen from alkaline water electrolysis and PEM electrolysis.

2.2. Fundamentals of PEM electrolysis

A PEM electrolyser stack consists of repeating cells that are electrically connected in series and reactant water/product gas connected in parallel. Thick metal plates (called end plates) from both

ends are added to structurally hold these cells inside the stack. At the core of each of these modules is a polymer membrane with cathode and anode catalyst layers coated on the both sides of the membrane to form what is called catalyst-coated membrane (CCM). The porous transport layer (PTL) is a layer that enhances water diffusion and water splitting reaction on the surface of the membrane in the electrolysis cells. Bipolar plates, as the name suggests, have a cathodic side and an anodic side. Their main function is to separate cells in the stack, and they have channels that facilitate the transport of water, hydrogen, and oxygen inside the stack (Mayyas, Ruth, Pivovar, Bender, & Wipke, 2019). Beside the cell stack, a PEM electrolyser plant also consists of secondary function subsystems, which together is called balance of plant (BOP).

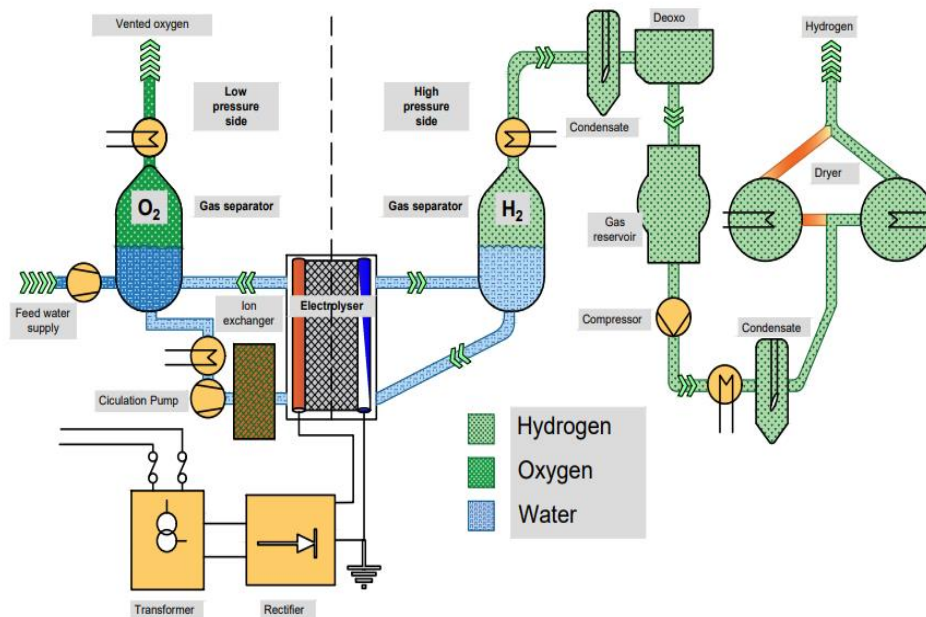


Figure 2. 1. Block diagram of industrial hydrogen production with PEM technology (IRENA, 2020)

The major subsystems in the BOP and key parts in each system include: i) Power supply: AC/DC rectifier, DC voltage transducer, and DC current transducer, ii) Deionized water circulation system: oxygen separator tank, circulation pump, piping, valves and instrumentation, and controls, iii) Hydrogen processing: dryer bed, hydrogen separator, tubing, and valves and instrumentation, iv) Cooling: plate heat exchanger, cooling pump, valves and instrumentation, and dry cooler, and v) Miscellaneous: compressed air valve, ventilation and safety requirements (combustible gas

detector and exhaust ventilation) (IRENA, 2020). (Figure 2. 1) represents a schematic of the PEM electrolyser system.

2.3. Fundamentals of Alkaline electrolysis

In an alkaline electrolysis setup, two microporous electrodes made of nickel or nickel-based steel are submerged in an electrolyte solution, typically 20% to 40% KOH. The cathode releases hydrogen, along with hydroxide ions (HO^-), through the process of water reduction. The hydroxide ions generated at the cathode move into the anode and are oxidized to produce water and oxygen gas. (Bessarabov & Millet, 2018).

Recent advancements in electrode design and the discovery of the zero-gap system in the Chlor-Alkali electrolyser have led to enhancements in the performance of alkaline electrolysis. The process involves the use of a diaphragm, which separates the anode and cathode. The diaphragm can be made of either asbestos (not currently used) or composite materials consisting of ceramic or microporous materials. The electrocatalyst plays a crucial role in improving the efficiency of water splitting to produce hydrogen. Most alkaline water electrolyser systems provide temperature control for the electrolyte to maintain an optimal temperature range. (Rashid, Al Mesfer, Naseem, & Danish, 2015).

Despite having its own basic components, an electrolyser requires additional components to function properly. These may include power electronics, which convert an electrical bus bar that supplies DC current to the cell, as well as a DC power distribution system that powers the electrodes and a streamlined gas-exit pipe used to direct the hydrogen and entrained gases out of the cell. Cooling systems are also necessary to remove waste heat generated by the cells, and systems for drying the hydrogen and oxygen produced may be required as well. (Services, 2004). The layout for a typical alkaline electrolysis plant is shown (Figure 2. 2).

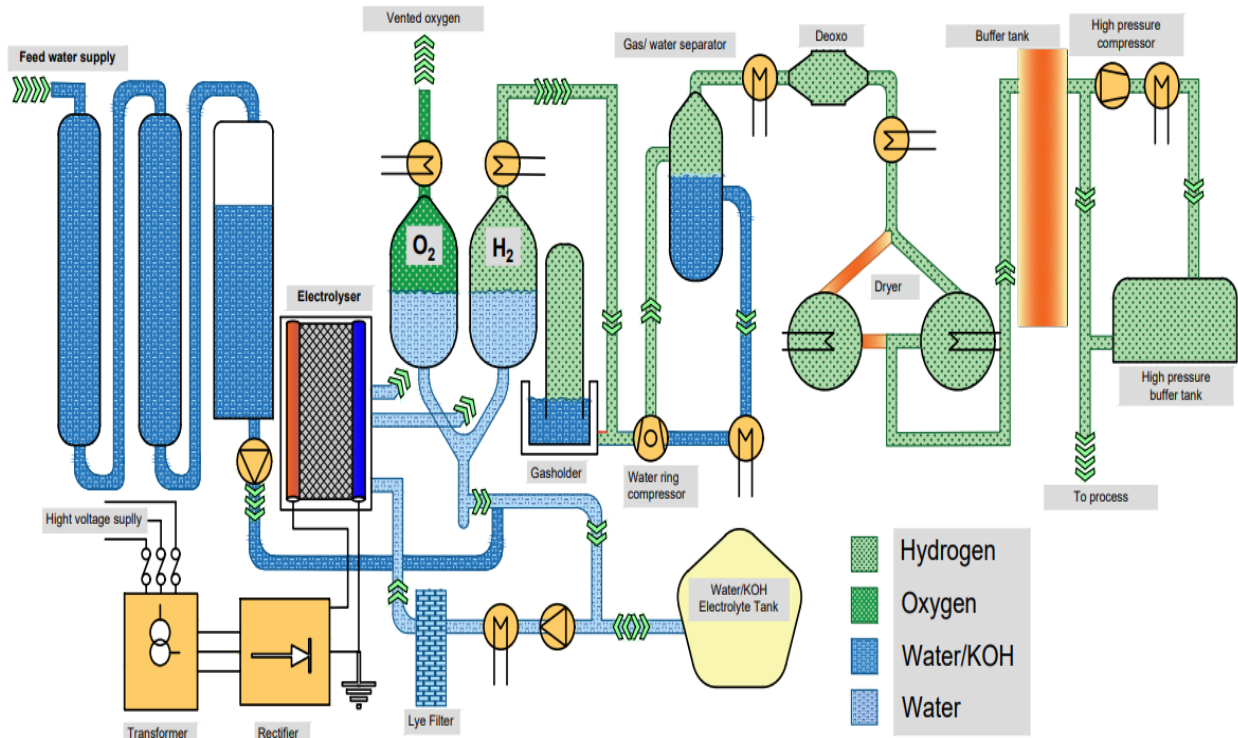


Figure 2. 2. Schematic block of the Alkaline electrolysis system (IRENA, 2020)

2.4. A review of the challenges and trends in water electrolysis science and technology

The roots of alkaline electrolysis date back to 1839, when the British scientist William Nicholson filed a patent for using an alkaline electrolyte to split water into hydrogen and oxygen.

In 1927, Norsk Hydro Electrolysers installed the first large-scale industrial alkaline water electrolyser for ammonium production. Shortly after, two additional plants were built in Norway, featuring a total of three hundred electrolysers and a hydrogen production capacity of over sixty thousand cubic meters per hour. (Paidar, Fateev, & Bouzek, 2016).

Throughout the 1960s and 1970s, researchers made notable advancements in the field of alkaline electrolysis technology, culminating in its commercialization for hydrogen production. A significant area of focus during this period was the utilization of novel materials in the construction of alkaline electrolysers. Early electrolysers utilized various materials, including graphite and stainless steel, as electrodes. However, these materials had several drawbacks, such as subpar

performance and high costs. In the 1980s, scientists started investigating alternative materials, like platinum and palladium, that offered superior performance and reduced costs.

Moreover, a significant portion of the twentieth century's development in alkaline electrolysis technology involved research and development of diaphragm membrane materials. This was because the separation process became more intricate with the discovery of these materials, requiring new methods and technologies to ensure the production of high-quality hydrogen. (Grigoriev, Fateev, Bessarabov, & Millet, 2020).

One of the conventional problems with Atmospheric Water Electrolysis (AWE) is that the maximum current density typically stays at 0.45 A/cm². This limitation can be traced back to the fact that at high current densities, bubbles tend to travel upwards along the electrode surface, forming a non-conductive layer of gas over the entire surface.

To address this issue, modern AWE cells have adopted the zero-gap configuration, which improves process efficiency but requires higher energy consumption and gas transport. (Grigoriev et al., 2020).

Centrotech company made some intriguing and promising discoveries regarding the water vapour electrolysis process. Notably, they were able to achieve current densities of up to 0.9 A/cm² without encountering the "bubble evolution problem." Additionally, they observed stable electrolysis parameters and good gas purity. However, managing the water balance in such a system proved to be challenging.

Despite this obstacle, Atmospheric Water Electrolysis (AWE) technology is becoming more versatile with advancements in cell design, particularly in situations where the cell or stack is powered by intermittent renewable energy sources. (Grigoriev et al., 2020).

W. Thomas Grubb conceived the idea of a sulfonated polystyrene ion-exchange membrane in the early 1950s. Subsequently, in 1966, the General Electric Company (GE) developed the first proton exchange membrane (PEM) water electrolyser, which was a major milestone in the history of electrolysis due to its superior efficiency and faster response time compared to other types of electrolysers. Despite its advantages, this initial version was inefficient and expensive, making it impractical for widespread use. However, GE's development of the PEM water electrolyser opened the door to electrolysis being used in various applications. Over the following decades, researchers

made significant progress in cell design, catalysts, and system integration, leading to the creation of more efficient and cost-effective PEM electrolyzers. In the 1970s, researchers utilized various materials, including polytetrafluoroethylene (PTFE), as a proton exchange membrane. However, these materials had certain shortcomings such as poor stability and high cost. In the 1990s, researchers began to explore alternative materials like polymer electrolyte membranes (PEMs), which offered improved performance and lower costs. However, there are two main challenges to achieving optimal performance with existing technology: the need to maintain isothermal operation as much as possible to minimize power loss and fluctuations during plateaus. (Allidières, Brisse, Millet, Valentin, & Zeller, 2019). Researchers are expanding the use of electrolysis technology in various fields, including hydrogen fuel production for transportation and electricity generation using hydrogen fuel cells. To meet this challenge, they are exploring new materials and designs that can withstand the high temperatures and pressures involved in these applications. However, producing electrolytic hydrogen on a multi-MW scale still requires several improvements to lower its costs. One of the main challenges with PEM technology is the high overpotential of oxygen evolution reactions, which necessitates the use of high-loading noble metal catalysts. Several cost and efficiency analyses have revealed that, at present, the cost of the catalysts is almost as significant as that of the costly titanium-based plates with special coatings, and is the primary factor in plant manufacturing balance. (Siracusano et al., 2017).

The development and implementation of low temperature electrolysis technology have been challenged by numerous electrocatalytic challenges, particularly in water electrolysis. Despite efforts to reduce noble metal loading, little significant progress has been achieved thus far. In contrast, various metals can serve as electrodes in alkaline electrolyzers. (e.g., Ni) (Khan et al., 2018). Moreover, (V. Kuleshov et al., 2016) new composite nickel coating has been proposed with a highly developed porous structure, which could lead to significant advancements. However, cost and lifespan are becoming increasingly important considerations. Electrocatalysts are more crucial in proton exchange membrane (PEM) electrolysis due to their acidic properties. Although traditional electrocatalysts like platinum and palladium are highly effective, they are also expensive and scarce. As a result, researchers are exploring alternative, more affordable and abundant electrocatalysts. However, these alternatives often have lower efficiency and require higher operating temperatures, which can increase overall costs and decrease the feasibility of low-temperature electrolysis. In PEM electrolysis, the anode electrocatalyst plays a key role. (Grigoriev

et al., 2020). Using hydrated IrO_2 with a high oxidation was introduced by (Siracusano et al., 2017) that a well-hydrated iridium oxide with a high oxidation state on the surface decreases the potential for an oxidation reaction to happen over time and increases the longevity of an electrolysis system. However, in order to obtain appropriate electrolysis cell parameters, the amount of (Ir) that contains the electrocatalyst could be quite small; however, a catalyst loading of 1-2 mg/cm² is needed for an acceptable lifespan (Grigoriev et al., 2020). As research continues and advances are made in the field of electrocatalysis, it is likely that many of the current issues with low temperature electrolysis will be overcome, paving the way for widespread adoption of this technology.

The performance of a water electrolysis cell can be evaluated by plotting its current-voltage curve, which shows the relationship between the cell's current output and the voltage applied to it. This curve can provide important information about the cell's efficiency and how it performs under different operating conditions. Moreover, the size of the cells used in industrial water electrolysis systems can range from small, laboratory-scale cells to large, multi-kilowatt cells that can produce hundreds or thousands of liters of hydrogen per hour. The size of the cell is typically determined by the required hydrogen production rate and the operating conditions of the system, such as the applied voltage, current density, and temperature.

The objective of most research and development (R&D) activities related to the pressure of hydrogen in water electrolyzers is to improve the efficiency and performance of these devices. This typically involves developing new materials and technologies that can increase the pressure of hydrogen production, reduce the cost of electrolysis, and improve the overall durability and reliability of the electrolyser however, high-pressure electrolysis can require more expensive and robust equipment to operate.

(Sartory et al., 2017) developed an existing system which is called asymmetric pressure electrolysis focuses on the most influencing factors on 155 bar high-pressure PEM electrolyser. This allows for more efficient hydrogen production in 70 bar while in 155 bar the stack efficiency and total efficiency are decreasing, or there is a situation 'unbalanced high pressure' conditions (Millet, 2011) can occur when the pressure of the hydrogen and oxygen gases produced by the electrolyser are not equal. This can happen for several reasons, such as unequal flow rates of the electrolyte solution, differences in the efficiency of the electrodes, or imbalances in the electrical

current applied to the electrodes. So that it can cause the electrolyser to become unstable and can potentially lead to damage or failure of the equipment. To prevent this from happening, electrolysers are typically designed with safety measures in place to maintain a balanced pressure and prevent unbalanced conditions from occurring. This can include pressure relief valves, automatic shut-off systems, and other protective measures to ensure the safe and stable operation of the electrolyser.

Currently there is an approach (Group)&(Bessarabov, Wang, Li, & Zhao, 2015) by using a reinforced SPEM. The variation of this type of electrolyte that has been strengthened or reinforced with additional materials, such as carbon nanotubes or graphene, to increase its durability and resistance to mechanical stress. This approach is being explored to improve the performance and stability of water electrolysers by providing a more robust and efficient electrolyte that can withstand high pressures and temperatures. it can be expensive and difficult to produce.

Another perspective features by (OLUFJENSEN, Chatzichristodoulou, Christensen, Bjerrum, & Li, 2019) is Polybenzimidazole, or PBI. The type of polymer that is known for its excellent chemical and thermal stability, as well as its high mechanical strength. These properties make it a potential material for use in electrolysis at intermediate temperatures (120-130 C), as it can withstand the harsh conditions of the electrolysis process without degrading. PBI-based membranes are also highly conductive, which makes them effective at transporting ions during the electrolysis process. however, using PBI-based membranes for intermediate temperature electrolysis is their relatively high cost compared to other types of membranes. Additionally, PBI-based membranes may be less flexible and more brittle than other types of membranes, which can make them more difficult to handle and install in some applications.

Water electrolysis is a technology that can be used for grid balancing and energy storage. In grid balancing, excess electricity from renewable energy sources such as solar and wind can be used to power a water electrolyser. The hydrogen can then be stored and used as a clean fuel source to generate electricity when needed, helping to balance the grid by reducing reliance on fossil fuels. In energy storage systems, water electrolysis can be used to store excess electricity in the form of hydrogen, which can be easily transported and used as a fuel source when needed. This can help to improve the reliability and flexibility of the electrical grid by providing a way to store and use excess renewable energy.(Allidières et al., 2019)&(Dincer & Acar, 2018).

There are many different methods for using artificial intelligence (AI) (Zahraee, Assadi, & Saidur, 2016)&(Sharifi, Pool, Jalilvand, Tabaeian, & Jooybari, 2019) in the design, planning, and control of water electrolysis systems for energy storage. One approach is to use machine learning algorithms to optimize the operation of the electrolysis system, such as by predicting demand for hydrogen fuel and adjusting the production of hydrogen accordingly. This can help to maximize the efficiency of the electrolysis process and reduce costs. Another approach is to use AI to design and control the electrolysis system itself, such as by using computer simulations to optimize the layout and configuration of the system to maximize performance and minimize costs. Moreover, water electrolyzers can play a key role in the digitalization of energy and economy by enabling the transition to a more sustainable and decentralized energy system and supporting the growth of a hydrogen economy. The integration of a water electrolyser with a smart home system would enable homeowners to take advantage of excess renewable energy, such as solar or wind power, that would otherwise be wasted.

Woven City is a proposed city in Japan(Toyota, January 06, 2020) that aims to combine solar energy and hydrogen technology to create a sustainable and resilient community. The city is being developed by Toyota and will feature a range of advanced technologies and infrastructure, including photovoltaic panels, water electrolyzers, and hydrogen fuel cell vehicles. the combination of solar energy and hydrogen technology in Woven City will enable the efficient and sustainable generation of electricity and hydrogen fuel, supporting the transition to a more sustainable and resilient energy system.

Hydrogen valleys are geographic regions or clusters of companies and organizations focused on the development and deployment of hydrogen technology and infrastructure (EU). The development of hydrogen valleys can help to accelerate the adoption of hydrogen technology, by fostering collaboration and cooperation among different stakeholders and providing a supportive environment for innovation and experimentation. The use of water electrolyzers for energy storage and generation has several advantages, including the fact that water is widely available and easy to obtain, and the resulting hydrogen fuel is clean and efficient.

As (Aminov & Bairamov, 2017) mentioned , One of the key advantages of using electrolysis techniques for hydrogen and oxygen production is that it allows for the efficient conversion of excess energy from NPPs into usable fuel. Hydrogen production through water electrolysis using

night off-peak energy from nuclear power plants (NPPs) has the potential to be competitive on the hydrogen market, especially when considering the additional costs of purification and transport. However, the excess energy is only available during certain times of the day, which can limit the overall output of the system.

There is another perspective that High-temperature electrolysis (HTE) systems in conjunction with high-temperature gas-cooled reactors (HTGRs) so the waste heat generated by the reactor can be used to power the electrolyser. with HTGRs can provide many potential advantages, including increased efficiency, the ability to use hydrogen as a fuel, and the potential to reduce greenhouse gas emissions.(Grigoriev et al., 2020).similarly as proposed in (AlZahrani & Dincer, 2016), A solar tower with an integrated high-temperature electrolyser system can be an effective way to produce hydrogen fuel. However, here will be some limitation, such as equipment, material, heather conditions and land for installation. To meet the challenges of the future, a new generation of water electrolyzers should be developed that can operate at high efficiencies and with low costs. This will require advances in materials and technology, as well as the overcoming of economic and logistical barriers to the widespread adoption of electrolysis technology. There are some codes and standards that are used to define the legal framework for hydrogen water electrolysis technology.

These codes and standards provide guidelines and requirements for the design, construction, operation, and maintenance of hydrogen water electrolysis systems. They are intended to ensure that these systems are safe and effective, and to promote the responsible use of hydrogen technology.

As can be seen in (AlZahrani & Dincer, 2016) , in the context of hydrogen technology, SWOT analysis can be used to assess the relative advantages and disadvantages of different types of hydrogen production systems, such PEM and Alkaline electrolyzers. For PEM electrolyser High efficiency, fast response time and Compact size are strengths points, in contrast high cost and fragile membranes are weakness points that recently is reported. However, in Alkaline electrolyser we can consider low cost and robust as an advantage while, limited scalability and long response time are negative points. These advantages and disadvantages cause some challenges in water electrolyzers. As Porous diaphragms can have several effects on the pressure of the cathode and anode. the performance of pressurized Alkaline100 bar was shown that by (N. Kuleshov et al.,

2019), it can help more stable pressure in the cell, as the diaphragm can act as a buffer to prevent sudden changes in gas pressure. Gases produced at the anode and cathode can leak through the diaphragm if the pressure inside the cell is high, which can be dangerous and explosive. Moreover, Operating the cell at elevated pressure can put additional stress on the diaphragm and other components, which can lead to damage or failure. So, it is vital to check the design of the cells to ensure they can operate at the desired pressure and in harsh conditions.

Corrosion, safety, performance, and maintenance issues can arise from a hot caustic electrolyte under pressure in an alkaline electrolyser.

There recent approach (Xiao et al., 2012), in alkaline electrolysis, ionomer-type polymers are a new material that are drawing attention because they have a superior ability to conduct hydroxyl ions and they have high chemical stability under operating conditions. However, the Compatibility with other materials may not be compatible with certain materials used in electrolysis, such as certain types of catalysts or electrodes. Moreover, the conductivity of ionomer-type polymer materials is generally lower than that of traditional ion exchange membranes, such as Nafion.

Commercial PEMFC products started to be developed in the late 1970s as a result of the late 1960s discovery of innovative materials including perfluoro sulfonic acid (PFSA) polymers. These early PEMFCs were primarily employed in the aerospace and defence sectors. Proton exchange membrane (PEM) electrolyzers are designed to operate over a wide range of current densities (Villagra & Millet, 2019).

There are several types of non-platinum catalysts that have been developed for the hydrogen evolution reaction (HER). These materials have the potential to be more cost-effective than platinum, and they can also be produced in larger quantities, making them more sustainable (AlZahrani & Dincer, 2016). However, non-platinum catalysts are generally less efficient than platinum, and they are also less stable over time. Researchers are continuing to work on developing and improving non-platinum catalysts to make them more efficient and stable. Moreover, the use of reduced IrO₂ content at the anode for the oxygen evolution reaction in PEM electrolyzers could potentially affect the cost of the electrolysis process (Rozain, Mayousse, Guillet, & Millet, 2016). However, the impact on efficiency and stability should also be considered. researchers have been developing new types of PFSA polymers with short side chains that are able to sustain higher operating temperatures, up to around 150°C. These materials have the potential to significantly

improve the performance of fuel cells. the ability to operate at elevated pressure and under strong pressure differences makes PEM an attractive choice for the direct storage of hydrogen in pressurized vessels and mobility applications. The International Energy Agency (IEA) has identified several key techno-economic characteristics of different electrolysis technologies. These characteristics include Efficiency, Capacity, Cost, Durability, Flexibility By considering these techno-economic characteristics, the IEA can identify the most promising electrolysis technologies for large-scale deployment in the hydrogen economy.

2.5. Large-scale water electrolysis

Research in large-scale water electrolysis aims to develop efficient and cost-effective 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 emissions is why this research is becoming increasingly significant.

In 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. These studies have generally found that the 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). In addition, The 6 MW PEM electrolysis project "Energiepark Mainz" using PEMEL technology, 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 H2Future 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,). 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.

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 to produce hydrogen from renewable energy sources. The goal of the project is to produce hydrogen at a cost of less than €2 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.

In Germany, the H2Future 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.

Lastly project aims to develop a large-scale hydrogen production facility that utilizes water electrolysis and biomass gasification to produce hydrogen. 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.

2.6. Techno-economic analysis for water electrolysis

Techno-economic analysis for water electrolysis can help identify the most cost-effective solution for producing hydrogen, considering the capital and operating costs of the system, as well as the efficiency of the electrolysis cells and the availability of cheap electricity. By carefully considering these and other factors, it is possible to determine the most economical way to produce hydrogen through electrolysis.

A 2009 study found that the projected cost of generating hydrogen using alkaline water electrolysis, with a capacity of 50,000 kg/day, was approximately \$5.20/kg. This cost estimation was based on various factors, including the cost of electricity at \$0.07/kWh and an electrolysis efficiency of 70%(Current, 2009),(Jang, Kim, Kim, Han, & Kang, 2022). However it is important to note that this cost is just an estimate and may not accurately reflect the actual cost of hydrogen production using this technology in all situations.

According to the Department of Energy's (DOE) Hydrogen and Fuel Cells Program Record, The average of the manufacturer-supplied electrolyser stack and balance of plant (BOP) costs in the United States in 2013 was \$5.14/kg for a production capacity of 1500 kg/day and \$5.12/kg for a production capacity of 50,000 kg/day (Ainscough, Peterson, & Miller, 2014).

A study of hydrogen production methods was conducted(B. Lee et al., 2017) which included AWE, PEMEC, and SMR Production capacities of 30, 100, and 300 Nm³/hr were evaluated. Results showed PEMEC to be the most cost-effective at 16.54 \$/kgH₂ for a 30 Nm³/hr capacity, while SMR had the lowest cost at 7.59 \$/kgH₂ for a 300 Nm³/hr capacity. This suggests SMR is more economical for large-scale hydrogen production and PEMEC for smaller scale. In addition

research on high-temperature electrolysis has been ongoing (Jang, Kim, Kim, Han, et al., 2022) The 750 Nm³/hr class of SOEC systems developed by Sunfire is designed for large-scale hydrogen production and could be used in a variety of applications such as power-to-gas, refinery, and chemical production.

(Ferrero, Gamba, Lanzini, & Santarelli, 2016) and(Tenhumberg & B ker, 2020) Two studies were conducted, one of them examined the efficiency and cost of various Power-to-Gas processes for converting excess renewable energy into hydrogen via water electrolysis. The other study focused on evaluating the ecological and economic impact of different water electrolysis technologies. "AWE systems were found to be the most cost-efficient for hydrogen production in both studies. They compared the economic feasibility by calculating hydrogen production costs. However, the first study assumed free electric cost using surplus renewable energy, which may not always be possible. The second study presented limited, basic results without detailed cost analysis, making it hard to determine the effect of different cost factors on hydrogen production cost."(Jang, Kim, Kim, Han, et al., 2022).

In addition, "a study was conducted to evaluate the economic efficiency of four different water electrolysis technologies(Jang, Kim, Kim, Han, et al., 2022): alkaline, proton exchange membrane, solid oxide with electric heaters and solid oxide with waste heat. The research found that the unit hydrogen production cost was 7.60, 8.55, 10.16, and 7.16 \$/kgH₂ for AWE, PEMEC, SOEC (E.H), and SOEC (W.H), respectively. However, the research does not provide any solutions on how to lower capital costs or the ways to implement subsidies and tax reductions to make it more competitive with other forms of hydrogen production".

An analysis was done (Okonkwo et al., 2022)to evaluate the costs and benefits of using solar power in Tunisia to generate electricity and hydrogen by water electrolyser. An Initial Cost analysis of a PV-HRS shows that the cost of PV system and electrolyzers are the major components of the total cost, representing 48.5% and 41% respectively, while the storage system cost is relatively low at 3.2%. The cost of producing 1 kg of hydrogen is 3.32€/kg and the total cost of the project is 2.34 million €. However, It is important to consider the cost-effectiveness of solar power compared to other renewable energy sources.

A techno-economic analysis was conducted (Jang, Kim, Kim, & Kang, 2022)to compare the cost of producing hydrogen using offshore wind power through different production methods:

distributed, centralized, and onshore. It was found that the most economical method was distributed hydrogen production, with a cost of \$13.811 per kg of hydrogen using PEM electrolysis and a 160 MW offshore wind power plant. Centralized and onshore production had slightly higher costs at \$13.847 and \$14.584 per kg, respectively. However, the research has not considered the impact of local regulations, taxes and subsidies on the cost of hydrogen production.

The study (J. M. Lee et al., 2022) investigated the effectiveness of various configurations of an integrated model combining a SOEC and SMR with high-temperature reactor (VHTR) for hydrogen production. The results revealed that when electricity and heat were provided by an SMR to the SOEC plant, the cost of hydrogen production fell between \$5.02 and \$7.60 per kg, and the CO₂ emission was the lowest at 0.36 kg per kg of H₂. The cost of electricity was identified as the most substantial factor in the overall cost.

(Nami, Rizvandi, Chatzichristodoulou, Hendriksen, & Frandsen, 2022) This research aims to evaluate the financial viability of producing green hydrogen using alkaline electrolysis and solid oxide electrolysis technologies. It examines the performance of an alkaline electrolyser operating under high pressure and temperature conditions, in comparison to a solid oxide electrolyser operating under high pressure. The objective is to analyze the potential economic impact of technical advancements under comparable conditions. Results indicate that while the high-temperature alkaline electrolyser performs better at low current densities, the cost of hydrogen production is still more costly at higher current densities. Furthermore, the energy consumption required for hydrogen compression in the low-pressure solid oxide electrolyser system results in increased operational costs. It is determined that the high-pressure solid oxide electrolyser is economically advantageous, even if the system's initial investment increases by 20% compared to the low-pressure solid oxide electrolyser.

As mentioned above, Further research and development is needed to make water electrolysis a cost-competitive option for large-scale hydrogen production. It's important to note that the techno-economic analysis should be done considering specific conditions and goals, as the optimal solution will vary depending on the specific application and desired outcomes. The future cost of electrolyzers is highly dependent on the results of techno-economic analysis, as it provides an understanding of the current costs and the potential for cost reduction. Techno-economic analysis is a crucial step in understanding the current and future costs of electrolyzers, and it provides

valuable insights for researchers and developers to work on ways to reduce the cost and improve the efficiency of the technology.

2.7. Multi criteria decision making (MCDM)

2.7.1. Introduction

MCDM has a long history, dating back to the 1950s. the French economist Marie-Jean-Pierre Dupuy introduced the concept of the "Outranking Method" which is a method for evaluating multiple criteria. In the 1960s, the American mathematician Kenneth Arrow proposed the "Arrow's Theorem" which stated that it is impossible to consistently rank alternatives using a set of criteria without imposing some form of ordering on the criteria themselves. Additionally, the development of computer technology and the increasing availability of data in the 1970s and 1980s allowed for the application of MCDM methods in a more efficient way, and made it possible to solve larger and more complex decision problems. The 1970s and 1980s were a period of significant growth and development for MCDM, with the introduction of important new methods (Köksalan, Wallenius, & Zionts, 2011).

Eisenhardt and Zbaracki define strategic decision(Eisenhardt & Zbaracki, 1992) making as the process of making decisions that have a significant impact on the long-term success of an organization, which are high-stakes, non-routine decisions that are often made under conditions of uncertainty and ambiguity, and often require a complex and integrative approach, and involve trade-offs between multiple conflicting objectives. MCDM is a valuable tool for strategic decision making, it is a systematic approach that allows decision-makers to evaluate multiple criteria and weigh them against each other, in order to identify the best possible solution. MCDM help organizations make better strategic decisions by providing a structured and transparent approach to decision-making, it also particularly useful in situations where there is a high degree of uncertainty or ambiguity, MCDM can help decision-makers to evaluate multiple scenarios and identify the best course of action, and also helps organizations to manage risk and uncertainty, by providing a framework for evaluating and mitigating potential risks.

The Multi-Criteria Decision Making (MCDM) process is a method that typically involves several steps(Munda, Nijkamp, & Rietveld, 1995) divided into two phases: pre-panel and panel. The pre-panel phase includes defining the problem, identifying evaluation criteria, generating a list of possible solutions and collecting data. The panel phase involves evaluating the alternatives,

ranking them, and choosing the best option. It's worth noting that the specifics of the MCDM method can vary depending on the specific method and application used.

The advantages and disadvantages of MCDM methods have been extensively studied and analyzed in various literature.(Triantaphyllou & Triantaphyllou, 2000b) These advantages and drawbacks have been clearly mentioned:

One of the main advantages of MCDM methods is their ability to handle complexity. These methods are well-suited for decision-making problems that involve multiple, conflicting criteria and can effectively handle the complexity of such problems. MCDM methods provide a structured and transparent process for decision-making, allowing for the incorporation of multiple perspectives, including both quantitative and qualitative criteria. This allows for a more comprehensive evaluation of alternatives and can lead to more robust and reliable decisions.

Another advantage of MCDM methods is their flexibility. They can be applied in a wide range of decision-making scenarios and the specific method used can be tailored to the specific problem at hand. Additionally, MCDM methods often provide a clear and transparent process for decision-making, allowing stakeholders to understand how decisions are made and providing a basis for accountability.

However, MCDM methods also have some disadvantages. One of the main drawbacks of MCDM methods is the high data requirements. These methods often require a significant amount of data, which can be difficult and costly to collect. Additionally, MCDM methods can be complex and difficult to understand and implement, which can limit their use in certain situations.

Another disadvantage of MCDM methods is the subjectivity involved. These methods can be subject to the biases and subjective judgment of the decision-maker or panel, which can affect the reliability of the results. Additionally, MCDM methods often require a degree of consensus among stakeholders, which can be difficult to achieve in practice.

Finally, MCDM methods are time-consuming and require a significant amount of time and resources to be implemented effectively.

Overall, while MCDM methods have several advantages, they also have some disadvantages. The choice of MCDM method, data availability, and the specific decision-making problem should be carefully considered before applying these methods.

Decision-making is a crucial aspect of sustainable energy development, as it involves choosing between different options for meeting energy needs while also considering environmental, social, and economic factors. The application of decision-making methods can help to identify the most sustainable solutions for energy development issues. One such method is multi-criteria decision-making (MCDM), which involves evaluating multiple options based on a set of criteria and can help to identify the best solution by considering both the benefits and drawbacks of each option. MCDM can be useful in dealing with sustainable energy development issues by providing a rigorous and transparent way to evaluate different options, and by considering the trade-offs between different factors, such as cost and environmental impact. Other methods such as cost-benefit analysis, life-cycle assessment, and risk analysis can also be used to evaluate the sustainability of energy development options and help decision-makers to make informed choices.

2.7.2. Multi-Criteria Decision Making (MCDM) as a Tool for Evaluating Hydrogen Production: An Overview of Recent Studies

There have been several studies that have used MCDM to evaluate different energy options, including hydrogen production.

(Abdel-Basset, Gamal, Chakraborty, & Ryan, 2021) The MCDM approach used in the study is a hybrid method that combines the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to an Ideal Solution (TOPSIS) method.

The study considers multiple criteria such as economic feasibility, environmental impact, technical feasibility, and safety to evaluate the various hydrogen production options. The options considered in the study include steam methane reforming, partial oxidation, and electrolysis. The study also considers different scenarios and uncertainties, such as changes in natural gas prices and carbon taxes, to evaluate the robustness of the results.

The results of the study show that steam methane reforming is the most suitable option for hydrogen production in the short term, due to its relatively low cost and high technical feasibility. However, in the long term, electrolysis is found to be the most sustainable option, as it generates hydrogen through the use of renewable energy sources, resulting in low greenhouse gas emissions.

The study concludes that the hybrid MCDM approach used in the study is a useful tool for evaluating sustainable hydrogen production options and can provide valuable insights to policymakers and industry professionals when making decisions related to hydrogen production.

(Ren, Li, Ding, & Dong, 2020)’’study introduces a new approach of multi-criteria decision making (MCDM) for evaluating the sustainability of hydrogen production technologies’’. The proposed framework is comprised of two stages, designed to screen out the most promising technologies based on their potential for sustainability and evaluate the remaining options in terms of trade-offs between economic, environmental, and social factors.

In the first stage of the MCDM framework, the authors employ a fuzzy best-worst method and a fuzzy Technique for Order of Preference by Similarity to an Ideal Solution (TOPSIS) method to identify the best alternatives by considering the preferences of decision-makers and the uncertainty of the information provided.

In the second stage, the authors propose a novel method that combines preference information on attributes and alternatives to evaluate the remaining technologies. This method utilizes a multi-objective optimization approach based on the Normalized Normal Constraint (NNC) method to account for the different priorities of the decision-makers and the uncertainty of the information. The study applies the proposed two-stage MCDM method to assess and compare the sustainability of several hydrogen production technologies, including steam methane reforming, partial oxidation, and electrolysis. The results of the study indicate that electrolysis is the most sustainable option among the technologies considered, due to its low greenhouse gas emissions and high potential for using renewable energy sources. In addition, in another study ‘‘assessment of hydrogen production technologies based on objective grey relational’’(W. Li, Ren, Ding, & Dong, 2020) presents a method for assessing the sustainability of different hydrogen production technologies.

The authors use a multi-criteria decision-making (MCDM) approach, which considers multiple factors or criteria in the evaluation process. In this case, the criteria include environmental impact, economic efficiency, and technical feasibility. The authors use objective grey relational analysis (OGRA), a method that uses gray systems theory to handle incomplete or uncertain data, to evaluate the sustainability of various hydrogen production technologies.

The study found that the OGRA method can effectively evaluate the sustainability of hydrogen production technologies and identified the technology of co-electrolysis of CO₂ and H₂O as the most sustainable option.

The study evaluated six different hydrogen production technologies: steam methane reforming (SMR), partial oxidation of methane (PEM), autothermal reforming of methane (ATR), co-electrolysis of CO₂ and H₂O, photoelectrochemical water splitting, and biological hydrogen production. The results showed that co-electrolysis of CO₂ and H₂O had the highest sustainability score, followed by PEM, ATR, SMR, photoelectrochemical water splitting, and biological hydrogen production.

The study in Taiwan (Chang, Hsu, & Chang, 2011) was done and the authors used the Fuzzy Delphi method as a multi-criteria decision-making technique to assess the sustainability of various hydrogen production technologies. The six criteria considered were environmental impact, economic efficiency, technical feasibility, safety, social acceptability, and resource availability. The Fuzzy Delphi method was chosen as it effectively handles uncertain and incomplete information by combining the Delphi method with fuzzy logic. The study evaluated seven different hydrogen production technologies, and the results revealed that hydrogen production via electrolysis by wind power and electrolysis by photovoltaic electricity were the top two technologies for further development.

(Thengane, Hoadley, Bhattacharya, Mitra, & Bandyopadhyay, 2014) The study used the AHP and Fuzzy AHP methods to evaluate the performance of different hydrogen production technologies. It aimed to compare the various hydrogen production technologies and determine which one is the most cost-effective and beneficial. The study evaluated eight different hydrogen production technologies using five criteria: greenhouse gas emissions, raw material and utilities consumption, energy efficiency, scalability, and waste disposal and atmospheric emissions. The technologies considered in the study included steam methane reforming, coal gasification, partial oxidation of hydrocarbons, biomass gasification, photovoltaic-based electrolysis, wind-based electrolysis, hydro-based electrolysis, and water splitting by chemical looping. The results of the study showed that while the fossil fuel-based processes appeared to be more cost-effective, the renewable-based processes had more benefits. However, the cost-benefit analysis results indicate that the process of water splitting by chemical looping is the most promising among the renewable approaches.

(Ceran, 2020) The article examines the results of a study comparing various methods for producing 1 million tons of 99.999% pure hydrogen through electrolysis in Poland. The study used a mathematical model to assess the use of green energy from photovoltaics (PV) to power the electrolysis process. The goal was to determine the best balance of environmental criteria for producing green hydrogen.

The results showed that using energy from photovoltaics only was the most favorable option when the environmental criteria were given a weight of 61%. However, the study also revealed that using energy from PV installations instead of the power grid would raise the cost of hydrogen production by 213%. This cost increase makes implementation unfeasible without government support.

The use of Multi-Criteria Decision Making (MCDM) methods is becoming increasingly important in the evaluation of green hydrogen production in Canada and Quebec. A study conducted by the National Research Council of Canada used AHP to evaluate the potential of different hydrogen production methods, including steam methane reforming, water electrolysis, and biomass gasification. The study considered factors such as the energy efficiency of the production process, the availability of feedstocks, and the environmental impact of hydrogen production.

Another study conducted by researchers at the Université Laval in Quebec used TOPSIS to evaluate the feasibility of hydrogen production from renewable sources, such as wind and solar energy. The study considered factors such as the capital costs of production, the energy efficiency of the process, and the emissions associated with hydrogen production.

These studies demonstrate the potential of MCDM as a tool for evaluating hydrogen production in Canada and Quebec Province. By providing a comprehensive and transparent evaluation process, MCDM can support informed decision-making in this field and help to promote the development of sustainable and economically viable hydrogen production systems.

2.7.3. MCDM classification

Multiple studies have presented different classifications of Multi-Criteria Decision Making (MCDM) methods.

- One of the earliest classifications was presented by Roy, where he grouped MCDMs into four categories: simple additive weighting: This method involves assigning weights to each criterion and combining the scores of the alternatives using a weighted sum.

- Weighting by similarity: This method is based on the notion of similarity between the alternatives and involves comparing the alternatives pairwise to find the best one.
- Weighting by eigenvectors: This method uses eigenvectors to determine the relative importance of the criteria.
- Weighting by evidential reasoning: This method involves using subjective beliefs and probabilistic models to make decisions (Roy, 1990).
- Another classification was introduced by Torgersen in 1991, where he divided MCDMs into three groups Value-based methods: This category involves methods that use quantitative information, such as numerical data, to make decisions.
- Preference-based methods: This category involves methods that use subjective information, such as preferences, to make decisions.
- Hybrid methods: This category involves methods that combine both quantitative and subjective information to make decisions (Bhole & Deshmukh, 2018).

Triantaphyllou's classification (Triantaphyllou & Triantaphyllou, 2000a): Triantaphyllou's classification is based on the decision-making process and divides MCDMs into four categories:

- Outranking methods: This category involves methods that compare the alternatives pairwise and eliminate the alternatives that are dominated by other alternatives.
- Compromise programming methods: This category involves methods that look for a compromise solution that balances the trade-off between the conflicting criteria.
- Interactive methods: This category involves methods that involve human participation in the decision-making process, such as negotiation and dialogue.
- Composite methods: This category involves methods that combine multiple decision-making methods to make decisions.

Zavadskas and Turskis' classification (Edmundas Kazimieras Zavadskas, Turskis, & Kildienė, 2014): Zavadskas and Turskis' classification is based on the mathematical models used for making decisions and divides MCDMs into seven categories:

- Classical methods: This category involves methods that use linear and non-linear models for making decisions, such as linear programming and non-linear programming.

- Distance-based methods: This category involves methods that use distance measures, such as Euclidean distance, to make decisions.
- Non-linear programming methods: This category involves methods that use non-linear programming models for making decisions.
- Multi-objective methods: This category involves methods that deal with multiple objectives and look for a compromise solution.
- Stochastic methods: This category involves methods that use probabilistic models and randomization to make decisions.
- Interactive methods: This category involves methods that involve human participation in the decision-making process.
- Expert-based methods: This category involves methods that use expert knowledge and judgment to make decisions.

Theodossiou's classification (Latinopoulos, Theodossiou, & Latinopoulos, 2011): Theodossiou's classification is based on the type of information used and the decision-making process and divides MCDMs into five categories:

- Value-based methods: This category involves methods that use quantitative information to make decisions.
- Preference-based methods: This category involves methods that use subjective information, such as preferences, to make decisions.
- Hybrid methods: This category involves methods that combine both quantitative and subjective information to make decisions.
- Model-based methods: This category involves methods that use mathematical models, such as linear programming and non-linear programming, to make decisions.
- Knowledge-based methods: This category involves methods that use knowledge, such as expert knowledge and judgment, to make decisions.

These classifications provide a useful framework for understanding and comparing the different MCDM methods available. They highlight the different approaches that can be taken to make decisions under multiple conflicting criteria and help researchers and practitioners choose the best method for their specific problem.

Selecting the appropriate MCDM framework for a particular decision-making problem depends on several factors, including:

1. The type of decision-making problem: Different MCDM frameworks may be more suited to different types of decision-making problems, such as problems involving multiple conflicting criteria or problems involving uncertainty.
2. The nature of the criteria: The choice of framework may depend on the nature of the criteria, such as whether they are quantitative or qualitative, and whether they are mutually dependent or independent.
3. The number of criteria: The number of criteria involved in the decision-making problem can also impact the choice of framework, as some methods may be better suited to problems with a small number of criteria while others may be more suitable for problems with a large number of criteria.
4. The level of detail required: Some MCDM frameworks may provide more detailed and comprehensive results, while others may be more suitable for problems that require a more simplified or streamlined approach.
5. The level of expertise and resources available: The availability of expertise and resources, such as personnel trained in the use of a particular method or the availability of software for conducting the analysis, can also impact the choice of framework.

Ultimately, the decision on which framework to use will depend on the specific requirements and constraints of the decision-making problem, as well as the preferences and objectives of the decision-maker (Kahraman, 2008).

Three Multi-Criteria Decision Making (MCDM) methods that are widely used in energy and techno-economic decisions related to green hydrogen production are:

1. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS): TOPSIS is a method that calculates the distance between each decision alternative and an ideal solution, in order to determine the best alternative. It is well-suited for energy and techno-economic decisions, as it allows for the consideration of multiple conflicting criteria, such as cost, environmental impact, and technical feasibility.
2. Analytical Hierarchy Process (AHP): AHP is a structured approach to organizing and prioritizing criteria in a decision-making problem. It is widely used in energy and techno-economic decisions, as it allows for the consideration of multiple criteria, such as cost, technical feasibility, and environmental impact. The method involves building a hierarchy

of criteria, and then using pairwise comparisons to determine the relative importance of each criterion.

3. Multi-Attribute Utility Theory (MAUT): MAUT is a decision-making method that involves combining multiple criteria into a single composite score for each decision alternative. The method uses subjective or objective data to determine the weights for each criterion, and then combines the scores for each criterion to arrive at a composite score for each alternative. MAUT is commonly used in energy and techno-economic decisions, as it allows for the consideration of multiple criteria, and provides a clear and intuitive way of combining the results into a single overall score.

All three methods provide a useful framework for energy and techno-economic decision-making in the context of green hydrogen production(A. Kumar et al., 2017). (

Table 2. 1)shows Strengths, Weaknesses, Opportunities, and Threats of Various MCDM Methods (Siksnelyte, Zavadskas, Streimikiene, & Sharma, 2018).

Table 2. 1. Strengths, Weaknesses, Opportunities, and Threats of Various MCDM Methods(Siksnyte et al., 2018)

Method	Strengths	Weaknesses	Opportunities	Threats
AHP, ANP	Continues to be a foundational method in MCDM; Its integration with AI and ML techniques has been explored.	Still prone to inconsistencies if not executed meticulously.	Application has broadened to areas like healthcare, supply chain management, and smart city planning.	Newer methods and computational techniques might overshadow its use.
Fuzzy Sets	Enhanced algorithms have improved its applicability in uncertain and vague scenarios.	It can become computationally intensive with large datasets.	Growing interest in its use in hybrid models.	Complexity can sometimes deter its usage in straightforward applications.
TOPSIS	Further standardization and software support have made its application smoother.	Can be sensitive to weight distribution.	Extended versions of TOPSIS have been developed to cater to a wider range of decision-making problems.	Requires careful pre-processing and understanding of data.
WASPAS, WASPAS-G	Its combined approach continues to make it attractive; Similar in purpose to methods like PROMETHEE but different in approach.	Still limited in its application across all domains.	Hybrid models, combining WASPAS with other techniques, are emerging.	Requires a balance in weight assignment for accuracy.
PROMETHEE, PROMETHEE II	Newer variants like PROMETHEE V and VI have been explored.	As with older methods, can be overshadowed by newer algorithms.	Usage in environmental impact studies has grown.	Its complexity can deter its use in certain scenarios.
VIKOR	Increased usage in solving multi-objective optimization problems.	Can be perceived as complex in certain applications.	Applications in renewable energy resource allocation and green supply chain have emerged.	As with other methods, potential computational errors.
BWM	Simplifies the pairwise comparison process; Requires fewer comparisons than AHP; Provides consistent weightings.	Still relatively new, so might not be as widely recognized or used as older methods.	Potential to become a dominant MCDM method given its efficiency.	Could face challenges in more complex decision scenarios or when paired with uncertain data.

Based on the strengths, weaknesses and opportunities of each MCDM method analysed in (Table 2. 1) we may concluded, we may conclude that the best MCDM approach might be a combination of some of MCDM to analyse techno-economic issues..

2.7.4. Uncertainties in Green Hydrogen Production Project Selection through MCDM

Uncertainty is a significant factor that must be considered when applying Multi-Criteria Decision Making (MCDM) techniques to the selection of green hydrogen production projects. There are various sources of uncertainty that can impact the decision-making process, such as fluctuations in the cost of inputs, changes in the regulatory environment, and technological advancements. These uncertainties can affect the feasibility and viability of the projects and must be considered to make informed decisions. To address these uncertainties, MCDM techniques incorporate sensitivity analysis and scenario analysis to assess the robustness of the decision-making process under different conditions. In conclusion, when applying MCDM to green hydrogen production project selection, it is essential to incorporate uncertainty and consider its impact on the outcome of the decision-making process. These sources of uncertainty can significantly affect the results of the evaluation and comparison of alternatives and can limit the reliability and robustness of the decision-making process.

1. **Data Uncertainty:** One of the main sources of uncertainty in MCDM is the data used for the evaluation and comparison of alternatives. The data collected for green hydrogen production projects may be inaccurate, incomplete, or unreliable, which can lead to incorrect or misleading results. This can occur due to limitations in data collection methods, the presence of outliers, or the existence of data errors.
2. **Model Uncertainty:** Another source of uncertainty in MCDM is the choice of the decision model and the criteria used for the evaluation and comparison of alternatives. Different models and criteria can result in different rankings of the alternatives, and the decision-maker must choose the most appropriate model and criteria based on their specific needs and requirements.
3. **Weighting Uncertainty:** The weighting of criteria is another source of uncertainty in MCDM. The weighting of criteria is subjective and depends on the decision-maker's preferences, which can vary from one decision-maker to another. This can result in different rankings of alternatives, even when the same data and criteria are used.

4. Scalability Uncertainty: The scalability of the green hydrogen production project is also a source of uncertainty. Scalability refers to the ability of the project to be expanded or replicated in the future, and it is a critical factor in the long-term success of the project. However, predicting the scalability of a green hydrogen production project is difficult, and it is subject to many uncertainties, such as technological advancements, changes in energy market conditions, and government policies(H.-C. Liu & Liu, 2016).

These sources of uncertainty can significantly impact the results of the evaluation and comparison of alternatives, and decision-makers must take them into account when making informed decisions. shows comprehensive SWOT analysis of MCDM methods applicable to the techno-economic assessment of watere electrolyzers.

Table 2. 2 SWOT Analysis for MCDM Methods Relevant to Techno-economic Assessment of Water Electrolysers(Siksnylyte et al., 2018)

Method	Strengths	Weaknesses	Opportunities	Threats
FBWM (Full Best-Worst Method)	Simplifies the pairwise comparison process, making it efficient for large-scale assessments; More consistent weighting than traditional methods; Can provide detailed insights into preference structures vital for complex technological assessments.	Still relatively new compared to methods like AHP; Might require more user familiarity and understanding.	Potential to offer more refined techno-economic evaluations for evolving electrolyser technologies; Can be combined with other methods for hybrid models.	Other established methods might be preferred in traditional settings, overshadowing FBWM's potential benefits.
TOPSIS	Well-established with clear logic; Suitable for ranking multiple alternatives based on closeness to an ideal solution; Can effectively handle both costs (economic) and benefits (technological efficacy) in evaluations.	Can be sensitive to weight distribution; Requires careful data normalization.	Offers robustness when comparing various water electrolyser technologies in diverse operating conditions; Widely supported by decision-making software tools.	Emergence of newer MCDM techniques might divert attention from TOPSIS for certain applications.
WASPAS Grey Interval	Combines advantages of WSM and WPM, making it versatile; The grey interval approach accommodates uncertainties inherent in technological and economic evaluations.	Grey interval analysis might be perceived as complex by some decision-makers.	Ideal for scenarios where there's uncertainty in techno-economic data (e.g., future costs or performance metrics of electrolyzers); Provides a nuanced perspective by addressing data vagueness.	Over-reliance on the grey system theory might complicate decision-making for stakeholders unfamiliar with the concept.

(Table 2. 2) shows that even WAPAS might be perceived as complex by some decision-makers in techno-economic assessment of water electrolyzers, it is versatile and it accommodates

uncertainties inherent to technologies and economic evaluations. Based on these strengths which are important for the present work, we consider WASPAS for this study. Furthermore a combination of FBWM, TOPSIS and WASPAS should be an important interesting approach of MCDM for water electrolyzers.

2.8. 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:

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.

CHAPTER 3 OVERALL METHODOLOGICAL APPROACH

In this study, a Multi-Criteria Decision Making (MCDM) framework has been established to assess the sustainability of hydrogen production technologies through water electrolysis from a techno-economic standpoint. The aim is to address the recognized gaps in the existing body of knowledge. The methodology chapter commences with a comprehensive explanation of the MCDM method, data analysis, validation, and limitations.

3.1. Methodology overview

The Multi-Criteria Decision Making (MCDM) methodology improves the accuracy of techno-economic analysis for hydrogen production by enabling a systematic evaluation of different hydrogen production options, taking into account factors such as technical performance, cost, environmental impact, and market potential, to determine the most suitable technology. This thesis studies to determine the key limiting parameters that have an impact on the technology's techno-economic viability. In other words, the aim is to identify and evaluate the factors that can influence the success of the hydrogen production process in terms of both its technical performance and its cost-effectiveness. The steps taken to achieve the objective are illustrated in (Figure 3. 1) As depicted in the figure the project was carried out in five main steps:

1. Making a Start-of-the-Art Literature Review and Determining Criteria for Techno-Economic Analysis of Hydrogen Production using Water Electrolysis.
2. Use MCDM Fuzzy Best-Worst Method (FBWM) to Obtain the Weight of Criteria.
3. Use interval grey TOPSIS and interval grey WASPAS to make technico-economic analysis. of hydrogen production from water electrolysis.
4. Determining the best MCDM method and identifying limiting parameters.
5. Levelized cost of Hydrogen for 5 MW PEM and Alkaline.

In (Figure 3. 1) each of these case study (shown as blue box), are broken-down into several intermediate steps (shown as white boxes), that are explained in the following sections.

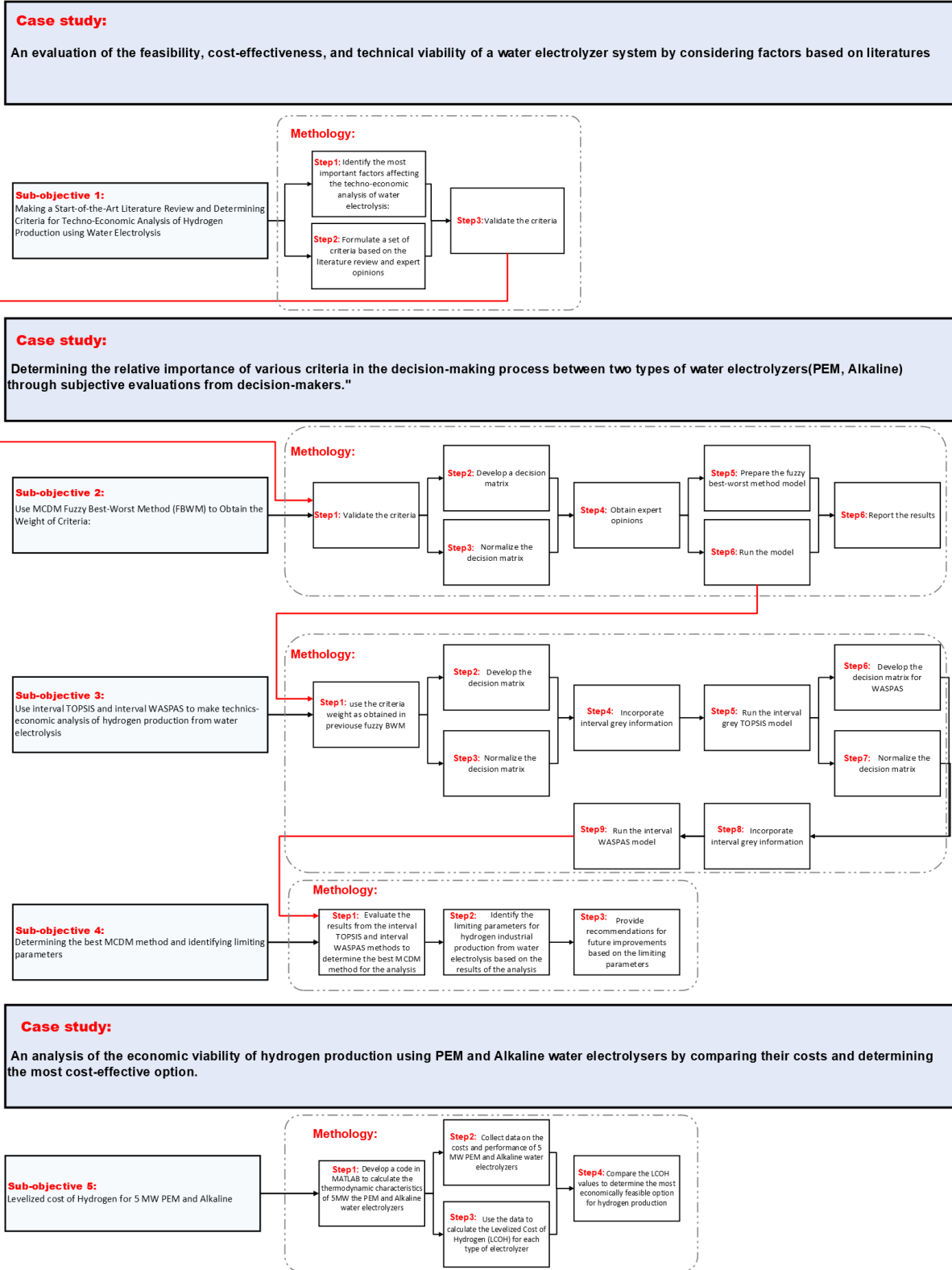


Figure 3. 1. Overview of methodology

3.1.1. Evaluating hydrogen production through water electrolysis with a literature review and technical-economic criteria

The purpose of this section is to tackle the initial sub-objective outlined in the thesis. Conducting a Literature Review offers a thorough understanding of the latest research and advancements within a specific field. Regarding Techno-Economic Analysis of Hydrogen Production through Water Electrolysis, it gives insight into the current trends and developments in the production of hydrogen and its economic feasibility.

MCDM tools play a crucial role in evaluating and ranking different options based on multiple factors. In this context, they assist in assessing various hydrogen production technologies and determining their economic viability. The determination of criteria for these tools is essential to consider the most crucial and relevant aspects in the evaluation process, leading to a more comprehensive and precise evaluation of the technologies and improved decision-making.

It can be noted that the evaluation of hydrogen production through water electrolysis, which involves a literature review and the application of technical-economic criteria, can be briefly summarized in the following three main steps:

- Identify the most important factors affecting the techno-economic analysis of water electrolysis: Based on the literature review.
- Formulate a set of criteria based on the literature review and expert opinions: Using the information gathered from the literature review and consulting with experts in the field, formulate a set of criteria that will be used to evaluate the viability of hydrogen production using water electrolysis.
- Validate the criteria: Conduct a survey or interview with relevant stakeholders to validate the criteria and ensure that they accurately represent the most important factors affecting the techno-economic analysis of hydrogen production using water electrolysis.

These criteria can be summarized into five main aspects:

1. Technical feasibility: This aspect assesses the technology's ability to produce hydrogen in a safe, efficient, and reliable manner. It considers factors such as energy consumption, production capacity, conversion efficiency, and durability of the system. The technical feasibility of a specific water electrolysis technology is a crucial

consideration because it determines whether the technology can produce hydrogen in a manner that meets the required standards.

2. **Economic viability:** This aspect evaluates the cost-effectiveness of the technology and its competitiveness in the hydrogen market. It considers factors such as capital costs, operating costs, and the revenue generated from hydrogen sales. The economic viability of a technology is critical because it determines whether the technology is economically feasible to implement and operate, and whether it can compete in the hydrogen market.
3. **Environmental sustainability:** This aspect assesses the technology's environmental impact, including its carbon footprint, the use of renewable energy sources, and the potential for waste and emissions. The environmental sustainability of a technology is important because it determines the technology's impact on the environment and whether it is in line with efforts to reduce greenhouse gas emissions and promote sustainable energy production.
4. **Technological factors:** This includes the availability of the technology, the level of technological development, and the potential for improvement and innovation. These factors are important because they determine the current state of the technology and its potential for growth and development in the future.
5. **Social factors:** This includes public acceptance, regulatory and policy frameworks, and the potential for social impact. These factors are important because they determine the public's perception of the technology and whether it will be widely adopted. Additionally, they assess the impact the technology may have on society and whether it aligns with the public's values and priorities.

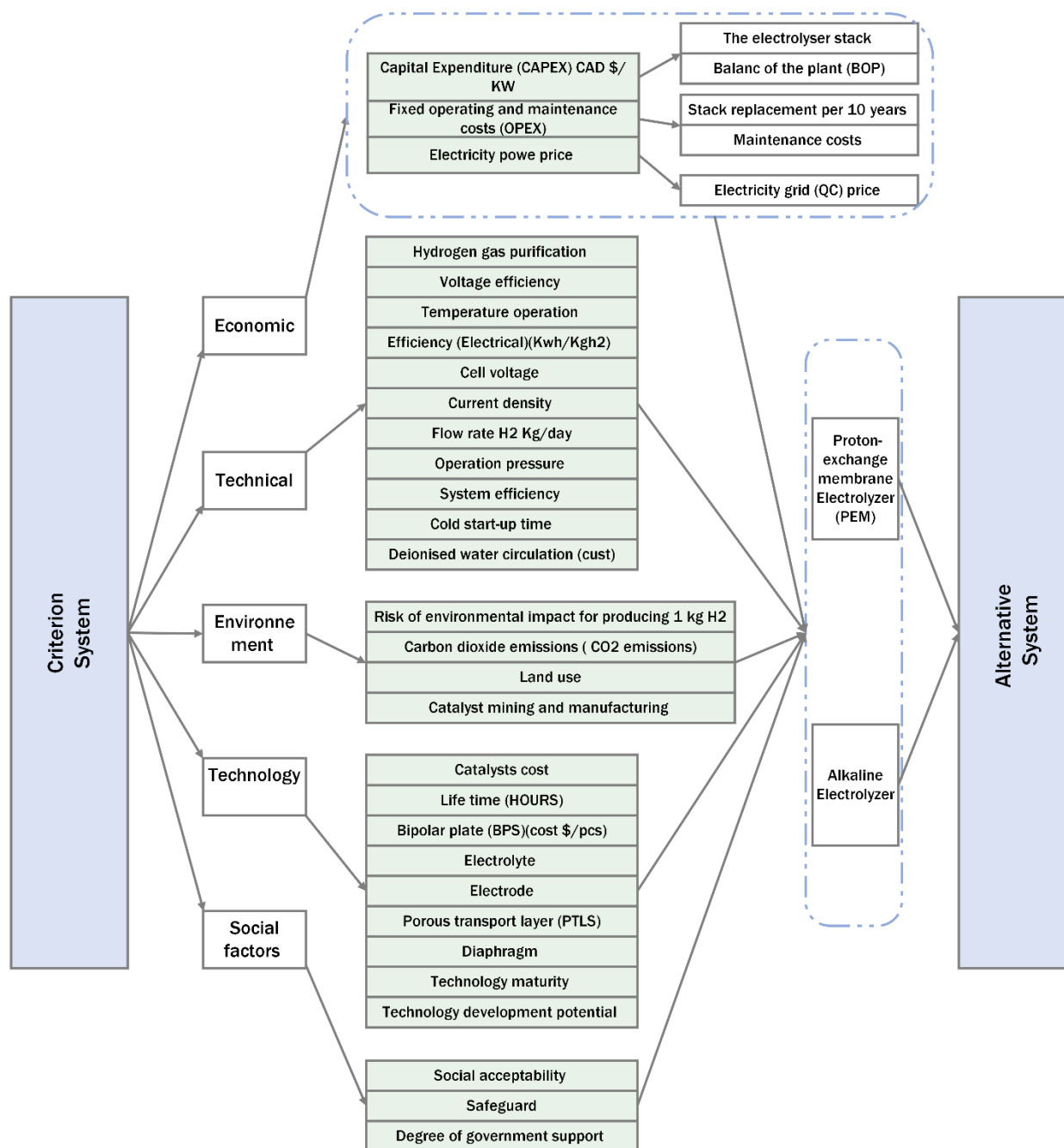


Figure 3. 2. Criteria system and alternative

Each of these aspects provides critical information about the technology and its suitability for hydrogen production, and a comprehensive evaluation of all five aspects is necessary to determine the overall feasibility and potential of the technology and can aid in decision-making about its implementation and use.

3.1.2. Use MCDM Fuzzy Best-Worst Method (FBWM) to Obtain the Weight of Criteria

This part of the methodology is designed to address the second sub-objective of this thesis. the MCDM Fuzzy Best-Worst Method (FBWM) can be used to obtain the weight of each criterion. The FBWM is a decision-making tool that uses fuzzy set theory to determine the relative importance of each criterion. It involves asking experts to rank the criteria based on their relative importance and then using that information to calculate the weight of each criterion.

This has been done through the following steps:

- Identify the criteria: First, you need to identify the criteria that are relevant to your decision. For example, the criteria for selecting a water electrolyser might include efficiency, cost, durability, reliability, and safety.
- Establish the decision-making team: The decision-making team should consist of experts in the field of water electrolyzers who are familiar with the criteria.
- Determine the linguistic terms: You need to determine the linguistic terms to represent the performance of each criterion. For example, for the criterion of efficiency, the linguistic terms could be "very high", "high", "moderate", "low", and "very low".
- Pairwise comparison: The decision-making team needs to compare the criteria pairwise to determine the degree of importance of each criterion with respect to the other criteria. For example, the team would compare the importance of efficiency with respect to cost, durability, reliability, and safety. The pairwise comparison can be represented by a matrix A , where a_{ij} is the degree of importance of criterion i with respect to criterion j . The matrix A should satisfy certain consistency requirements, such as the transitivity property. The decision-makers can use their expertise to provide the values for a_{ij} .
- Calculate the best-worst values: Using the pairwise comparisons, calculate the best and worst values for each criterion. The best value represents the highest degree of importance, while the worst value represents the lowest degree of importance.
- Calculate the degree of optimism: The degree of optimism represents the level of optimism of the decision-makers with respect to each criterion. It is calculated by subtracting the worst value from the best value.

- Calculate the fuzzy weights: The fuzzy weights are calculated using the degree of optimism for each criterion. The higher the degree of optimism, the higher the weight.
- Normalize the fuzzy weights: Finally, you need to normalize the fuzzy weights so that they add up to 1. This is done by dividing each fuzzy weight by the sum of all fuzzy weights.

The fuzzy best-worst method allows decision-makers to consider multiple criteria and their degree of importance in a systematic and structured way. By using linguistic terms, the method can handle imprecise and uncertain information, which is common in decision-making in real-world situations.

3.1.3. Use interval TOPSIS and interval WASPAS to make technico-economic analysis of hydrogen production from water electrolysis.

The third objective of this study is to perform a technical-economic analysis of two hydrogen production technologies, namely PEM and Alkaline water electrolysis, utilizing the interval TOPSIS and interval WASPAS techniques. The weightage of criteria for the analysis was determined via Fuzzy BWM. These two multi-criteria decision-making methods are widely employed to offer a comprehensive evaluation of alternative solutions while also accommodating the uncertainty and imprecision related to the criteria.

Interval TOPSIS is used to determine the relative closeness of the alternatives to the ideal solution, considering both the distance to the ideal solution and the distance to the anti-ideal solution. This method is suitable for situations where the decision-maker is concerned about the trade-offs between criteria and seeks an optimal solution with respect to multiple criteria. Interval TOPSIS can handle the imprecision or uncertainty associated with the criteria by considering intervals instead of precise values.

Interval WASPAS, on the other hand, is used to evaluate the deviation of the alternatives from the ideal solution and the anti-ideal solution, considering the weights of the criteria. This method is suitable for situations where the decision-maker is more concerned about the deviation from the ideal solution and seeks a solution that is as close to the ideal solution as possible. Interval WASPAS is also able to handle the imprecision or uncertainty associated with the criteria by considering intervals instead of precise values.

This has been done through the following steps:

1. Develop the decision matrix: The decision matrix consists of the alternatives (PEM and Alkaline water electrolysis) and the criteria obtained from Fuzzy BWM, along with their weights. This matrix is used as input for both interval TOPSIS and interval WASPAS.
2. Determine the intervals: Interval TOPSIS and interval WASPAS require intervals for each criterion, which represent the acceptable range of values for each criterion. These intervals can be determined based on expert opinions or based on previous research and literature.
3. Normalize the decision matrix: Normalization is done to ensure that all criteria have the same scale and range. This is important since some criteria may have a larger range or a higher impact on the final decision than others. Normalization can be done using different methods, such as linear normalization, min-max normalization, or standardization.
4. Calculate the weighted normalized decision matrix: Multiply the normalized decision matrix by the weight of each criterion obtained from Fuzzy BWM.
5. Determine the ideal and anti-ideal solutions: The ideal solution represents the best possible performance for each criterion, while the anti-ideal solution represents the worst possible performance. The ideal solution is obtained by selecting the maximum value for each criterion, while the anti-ideal solution is obtained by selecting the minimum value for each criterion.
6. Calculate the distance between each alternative and the ideal and anti-ideal solutions: The distance between each alternative and the ideal and anti-ideal solutions is calculated for each criterion. This is done using a distance function such as Euclidean distance or Manhattan distance.
7. Calculate the relative closeness to the ideal solution: The relative closeness to the ideal solution is calculated for each alternative using a closeness function. For interval TOPSIS, the closeness function is based on the distance to the ideal solution and the distance to the anti-ideal solution, while for interval WASPAS, it is based on the deviation from the ideal solution and the deviation from the anti-ideal solution.
8. Rank the alternatives: Rank the alternatives based on their relative closeness to the ideal solution. The alternative with the highest rank is the best choice.
9. Interpret the results: Finally, interpret the results by analyzing the rankings and considering the sensitivity analysis. Sensitivity analysis can be used to examine how the results change with variations in the intervals, weights, or decision matrix.

the combination of these two methods provides a powerful tool for the analysis and evaluation of hydrogen production technologies from water electrolysis.

3.1.4. Determining the best MCDM method and identifying limiting parameters

After performing the technical-economic analysis using interval TOPSIS and interval WASPAS methods, it is important to identify the limiting parameters for hydrogen production from water electrolysis. Limiting parameters are the parameters that have the greatest impact on the performance of the system and that can potentially hinder the industrial production of hydrogen. Here are the steps to identify the limiting parameters:

- Review the results of the technical-economic analysis: Carefully review the results of the analysis to identify any trends or patterns in the data. This will help to identify the parameters that have the greatest impact on the performance of the system.
- Rank the parameters: Once the important parameters have been identified, rank them in order of importance based on their impact on the system's performance. This ranking can be done using a variety of methods such as statistical analysis or expert opinions.
- Determine the threshold values: Determine the threshold values for the parameters that have been identified as limiting parameters. These values represent the upper or lower limits beyond which the system's performance will be significantly affected.
- Compare with industry standards: Compare the threshold values with industry standards to see how the system's performance measures up against best practices in the industry.
- Provide recommendations: Once the limiting parameters have been identified and analyzed, provide recommendations for future improvements that can be made to the system to address these limitations.

The limiting parameters is an important step in understanding the performance of the system and making recommendations for improvements. By following these steps, it is possible to gain a better understanding of the system's performance and identify areas for improvement.

3.1.5. Levelized cost of Hydrogen for 5 MW PEM and Alkaline

The levelized cost of hydrogen (LCOH) is a metric used to estimate the total cost of producing and delivering hydrogen over the lifetime of a hydrogen production system. The LCOH takes into

account all of the costs associated with producing hydrogen, including the initial capital cost, operation and maintenance costs, and the cost of the energy used to produce the hydrogen.

Developing a MATLAB code for calculating the thermodynamic characteristics of a 5 MW water electrolyser and the corresponding LCOH can be achieved by following these steps:

- Define the inputs: The first step in developing a MATLAB code for calculating the LCOH for a 5 MW water electrolyser is to define the inputs required for the calculations. These inputs may include the efficiency of the electrolyser, the cost of electricity, and the expected lifetime of the electrolyser.
- Determine the thermodynamic characteristics: The thermodynamic characteristics of the electrolyser can be calculated using standard thermodynamic equations, such as the Nernst equation, which relates the potential difference between the electrodes to the equilibrium potential of the cell. Other relevant thermodynamic properties, such as the enthalpy and entropy changes of the electrochemical reactions, can also be calculated using standard thermodynamic equations.
- Calculate the energy efficiency: The energy efficiency of the electrolyser is determined by calculating the amount of hydrogen produced per unit of electricity consumed. This can be calculated using the thermodynamic characteristics of the system and the known electrical parameters of the system.
- Calculate the cost of electricity: The cost of electricity is a critical factor in the calculation of the LCOH. This can be obtained from energy market data or can be estimated using data on the cost of energy in the region where the electrolyser is located.
- Estimate the lifetime of the electrolyser: The lifetime of the electrolyser is an important factor in the calculation of the LCOH. This can be estimated based on the expected lifespan of the materials used in the electrolyser and the anticipated maintenance requirements.

By considering all of these factors, the LCOH provides a more comprehensive estimate of the total cost of producing and delivering hydrogen than other metrics, such as the cost per kilogram of hydrogen produced. To determine the LCOH for a 5 MW proton exchange membrane (PEM) or alkaline water electrolysis system, the following steps can be followed:

The Levelized Cost of Hydrogen (LCOH) for a 5 MW Proton Exchange Membrane (PEM) and Alkaline water electrolyzers can be calculated by following these steps:

- Define the inputs: The first step is to define the inputs required for the calculations. These may include the efficiency of the electrolyser, the cost of electricity, the capital cost, and the expected lifetime of the electrolyser.
- Determine the hydrogen production rate: The hydrogen production rate can be calculated using the known efficiency of the electrolyser and the known electrical power input.
- Calculate the cost of electricity: The cost of electricity is a critical factor in the calculation of the LCOH. This can be obtained from energy market data or can be estimated using data on the cost of energy in the region where the electrolyser is located.
- Estimate the lifetime of the electrolyser: The lifetime of the electrolyser can be estimated based on the expected lifespan of the materials used in the electrolyser and the anticipated maintenance requirements.
- Develop a financial model: A financial model can be developed to estimate the total cost of producing and delivering hydrogen over the lifetime of the electrolyser. This includes the initial capital cost, operation and maintenance costs, and the cost of electricity.
- Calculate the LCOH: The LCOH can be calculated by dividing the total cost by the total amount of hydrogen produced over the lifetime of the electrolyser.
- Analyze the results: The results of the LCOH calculation can be analyzed to understand the impact of different variables, such as the cost of electricity and the efficiency of the electrolyser, on the LCOH.
- Compare the results: The LCOH for the PEM and Alkaline water electrolyzers can be compared to determine which type of electrolyser is more cost-effective.

By following these steps, the LCOH for a 5 MW PEM and Alkaline water electrolyzers can be calculated. The calculated LCOH can be used to evaluate the economic feasibility of using these electrolyzers for hydrogen production. The results can be used to make informed decisions regarding the design and operation of hydrogen production facilities, and to help guide investment decisions in the hydrogen industry.

The results obtained using the methodology were critical in identifying the most economically feasible option for hydrogen production. A chart can be used to represent the LCOH values for the two types of water electrolyzers findings of this study can be used by decision-makers to make informed decisions about hydrogen production from water electrolysis.

**CHAPTER 4 ARTICLE1 1: A CRITICAL REVIEW OF THE TECHNO-
ECONOMIC ANALYSIS OF THE HYDROGEN PRODUCTION FROM
WATER ELECTROLYSERS USING MULTI-CRITERIA DECISION
MAKING (MCDM)**

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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 microgrid 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 electrolyzers. 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 electrolyzers 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.

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

4.1. Introduction

(Table 4. 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 4. 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	Euro Asia	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 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 electrolyzers 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 electrolyzers 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 electrolyzers is the development of efficient and cost-effective electrolyzers that can operate at scale. There is a need for further innovation in the design and manufacturing of electrolyzers to improve their efficiency and reduce their overall cost(Jang, Kim, Kim, Han, et al., 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

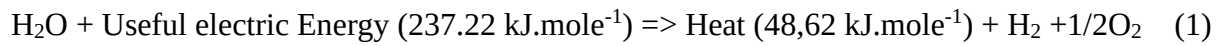
(IRENA), the cost of green hydrogen needs to drop by at least 50% by 2030 to become competitive with fossil-fuel-based hydrogen in many applications, and by up to 85% to compete in energy-intensive industries like steel and ammonia production. Several factors contribute to the high cost of green hydrogen production. First, the cost of renewable electricity, the main input for electrolysis, needs to continue to decrease. Second, the cost of electrolyzers 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 electrolyzers 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 electrolyzers 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.

4.2. Water electrolysis technologies-a summary

4.2.1. Introduction to water electrolysis 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:



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 $\Delta H = 285.84 \text{ kJ.mole}$. From this energy a minimum required or thermos-neutral voltage (V_{Tn}) for the water electrolysis is obtained from the classical relation:

$$\Delta H = -nFV_{Tn} \quad (2)$$

Where

$n=2$ is the number of electrons involved;

$F = 96500 \text{ Coulons.mole}^{-1}$ 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):

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

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):

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

Where

T = temperature in Kelvin

The basic reactions of water electrolysis using alkaline and acidic electrolytes are respectively shown in (Figure 4. 1) and (Figure 4. 2).

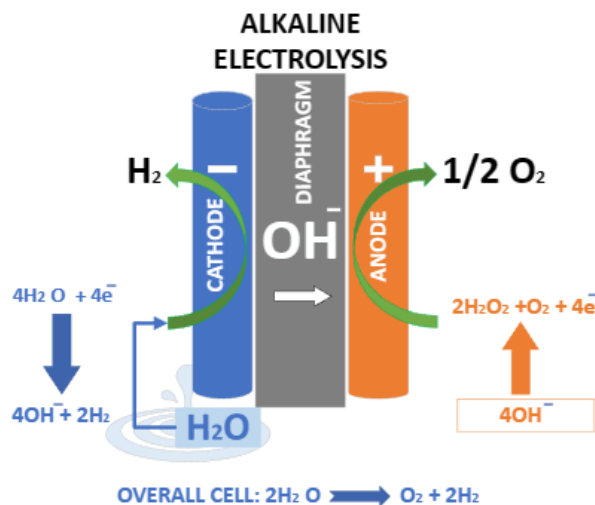


Figure 4. 1 Schematic principle of Alkaline water splitting (Shiva Kumar & Himabindu, 2019)

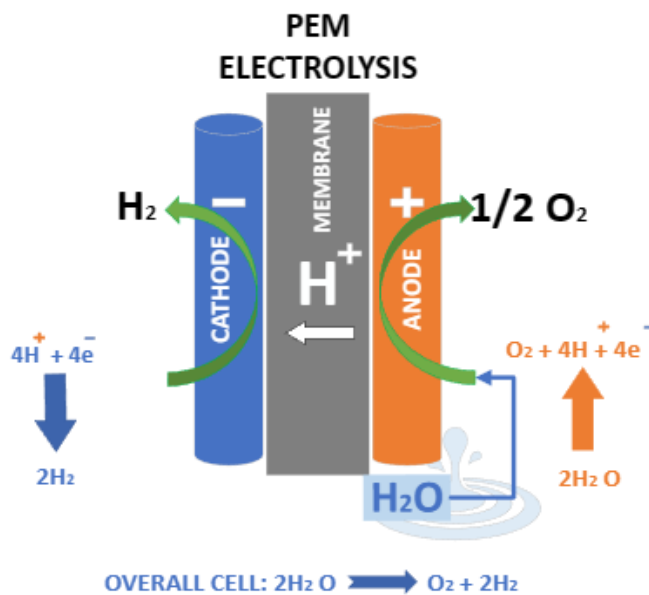


Figure 4. 2. Schematic principle of PEM water splitting (Shiva Kumar & Himabindu, 2019)

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 electrolyzers. This helps to make the splitting at a technical lower voltage. The hydrogen production cost from

industrial electrolyzers is also very dependant of the variation of the applied potential to the cells. The overvoltage (η) 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):

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

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 electrolyzers, 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):

$$V_{app} = V_{eq} + \eta_a + |\eta_c| + \eta_{\Omega} \quad (6)$$

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.

$\eta_{\Omega} = IR$ 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 4. 3) shows the relative representation of the variation of the various overvoltage with the operating current. At the operating current density of the electrolyzers (1A.cm^{-2} for PEM electrolyzers), the anodic overvoltage and the ohmic drops are the most important losses of the cell.

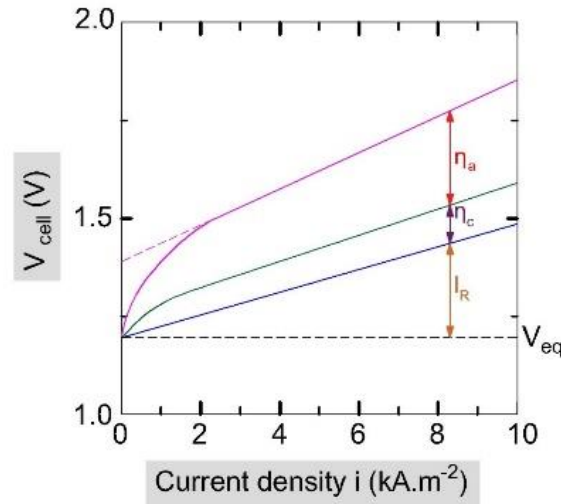


Figure 4. 3. Variation of the different contributions of the cell voltage of a water electrolysis cell(Savadogo, 2000)

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

$$C_E = aq\eta (V_{eq} + \eta_a + |\eta_c| + \eta_\Omega) \quad (7.a)$$

or

$$C_E = aq\eta = aq(b_a \ln(\frac{i}{i_0})) + b_c \ln(\frac{i}{i_0}) + IR) \quad (7)$$

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 electrolyzers 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 electrolyzers 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_{H_2}) given by:

$$f_{H_2} = \eta_F \frac{I_{cell} N_{cell}}{ZF} \frac{22.41}{1000} 3600$$

N_{cell} = number of electrolysis cell

I_{cell} 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/m³

In comparison to the alkaline electrolyser, the PEM electrolyser operates at high current density and low potential.

(Table 4. 2). Indicates the overview of the Technical Features of the five Common Water Electrolysis Technologies. The Alkaline electrolyzers 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 electrolyzers exhibit low operating potential range (1.4 to 2.4 Volts) and high current density (1 to 2 A.cm⁻²). The features of the AEM electrolyzers 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 4. 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). The highest 67

Table 4. 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	$2\text{OH}^- \rightarrow \text{H}_2\text{O} + 1/2 \text{O}_2 + 2\text{e}^-$	$2\text{OH}^- \rightarrow \text{H}_2\text{O} + 1/2 \text{O}_2 + 2\text{e}^-$	$\text{H}_2\text{O} \rightarrow 2\text{H}^+ + 1/2 \text{O}_2 + 2\text{e}^-$	$\text{O}_2 \rightarrow 1/2 \text{O}_2 + 2\text{e}^-$	Oxidation of organic matter by electroactive bacteria (e.g., Acetate $\rightarrow 2\text{HCO}_3^- + 4\text{H}^+ + 4\text{e}^-$)
Cathode Reaction	$\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2\text{OH}^-$	$\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2\text{OH}^-$	$2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$	$\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 1/2 \text{O}_2$	$2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$
Overall cell	$\text{H}_2\text{O} \rightarrow \text{H}_2 + 1/2 \text{O}_2$	$\text{H}_2\text{O} \rightarrow \text{H}_2 + 1/2 \text{O}_2$	$2\text{H}_2\text{O} \rightarrow \text{H}_2 + 1/2 \text{O}_2$	$\text{H}_2\text{O} \rightarrow \text{H}_2 + 1/2 \text{O}_2$	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/cm ²	0.2–2 A/cm ²	1–2 A/cm ²	0.3–1 A/cm ²	0.1 - 1 A/m ²
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
H ₂ 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 H ₂	51.5-66 kWh/Kg H ₂	47-66 kWh/Kg H ₂	35-50 kWh/Kg H ₂	Varies based on system design
Electrical Efficiency (system)	50-78 kWh/Kg H ₂	57-69 kWh/Kg H ₂	50-83 kWh/Kg H ₂	40-50 kWh/Kg H ₂	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 cm ²	<300 cm ²	cm ²	cm ²	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 → 2HCO ₃ ⁻ + 4H ⁺ + 4e ⁻)

Table 4. 3. Shows the 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/cm ²	> 2 A/cm ²	> 2 A/cm ²	> 2 A/cm ²
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%
H ₂ purity	Same as 2020	> 99.9999%	> 99.9999%	> 99.9999%
Voltage efficiency (LHV)	>80%	> 70%	> 75%	> 85%
Electrical efficiency (stack)	< 42 kWh/Kg H ₂	< 42 kWh/Kg H ₂	< 42 kWh/Kg H ₂	< 35 kWh/Kg H ₂
Electrical efficiency (system)	< 45 kWh/Kg H ₂	< 45 kWh/Kg H ₂	< 45 kWh/Kg H ₂	< 40 kWh/Kg H ₂
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 cm ²	30 000 cm ²	1 000 cm ²	500 cm ²

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),

4.2.2. 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).

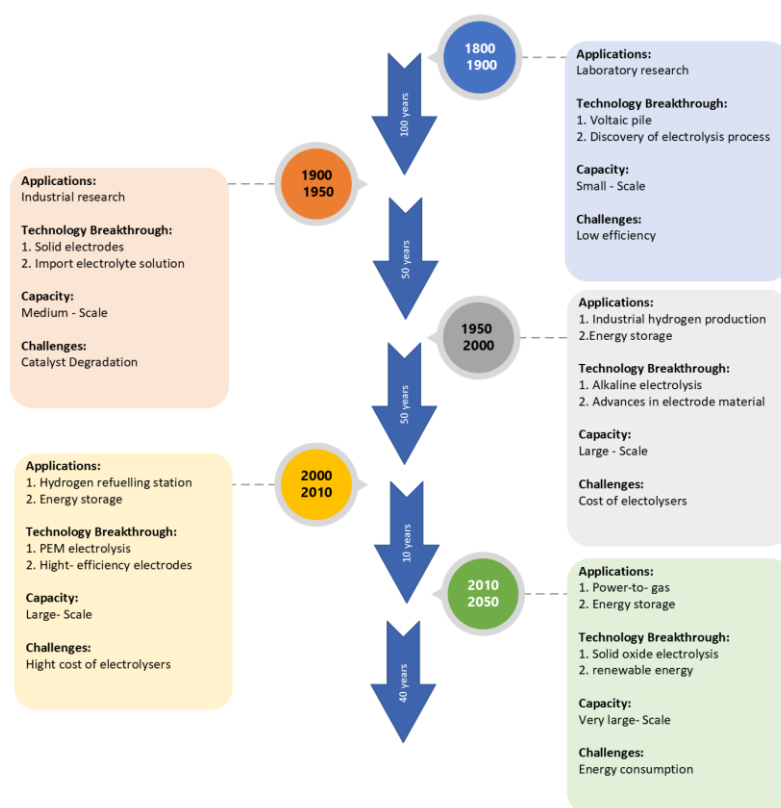


Figure 4. 4. Challenge, application and technology of different generation of electrolyzers(Shiva Kumar & Lim, 2022)

Commercial electrolyzers which are mass-produced include Liquid Alkaline Electrolyzers (AE) and Acidic Solid Polymer Electrolyte Membrane Electrolyzers (PEM-electrolyser). Advanced technologies in development are based on Solid Anion Exchange Membranes (AEM) and Solid Oxide Electrolyzers (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 3.2 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 of commercial alkaline electrolysers were installed worldwide and those of the PEM electrolysers technologies where 89 MW (IEA, 2021). 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

4.2.3. 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 4. 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 4. 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 4. 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(X. 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 4. 7) of the schematic block of alkaline electrolyser system (IRENA, 2020).

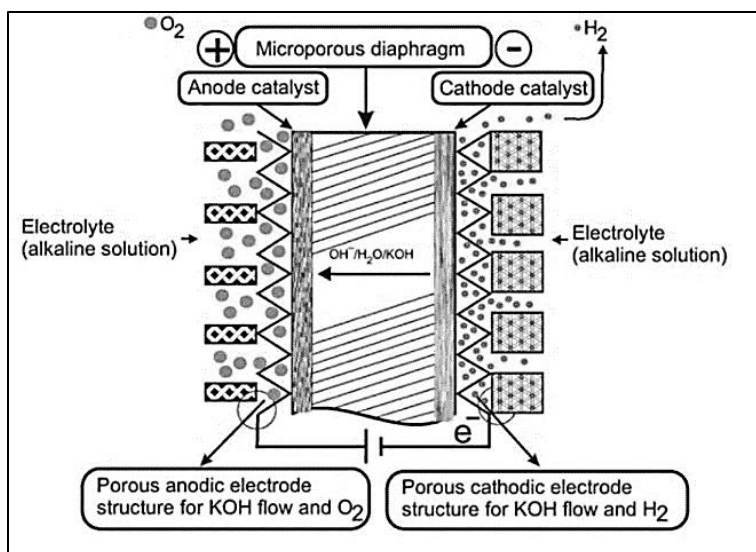


Figure 4. 5 . schematic diagram representing the design of the zero-gap cell with a microporous separator. (Bessarabov & Millet, 2018)

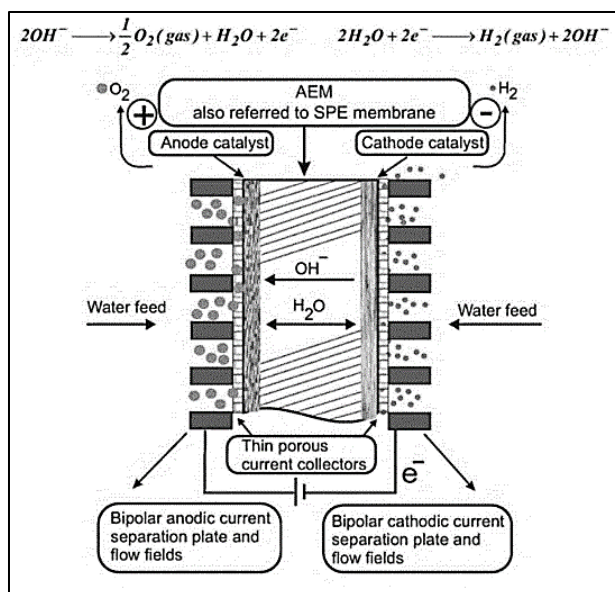


Figure 4. 6. Diagram showing the operation of the classical liquid (with diaphragm or ion membrane) alkaline electrolyser or Anion Exchange Membrane (AEM) electrolyser if the electrolyte is an anion exchange solid polymer electrolyte membranes (Bessarabov & Millet, 2018)

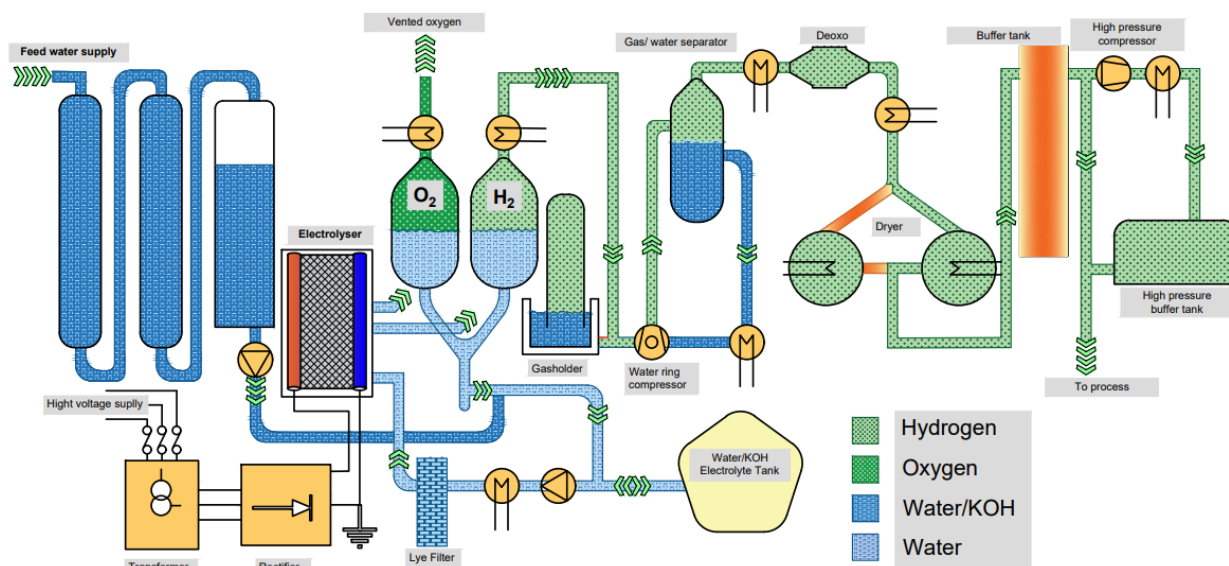


Figure 4. 7. Schematic block of the Alkaline electrolysis system (IRENA, 2020)

Table 4. 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)

4.2.4. Descriptions of PEM electrolyzers

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 4. 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 et al., 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. The bipolar plates are also responsible for distributing the reactant water/product gases uniformly across the surface of the catalyst-coated membrane (Mayyas et al., 2019). Proton exchange membrane (PEM) electrolyzers 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 4. 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.

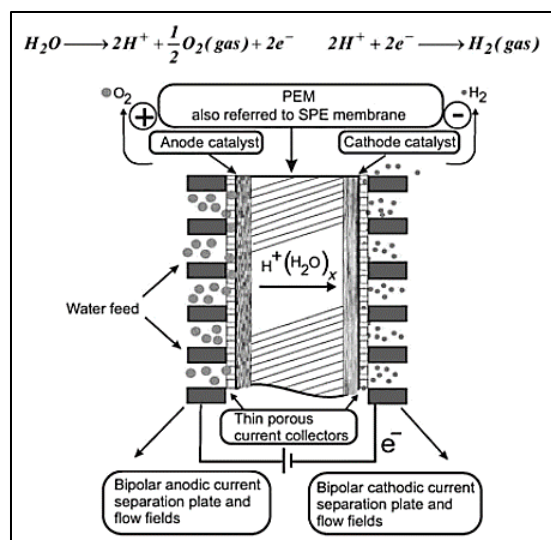


Figure 4. 8. Schematic representing the operation of the PEMEC electrolysis process (Bessarabov & Millet, 2018).

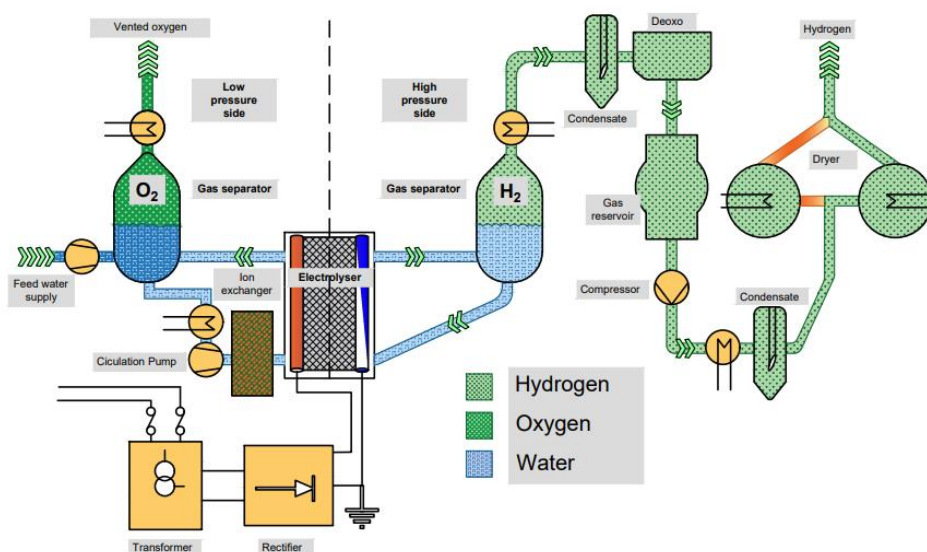


Figure 4. 9. Block diagram of industrial hydrogen production with PEM technology (IRENA, 2020)

4.2.5. Status of the Trends and Challenges for Alkaline and PEM electrolyser technologies

4.2.5.1. Alkaline electrolyzers 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).

Alkaline electrolyzers have been around for over a century and have undergone significant changes and improvements over time. The first-generation alkaline electrolyzers were developed in the early 1900s and used asbestos diaphragms to separate the anode and cathode compartments. These electrolyzers 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 electrolyzers 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 electrolyzer. the electrodes in first-generation alkaline electrolyzers were typically made of nickel and iron, which had low efficiency and durability. Second-generation electrolyzers used platinum-coated electrodes, which improved efficiency but were expensive. Third-generation alkaline electrolyzers 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 electrolyzer 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 et al., 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(N. Kuleshov et al., 2019). This trend is evident in the size of alkaline electrolyzer installations, which have been steadily increasing over the years. Large-scale alkaline electrolyzers 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 electrolyzers 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 et al., 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 4. 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, RuO ₂ , 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)

4.2.5.2. PEM Electrolysers challenges and trends

(Figure 4. 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 et al., 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 et al., 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 et al., 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 et al., 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 electrolyzers, 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 electrolyzers' 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(N. 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 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 electrolyzers 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 electrolyzers promise to address the key challenges of cost reduction, efficiency improvement, and scalability (David Parra, 2016).

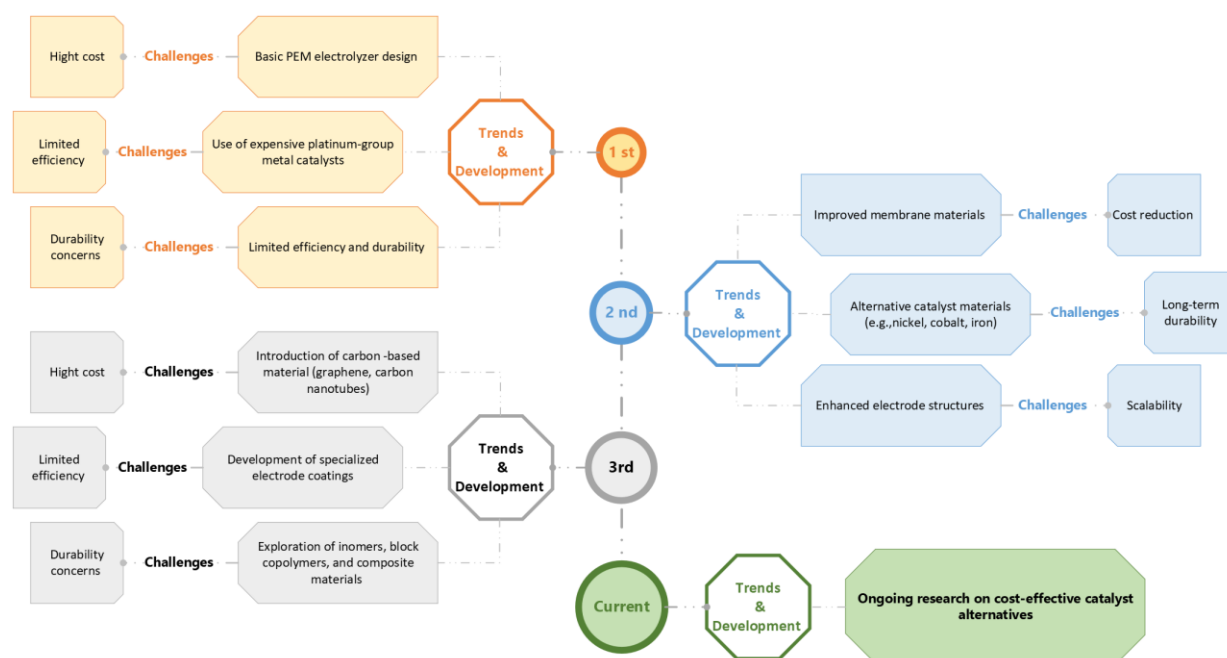


Figure 4. 10. Diagram of the PEM challenges and trends in different generations of the technology (Jourdani et al., 2017)

4.2.6. Cost-Cutting Measures and Markets for large scale plants

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/cm^2 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 4. 11) and (Table 4. 2)**. European union plans to install 40 GW of renewable hydrogen electrolyzers 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.

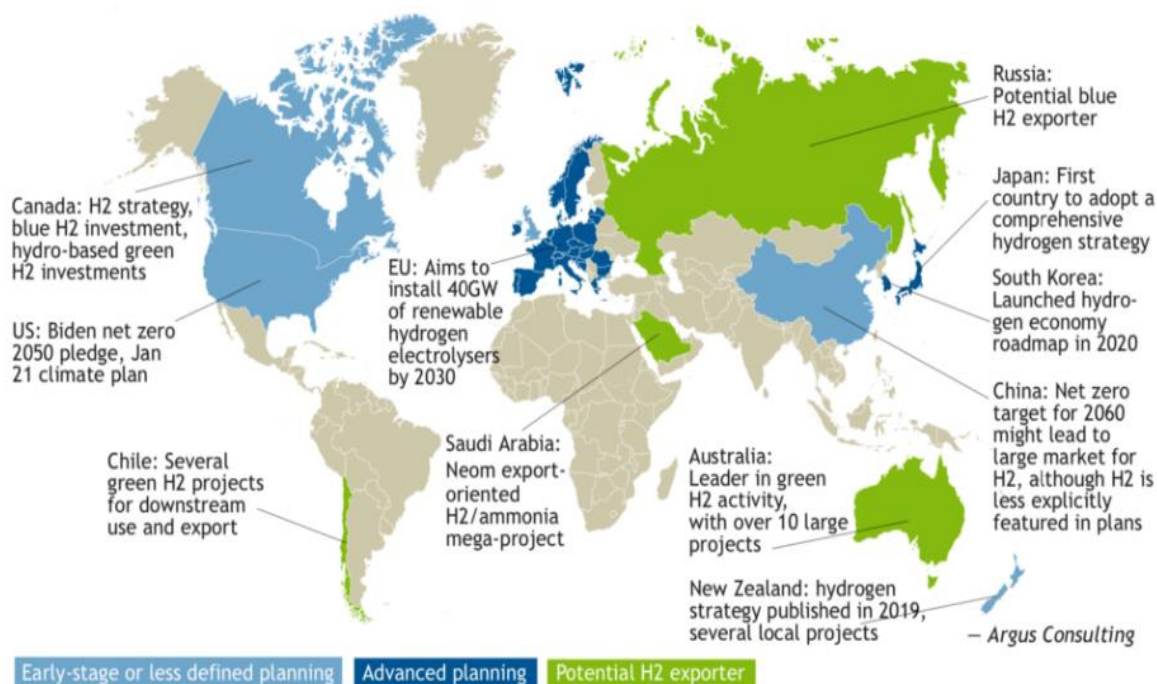


Figure 4. 11. hydrogen strategy for various regions and countries worldwide (IEA, 2013)

Table 4. 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 electrolyzers 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. (Savadogo, Fradette, Chaouki, Neisiani, & Tanguy, 2020b),(Savadogo, Fradette, Chaouki, Neisiani, & Tanguy, 2020a)

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 electrolyzers 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 et al., 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 H₂ 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 electrolyzers power plants by 2030 based on renewable energy power.

Table 4. 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.

4.3. Multi-criteria decision making (MCDM)

4.3.1. Introduction

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.
- a. 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.

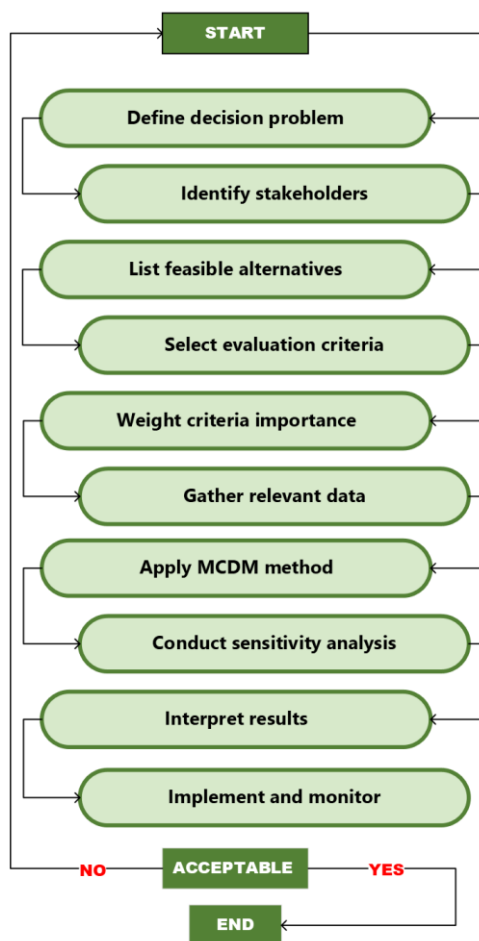


Figure 4. 12. Common procedure for MCDM analysis(Zopounidis & Pardalos, 2010)

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 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.

4.3.2. 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 et al., 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 is 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, 2000b).

(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, 2000b)

4.3.3. MCDM for sustainable energy planning implementation

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).

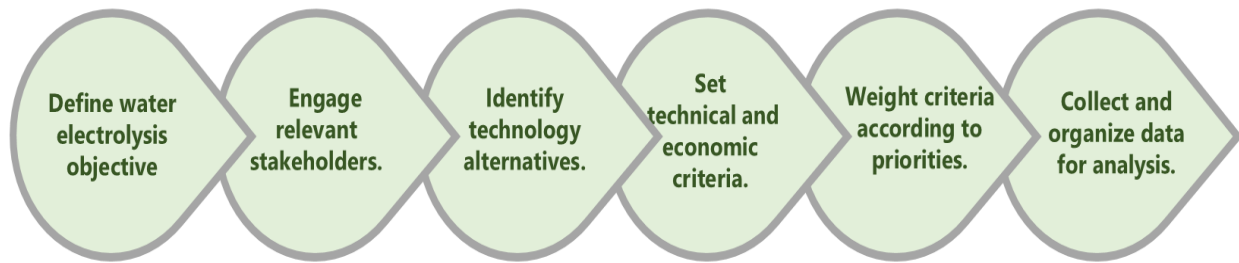


Figure 4. 13. Decision-making process for water electrolyzers (A. Kumar et al., 2017).

4.3.4. 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 electrolyzers. These factors include the following aspects.

- ❖ **Efficiency:** Higher efficiency leads to reduced energy consumption and lower
- ❖ **operational costs;**
- ❖ **Durability:** Long-lasting electrolyzers reduce maintenance and replacement costs, contributing to lower overall expenses.

- ❖ Response time: Fast response times allow electrolyzers 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 electrolyzers 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 electrolyzers 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 electrolyzers, 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 $\$/\text{m}^2$: Bipolar plates affect the cost, efficiency, and durability of the system. Comparing the costs of different materials and designs can help identify optimal 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.

Table 4. 8. 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

4.3.5. 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:

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.

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.

4.4. 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.

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.

4.5. Conclusion

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 less 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.

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**CHAPTER 5 ARTICAL 2: TECHNO ECONOMIC ANALYSIS OF
HYDROGEN PRODUCTION BY WATER ELECTROLYSERS USING
MCDM METHODS**

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Abstract

Hydrogen, a crucial clean and renewable energy source, addresses pressing challenges of energy security and environmental pollution. Water electrolysis for hydrogen production is a promising approach to satisfy the growing demand for sustainable energy. This study performs a techno-economic analysis of hydrogen production using Alkaline and Proton Exchange Membrane (PEM) electrolyzers and evaluates their performance with Multi-Criteria Decision-Making (MCDM) techniques. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Weighted Aggregated Sum Product Assessment (WASPAS) interval methods are used for comparison, while Best Worst Method (BWM) with fuzzy logic assigns evaluation criteria weights. The evaluation framework covers five aspects, including environmental, technical, technological, economic, and social factors, divided into 30 sub-criteria. These insights offer a comprehensive understanding of each electrolyser's strengths and weaknesses, helping stakeholders make informed decisions about cost reduction in hydrogen production technologies. Although cost results favour Alkaline electrolyzers, PEM electrolyzers are attractive for specific applications where their benefits justify the higher initial cost, choosing between Alkaline and PEM electrolyzers dependent on a given hydrogen production project's requirements.

Keywords: Sustainable, hydrogen Renewable energy, PEM electrolyser, Alkaline electrolyser, Multicriteria decision-making, MCDM

5.1. Introduction

Hydrogen serves as a versatile energy medium with numerous applications in various industrial processes. With a substantial global production of 70 million tonnes per year, it is primarily used in petroleum extraction and refining, as well as ammonia manufacturing. Nevertheless, the rising interest in electrochemically generated hydrogen presents promising opportunities for electricity storage and as an eco-friendly energy medium for various utilisations including the transportation industry. A key benefit of this hydrogen production method is its ability to provide a clean and efficient means of storing surplus electricity generated by power plants including renewable sources. In particular renewable electricity plants based on Solar PV and wind are well indicated for the production of hydrogen by the net of the sun and the wind respectively. Accordingly, excess of electricity of a grid or dedicated solar or wind power plants can be harnessed to produce hydrogen, which can then be storage for future electricity generation when required(IEA, 2023).

The International Energy Agency highlights that electrolysis is a promising technique for hydrogen production, with "green" hydrogen increasingly generated through this method to lower greenhouse gas emissions and foster sustainable energy generation. Moreover, hydrogen fuel cell vehicles, which only emit water vapour, serve as a zero-emission alternative to conventional gasoline-powered vehicles. The IEA reports that out of the hydrogen produced globally, approximately 4% or 2.8 million tons were derived from water electrolysis. Hydrogen can also be employed in fuel cells to produce heat and power for residential, commercial, and industrial uses. With the expansion of hydrogen refuelling infrastructure, fuel cell vehicles have the potential to significantly transform the transportation industry (IRENA, 2019).

The production of green hydrogen based on electrolyzers is accelerating, as they offer an environmentally friendly and sustainable substitute during their utilisation to conventional hydrogen production methods which involve hydrocarbon fuel processes (Commission, 2021). Although the upfront investment for electrolyzers can be substantial, their decentralized functionality makes them appropriate for various applications. Nevertheless, the expense of materials employed in their assembly, like platinum-based electrodes at the cathode and or iridium based electrodes and others at the anode represent parts of the limiting factors responsible for the high cost of the hydrogen production using PEM electrolyzers. The iridium charge per kW power of the electrolyser is 1.3 to 2 g/kW. The platinum estimated charge per kW power of the electrolyser is 0.5 to 1 g/kW. The commercial PEM electrolyser system of 5 MW needs at least 2,5 kg of Pt and 6.5 kg of iridium. The annual production of platinum in 2022 was 190 tons. The annual production of iridium in 2022 was 7.7 tons (statista, 2023b). The platinum cost per kilogram was 33 755\$/kg in 2022 (Statista, 2023a). The iridium price in 2022 was between 80 700 \$/kg to 161 400 \$/kg (Umicore, 2023). The specific energy of platinum extraction is 67,5 kWh/kg of Pt and involves the production of 12,5 tons of CO₂/kg of Pt and that of iridium is 10 tons of CO₂/kg of Ir (IRENA, 2020). Other critical materials used in alkaline or PEM electrolyzers are: Cobalt for PEM and Nickel for Alkaline Electrolyser. These costly materials can notably elevate the total production cost (DOE, 2021). Addressing this issue, ongoing research aims to identify cost-effective non nobles and available for materials used in electrolyser manufacturing. Multiple aspects contribute to the high cost of green hydrogen production. Firstly, the price of renewable electricity, which serves as the primary input for electrolysis, must keep dropping. Secondly, technological advancements, scaled-up production, and intensified competition among providers

must drive down electrolyser costs. Lastly, the expenses associated with producing and transporting water for electrolysis must be minimized (IRENA, 2020). A thorough techno-economic assessment of water electrolysis can help identify the best strategy for hydrogen production, considering factors such as capital and operational costs, electrolysis cell performance, and the accessibility of inexpensive electricity. By closely analyzing these elements, the most economically viable approach for producing hydrogen through electrolysis can be established. As stated by the U.S. Department of Energy's (DOE) Hydrogen and Fuel Cells Program Record, the mean cost of electrolyser stack and balance of plant (BOP) components, as provided by manufacturers in the United States in 2013, stood at \$5.14/kg for a daily production capacity of 1,500 kg and \$5.12/kg for a daily production capacity of 50,000 kg (Ainscough et al., 2014). A comparative analysis of hydrogen production techniques, such as AWE (Alkaline Water Electrolyser), PEMEC (PEM Electrolyser), and SMR (Steam Methane Reforming), was performed (B. Lee et al., 2017) for production capacities of 30, 100, and 300 Nm³/hr. The findings revealed that PEM Electrolyser was the most cost-effective option at \$16.54 per kgH₂ for a 30 Nm³/hr capacity. In contrast, SMR demonstrated the lowest cost at \$7.59 per kgH₂ for a 300 Nm³/hr capacity. These results indicate that SMR is a more economical choice for large-scale hydrogen production, while PEMEC is better suited for smaller scale operations.

An investigation was carried (Jang, Kim, Kim, & Kang, 2022) out to assess the cost-effectiveness of four distinct water electrolysis technologies: alkaline (AWE), proton exchange membrane (PEM), solid oxide with electric heaters, and solid oxide with waste heat. The study determined that the per-unit hydrogen production costs were \$7.60, \$8.55, \$10.16, and \$7.16 per kgH₂ for AWE, PEMEC (PEM Electrolyser), SOEC-E.H (Solid Oxide Electrolyser-Electric Heat), and SOEC-W.H (Solid Oxide Electrolyser-Waste Heat), respectively. Nevertheless, the research does not offer suggestions for reducing capital expenses or implementing subsidies and tax cuts to enhance competitiveness with other hydrogen production methods. An evaluation of the costs and benefits of using solar power in Tunisia (Okonkwo et al., 2022) for electricity and hydrogen production via water electrolysis was conducted. The initial cost analysis of a PV-HRS reveals that the major expenses are the PV system (48.5%) and electrolysers (41%), while the storage system cost is relatively low at 3.2%. Producing 1 kg of hydrogen costs 3.32€/kg, and the project's total cost is 2.34 million €.

These various considerations of parameters effect on the hydrogen cost do not indicate which parameters among others may limit the cost of the green hydrogen produced from water electrolysis.

However, to compare the cost-effectiveness of green hydrogen production from Polymer electrolyser or alkaline electrolyser or its production from renewable energy sources like solar photovoltaic power, hydro power, or wind power, Multi-Criteria Decision Making (MCDM) methods or Multi-Criteria Decision Analysis (MCDA) method is a practical tool for this techno-economic assessment.

During the last decades different types of MCDM methods have been introduced and developed. The differences between the various methods are related on the level of algorithms complexity, the criteria of the weighting, how to represent the evaluation of the criteria, how to aggregate the data and to consider or not possible uncertain data (Bączkiewicz, Wątróbski, Kizielewicz, & Sałabun, 2021).

Previously our group used MCDA methods as ELECTREI, ELECTRE III with Fuzzy, TOPSIS, VIKOR, ELECTRE IV and TOPSIS for materials selection for various applications including sensitive components for aerospace applications (Shanian & Savadogo, 2006a), (Shanian & Savadogo, 2009) or bipolar plates for Polymer Electrolyte Fuel Cell Applications (Shanian & Savadogo, 2006b), (Shanian & Savadogo, 2006a); (Shanian & Savadogo, 2006c); (Shanian & Savadogo, 2006b). 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 materials considered for this application. In all cases, it was found good agreement between the results of the MCDC methods being used for the material selection and available experimental data the data bases of the Cambridge Engineering Selector (CES). It was concluded that the proposed approaches may be applied to other problems of material selections for energy applications.

In the case of hydrogen energy, by considering factors such as technological parameters, cost-effectiveness, environmental impact, technical efficiency, the offer of hydrogen and the intensity of the hydrogen demand or the utilisation sector, MCDM may help to forecast the green hydrogen development and stakeholders to take appropriate decision by identifying the most suitable cost effective of the technology for green hydrogen production in the future for the user's specific needs.

The study employed (Thengane et al., 2014) AHP and Fuzzy AHP methods to assess and compare the cost-effectiveness and benefits of various hydrogen production technologies. Eight technologies were evaluated using five criteria: greenhouse gas emissions, raw material and utilities consumption, energy efficiency, scalability, and waste disposal and atmospheric emissions. While fossil fuel-based processes were more cost-effective, renewable-based processes offered greater benefits. The cost-benefit analysis indicated that water splitting by chemical looping was the most promising among renewable approaches (Ren et al., 2020). The study presents a novel multi-criteria decision making (MCDM) approach for assessing the sustainability of hydrogen production technologies. The two-stage framework aims to identify the most promising technologies based on sustainability potential and then evaluate the remaining options, considering trade-offs among economic, environmental, and social factors. In the first stage of the MCDM framework, the authors use fuzzy best-worst and fuzzy TOPSIS methods to determine the top alternatives, considering decision-makers' preferences and information uncertainty. In the second stage, they introduce a new method that combines preference data on attributes and alternatives for evaluating the remaining technologies. This method applies a multi-objective optimization approach using the NNC method to address varying priorities and information uncertainty. The two-stage MCDM method is used to assess and compare the sustainability of hydrogen production technologies, such as steam methane reforming, partial oxidation, and electrolysis. The study's findings reveal that electrolysis is the most sustainable choice due to its low greenhouse gas emissions and high potential for utilizing renewable energy sources. The study (Abdel-Basset et al., 2021) employs a hybrid MCDM method that combines AHP and TOPSIS to evaluate various hydrogen production options based on criteria such as economic feasibility, environmental impact, technical feasibility, and safety. It examines steam methane reforming (SMR), partial oxidation, and electrolysis, considering different scenarios and uncertainties like fluctuating natural gas prices and carbon taxes.

The findings reveal that steam methane reforming is the most suitable short-term hydrogen production option due to its lower cost and high technical feasibility. In the long term, however, electrolysis emerges as the most sustainable choice, as it uses renewable energy sources and produces low greenhouse gas emissions. The study highlights the hybrid MCDM approach's usefulness in assessing sustainable hydrogen production options, offering valuable insights for policymakers and industry professionals in their decision-making processes.

This study performs, for the first time, a techno-economic analysis of hydrogen production using Alkaline and Proton Exchange Membrane (PEM) electrolyzers and evaluates their performance with Multi-Criteria Decision-Making (MCDM) techniques. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Weighted Aggregated Sum Product Assessment (WASPAS) interval methods are used for comparison, while Best Worst Method (BWM) with fuzzy logic assigns evaluation of criteria weights. The evaluation framework covers five aspects which include environmental, technical, technological, economic, and social factors, divided into 30 sub-criteria.

5.2. Objectives of this paper

Although the techno economic and MCDM methods employed for electrolytic hydrogen production and water electrolysis projects have been addressed in existing literature, there remain significant needs to develop new relevant knowledge in the electrolyzers' business for the main commercial technologies, which can be summarized as follows:

- The investigation on the key factors that influence the techno-economic analysis cost and efficiency of hydrogen production through water electrolysis.
- The hierarchic comparison using MCDM methods of alkaline and PEM electrolyzers, in terms of efficiency, reliability, performance, cost, social and environmental impacts.
- The utilisation of the Fuzzy best-worst method (FBWM) to determine the weight of each criterion in a techno-economic analysis of hydrogen production through water electrolysis and identify the key limiting parameters for industrial hydrogen production from water electrolysis using MCDM methods.
- The determination of the ability of MCDM methods to guide decision-makers to identify the most appropriate hydrogen production technology.

To succeed in the development of such new knowledge using MCDM, some fundamental criteria must be defined and can be summarized into five main aspects:

1. Technical feasibility which considers factors such as energy consumption, production capacity, conversion efficiency, and durability of the system.
2. Economic viability which considers factors such as capital costs, operating costs, and the revenue generated from hydrogen sales.

3. Environmental sustainability which assesses the technology's environmental impact, including its carbon footprint, the use of renewable energy sources, and the potential for waste and emissions.
4. Technological factors which include the availability of the technology, the level of technological development, and the potential for improvement and innovation.
5. Social factors which include public acceptance, regulatory and policy frameworks, and the potential for social impact.

To obtain the best weight for each criterion, MCDM Fuzzy Best-Worst Method (FBWM) is used. Accordingly, the following steps are achieved:

- Identify the criteria like the efficiency, cost, durability, reliability, and safety of the electrolyser.
- Establish the decision-making team with experts in the field of water electrolyzers.
- Determine the linguistic terms like for example: "very high", "high", "moderate", "low", and "very low" for the electrolyser efficiency.
- Pairwise comparison like the importance of efficiency with respect to cost, durability, reliability, and safety in a form of a matrix A , where a_{ij} is the degree of importance of criterion i with respect to criterion j . The matrix A should satisfy certain consistency requirements, such as the transitivity property. The decision-makers can use their expertise to provide the values for a_{ij} .
- Calculate the best-worst values by using the pairwise comparisons, calculate the best and worst values for each criterion.
- Calculate the degree of optimism by subtracting the worst value from the best value.

(Figure 5. 1) shows the schematic representation of the MCDM evaluation system used in this work. This diagram represents a criterion system that includes economic, technical, environmental, and technological aspects, social factors) linked to an alternative system (PEM electrolyser, alkaline electrolyser) by sub-criteria such as CAPEX, OPEX, Electricity cost, hydrogen gas diffusion, voltage efficiency, CO₂ emissions, land use, ..., catalyst cost, lifetime, BOP(Balance Of the Plant), social acceptability.

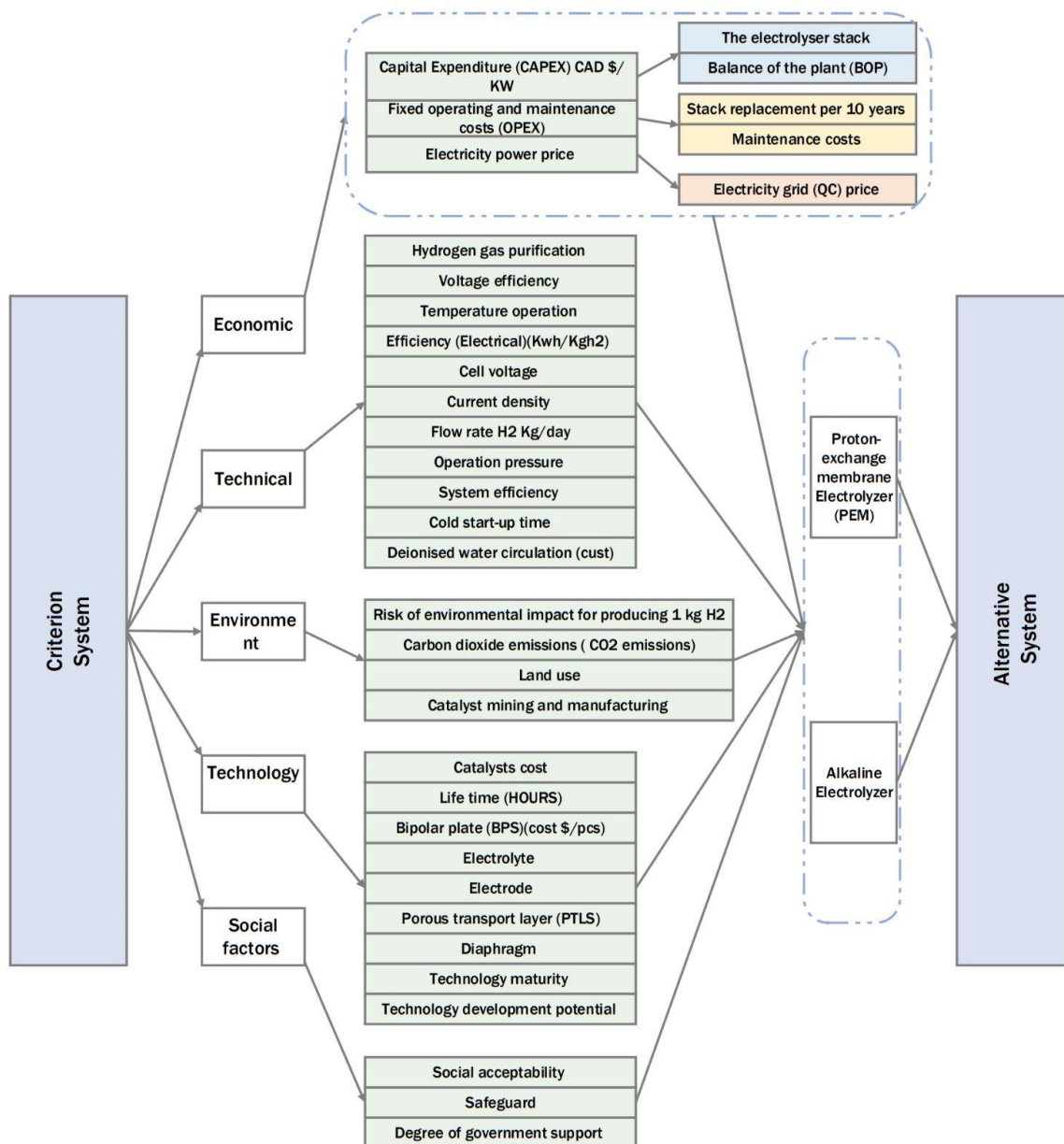


Figure 5. 1. Schematic representation of the link between the Criterion system and the alternative system

Each category of criterion encompasses various other criteria and sub criteria to produce a number of criteria known as a criterion system. This paper features a selection of 30 criteria across these five aspects to create a comprehensive criterion system (Table 5. 1)The chosen criterion system encompasses nearly all commonly used criteria for assessing water electrolyzers, providing a solid foundation for evaluating alternative water electrolysis technologies. This approach presented here

for the first time is also based on the combination of MCDM methods (See section 5.3.1) which has never been used before and ensure more reliability of the evaluation process.

Table 5. 1 Criterion sytem formed from interaction between the 5 main aspects and the various criteria and subcriteria to give 30 criteria

Aspects	Criteria	Sub Criteria	Code
Economic (A)	Capital Expenditure (CAPEX) (A1)	The electrolyser stack	A1-1
		Balance of the plant (BOP)	A1-2
	Fixed operating and maintenance costs (OPEX) (A2)	stack replacement per 10 years	A2-1
		Maintenance costs	A2-2
	Electricity power price (A3)	electricity grid (QC)price	A3-1
		Electricity renewable (wind) energy	A3-2
Technical (B)	Current density	-	B1
	Flow rate H2 Kg/day	-	B2
	Deionized water circulation(cost)	-	B3
	Temperature operation	-	B4
	Efficiency (Electrical)(Kwh/KgH2)	-	B5
	Operation pressure	-	B6
	Voltage efficiency	-	B7
	hydrogen gas purification	-	B8
	Cell voltage	-	B9
	System efficiency	-	B10
	Cold start-up time	-	B11
Environment (C)	Land use	-	C1
	Carbon dioxide emissions (CO ₂ emissions)	-	C2
	Risk of environmental impact for producing 1 kg H2	-	C3
	catalyst mining and manufacturing	-	C4
Technology (D)	catalysts	-	D1
	Lifetime (HOURS)	-	D2
	bipolar plate (BPS) (cost \$/pcs)	-	D3
	Electrolyte	-	D4
	Electrode	-	D5
	Porous transport layer (PTLS)	-	D6
	Diaphragm	-	D7
	Technology maturity	-	D8
	Technology development potential	-	D9
Social factors (E)	Social acceptability	-	E1
	Safeguard	-	E2
	Degree of government support	-	E3

5.3. MCDM Methods used to operate the schematic representation of figure.

5.3.1. Introduction

In this study, a Multi-Criteria Decision Making (MCDM) or Multi criteria Decision Analysis (MCDA) framework has been established to assess the sustainability of hydrogen production technologies through water electrolysis from a techno-economic standpoint, in which. The Fuzzy Best-Worst Method (FBWM) is applied within the MCDM framework to establish the weight of different criteria. Following this interval grey TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and the interval grey WASPAS (Weighted Aggregated Sum Product Assessment) are utilized to conduct a techno-economic analysis of hydrogen production via water electrolysis. In the final stage, the most suitable MCDM method is determined, and the limiting parameters are identified for further investigation. A short introduction of each of those MCDM methods are shown in the followings

5.3.2. Fuzzy best-worst MCDM method

The Best-Worst Method (BWM) was introduced by (Rezaei, 2015) as an extension to the Analytic Hierarchy Process (AHP) (Saaty, 1996) and Analytic Network Process (ANP) (Saaty, 1980) methodologies. BWM is a pairwise comparison-based method that simplifies the decision-making process by reducing the number of comparisons required. It involves comparing the best (most desirable) and worst (least desirable) criteria or alternatives in a decision problem.

Roberts in 1986 (Roberts, 1986) introduced the fuzzy set theory as a mathematical approach to handle uncertainty, imprecision, and vagueness that often occur in real-world situations (Zadeh, 2015). A fuzzy set is a set whose elements have degrees of membership between 0 and 1, as opposed to crisp sets, where elements have a binary membership of either 0 or 1. In fuzzy set theory, an element can belong to a set with a certain degree of truth, which is represented by a membership function.

A fuzzy set A is defined as a collection of ordered pairs of elements (x) from the universe of discourse (X) and their corresponding membership values ($\mu_A(x)$):

$$A = \{(x, \mu_A(x)) \mid x \in X\} \quad (1)$$

The membership function (μ) maps the elements of the universe of discourse (X) to their membership values in the interval $[0, 1]$:

$$\mu(x): X \rightarrow [0, 1] \quad (2)$$

The Fuzzy Best-Worst Method (FBWM) was developed as an extension of the BWM to handle the uncertainty and vagueness often encountered in real-world decision-making scenarios. By incorporating fuzzy set theory, FBWM allows decision-makers to express their preferences using linguistic variables, thereby capturing the inherent uncertainty and imprecision in their judgment (S. Guo & Zhao, 2017).

The use of linguistic variables in (Table 5. 2) and the FBWM method provide a more flexible and intuitive way for decision-makers to express their preferences and opinions, and the transformation rules allow for the conversion of these linguistic variables into numerical values that can be used in mathematical operations. This approach helps to handle imprecise and uncertain information in real-world decision-making situations, leading to more accurate and effective decision-making.

Table 5. 2. fuzzy transformation rules of linguistic variables

Linguistic Variable	Transformation Rule
Low	0
Medium Low	0.33
Medium	0.67
Medium High	0.83
High	1

The subjective assessments of the decision-makers are required to be converted into fuzzy ratings (Table 5. 3), represented as Triangular Fuzzy Numbers based on (Saaty, 1980), (S. Guo & Zhao, 2017)

Table 5. 3. Transformation rules of linguistic variables of decision-makers

Linguistic terms	Membership function
Equally importance (EI)	(1,1,1)
Weakly important (WI)	(2/3,1,3/2)
Fairly important (FI)	(3/2,2,5/2)
Very important (VI)	(5/2,3,7/2)
Absolutely Important (AI)	(7/2,4,9/2)

The steps for determining the fuzzy weights of alternatives in the fuzzy best worst method (FBWM) in Multi-Criteria Decision Making (MCDM) are as follows:

Step1. the decision criteria system provides a framework for decision-makers to assess the performance of different alternatives. It helps to ensure that all relevant factors are considered and evaluated consistently and comprehensively, leading to more informed and effective decision-making.

Step2. Construct a comparison matrix for each criterion, which contains the linguistic variables and the degree of preference or importance of one variable over another and for each criterion, determine the best and worst values of each alternative based on the comparison matrix. We represent the best criterion with C_B and the worst criterion with C_W .

Step3. In this step, decision-makers compare the best criterion with other criteria using a predefined linguistic scale, such as (Table 5. 1). The comparison is between the best criterion (C_B) and the other criteria (j), with the best criterion's comparison with the worst criterion being the highest among all. The comparison of C_{BB} with itself is equal to (1,1,1). The comparison being evaluated in this step is represented as a_{1B} , and the comparison of the worst criterion C_{WW} with itself is also equal to (1,1,1) the comparison relations (3) and (4) are as follow (S. Guo & Zhao, 2017):

$$\tilde{A}_w = (\tilde{a}_{1w}, \tilde{a}_{2w}, \dots, \tilde{a}_{3w}) \quad (3)$$

$$\tilde{A}_B = (\tilde{a}_{B1}, \tilde{a}_{B2}, \dots, \tilde{a}_{B3}) \quad (4)$$

Where

$\tilde{A}_w$ and $\tilde{A}_B$ represents the fuzzy others-to-worst vector and the fuzzy best to others vector respectively

$\tilde{a}_{ij}$ is defined as a fuzzy reference comparison (preference of criterion i to criterion j)

Which is a triangular fuzzy number..

$\tilde{a}_{iw}$ and $\tilde{a}_{Bj}$ respectively. represents the fuzzy preference of criterion i over the worst criterion and the fuzzy preference of the best criterion over criterion j ,

consider $C_w, i=1,2,\dots,n$ $\tilde{a}_{Bj}$, $\tilde{a}_{ww}=(1,1,1)$ and $\tilde{a}_{BB}=(1,1,1)$

Step4. Determining the Optimal Fuzzy Weights, The weight in which, for each pair $\frac{\tilde{w}_B}{\tilde{w}_j}$ and $\frac{\tilde{w}_j}{\tilde{w}_w}$

Where $\tilde{w}_w$ and $\tilde{w}_j$ and $\tilde{w}_B$ are triangular fuzzy number and are different from that in BWM the following relation (5) and (6) (S. Guo & Zhao, 2017) will be as follows:

$$\frac{\tilde{w}_b}{\tilde{w}_j} = \tilde{a}_{Bj} \quad (5)$$

$$\text{and } \frac{\tilde{w}_j}{\tilde{w}_w} = \tilde{a}_{jw} \quad (6)$$

To establish this condition for all j , we need to find a solution where the maximum absolute differences, $|\frac{\tilde{w}_b}{\tilde{w}_j} - \tilde{a}_{Bj}|$ and $|\frac{\tilde{w}_j}{\tilde{w}_w} - \tilde{a}_{jw}|$ be minimal for all j . Considering the non-negativity of the counters and the conditions of the sum of the weights, the following problem(7) (S. Guo & Zhao, 2017) is obtained.

$$\begin{aligned} & \text{Min, MaxJ } [|\frac{\tilde{w}_b}{\tilde{w}_j} - \tilde{a}_{Bj}|, |\frac{\tilde{w}_j}{\tilde{w}_w} - \tilde{a}_{jw}|] \\ & \sum_j R(\tilde{w}_j) = 1 \\ & l_j^w \leq m_j^w \leq u_j^w, \quad l_j^w \geq 0 \quad \text{For all } j \\ & R(\tilde{a}_i) = \frac{l_i + 4m_i + u_i}{6} \end{aligned} \quad (7)$$

Where l, m and u respectively represent the lower, modal and upper value of the support of $\tilde{a}$ all of which are crisp numbers which is $\tilde{a}$ represent the ranking of triangular fuzzy number. A Triangular Fuzzy Number can be expressed in the form of a triplet, represented as (l, m, u) . (Carlsson & Fullér, 2001)

The problem of the above relation model can be transformed into the following problem (8)(S. Guo & Zhao, 2017):

$$\begin{aligned} & \min \xi \\ & \text{s.t.} \end{aligned}$$

$$\begin{aligned}
|\frac{\tilde{w}_b}{\tilde{w}_j} - \tilde{a}_{Bj}| &\leq \tilde{a} && \text{For all } j \\
|\frac{w_j}{w_w} - \tilde{a}_{jw}| &\leq \tilde{a} && \text{For all } j \\
\sum_j R(\tilde{w}_j) &= 1 \\
l_j^w \leq m_j^w \leq u_j^w, \quad l_j^w \geq 0 \quad w_j \geq 0, &\text{ for all } j && \text{For all } j
\end{aligned} \tag{8}$$

Where $\tilde{w}_j = (l_j^w, m_j^w, u_j^w)$ represent the fuzzy weight of criterion j,

By solving the above problem, the optimal weights $(\tilde{w}_1^*, \tilde{w}_2^*, \dots, \tilde{w}_n^*)$ and ξ^* are obtained.

The Consistency Ratio (CR) is a vital indicator used to assess the degree of consistency in pairwise comparisons within the Fuzzy Best-Worst Method (FBWM). The comparisons in the Fuzzy Best-Worst Method (FBWM) are considered fully consistent when the following relationship (9)(S. Guo & Zhao, 2017) holds for all j's:

$$a_{BW} = a_{Bj} \times a_{jw} \quad [a_{BW} \in] \tag{9}$$

Where a_{BW} , a_{Bj} , and a_{jw} are the fuzzy preference of the best criterion over the worst criterion, the fuzzy preference of the best criterion over the criterion j, and the fuzzy preference of the criterion j over the worst criterion, respectively. When the consistency ratio relation (10) is closer to zero, the comparisons are more consistent and stable, and when it is closer to one, the comparisons are less consistent and stable.

Ensuring a low consistency ratio in the FBWM is crucial to maintaining the reliability of decision-makers' judgments in multi-criteria decision-making problems.

$$(\text{CR}) = \frac{\xi^\wedge}{\text{Consistency index}} \tag{10}$$

Where ξ represent the optimized inconsistency index, and CI represent the Consistency index, a measure to check the consistency of the pairwise comparisons. measure of inconsistency, known as the optimized inconsistency index ($\xi^\wedge$), is calculated by taking the geometric mean of the individual inconsistency indices for all the pairwise comparisons. This overall measure is then used to calculate the consistency ratio (CR), which is a key indicator of the reliability of the decision-making process(S. Guo & Zhao, 2017).

Table 5. 4. Values of the Consistency Index (CI) for fuzzy BWM for various linguistic terms (S. Guo & Zhao, 2017)

Absolutely important	Very important	Fairly Important	Weakly important	Equally importance	aBw
(3.5,4,4.5)	(2.5,3,3.5)	(1.5,2,2.5)	(0.67,1,1.5)	(1,1,1)	
8.04	6.69	5.29	3.8	3	Consistency Index

The values of the consistency index show clearly that the worst situation for a technology is the equally importance.

5.3.3. TOPSIS method

Interval TOPSIS is an extension of Grey TOPSIS, which enhances the traditional TOPSIS method for decision-making. Grey TOPSIS is an extension of the traditional TOPSIS, which incorporates grey relational analysis to tackle uncertainty and incomplete information. However, Grey TOPSIS is limited in addressing interval-valued data. To resolve this limitation, Interval TOPSIS has been developed as a further extension of Grey TOPSIS. Grey numbers allow for the representation of uncertainty in the form of an interval, with a lower and upper bound. While Grey TOPSIS effectively handles uncertain data, it does not fully capture the potential of interval-valued data in decision-making. Interval TOPSIS builds upon the foundation of Grey TOPSIS by incorporating interval arithmetic and the concept of interval-valued grey numbers. This extension aims to provide a more comprehensive approach for dealing with uncertainties and interval-valued data. The steps of the Interval TOPSIS method and its relations present by (G.-D. Li, Yamaguchi, & Nagai, 2007),(Jahanshahloo, Lotfi, & Izadikhah, 2006).

Step1. The decision matrix for this method, as in other methods, is composed of columns representing the criteria and rows representing the alternatives under consideration. In this step, the method's decision matrix needs to be established. The VIKOR, the acronym, in Serbian of ‘‘Multicriteria Optimization and Compromise Solution’’ (Duckstein & Opricovic, 1980) decision matrix (11) includes a matrix with columns for criteria and rows for research alternatives. To address qualitative criteria in this method, a 7-point linguistic scale, as shown in (Table 5. 5), is utilised (G.-D. Li et al., 2007).

$$\begin{bmatrix} [\underline{x}_{11}, \bar{x}_{11}] & \cdots & [\underline{x}_{1n}, \bar{x}_{1n}] \\ [\underline{x}_{21}, \bar{x}_{21}] & \cdots & [\underline{x}_{2n}, \bar{x}_{2n}] \\ \vdots & \ddots & \vdots \\ [\underline{x}_{m1}, \bar{x}_{m1}] & \cdots & [\underline{x}_{mn}, \bar{x}_{mn}] \end{bmatrix} \quad (11)$$

We assume $A_1, A_2, \dots, A_m$ our m possible alternatives that decision-makers have to select from, and $C_1, C_2, \dots, C_n$ are the criteria employed to measure the performance of these alternatives. Here, x_{ij} represents the rating of alternative A_i in terms of criterion C_j . This value is not known precisely, and we can only affirm that x_{ij} falls within the interval $[\underline{x}_{ij}, \bar{x}_{ij}]$

Table 5. 5. linguistic scale and interval numbers (G.-D. Li et al., 2007)

Scale	Linguistic Term
[0,1]	Extremely Low
[1,3]	Low
[3,4]	Slightly Low
[4,5]	Medium
[5,6]	Slightly High
[6,9]	High
[9,10]	Extremely High

Step2. Normalize the decision matrix. Normalize the interval-valued decision matrix by dividing each element by the square root of the sum of squares of its corresponding column elements and use of the relations (12) and (13). This step ensures comparability across different criteria.

$$\bar{x}_{ij}^* = \frac{\bar{x}_{ij}}{\sqrt{\sum_{j=1}^m (\underline{x}_{ij}^2 + \bar{x}_{ij}^2)}} \quad (12)$$

$$\underline{x}_{ij}^* = \frac{\underline{x}_{ij}}{\sqrt{\sum_{j=1}^m (\underline{x}_{ij}^2 + \bar{x}_{ij}^2)}} \quad (13)$$

Where $\underline{x}_{ij}^*$ and $\bar{x}_{ij}^*$ are the normalized interval valued. now interval $[\underline{x}_{ij}^*, \bar{x}_{ij}^*]$ is normalized of interval $[\underline{x}_{ij}, \bar{x}_{ij}]$

Step3: Calculate the weighted normalized in the decision matrix. Multiply each element in the normalized decision matrix, by the corresponding criterion's weight w_j in relation (14) and (15). The weights represent the relative importance of each criterion in the decision-making process.

$$\underline{x}'_i = w_j \underline{x}_{ij}^* \quad (14)$$

$$\overline{x}'_i = w_j \overline{x}_{ij}^* \quad (15)$$

Step4. Determine the interval ideal and negative-ideal solutions for each criterion; identify the interval-valued ideal solution (the best performance among alternatives) and the interval-valued negative-ideal solution (the worst performance among alternatives). Positive and negative ideals are obtained from the following relationships:

In these relationships (16) and (17), I represent criteria with a positive aspect, and J represents criteria with a negative aspect. v_i^+ and v_i^- are the ideal value for the i^{th} criterion and anti-ideal value for the i^{th} criterion respectively.

$$\overline{A}^+ = \{v_1^+, \dots, v_n^+\} = \left\{ \left(\max_j \overline{x}_i | i \in I \right), \left(\min_j \underline{x}'_i | i \in J \right) \right\} \quad (16)$$

$$\overline{A}^- = \{v_1^-, \dots, v_n^-\} = \left\{ \left(\min_j \underline{x}'_i | i \in I \right), \left(\max_j \overline{x}_i | i \in J \right) \right\} \quad (17)$$

Step5. Determining the distance of alternatives from positive and negative ideals. Using the following relationships (18) and (19), the distance of alternatives (d^+ distance between the j^{th} alternative from the positive ideals and d^- distance between the j^{th} alternative from the negative ideals) is calculated.

$$d_j^+ = \left\{ \sum_{i \in I} (\overline{x}_{ij} - v_i^+)^2 + \sum_{i \in J} (\underline{x}'_{ij} - v_i^+)^2 \right\}^{\frac{1}{2}} \quad j = 1, 2, \dots, m \quad (18)$$

$$d_j^- = \left\{ \sum_{i \in I} (\underline{x}'_{ij} - v_i^-)^2 + \sum_{i \in J} (\overline{x}_{ij} - v_i^-)^2 \right\}^{\frac{1}{2}} \quad j = 1, 2, \dots, m \quad (19)$$

Step6. Calculating the similarity index and ranking alternatives by using the following relationship (20), we calculate the similarity index (CL). This index is a metric used to rank different

alternatives based on their proximity to the ideal solution and their distance from the anti-ideal solution of the alternatives and rank them accordingly. CL for each alternative is a value between 0 and 1. A higher value of CL indicates that the alternative is closer to the ideal solution and further from the anti-ideal solution, Therefore, with the help of the closeness coefficient, we can figure out the order of all options and choose the best one from the list of possible choices.

$$CL = \frac{d_j^-}{(d_j^- + d_j^+)} \quad j = 1, 2, \dots, m \quad (20)$$

5.3.4. Weighted Aggregated Sum Product Assessment with Grey Values (WASPAS-G)

The WASPAS (Weighted Aggregated Sum Product Assessment) method is a modern multi-criteria decision-making technique, introduced by Zavadskas et al. (E. K. Zavadskas, Turskis, & Antucheviciene, 2015). This method combines two models: WSM (Weighted Sum Model) and WPM (Weighted Product Model), providing higher accuracy compared to independent methods. The steps of the grey model and all relation and equation for this method are outlined below (E. K. Zavadskas et al., 2015).

Step1. The decision matrix (21) for this method, like other methods, known as the VIKOR decision matrix, consists of columns representing various criteria and rows signifying the different alternatives under evaluation. In this phase, the formation of the decision matrix is essential. It includes a matrix containing columns dedicated to criteria and rows for the research alternatives being assessed. To incorporate qualitative criteria within this method, a 7-point linguistic scale is utilized, as demonstrated in (Table 5. 5). $\otimes X$ represents the grey evaluations of the i -th alternative with respect to the j -th attribute.

$$\otimes X = \begin{bmatrix} [\underline{x}_{11}, \bar{x}_{11}] & \dots & [\underline{x}_{1n}, \bar{x}_{1n}] \\ [\underline{x}_{21}, \bar{x}_{21}] & \dots & [\underline{x}_{2n}, \bar{x}_{2n}] \\ \vdots & \ddots & \vdots \\ [\underline{x}_{m1}, \bar{x}_{m1}] & \dots & [\underline{x}_{mn}, \bar{x}_{mn}] \end{bmatrix} \quad (21)$$

Step2. In this step, we need to normalize the decision matrix. If the criteria have a positive aspect, we use equation (22), and if the criteria have a negative aspect, we use equation (23)(E. K.

Zavadskas et al., 2015).where $\otimes \bar{x}_{ij}$ represents normalized decision matrix and $\bar{x}_{ij\alpha}$ represents normalized maximal values .The initial stage involves pinpointing both the favorable and unfavorable criteria. For every positive criterion assign the highest value within its range to the respective column and divide by the maximum value. Conversely, for each negative criterion, allocate the lowest value within its range to the corresponding column, divide by the minimum value, and subsequently invert the sequence of values.in the (Table 5. 6) Normalized matrix is calculated.

$$\otimes \bar{x}_{ij} = \frac{\otimes x_{ij}}{\max_i \otimes x_{ij}},$$

$$i. e. \bar{x}_{ij\alpha} = \frac{x_{ij\alpha}}{\max_i \otimes x_{ij\beta}} \quad \text{and} \quad \bar{x}_{ij\beta} = \frac{x_{ij\beta}}{\max_i \otimes x_{ij\beta}} \quad (22)$$

$$\otimes \bar{x}_{ij} = \frac{\min_i \otimes x_{ij}}{\otimes x_{ij}} \quad (23)$$

$$i. e. \bar{x}_{ij\alpha} = \frac{\min_i \otimes x_{ij\alpha}}{x_{ij\beta}} \quad \text{and} \quad \bar{x}_{ij\beta} = \frac{\min_i \otimes x_{ij\alpha}}{x_{ij\alpha}}$$

Table 5. 6. Normalized matrix (interval WASPAS) for the technology subcriteria of PEM and Alkaline Electrolysers

	PEM	Alkaline
The electrolyser stack	[0.232,0.522]	[0.357,1]
Balance of the plant (BOP)	[0.264,0.595]	[0.357,1]
stack replacement per 10 years	[0.444,1]	[0.342,0.958]
Maintenance costs	[0.345,1]	[1.378,0.447]
electricity grid (QC)price	[0.753,1]	[0.753,1]
Electricity renewable (wind) energy	[1,1]	[1,1]
Current density	[0.5,1]	[0.1,0.4]
Flow rate H ₂ Kg/day	[0.793,1]	[0.214,0.536]
Deionised water circulation	[0.264,0.595]	[0.357,1]
Temperature operation	[0.625,1]	[0.556,0.714]
Efficiency (Electrical)(Kwh/KgH ₂)	[0.682,0.957]	[0.682,1]
Operation pressure	[1,1]	[0.5,0.5]
Voltage efficiency	[0.735,1]	[0.735,1]
hydrogen gas purification	[0.999,1]	[0.999,1]
Cell voltage	[0.56,1]	[0.467,1]
System efficiency	[0.602,1]	[0.602,0.94]
Cold start-up time	[0.25,1]	[0.167,1]
Land use	[0.033,1]	[0.003,0.1]
Carbon dioxide emissions (CO ₂ emissions)	[0.129,0.129]	[1,1]
Risk of environmental impact for producing 1 kg H ₂	[0.5,0.6]	[0.75,1]
catalyst mining and manufacturing	[0.444,0.667]	[0.8,1]
catalysts	[0.034,0.076]	[0.357,1]
Lifetime(HOURS)	[0.063,1]	[0.75,0.75]
bipolar plate (BPS)(cost \$/pcs)	[0.5,0.5]	[1,1]
Electrolyte	[0.333,0.5]	[0.75,1]
Electrode	[0.6,0.6]	[1,1]
Porous transport layer(PTLS)	[0,0]	[1,1]
Diaphragm	[1,1]	[0,0]
Technology maturity	[0.4,0.5]	[0.9,1]
Technology development potential	[0.667,1]	[0.444,0.556]
Social acceptability	[0.9,1]	[0.5,0.6]
Safeguard	[0.6,0.75]	[0.75,1]
Degree of government support	[0.667,1]	[0.444,0.556]

Step3. we need to calculate the values of the Weighted Sum Model (WSM), which is calculated using the following formula (24). In this formula, $\otimes \hat{x}_{ij}$ represents the normalized weighted value, which is obtained from the following relationship (25), In this relationship, $\otimes w_j$ is the weight (normalized) of the criteria obtained from the Gray AHP method (E. K. Zavadskas et al., 2015). $\otimes \bar{x}_{ij}$ represents the matrix of normalized decision values. The grey value $\otimes S_i$ represents the additive optimality function (WSM) for i the alternative.

$$\otimes S_i = \sum_{j=1}^n \otimes \hat{x}_{ij}, j = 1, \dots, m, \text{ or} \quad (24)$$

$$\otimes S_i = 0.5 \sum_{j=1}^n (\hat{x}_{ij\alpha} + \hat{x}_{ij\beta})$$

$$\otimes \hat{x}_{ij} = \otimes \bar{x}_{ij} \times \otimes w_j \quad (25)$$

Step4. In this step, we need to calculate the values of the Weighted Product Model (WPM), which is calculated using the following formula (26) (E. K. Zavadskas et al., 2015). the geometric mean (P) is also obtained through the multiplication of the normal distance numbers, raised to the power of the criteria weights. Finally, we compute the WASPAS index. The grey value $\otimes P_i$ represents optimality function according to WPM, where $\otimes w_j$ is the grey weight of the j attribute and $\otimes \hat{x}_{ij}$ is the grey normalized rating of the i -th alternative with respect to the j -th attribute. $\otimes \bar{x}^{\otimes w_j}$ the weight exponent to the corresponding grey normalized decision value, representing the weighted power of each decision value in the final computation of $\otimes P_i$.

$$\otimes P_i = \prod_{j=1}^n \otimes \bar{x}^{\otimes w_j}, j = 1, \dots, m, \text{ or} \quad (26)$$

$$\otimes P_i = \prod_{j=1}^n 0.5 (\otimes \bar{x}_{j\alpha}^{\otimes w_j} + \otimes \bar{x}_{j\beta}^{\otimes w_j}), j = 1, \dots, m$$

Where α refers to the lower bound of the j -th decision criterion under uncertainty. $\otimes \bar{x}_{j\alpha}^{\otimes w_j}$ is raised to the power of the weight assigned to that criterion. $\otimes \bar{x}_{j\beta}^{\otimes w_j}$ represents the upper bound of the j -th decision criterion raised to the power of the weight of that criterion.

Step5. In this relationship, the VIKOR index is obtained using the following formula (27) and

In this formula, the value of λ is obtained from the following relationship (28) (E. K. Zavadskas et al., 2015). Lambda (λ) (4.26) serves as a parameter that establishes the relative significance of the WSM and WPM in the comprehensive evaluation. Altering λ consequently modifies the influence of the WSM and WPM on the overall assessment. Specifically, increasing λ amplifies the WSM's impact on the evaluation while diminishing the WPM's influence. In contrast, decreasing λ enhances the WPM's impact while reducing the WSM's influence. The value of λ can be ascertained based on the objectives and priorities of the decision-making process and the attributes of the alternatives under comparison. The alternative exhibiting the highest overall score according to the WASPAS method is deemed the most optimal choice.

$$\otimes Q_i = \lambda \sum_{j=1}^n \otimes \hat{x}_{ij} + (1 - \lambda) \prod_{j=1}^n \otimes \bar{x}^{\otimes w_j} \quad (27)$$

$$\lambda = 0, \dots, 1$$

$$\lambda = 0.5 \frac{\sum_{i=1}^m P_i}{\sum_{i=1}^m S_i} \quad (28)$$

Where $\otimes Q_i$ the overall score for the i-th alternative, computed based on the aggregation of the weighted normalized values for each criterion ($\otimes \hat{x}_{ij}$) and the geometric mean of the grey interval normalized values raised to their corresponding weights ($\otimes \bar{x}^{\otimes w_j}$). This score provides a comprehensive evaluation of the i-th alternative according to all the criteria and their weights.

The values of P_i and S_i are converted to definite numbers using the following relationships (29) and finally, using the VIKOR index value, we can rank the alternatives.

$$P_i = 0.5(P_{i\alpha} + P_{i\beta}) \quad (29)$$

$$S_i = 0.5(S_{i\alpha} + S_{i\beta})$$

Using the above methods applied to the schematic representation of (Figure 5. 1) allow us to generate data which are used to make decision on the ability of an electrolyser technology to be economically viable. To complete this method of analysis, we may integrate the parameters of the determination of the Levelized cost of hydrogen.

5.3.5. Parameters used to determine levelized cost of Hydrogen for 5 MW PEM and Alkaline Electrolysers

The levelized cost of hydrogen (LCOH) is a metric used to estimate the total cost of producing and delivering hydrogen over the lifetime of a hydrogen production system. The LCOH takes into account all of the costs associated with producing hydrogen, including the initial capital cost, operation and maintenance costs, and the cost of the energy used to produce the hydrogen.

We develop MATLAB code for calculating the characteristics of a 5 MW water electrolyser and the corresponding LCOH can be achieved by following these steps:

- The first step is to develop a MATLAB code to calculate the LCOH for a 5 MW water electrolyser and to define the inputs required for the calculations. These inputs may include the efficiency of the electrolyze, its cost of electricity, and its expected lifetime.
- The second step is to use the result of the first step and to calculate the characteristics of the electrolyse using equations, such as the Nernst equation, which relates the potential difference between the electrodes to the equilibrium potential of the cell. Other relevant properties, such as the enthalpy and entropy changes of the electrochemical reactions, can also be calculated using standard data of reactions
- The third step is to calculate in kg/kWh the hydrogen produced per unity electricity consumed.
- The fourth step is to obtained or estimated the cost of electricity from energy market data or using data on the cost of energy in the region where the electrolyser is located.
- Finally, we estimate the lifetime of the electrolyse based on the expected lifespan of the materials used in the electrolyser and the anticipated maintenance requirements.

Using all these factors we determine the LCOH for a 5 MW proton exchange membrane (PEM) or alkaline water electrolysis system and make comparison of data of the two technologies.

A chart is used to represent the LCOH values for the two types of water electrolyzers.

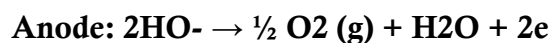
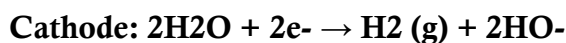
5.3.5.1. Why in Figure 1 PEM and Alkaline electrolyzers are only considered as alternatives among the others

The process of selecting the most suitable water electrolyser for techno-economic analysis using the Multi-Criteria Decision Making (MCDM) method is based on their maturity for commercial mass production and the rate of their implementation worldwide presently and in the next future. During the year 2020, 176 MW of commercial alkaline electrolyzers were installed worldwide and those of the PEM electrolyzers technologies were 89 MW (IEA, 2021) the other not specified technologies (probably mainly hydrogen production from chloro-alkaline) were 21 MW. 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.

Accordingly, among various water electrolyzers, Proton Exchange Membrane (PEM) and Alkaline electrolyzers have emerged as prominent options, each with its own unique set of advantages and challenges. By thoroughly evaluating and comparing the technical, economic, and environmental aspects of these alternatives, decision-makers can effectively identify the most appropriate technology to adopt, ensuring long-term benefits and sustainability in the energy sector.

5.3.5.2. Alkaline Electrolyser

Alkaline electrolyzers, a well-established and dominant technology, operate at continuous current densities of 2000-4000 A/m² and temperatures between 80°C and 90°C (Pletcher & Xiaohong, 2011). Their theoretical efficiency can reach 80%, but in practice, it ranges from 63% to 70% due to the lower heating value of gaseous hydrogen (Turner et al., 2008).



Their theoretical efficiency can reach 80%, but in practice, it ranges from 63% to 70% due to the lower heating value of gaseous hydrogen (Bessarabov & Millet, 2018). The electrolytic cell features a permeable membrane allowing water and alkaline electrolyte to pass through. The zero-

gap cell concept, where both electrodes press against the membrane, has been developed for efficient electrolysis(Phillips, Edwards, Rome, Jones, & Dunnill, 2017).

Advancements in electrode design and the zero-gap system have enhanced alkaline electrolysis performance. The process uses a diaphragm, made of composite materials like ceramic or microporous materials, to separate the anode and cathode. Temperature control is crucial for maintaining optimal electrolyte conditions(Rashid et al., 2015). Proper electrolyser function requires additional components, such as power electronics, DC power distribution systems, gas-exit pipes, cooling systems, and possibly hydrogen and oxygen drying systems (Figure 5. 2). The block diagram of the Alkaline electrolyser involves a lot of components which may impact the maintenance of the system.

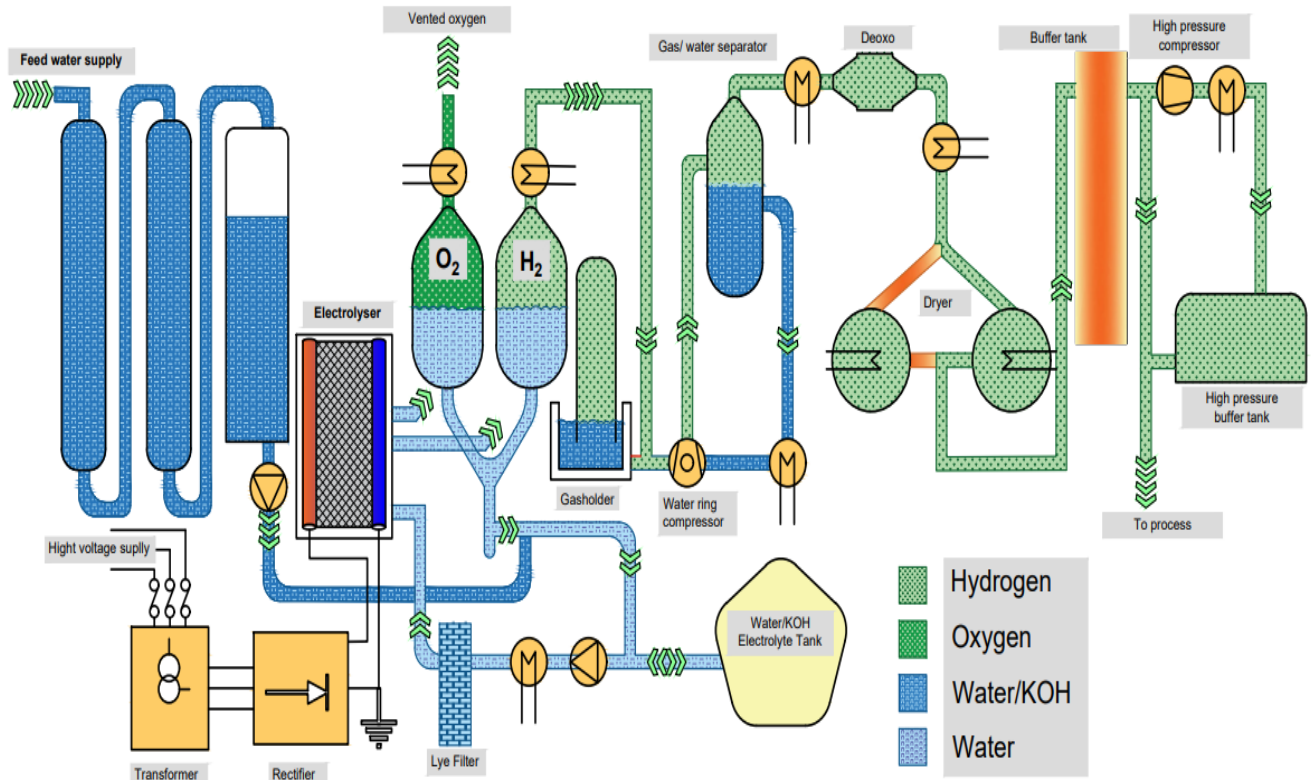
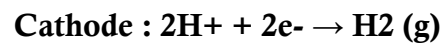
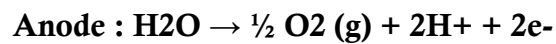


Figure 5. 2. Schematic block of the Alkaline electrolysis system (IRENA, 2020)

5.3.5.3. PEM Electrolyser

A common configuration of a PEM electrolyser stack consists of multiple cells connected in series electrically, with parallel water and gas flow. Thick metal end plates hold these cells together. Each cell features a catalyst-coated membrane (CCM), comprising an acidic proton conductor polymer membrane which separates the anode and the cathode catalyst layers coated on their respective electrodes. A porous transport layer (PTL) enhances water diffusion and the water splitting reaction on the membrane surface. Bipolar plates separate the cells and include channels for water, hydrogen, and oxygen transport (Mayyas et al., 2019). When the stack is connected to a electric power (grid our renewable energy sources), the reactions at the electrodes surfaces are:



In comparison to alkaline electrolyzers, PEM electrolyzers are less commercially developed because the technology emerged in the 1980's and the alkaline technology was used since the 1920's. In addition PEM electrolyzer use more expensive materials like platinum, iridium or cobalt as catalysts and costly solid proton conducting membrane materials (Savadogo et al., 2020b) than alkaline technology which uses less expensive Ni catalyst electrodes and diaphragms. PEM electrolyzers are fed with deionized water. As indicated on the above equation reactions, during the process, water is oxidized at the anode, producing protons and gaseous oxygen. These protons then move to the cathode via the solid acidic proton exchange membrane. The electron provided by the electricity through the external circuit of the stack arrives at the surface of the cathode and discharges the proton to allow hydrogen gas production. The operating current density is between 10 000 and 20 000 A m^{-2} . The operating temperature is between 60 °C and 80 °C. The electrolyzer design allows an efficient gas separation with a higher hydrogen purity and higher energy efficiency compared to alkaline electrolyzers (Yujing, Gendi, Junbo, & Yong, 2019).

PEM electrolyzer plants also comprise major subsystems, including power supply, deionized water circulation, hydrogen processing, cooling, and miscellaneous components like ventilation and safety features (Mayyas et al., 2019). These subsystems collectively ensure the efficient operation of the PEM electrolyzer system (Figure 5. 3). The block diagram of the PEM Electrolyzer system exhibits less component than the Alkaline system. On the other hand, it is fed by deionised water rather than a chemical such as KOH in the case of alkaline Electrolyzer which involves specific handlings. Thus, operating and maintenance costs are different. The environment impacts will be also different.

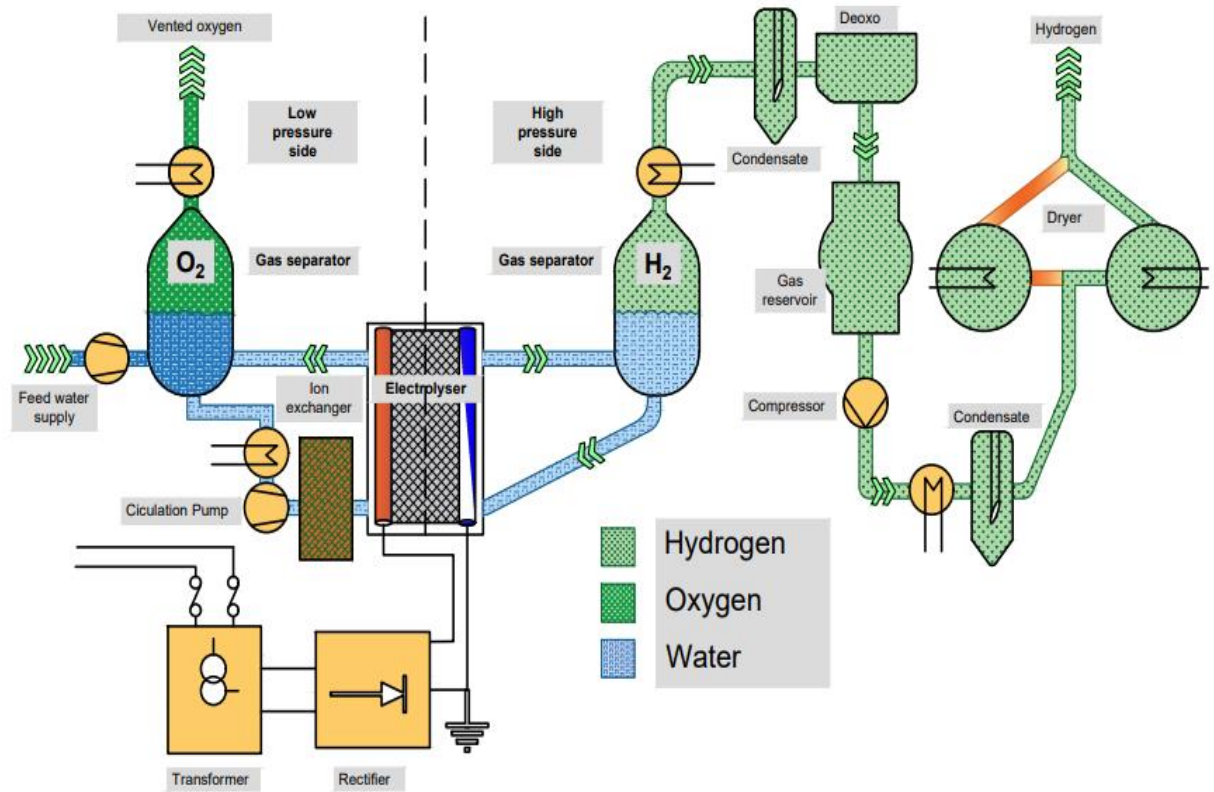


Figure 5. 3. Block diagram of industrial hydrogen production with PEM technology (IRENA, 2020)

5.3.5.4. Criteria weight

In this section the fuzzy weight is directly obtained from solving the model in Lingo software, then these fuzzy weights are calculated by the relation (9) (S. Guo & Zhao, 2017) and after that it has become to final weight as described in Section (2-1). By following this procedure, the fuzzy weights of criteria are initially determined, and the overall weight of each criterion is subsequently obtained. The weights are presented in (Table 5. 7). It is important to note that crisp numbers are used to represent all weights in the subsequent calculations.

Table 5. 7. Overall Fuzzy Weigh of each of the main criteria or aspects, their Crisp Weight and their final rank

Code	Criteria	Fuzzy Weight	Crisp Weight	Rank
A	Economic	(0.314,0.326,0.372)	0.332	1
B	Technical	(0.214,0.222,0.251)	0.226	2
C	Environment	(0.129,0.138,0.167)	0.141	4
D	Technology	(0.175,0.202,0.251)	0.206	3
E	Social factors	(0.092,0.092,0.103)	0.094	5

For instance, the economic criteria weight is (0.314, 0.326, 0.372), resulting in a final weight of 0.332. Therefore, the economic criterion has the highest weight of 0.332 among all criteria. The technical criterion, with a weight of 0.226, ranks second, while the technology criterion, with a weight of 0.206, ranks third. The social factors have the last rank for the Crisp Weight because the cost and the technology efficiency are the most important sub criteria considered in this analysis.

(Figure 5. 4) shows the mature technology (which has the highest life time) has high weight, The lifetime and technology development potential are two essential criteria when evaluating water electrolyzers. However, while both are crucial, there are reasons why the lifetime of an electrolyser might be considered more important than its technology development potential:

Return on Investment (ROI): Longer lifetimes generally mean that the initial capital investment in an electrolyser can be spread over many years, leading to a better return on investment. If an electrolyser has a short lifespan, even if it's technologically advanced, it may need frequent replacements or major maintenance, which could increase the overall cost.

Operational Reliability: Longer lifetimes usually correlate with consistent performance and reduced maintenance needs. A technology that needs frequent replacements or is prone to breakdowns might disrupt operations, even if it offers certain advanced features.

Economic Impact: A longer lifetime allows for stable operations and predictable costs, making financial planning and management easier for businesses. A shorter-lived but technologically superior electrolyser might require adjustments in budgeting for replacements or updates, potentially causing financial strain.

Environmental Impact: Continual replacements or disposals due to a shorter lifetime can have environmental consequences. Production, transportation, and disposal of equipment all have environmental footprints. A longer-lived electrolyser, even if slightly less efficient, might have a smaller overall environmental impact than a more advanced but short-lived one. But if the short-lived one has less significant consequences on the environment more analysis is needed (Table 5. 1) display the final weights obtained from the software after formulating the linear optimization model and solving it.

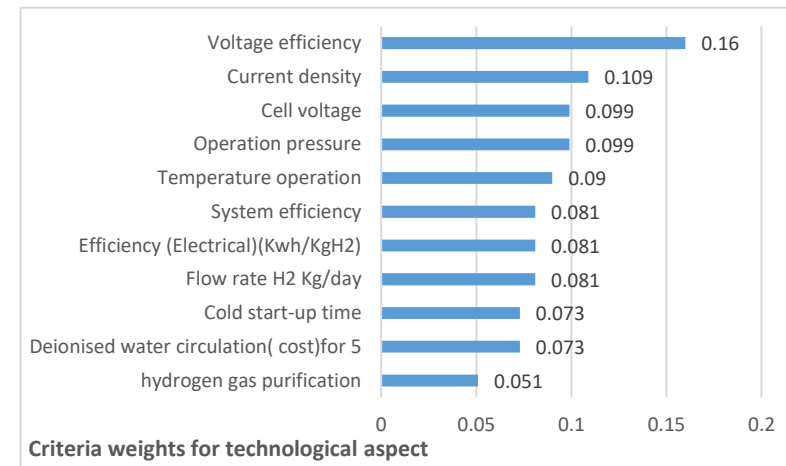
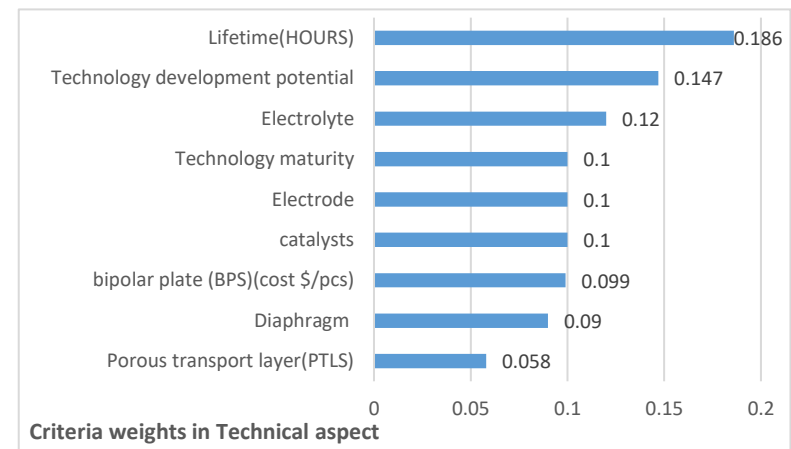
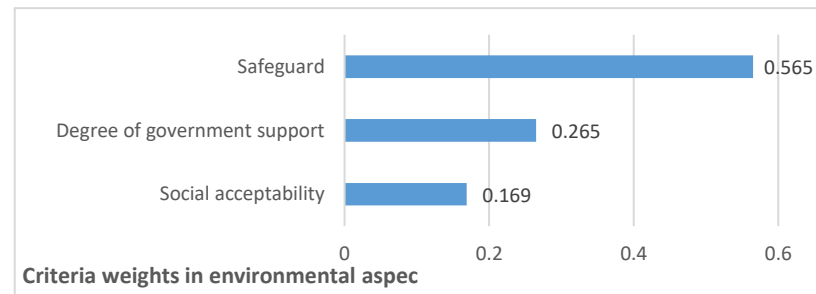
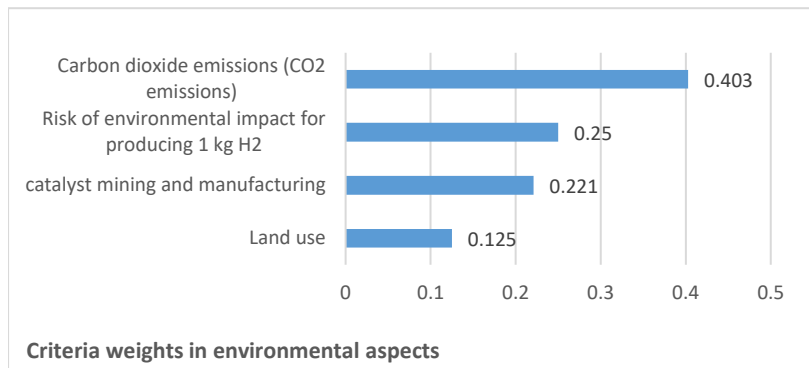
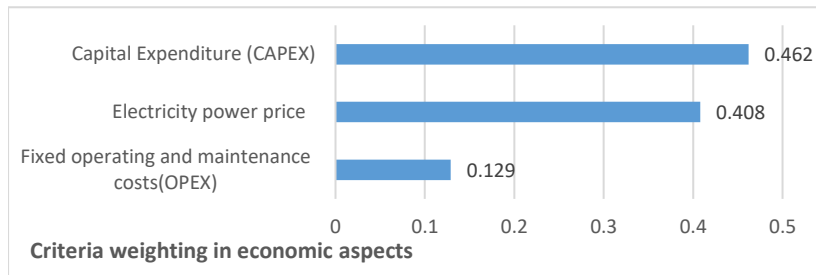


Figure 5. 4. Examples of the process of the Criteria weighting

Table 5. 8. Global weight of the criterion system of the 30 criteria

Dimensions	weight	Criteria	weight	Sub Criteria	Weight	Global weight
Economic (A)	0.332	(A1)	0.462	A1-1	0.502	0.0770
				A1-2	0.497	0.0762
		(A2)	0.129	A2-1	0.67	0.0287
				A2-2	0.329	0.0141
		(A3)	0.408	A3-1	0.289	0.0391
				A3-2	0.709	0.0960
Technical (B)	0.226	B1	0.109	-	-	0.0246
		B2	0.081	-	-	0.0183
		B3	0.073	-	-	0.0165
		B4	0.090	-	-	0.0203
		B5	0.081	-	-	0.0183
		B6	0.099	-	-	0.0224
		B7	0.160	-	-	0.0362
		B8	0.051	-	-	0.0115
		B9	0.099	-	-	0.0224
		B10	0.081	-	-	0.0183
		B11	0.073	-	-	0.0165
Environment (C)	0.141	C1	0.125	-	-	0.0176
		C2	0.403	-	-	0.0568
		C3	0.250	-	-	0.0353
		C4	0.221	-	-	0.0312
Technology (D)	0.206	D1	0.100	-	-	0.0206
		D2	0.186	-	-	0.0383
		D3	0.099	-	-	0.0204
		D4	0.120	-	-	0.0247
		D5	0.100	-	-	0.0206
		D6	0.058	-	-	0.0119
		D7	0.090	-	-	0.0185
		D8	0.100	-	-	0.0206
		D9	0.147	-	-	0.0303

Dimensions	weight	Criteria	weight	Sub Criteria	Weight	Global weight
Social factors (E)	0.094	E1	0.169	-	-	0.0159
		E2	0.565	-	-	0.0531
		E3	0.265	-	-	0.0249

5.3.5.5. Multicriteria assessment

This section aims to determine the final order of preference for cost and factors related to technology, configuration, and technical aspects, which play a crucial role in reducing costs or increasing the efficiency of each water electrolysis technology, considering all criteria defined in Section 4. To simplify the evaluation of MCDM methods, (Table 5. 8) summarizes the relevant values of each technology concerning all criteria. For our analysis, we took into account all criteria that directly impact costs. This includes economic sub-criteria and other factors where a higher value has a negative effect, such as increasing costs, causing degradation, or adversely affecting efficiency. Conversely, criteria like technological maturity, efficiency, and social acceptability were viewed positively, where a higher value indicates better performance or desirability. Additionally, some criteria related to environmental impact or potential hazards were considered under the principle that 'less is better' In our research, the following graph and the study (Ruth, Mayyas, & Mann, 2019) serve as a representative example from the literature review that we conducted, highlighting critical criteria relevant to the cost of electrolyzers, specifically for both PEM and Alkaline types

The selection was informed by extensive literature review and comprehensive research on the cost dynamics of electrolyzers. A notable chart from IRENA (Figure 5. 5) and (Figure 5. 6) (E. IRENA, 2020) illustrates how various criteria contribute to the costs associated with electrolyzers. This study of IRENA and one (Ruth et al., 2019) serve as a representative example from the literature review that we conducted, highlighting critical criteria relevant to the cost of electrolyzers, specifically for both PEM and Alkaline types.

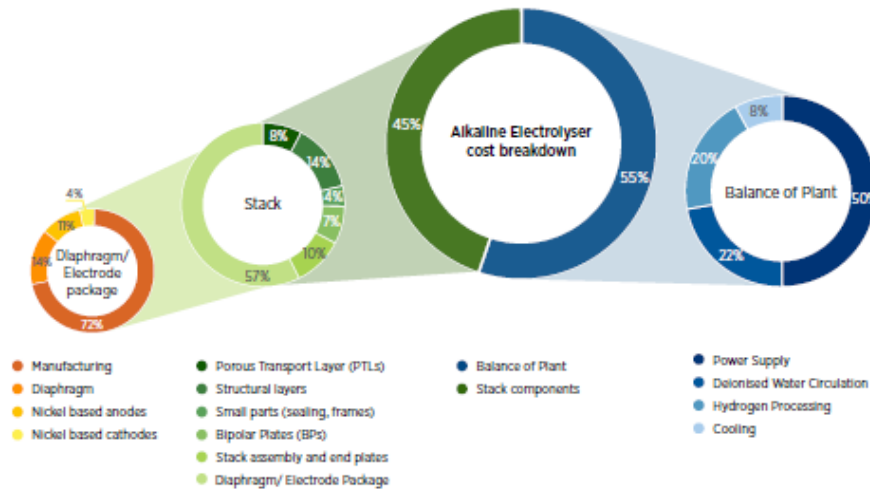


Figure 5. 5. Cost breakdown for a 1MW Alkaline electrolyser, moving from full system, to stack, to CCM (E. IRENA, 2020)

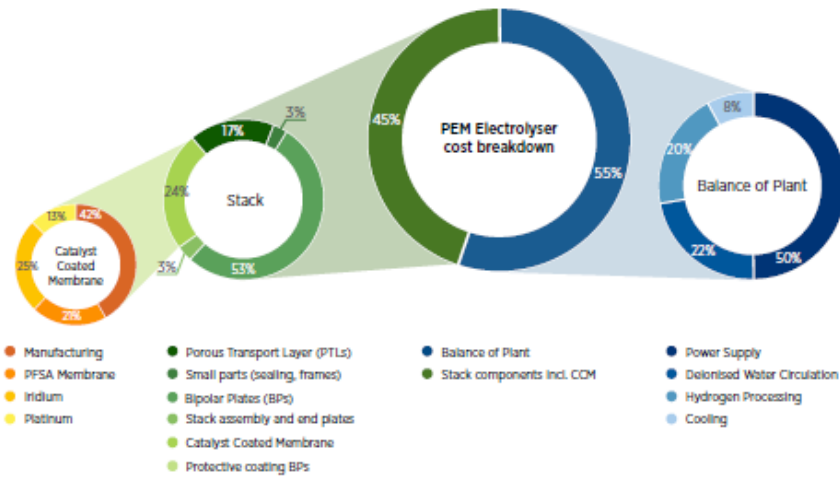


Figure 5. 6. Cost breakdown for a 1MW PEM electrolyser, moving from full system, to stack, to CCM (E. IRENA, 2020)

The next step involves constructing the decision matrix. It is important to note that the ranges shown in (Table 5. 8) are defined by a specific interval number. Therefore, using an interval grey approach in this case is appropriate. Consequently, in this study, the ranges in (Table 5. 8) are based on cost and efficiency, each criterion is labeled as negative if a higher value is detrimental, or positive if a higher value is beneficial. Since most selected MCDM methods have a mathematical structure, qualitative values in (Table 5. 9) must be converted to numerical ones before creating

the decision matrix. This can be accomplished using linguistic conversions (Li, Yamaguchi, & Nagai, 2007). The decision matrix is then constructed, as displayed in (

Table 5. 10) a structured comparison of two technologies is conducted using the TOPSIS and WASPAS interval methods of MCDM. Closeness coefficient and ranking the alternatives.

As it can be seen in (Table 5. 12) for TOPSIS, to determine the similarity of each alternative solution to the ideal solution, the similarity index (CL) is calculated. (Table 5. 11), Calculation of weighted average(S), geometric mean(P) and Index of WASPAS (Weighted Aggregated Sum Product Assessment) for ranking the alternatives is done. As λ is a parameter that determines the relative importance of the WSM (Weighted Sum Model) and WPM (Weighted Product Model) in the overall assessment. When λ is changed, the influence of the WSM and WPM on the overall assessment changes as well.

Table 5. 9. Data from the litterature of quantitative and quality parameters of the water electrolysis technologies attending to all factors shown in (Table 5. 6)(Savado et al., 2020a),(IRENA, 2020) ,(Bhandari, Trudewind, & Zapp, 2014)

Criteria	Alkaline Electrolyser	PEM Electrolyser
Economic		
(CAPEX) CAD /KW	670.5-1877.64 CAD /KW	1070.79-2409.70 CAD / KW
The electrolyser stack	335.25-938.82CAD	642.58 -1445.88 CAD
(BOP) Balance of the plant	254.79-713.50CAD	428.37 -963.84 CAD
(OPEX)		
stack replacement per 10 years	167.62-469.41CAD	160.62-361.41 CAD
Maintenance costs	1.14-0.37CAD/kg	1.48-0.51CAD/kg
electricity grid (QC)price	0.097CAD/kwh	0.097CAD/kwh
Technical		
hydrogen gas purification	99,9%-99,9998	99,9-99,9999%
Voltage efficiency	50-68%	50-68%
Temperature operation	70-90 Oc	50-80 oC
Efficiency (Electrical)(Kwh/KgH ₂)	45-66 kWh/kg de H ₂	47-66 kWh/kg H ₂
Cell voltage	1,4V-3 V	1,4-2,5 V
Current density	0,2 -0,8 A/cm ²	1-2 A/cm ²
Flow rate H ₂ Kg/day	104-260kg/day	385 -485.46kg H ₂ /day
Operation pressure	< 30 bars	30 bar
System efficiency	50-78 %	50-83%

Cold start-up time	5-30min	5-20min
Deionised water circulation(cost)	22%of BOP cost	22%OF BOP cost
Environment		
Risk of negative environmental impact for producing 1 kg H ₂	15times less than PEM	15times more than Alkaline
Carbon dioxide emissions (CO ₂ emissions	low	medium
Land use	(cell area)<4m ²	(cell area)<0.3m ²
catalyst mining and manufacturing	medium(hazard)	high(hazard)
Technology		
catalysts cost	6% (stack cost)	41% (from stack cost)
Lifetime (HOURS)	60 000 h	50 000-80 000
bipolar plate (BPS)(cost \$/pcs)	20\$/kw	40\$/kw
Electrolyte	Low (cost)	High (cost)
Electrode	assembly cost 60\$/kw	assembly cost100\$/kw
Porous transport layer (PTLS)	no (impact on the cost)	high (impact on the cost)
Diaphragm	high impact on the cost	0 no impact on the cost
Technology maturity	high	medium
Technology development potential	medium	high
Social factors	-	-
Social acceptability	high	very high
Safeguard	low(hazard)	Medium(hazard)
Degree of government support	medium	high

Table 5. 10. Decision matrix of the technology aspects for combined TOPSIS and WAPAS

	PEM	Alkaline
The electrolyser stack	[642.58,1445.88]	[335.25,938.82]
Balance of the plant(BOP)	[428.37,963.84]	[254.79,713.5]
stack replacement per 10 years	[160.62,361.41]	[167.62,469.41]
Maintenance costs	[0.51,1.48]	[1.14,0.37]
electricity grid (QC)price	[0.073,0.097]	[0.073,0.097]
Electricity renewable (wind) energy	[0.035,0.035]	[0.035,0.035]
Current density	[1,2]	[0.2,0.8]
Flow rate H2 Kg/day	[385,485.46]	[104,260]
Deionised water circulation(cost)for 5	[94.24,212.04]	[56.05,156.97]
Temperature operation	[50,80]	[70,90]
Efficiency (Electrical)(Kwh/KgH2)	[47,66]	[45,66]
Operation pressure	[30,30]	[15,15]
Voltage efficiency	[0.5,0.68]	[0.5,0.68]
hydrogen gas purification	[99.9,99.9999]	[99.9,99.9998]
Cell voltage	[1.4,2.5]	[1.4,3]
System efficiency	[0.5,0.83]	[0.5,0.78]
Cold start-up time	[5,20]	[5,30]
Land use	[0.01,0.3]	[0.1,4]
Carbon dioxide emissions (CO2 emissions)	[72,72]	[9.3,9.3]
Risk of environmental impact for producing 1 kg H2	[5,6]	[3,4]
catalyst mining and manufacturing	[6,9]	[4,5]
catalysts	[263.45,592.81]	[20.11,56.32]
Lifetime(HOURS)	[5000,80000]	[60000,60000]
bipolar plate (BPS)(cost \$/pcs)	[40,40]	[20,20]
Electrolyte	[6,9]	[3,4]
Electrode	[100,100]	[60,60]
Porous transport layer(PTLS)	[6,9]	[0,0]
Diaphragm	[0,0]	[6,9]
Technology maturity	[4,5]	[9,10]
Technology development potential	[6,9]	[4,5]
Social acceptability	[9,10]	[5,6]
Safeguard	[4,5]	[3,4]
Degree of government support	[6,9]	[4,5]

Table 5. 11. Weighted average(S),geometric mean(P) and Index of WASP

	S	P	Q	Rank
PEM	0.636	0.548	0.587	2
Alkaline	0.749	0.690	0.717	1
	$\sum S=1.384$	$\sum p=1.238$	$\lambda=0.447$	

Table 5. 12. Ranking alternatives in TOPSIS

	d+	d-	CL	Rank
PEM	0.0962	0.0752	0.4388	2
Alkaline	0.0625	0.1026	0.6216	1

5.4. Analysis results and discussion

5.4.1. Analysis for MCDM

The TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and WASPAS (Weighted Aggregated Sum Product Assessment) MCDM (Multi-Criteria Decision Making) methods have been applied for ranking), and the Fuzzy BWM (Best-Worst Model) method has been used for weighting criteria to determine the most appropriate water electrolysis technologies for hydrogen production. These methods assessed various factors, including economic, environmental, technical, technology, and social aspects, which are crucial for prioritizing technologies in sustainable hydrogen production.

The distribution of importance assigned to economic, environmental, and social factors is shown in (Error! Reference source not found.), with the economic factor being the most important. In (Error! Reference source not found.), the economic factor is divided into Investment costs and O&M for better comprehension. The remaining share is evenly distributed among social, environmental, technology, and technical factors. Technical and technology factors correspond to the criteria with the highest weight values in (Error! Reference source not found.).

(Figure 5. 8)shows that the maintenance costs of Alkaline Electrolyser (SE) are higher than the PEM Electrolyser. In contrary the cold of PEM technology is better than the AE technology. With a high social acceptance, a less land use, a high potential of technology development, a low

operating and maintenance and others the results in (Figure 5. 11)also indicate that PEM Electrolyser is the preferred method for sustainable hydrogen production, although AE ranks highest based on costs. This can be attributed to AE scoring well on almost all economic-related criteria, but performing relatively poorly on hydrogen flow rate, voltage efficiency, current density, and gas purification, as shown in (Figure 5. 9).

In this study, two different MCDM methods were employed to rank technologies while focusing on costs and considering 30 sub-criteria for detailed assessment of each electrolyser. This approach ensured coherent and consistent rankings. All methods determined that, given the specifications of the two water electrolyser technologies and the specific goal of producing low-cost hydrogen,

Alkaline Electrolyser (AE) is the best technology. However, for producing more and purer hydrogen, PEM is considered more reliable.

Alkaline presents the best scores in economic criteria, where PEME does not perform as well. Alkaline electrolysers have lower capital and operating costs, due to factors such as lower-cost catalysts and materials. However, it's important to note that specific applications and conditions may influence the cost-effectiveness of PEM and Alkaline electrolysers, and other factors such as durability, efficiency, and operational flexibility should also be considered when making a decision.

For Evaluating alternatives against each criterion, Higher purity hydrogen from PEM electrolyzers offers several benefits: enhanced fuel cell performance, expanded application potential, longer component lifespan, and better overall efficiency. These advantages contribute to improved system operation, reduced maintenance costs, and wider applicability in industries requiring ultra-high purity hydrogen.

PEM electrolyzers, with shorter cold start-up times compared to alkaline electrolyzers, offer several operational advantages. These include rapidly increasing hydrogen production in response to fluctuating power supplies or demands, making them ideal for integration with renewable energy sources like solar or wind power. Their quicker start-up times lead to reduced energy consumption during the start-up phase, contributing to better overall energy efficiency and lower operational costs. Additionally, their shorter cold start-up times allow for greater operational flexibility, enabling more frequent on-off cycling without causing substantial wear or negatively impacting performance. This is especially important when working with variable energy sources or

applications with changing hydrogen demand. Furthermore, their adaptability to variable power loads makes PEM electrolyzers efficient energy storage and grid-balancing solutions, helping stabilize the electrical grid by adjusting hydrogen production based on energy supply and demand.

Voltage efficiency is a crucial factor in evaluating the performance of electrolyzers, including both PEM and alkaline types. It refers to the ratio of the theoretical minimum voltage required to split water into hydrogen and oxygen (1.23 V at room temperature) to the actual voltage applied during the electrolysis process. A higher voltage efficiency means that the electrolyzer operates closer to the theoretical minimum voltage, resulting in lower energy consumption and reduced operational costs. Optimizing voltage efficiency is essential for enhancing the overall efficiency of the electrolysis process, making hydrogen production more economically viable and sustainable, particularly when coupled with renewable energy sources. Factors that influence voltage efficiency include electrolyte type, electrode materials, operating temperature, and current density. By carefully selecting and optimizing these parameters, electrolyzers can achieve higher voltage efficiencies, contributing to the broader adoption of hydrogen as an energy carrier in various applications.

Alkaline electrolyzers (AE) have traditionally been more cost-effective compared to Proton Exchange Membrane (PEM) electrolyzers due to their simpler design and the use of less expensive materials. The lower stack cost of AE has been a key driver for their widespread adoption, particularly in large-scale hydrogen production facilities. As a result, many industries have chosen alkaline electrolyzers for their hydrogen production needs, prioritizing the lower initial investment and affordability of the technology.

In recent years, PEM electrolyzers have gained more traction due to their higher efficiency, lower maintenance requirements, and faster response time to changing electricity supply. Furthermore, advances in materials science and manufacturing processes have led to a reduction in PEM electrolyzer costs, narrowing the gap between the two technologies. Consequently, when taking into account the total cost of ownership and the payback period, PEM electrolyzers can potentially offer greater long-term value, especially when integrated with renewable energy sources to produce green hydrogen. This combination of factors has resulted in the growing interest in PEM electrolyzers as a preferred solution for hydrogen production in various industries. Nevertheless,

the choice between AE and PEM ultimately depends on the specific application and requirements, such as the desired hydrogen purity, production scale, and available resources.

The λ parameter determines the relative importance of WSM (Weighted Sum Model) and WPM (Weighted Product Model) which are related to the effect of the alternatives in the overall assessment. The value of λ ranges between 0 and 1, with $\lambda = 0.5$ often used as a starting point, indicating an equal weighting between WSM and WPM.

When λ is closer to 1, the WASPAS method is more aligned with the Weighted Sum Model (WSM). WSM is an additive model, which means that it's better suited for criteria that can be compensated, i.e., a poor performance in one criterion can be offset by a good performance in another criterion.

When λ is closer to 0, the WASPAS method aligns more with the Weighted Product Model (WPM). WPM is a multiplicative model, meaning it's better suited for criteria that are non-compensatory, i.e., a poor performance in one criterion cannot be made up by a good performance in another criterion. When λ is increased, WSM has a greater influence, while WPM has a lesser influence, and vice versa.

The λ value can be determined based on the specific goals and priorities of the decision-making process and the characteristics of the alternatives being compared. The alternative with the highest overall score according to the WASPAS method is considered the best overall alternative. (Figure 5. 10) shows the sensitivity analysis of the WASPAS method to different λ , if the λ for PEM is smaller than for Alkaline, it implies that the decision-making for PEM electrolyzers leans more towards the non-compensatory model (WPM), meaning the weaknesses in one criterion cannot be compensated by strengths in another.

This could imply that while PEM might have advantages in certain aspects (perhaps technical or environmental), its economic performance (a key consideration) can't be compensated by these strengths, hence it might not be the optimal choice if economic factors weigh heavily in the decision-making process.

On the other hand, a higher λ value for Alkaline (Figure 5. 10) electrolyzers suggests a greater alignment with the compensatory model (WSM), meaning good performance in one area could offset poorer performance in another. Thus, even if Alkaline electrolyzers might not perform as well as PEM electrolyzers in some areas, their superior economic performance compensates for

these weaknesses, making them a better choice under the given criteria and weights. Although both the WASPAS and TOPSIS methods are widely used MCDM techniques, and we obtain similar results for the economic mission of PEM and Alkaline electrolyzers, WASPAS offers greater flexibility and may provide more accurate and robust results by combining the strengths of both additive and multiplicative aggregation techniques. Furthermore, its sensitivity analysis capabilities can enhance the overall decision-making process by offering insights into the impact of changes in the λ parameter.

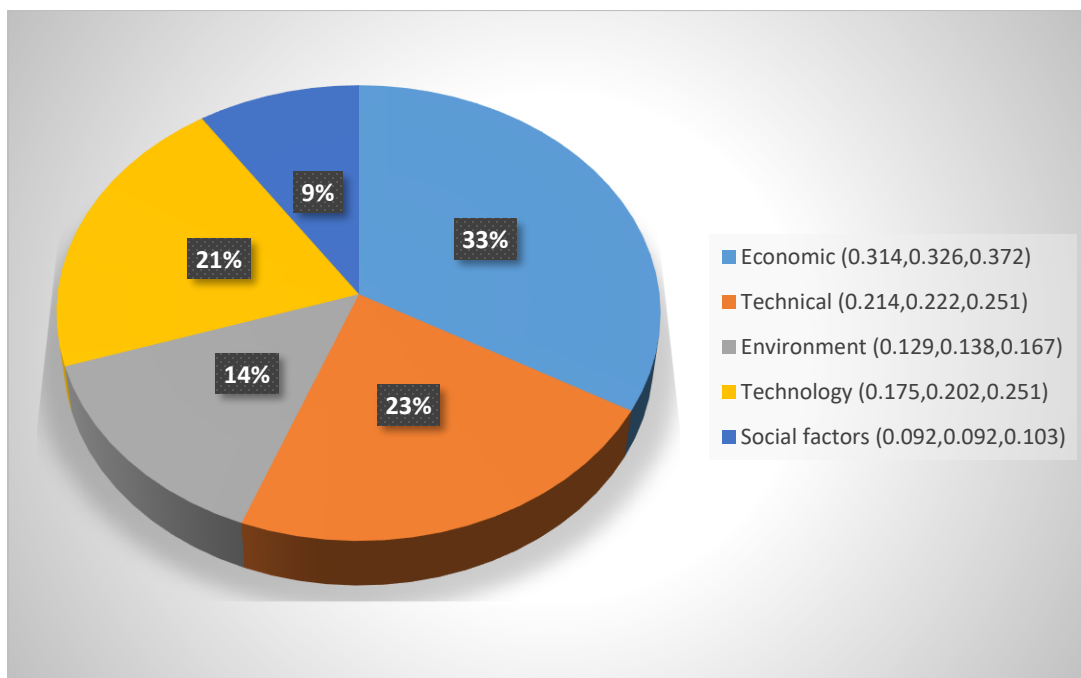


Figure 5. 7. Distribution of importance for water electrolyzers assigned to economic, Technical, environmental, technological, and social factors, with the economic factor being the most important.

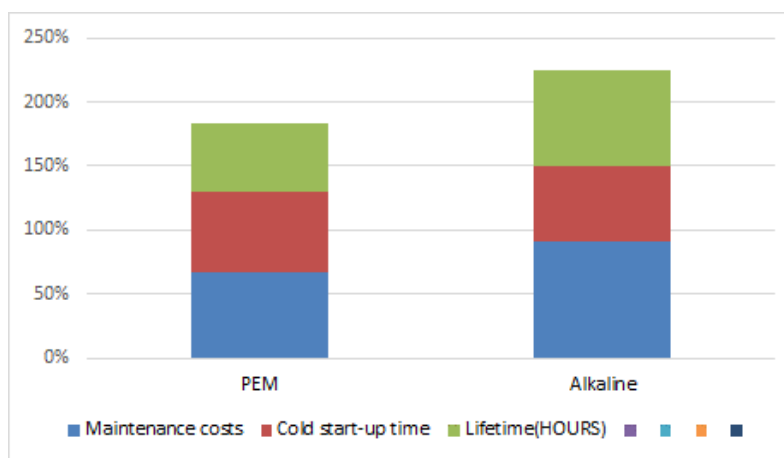


Figure 5. 8. Distribution of importance of criteria comparison in Alkaline and PEM

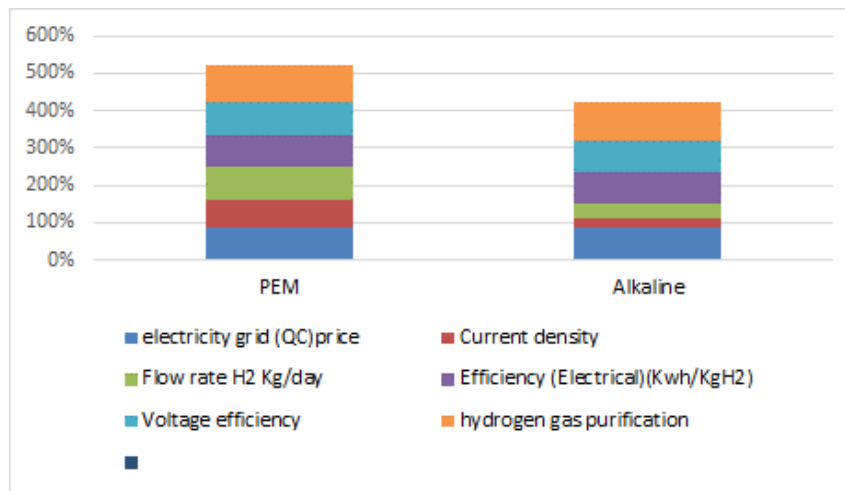


Figure 5. 9. Distribution of importance of some technological subcriteria comparison for Alkaline and PEM Electrolyser sytems

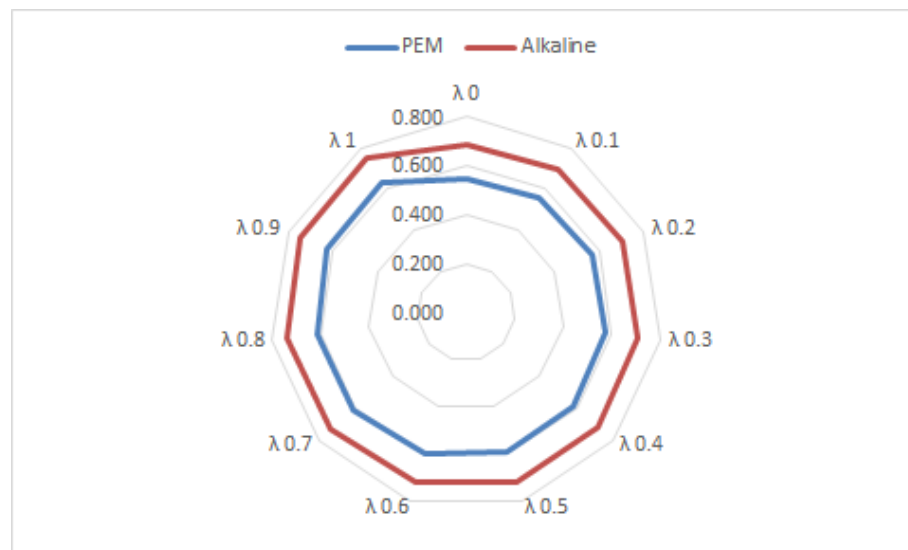


Figure 5. 10. WASPAS sensivity analysis with the change of λ value.0

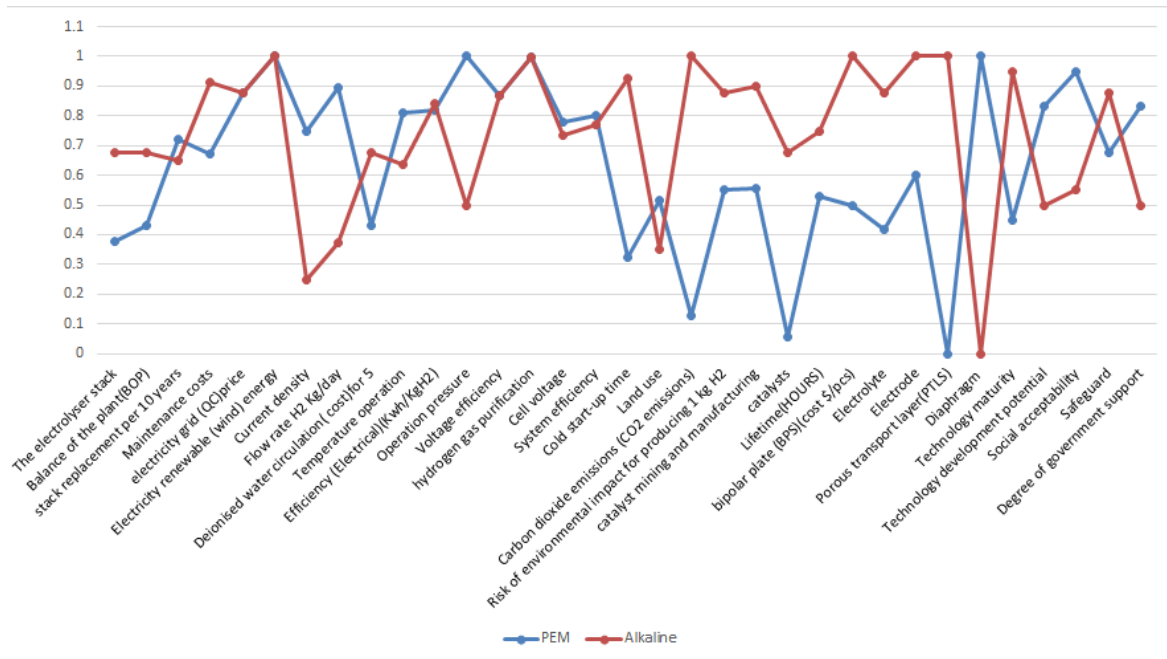


Figure 5. 11. Distribution of importance of criteria comparison in Alkaline and PEM

5.4.2. . Analysis results for Hydrogen Cost

5.4.2.1. Cases summary and cost data

To assess the economic characteristics of a grid-connected hydrogen production plant, two, system cases were analyzed - the AE system and the PEM Electrolyser system. The numerical models of each water electrolysis system are depicted in (Table 5. 12) both system cases were considered as 5 MWeI for low-temperature electrolysis class plant technologies. The operating point was calculated using a MATLAB code which was developed to model the thermodynamic characteristics of PEM and Alkaline electrolysis for hydrogen production (Table 5. 15). The data for this analysis was obtained from the research studies by(Akrami, Nemati, Nami, & Ranjbar, 2018) and (Ulleberg, 2003).

The cost of hydrogen was determined using the method presented in the studies by (Nicita, Maggio, Andaloro, & Squadrito, 2020) and (Jang, Kim, Kim, & Kang, 2022). The cost data in ((Jang, Kim, Kim, & Kang, 2022))and (Table 5. 14) was based on the reference year 2019 (Savadogo et al., 2020a)

The plant's operating lifetime was set to 25 years, and the stacks were completely replaced every 10 years throughout the lifespan The capacity factor was set as 97% as a reference condition, with

the system degradation rate decreasing by 10% over the stack's lifetime, taking into account the variable capacity factors. The electric cost was calculated based on the cost in Quebec, Canada, which is approximately CAD\$0.097/kWh. The use of 10 kg of water to produce 1 kg of hydrogen was assumed, considering some losses incurred during the hydrogen purification process, and the total cost was calculated based on the price presented. KOH was only utilized in the AE system to create electrolyte solutions.

The main assumptions made for the economic analysis in this study are as follows (Table 5. 14).

- 5 MWel hydrogen production plants for each electrolysis type are compared.
- The discount rate (r) and tax rate (TR) are applied at 8% and 30% respectively for the net present value calculation.
- The selling price for O₂ is 0.054 \$/kg O₂ and 9\$/kg H₂. (Jang, Kim, Kim, & Kang, 2022)

Table 5. 13. Set of economic criteria used for levelized cost of Hydrogen

Formula	Expression	Explanation
LCOH (Levelized Cost of Hydrogen)	$LCOH = \frac{(CAPEX + OPEX)}{H_2 Produced}$ (29)	LCOH stands for Levelized Cost of Hydrogen. This formula calculates the total cost of producing hydrogen, including capital expenses (CAPEX) and operational expenses (OPEX), and divides it by the total amount of hydrogen produced. This gives the average cost of producing one unit of hydrogen.
CAPEX (Capital Expenditures)	$CAPEX = I \times (1 + i)^n \times \frac{1}{CRf + RC}$ (30)	CAPEX stands for Capital Expenditures. This formula calculates the initial investment required to build and install the electrolysis system. It includes the installation cost (I), the inflation rate (i), the life of the system (n), the capital recovery factor (CRF), and the replacement cost (RC). The CRF is a factor that converts the present value of future cash flows into an equivalent capital cost.
OPEX (Operational Expenditures)	$OPEX = FC + v_c + P_{OM}$ (31)	OPEX stands for Operational Expenditures. This formula calculates the ongoing operational expenses of running the electrolysis system. It includes fixed costs (FC), variable costs (VC), and plant operating and maintenance expenses (POM). Fixed costs are expenses that do not vary with the level of production, while variable costs are expenses that do. POM represents the expenses associated with maintaining and repairing the system.

NPV (Net Present Value)	$NPV = \frac{-CAPEX + \sum (H_2 \text{ Produce d} \times LCOH)}{(1+r)^t} \quad (32)$	NPV stands for Net Present Value. This formula calculates the present value of the cash flows associated with the hydrogen production system, taking into account the time value of money. It subtracts the initial investment (CAPEX) from the sum of the discounted cash flows over the life of the system. The discount rate (r) represents the cost of capital, and the time period (t) represents the year in which the cash flow occurs.
IRR (Internal Rate of Return)		IRR stands for Internal Rate of Return . This formula calculates the rate at which the present value of the cash inflows equals the present value of the cash outflows over the life of the hydrogen production system. The IRR represents the rate of return earned on the initial investment (CAPEX), and is a measure of the system's profitability.
CRF (Capital Recovery Factor)	$RF = \frac{r \times (1+r)^n}{(1+r)^n - 1} \quad (33)$	CRF stands for Capital Recovery Factor. This formula is used to convert the present value of future cash flows into an equivalent capital cost. It includes the discount rate (r) and the life of the system (n). The CRF is used in the calculation of CAPEX.

Table 5. 14. Input data for economic evaluation(Savadogo et al., 2020a).

Cost factor	value
Construction Period	2 years
Capital Expenses (CAPEX)	25% spent in year 1, 75% spent in year 2
Installation Cost	20% of CAPEX
Site Preparation	1% of CAPEX
Engineering and Design	5% of CAPEX
Maintenance and OPEX	3% of CAPEX, stack replacement every 10 years
Installation Lifetime	25 years with a 97% usage factor for the base scenario
Electricity Cost Canada	USD 0.07-0.10 per kWh
Capex and Opex	Reference year 2019

Table 5. 15. Technical results of the system thermodynamic modeling

The system simulation Alkaline		The PEM electrolyzer modeling	
W_{stack}	100 kw	η_{PEM}	60.57 %
U_{ely}	208.3333volt	$n_{H_2,out}$	0.0063 kmol/s
r_{hat}	6.3937e-05A/m2	$m_{H_2,out}$	0.2020 kg/s
s_{hat}	0.1601 S/m	V_0	1.1823
t_{hat}	0.0594	$V_{act,a}$	0.6804
$I_{density}$	19.2 A/m2	$V_{act,c}$	0.1891
ΔG	272818.14 J	V_{cell}	2.0522
U_{rev}	1.4138 volt	V_{ohm}	4.84e-04
U_{th}	1.4724volt	$W_{PEM_singlecell}$	0.1026
U_{cell}	1.6012 volt	n_{cell}	4.8728e+04
η_f	57.80%	N_{cell}	48729
$\dot{m}_{H_2}$	68.44 kg/hr	LHV_{H_2}	1.2022e+05 kj/mol
$\dot{Q}_{gen}$	8044.90 watts	Q_{PEMHX}	52.3469
$\dot{Q}_{loss}$	357.30w watts	R_{PEM}	9.685e-06
$\dot{Q}_{cool}$	1369.058 watts	$N_{H2_out} (\frac{kmol}{s})$	0.0126

5.4.3. Analysis results and discussion for cost Hydrogen

The hydrogen production rate was determined by taking into account the power consumption and operating efficiency of each plant when a 5 MW power supply was provided. The rate was higher in the order of PEMEC > AWE. The highest rate was recorded for the PEM plant, at 780042.96 kgH₂/year, due to its high system efficiency. On the other hand, the Alkaline plant produced 578149.488 kgH₂/year. The Life Cycle Cost of Hydrogen (LCOH) also followed the same order. The LCOH was calculated by comparing the cost incurred over the plant's lifespan with the amount of hydrogen produced during that time.

AWE systems were found to be the most economical for hydrogen production, with an investment cost of CAD\$7.60 per kg, compared to CAD\$8.66 per kg for PEM. The main differences between

the electrolysis types were observed in maintenance and stack replacement costs. Electric costs alone accounted for at least half of the LCOH formation. The cost of the stack replacement was largely influenced by the stack price, and since the PEM stack was more expensive, it had a significant impact on both the AWE and PEMEC cases.

A profitability analysis of the project was conducted using the Net Present Value (NPV) and the Internal Rate of Return (IRR). The payback period (PBP) was defined as the point where NPV becomes positive. If NPV is negative at the end of the project, it indicates that profitability cannot be expected. The IRR was calculated to be 9.85% for the Alkaline electrolyser, which is higher than the set discount rate of 8%, indicating a net income.

5.5. Conclusion

In summary, this study utilized The TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and WASPAS (Weighted Aggregated Sum Product Assessment), and Fuzzy BWM (Best-Worst Model) MCDM (Multi-Criteria Decision Making) methods to evaluate water electrolysis technologies for hydrogen production. The economic, environmental, technical, technology, and social factors were considered as main criteria. The alternatives were AE and PEM Electrolyser. Although Alkaline (AE) technology emerged as the most cost-effective, PEM Electrolyser was identified as the preferred choice for sustainable hydrogen production due to its superior performance in other important criteria.

The WASPAS method's sensitivity analysis provided valuable insights into the decision-making process, while the assessment of hydrogen production rates and LCOH confirmed AE systems as the most economical option. This comprehensive evaluation of water electrolysis technologies offers crucial guidance for decision-makers, emphasizing the need to consider a range of factors to ensure well-rounded and robust decision-making in sustainable hydrogen production.

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CHAPTER 6 GENERAL DISCUSSION

Hydrogen production via water electrolysis has become increasingly important due to its role in decarbonization, energy transition, and versatility. Using renewable energy sources like solar and wind, water electrolysis generates green hydrogen with minimal emissions, making it a sustainable option. It also addresses renewable energy intermittency by converting excess electricity to hydrogen for later use or other applications, ensuring grid stability. Technological advancements in PEM and Alkaline electrolyzers have improved efficiency, durability, and cost-effectiveness, making hydrogen production competitive. MCDM methods are vital for selecting the best alternative and understanding the strengths and weaknesses of various water electrolysis technologies, facilitating informed decision-making, and promoting cost reduction and improvement.

Considering the importance of hydrogen production and the need for effective decision-making, the main objective of this thesis was to determine criteria that impact cost for early-stage design decision-making by evaluating sustainability criteria. This approach allows for a comprehensive assessment of various aspects of water electrolysis technologies, including environmental, economic, technical, technology, and social factors, enabling stakeholders to make informed choices about hydrogen production technologies based on their priorities and objectives. By focusing on the criteria that impact cost, this thesis contributes to the development of more cost-effective and sustainable hydrogen production methods, ultimately supporting the global transition towards a low-carbon economy.

The study identifies key criteria that can significantly reduce costs and improve efficiency. By employing Fuzzy Best Worst Method (BWM) - an important multi-criteria decision-making technique for weighting criteria - the research highlights the strengths and weaknesses of each criterion in various aspects of water electrolysis technologies. These aspects encompass environmental, economic, technical, technology, and social factors, and the analysis takes into account 30 sub-criteria that impact cost.

The Fuzzy BWM is particularly relevant for this study because it accounts for the inherent uncertainty and vagueness in the decision-making process. It allows for the incorporation of expert judgments and provides a clear understanding of the relative importance of each criterion, making it an ideal tool for evaluating complex systems such as water electrolysis technologies.

One of the key findings of the study is that voltage efficiency is more important in water electrolyzers compared to other criteria. This is because voltage efficiency directly impacts the overall energy consumption of the electrolyser, which in turn influences the operational costs and environmental footprint. Improvements in voltage efficiency can lead to significant reductions in energy consumption and greenhouse gas emissions, making it a critical factor in the adoption and deployment of water electrolysis technologies.

The study also finds that capital expenditure (CAPEX) holds more weight in the economic aspect of water electrolysis technologies. This is because the initial investment in equipment, infrastructure, and installation is often a major barrier to the implementation of new technologies. As the cost of electrolyzers decreases, their adoption becomes more feasible, ultimately contributing to the growth and success of the industry.

Another crucial finding is the substantial impact of the electrolyte on efficiency and cost reduction. The choice of electrolyte significantly affects the overall performance of the electrolyser, as it influences factors such as conductivity, stability, and safety. By selecting an appropriate electrolyte, it is possible to improve the efficiency of the electrochemical process, reduce energy consumption, and ultimately lower the costs associated with water electrolysis.

the study employs Interval TOPSIS, a robust multi-criteria decision-making method capable of accommodating varying ranges of values for each criterion. By utilizing interval-valued numbers, Interval TOPSIS captures the inherent uncertainty and variability in the evaluation process, leading to a more accurate, reliable, and comprehensive ranking of the alternatives.

The results of the Interval TOPSIS analysis reveal that Alkaline water electrolyzers are more cost-effective compared to PEM electrolyzers. This finding is based on the comprehensive assessment of the alternatives, considering the criteria weights obtained through the Fuzzy BWM, and taking into account the full range of possible values for each criterion.

The outcome of this study not only contributes to a better understanding of the relative advantages and disadvantages of PEM and Alkaline water electrolyzers but also serves as a valuable guide for policymakers, researchers, and industry stakeholders in making well-informed decisions regarding the development and deployment of these technologies. By utilizing robust multi-criteria decision-making methods such as Fuzzy BWM and Interval TOPSIS, the research underscores the importance of considering multiple criteria and their respective weights in the assessment of water

electrolysis technologies. This comprehensive approach ultimately supports the accelerated adoption and widespread implementation of cost-effective and sustainable water electrolysis solutions in pursuit of a more sustainable global energy landscape.

In addition to the Interval TOPSIS method, this study also employs the Weighted Aggregated Sum Product Assessment (WASPAS) Interval method to further validate the cost-effectiveness of Proton Exchange Membrane (PEM) and Alkaline water electrolyzers. The WASPAS Interval method is another robust multi-criteria decision-making technique, which combines the strengths of the Weighted Sum Model (WSM) and the Weighted Product Model (WPM) to provide a more comprehensive evaluation of alternatives.

The WASPAS Interval method is particularly suitable for ranking water electrolyzers because it offers a balanced approach to decision-making, considering both the additive and multiplicative aspects of the evaluation process. This method ensures a more accurate and reliable assessment, taking into account the full range of possible values for each criterion while also capturing the inherent uncertainty and variability in the evaluation process.

The results obtained from the WASPAS Interval analysis corroborate the findings of the Interval TOPSIS method, confirming that Alkaline water electrolyzers are more cost-effective compared to PEM electrolyzers. This outcome reinforces the conclusion that Alkaline water electrolyzers are a more viable option for low-cost hydrogen production, based on the comprehensive assessment of the alternatives and the criteria weights obtained through the Fuzzy BWM.

To further enhance the reliability and accuracy of the study, a sensitivity analysis is conducted using the lambda parameter in the WASPAS Interval method. The sensitivity analysis is crucial because it helps identify the robustness of the results and their dependence on the weighting of the criteria. By performing a lambda sensitivity analysis, the study ensures that the ranking remains consistent under various weighting scenarios, ultimately providing greater confidence in the overall findings.

Finally, a MATLAB code was developed to analyze the thermodynamic characteristics of 5 MW Alkaline Water Electrolysis (AWE) and Proton Exchange Membrane Electrolysis Cell (PEMEC) systems. Understanding these thermodynamic characteristics provides valuable insights into the performance and efficiency of water electrolysis technologies. Developing a code for analyzing these characteristics allows for a more comprehensive and systematic approach to evaluating and

comparing different electrolysis systems, (LCOH) is an essential metric for assessing the economic viability of hydrogen production technologies. It takes into account the costs incurred over the plant's lifespan and compares them with the amount of hydrogen produced during that time. This metric is crucial as it helps identify the most cost-effective technology, enabling policymakers and industry stakeholders to allocate resources more efficiently and promote the large-scale adoption of hydrogen as a sustainable energy source.

In this study, the (LCOH) was calculated using the thermodynamic characteristics and system efficiencies of both AWE and PEMEC systems, considering the grid electricity costs in Quebec as an example. The hydrogen production rate was determined by taking into account the power consumption and operating efficiency of each plant when a 5 MW power supply was provided. The rate was higher in the order of PEMEC > AWE, with the highest rate recorded for the PEM plant at 780,042.96 kgH₂/year, attributed to its high system efficiency. In contrast, the Alkaline plant produced 578,149.488 kgH₂/year. The LCOH followed the same order.

AWE systems were found to be the most economical for hydrogen production, with an investment cost of CAD\$7.60 per kg, compared to CAD\$8.66 per kg for PEM. The main differences between the electrolysis types were observed in maintenance and stack replacement costs. Electric costs alone accounted for at least half of the LCOH formation. The cost of the stack replacement was largely influenced by the stack price, and since the PEM stack was more expensive, it had a significant impact on both the AWE and PEMEC cases.

A profitability analysis of the project was conducted using the Net Present Value (NPV) and the Internal Rate of Return (IRR). The payback period (PBP) was defined as the point where NPV becomes positive. If NPV is negative at the end of the project, it indicates that profitability cannot be expected.

This study not only offers valuable insights into the hydrogen production rate and LCOH for PEMEC and AWE systems under a 5 MW power supply but also highlights the importance and benefits of developing a code for analyzing the thermodynamic characteristics of water electrolyzers. The findings emphasize the significance of considering both thermodynamic characteristics and economic factors when selecting electrolysis technologies for hydrogen production. Furthermore, future research should focus on enhancing system efficiency, reducing

costs, and exploring alternative decision-making methods to ensure the long-term viability and profitability of hydrogen production plants.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

In recent years, the global focus on sustainability and renewable energy has intensified, and hydrogen production through water electrolysis has emerged as a promising solution for clean energy generation. This study aimed to address the techno-economic challenges and opportunities in the development of water electrolysis technologies, focusing on the application of multi-criteria decision-making (MCDM) methods to evaluate and compare the performance of Proton Exchange Membrane (PEM) and Alkaline water electrolyzers. The comprehensive analysis provided in this research has shed light on key factors that influence the efficiency and cost-effectiveness of these technologies, offering valuable insights to guide future research and development in the field.

The research provided valuable insights into the relative advantages and disadvantages of PEM and Alkaline water electrolyzers, and served as a guide for policymakers, researchers, and industry stakeholders in making informed decisions regarding the development and deployment of these technologies.

Key findings of the study include the importance of voltage efficiency, the significant weight of capital expenditure (CAPEX) in the economic aspect of water electrolysis technologies, and the impact of electrolyte selection on efficiency and cost reduction. Additionally, the study emphasized the benefits of utilizing robust multi-criteria decision-making methods such as Fuzzy BWM, Interval TOPSIS, and WASPAS Interval for evaluating complex systems like water electrolysis technologies. In addition, Although Alkaline (AE) technology emerged as the most cost-effective, PEME was identified as the preferred choice for sustainable hydrogen production due to its superior performance in other important criteria.

Although Alkaline (AE) technology emerged as the most cost-effective solution, our weighting criteria highlighted that certain technical or technological criteria related to Proton Exchange Membrane (PEM) are crucial. This suggests that while AE may be economically advantageous, PEME offers superior performance in other essential areas. As such, PEME was identified as the preferred choice for sustainable hydrogen production. These findings underscore the importance of a holistic evaluation approach – one that doesn't solely focus on cost but also considers other performance-related criteria.

This revised paragraph emphasizes the nuanced differences between the two technologies and how multi-criteria evaluation can bring about a more comprehensive understanding of their potential applications and benefits.

7.2. Recommendations

Based on the findings and conclusions drawn from the study, the following recommendations are proposed for future research and development in the field of hydrogen production through water electrolysis:

- **Enhance voltage efficiency:** Prioritize research and development efforts that focus on improving voltage efficiency in water electrolyzers, as this directly influences overall energy consumption, operational costs, and the environmental footprint of hydrogen production.
- **Minimize capital expenditure:** Develop innovative solutions and technology advancements to decrease the initial investment required for water electrolysis technologies. Reducing CAPEX can facilitate the adoption of these technologies and contribute to the growth of the hydrogen production industry.
- **Optimize electrolyte selection:** Continue researching and developing new electrolytes that can improve the efficiency of the electrochemical process, reduce energy consumption, and ultimately lower the costs associated with water electrolysis.
- **Apply MCDM techniques:** Utilize MCDM methods in future techno-economic analyses of hydrogen production systems to ensure comprehensive, reliable, and accurate evaluations that consider multiple criteria and their respective weights.
- **Investigate thermodynamic characteristics:** Develop and refine codes for analyzing the thermodynamic characteristics of water electrolyzers to better understand their performance and efficiency. This will enable more informed decision-making when selecting electrolysis technologies for hydrogen production.
- **Improve system efficiency and cost reduction:** Future research should focus on advancing technologies and solutions that enhance system efficiency and lower costs, ensuring the long-term viability and profitability of hydrogen production plants.

- Explore alternative decision-making methods: Consider the application of alternative MCDM techniques and decision-making methods to better evaluate and compare different hydrogen production technologies and systems.

By implementing these recommendations, researchers, policymakers, and industry stakeholders can contribute to the ongoing development and adoption of sustainable, efficient, and cost-effective hydrogen production technologies, ultimately leading to a cleaner and more sustainable global energy landscape.

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