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Research paper

Green hydrogen production by proton exchange membrane electrolysis: a sustainable approach

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Abstract

Extending worldwide request for sustainable energy can be attributed to two con-templations: the decrease of conventional energy sources and climate change. Proton exchange membrane (PEM) electrolysis generates green hydrogen, as attainable sub-stitute for clean and economical energy. In this study the 7,9 UN sustainable goals were applied for the proton exchange membrane (PEM) electrolysis, that split water to oxygen and hydrogen as clean fuel. The goals applied though out all the PEM electrolysis part, to ensure that the method of generating hydrogen through PEM is a sustainable approach for the future clean fuel, within its production with zero carbon emission and within its application in the fuel cells. Results approved that PEM electrolysis offers fast reaction times during load changes, excellent efficiency, and modular stability. It consumes less clean energy and runs at lower pressures and temperatures, which reduces system costs which were aligned with the goals 7. The Current developments in catalysts and membrane materials approved the durability and efficiency which represents UN goal No 9. for the sustainable industry innovative resources for our future cities.

Keywords: *Green Hydrogen 1; PEM Principles2; Membrane Materials3; UN Goals 4; PEM Challenges5;PEM Efficiency 6.*

1. Introduction

UNs 17 sustainable development goals, represent the road map for smart cities and development economy to assign better life and maintainable resources for our future generation. Goal 7: Affordable and clean energy, and Goal 9: Industry, innovation and infrastructure can be applied to solve the world's population rise and the request for energy resources that increases over the decades, With limited access to these resources and an ever-growing need for more sustainable energy solutions, two main causes driving the global demand for renewable energy: the change in climate and the necessity for sustainable sources. One of the pressing issues facing the world today is climate change. To combat climate change, we need to find ways to reduce our carbon footprint, [1], [2].

As a result, hydrogen has become an increasingly important and cost-effective energy storage option [3], [4]. Hydrogen is generated by various methods, each with a different environmental impact and associated with a different assign "colour"". Today, various colours are used to categorize hydrogen based on the CO_2 emissions associated with hydrogen production [6]. No CO_2 emissions produced within the green hydrogen manufacturing process. The developed technology for hydrogen generation is the electrochemical water split, [7]. Generally, "green hydrogen" is the hydrogen produced by electrolysis cells driven by renewable electricity. Hydrogen can convert back into electrical energy in fuel cells or used in combustion engines as fuel and mechanical energy generators in turbines.

Green hydrogen produced using low-emission methods amounts to less than 1 million tons with only 0.35 kilo ton of H_2 coming from water electrolysis. One kilogram of hydrogen formed by electrolysis, associated with eight kilograms of oxygen generation, which requires 50–55 kWh of electricity and nine kg of pure water. The cost of $4–5 per kilogram of green H2 is more expensive than the low cost of $1–2/kg H2 for other produced hydrogen. So, the main problem is to figure out how to produce hydrogen for use at prices comparable to the present without releasing CO_2 into the atmosphere [12 - 15].

The most well-known and efficient method of water splitting is electrolysis, which is broadly used in industry [16]. Electrolysis occurs when an electric current flows through the electrodes, causing the movement of electrons. There are many different types of electrolysis technologies. Some are already commercially available, while others are still in research and development. Alkaline, proton electrolysis membrane, solid oxide, and anion exchange membrane, are the most water splitting technologies based on the technology readiness level (TRL) and their market spread. [17], Table 1.

Table 1: Comparison of Water Electrolysis Technologies, [17]

Cell	Alkaline Cell (AL)	Proton Electrolysis membrane (PEM)	Solid Oxide (SO)	Anion Exchange membrane (AEM)
Technology Reading Level (TRL)	8–9	8	5–6	3–4
Market penetration	Bulky scale	Fast expansion	Restricted development	Laboratory scale

*TLR range from 1-9, 1; is the basic research until 9 : the system is lunch and operationally tested.

All electrolysis technologies work with similar reaction of water splitting, but this report concerns the polymer membrane electrolysis (PEM) [18]. The reaction can be described as following equation 1:

$H_2O(l)+237.2 kJmol^{-1}(energy)+48.6 kJmol^{-1}(heat)\rightarrow H_2(g)+0.5\ O_2(g)$ (1), [19]

PEM cell is a promising technology that offers a clean and efficient energy source that could alleviate the global energy problem. However, there are still some issues that need to be considered. The high price of platinum group metals (PGMs) which is applied as catalysts in PEM cells [20 - 23].
Many electrolysis technologies were researched, the PEM is an efficient, wide-open research and development future approach. A study of the production process starting from the renewable energy resources to the production of hydrogen through reviewing the materials and procedures applied in the PEM technology will enhance the knowledge of the opportunities to the global utilization of the PEM as fuel production source. In addition to know the challenges that can be resolved to raise green hydrogen production as an economic, environmental energy method.
Different green production with its ecnomical benefites and enviromntal impact were studied and associated with UNs goal as energy road map,[24]. The lack of clean energy and the increse of carbon footprints , a reserch was conducted to green hydrgen storage in ,[25]. Research ,[26], implemented the UNs goal to PEM water electrolysis and assesed the available energy technologies through the energy and its efficencies. The use of green hydrogen in watertretment plants were coupled with UN goal 7 to insure cost reduction ,[27]. The production of hyrogen from wind,solar, nuclear resources …,ect was studied to present the devolpment goals and energy challenges of water electrolysis ,[28].
Inspite that some reserches worked to link UNs devolpment goals with green hydrogen production[24,25,26,27,28], mainly goal 7, there are few reserch that conect the PEM electrolysis green hydrogen production method with the UNs goals and no study have related the clean energy withUN goal 9.
So, this article targets to explore the manufacture of green hydrogen through proton exchange membrane (PEM) electrolysis as a sustainable energy approach for the future, linking the study with UN development goals 7 and 9. It investigates the parts of the PEM electrolysis cells, the anode and cathode materials and their progression. Sustainable PEM electrolysis opportunities and the challenges are also discussed.

2. Materials and methods

2.1. Resources for green hydrogen production

Goal 7 ; which is affordable and clean energy goal is related to the renewable resources that can be utilized in green hydrogen generation. The applied energies are, solar energy, wind energy and hybrid energy.

2.2. Green hydrogen from solar energy

It is possible to electrolyze water to produce hydrogen using electricity generated by photovoltaic (PV) panels. This is one of the convenient techniques of producing hydrogen. Unfortunately, the high installation costs and lower efficiency of PV-based hydrogen production compared to fossil fuels are a major drawback today [29]. Purnami et al [30] investigated the effectiveness of solar-powered water electrolysis using pulse, magnetic, light, and ultrasonic electric fields. Toghyani et al [31] found that efficiency increases when hydrogen refueling stations are connected to the electricity grid. Clouds and operating temperatures are two factors that limit the 20% electricity yield that photovoltaics can achieve. This problem can be solved with hybrid systems that utilize renewable energy sources, but the price per kWh decreases.

2.3. Green hydrogen production from wind

Wind energy employs the same component as the previously mentioned sun-oriented energy to electrolyze water. It is the best and cleanest method to create hydrogen. In terms of hydrogen generation, it is cheaper and more effective than other renewable energy sources. In any case, for electrolysis, an appropriate hydrogen capacity framework and a progressed wind turbine structure are required to deliver hydrogen from wind energy [32]. Wind speed estimation can move forward the framework reliability and decrease misplaced costs. Another wind energy constraint is the generation inconstancy, which is the main difficulty of wind operation. It is broadly conceded that the inconstancy in power generation can be decreased by power blending from geologically or technologically diverging sources.

2.4. Green hydrogen production from a hybrid system

Han and Vinel, [32], generate an optimum solar- wind system with seventeen times more than single wind system efficiency. So, hybrid renewable energy framework (Figure 1) has appeared to be a possibly compelling arrangement to energy productivity, [33]. The benefits of hybrid systems depend on a variety of renewable energy sources to guarantee a dependable, continuous power supply. As a result, the expanded energy mix will decrease gas emission and balance the difficulties of a single renewable vitality source [34], [35].

Fig. 1: Green Hydrogen Generation from Hybrid System.

3. Components of the PEM water electrolysis cell

The UN goal 9 which concerns about industry, innovation and infrastructure , applied to the electrolysis assembly . The PEM comprises of (MEA) membrane electrodes assembly, (GDL) gas diffusion layers and the catalyst layers CLS or known as separator plates. The water is pumped onto the anode side, where oxygen evolution reactions (OER) take place. The injected water diffuses through separator plates and GDL and comes to the electrode surface. The water particles are split into protons, oxygen, and electrons. Oxygen returned to the cell through the anode surface, the GDL and the separator plates. The protons move through the membrane to the cathode side, where the electrons move from the current collectors to the cathode surface and recombine with the protons to create hydrogen molecules. In the PEW cell, the main component is the MEA, which divides the cell into two halves (anode and cathode) is shown in Figure 2.

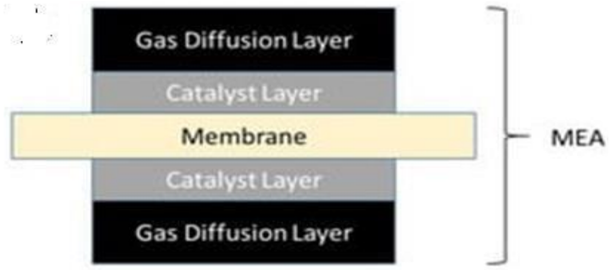

Fig. 2: PEM Water Electrolysis Cell.

3.1. Membrane

Anode and cathode electrocatalysts, an ionomer solution, and a membrane make up the membrane electrode assembly, which costs twenty four percent of the entire cell. Membrane is the main part of PEM cell. Perfluorosulfonic acid membranes is the most widely utilized polymer membranes, such as Aciplex®, Fumapem®, Nafion®, and Flemion® [36, 37]. The Special characteristics of these membranes the strength, efficiency, oxidative stability,
proton conductivity, dimensional stability during temperature variations, and exceptional durability. Nonetheless, Nafion® 115, 117, and 212 membranes are currently typically utilized for PEM water electrolysis due to their many advantages, including the ability to operate at greater current densities (2 A/cm^2) [38]. R
The required quantity of electrocatalyst was ultrasonically treated for approximately 30 minutes together with isopropanol, water, and an ionomer solution (such as Nafion® Ionomer) to create a homogenous electrocatalyst slurry. The ionomer increases the cell's efficiency by decreasing the ohmic loss and accelerating proton transfer from electrode layers to the membrane. Furthermore, ionomer solution serves as a binder, providing the catalyst's dimensional stability as well as the electrodes' mechanical stability and long-term viability [39]. ead.

3.2. Basic anodic and cathodic materials

The specified amount of electrocatalyst was ultrasonically treated for roughly 30 minutes beside isopropanol, water, and an ionomer solution (such as Nafion ® Ionomer) to form a homogenous electrocatalyst slurry. The ionomer increments the cell's productivity by decreasing the ohmic loss and accelerating proton exchange from the anode to cathode through the membrane. Moreover, the ionomer arrangement serves as a cover, giving the catalyst's dimensional stability as well as the electrodes' mechanical stability and long-term viability [39], [40], Table 2.

Table.2: Examples of Ir, Ru Electrocatalysts in PEM Water Electrolysis

Anode Electrode	Cathode Electrode	Loading of Anode (mg/cm^2)	Loading of Cathode (mg/cm^2)	Membrane Cell	Operating Temp (ºC)	Voltage at 1 A/cm^2	Ref.
Ir-Black	Pt black	2.0	0.8	Nafion-117	90	1.71	[41]
RuO2	40% Pt-C	10	0.4	Nafion-115	-	1.88	[42]
IrO2	30% Pt-C	1.5	0.5	Nafion-1035	80	1.67	[43]
RuO2	46% Pt -C	1.0	0.2	Nafion-117	80	1.68	[44]

Although the green hydrogen research field is immediately being developed to find an approach to lower the IrO2 loading required for the highly corrosive anode side of PEM by improving the catalyst insert. Table 4 shows some recently discovered Ir-based catalysts such as Ru0.9Ir0.1O2 [44] and lrO2@TiO2, [45], which can maintain a stable current density of 1 to 2 A /cm^2 between 1.6 to 1.8 V for hundreds of hours. In addition, the nanostructure of Ir (IrO2 nanoneedles [46], nano-sized IrOx , [47] affects the functions of the PEM electrolysis as a whole by improving the mass transfer capacity and electrochemical surface area [48].
A case of perpetual substitutions on the cathode side was proposed to make HER cathodes with restricted platinum loading through applying galvanic displacement of Pt nanoparticles on a carbon paper (CP) substrate and Co-dendritic deposition, driving to high activity and durability, [49]. Maximilian et al. explored the utilize of carbon-supported platinum (Pt-C) with 0.5-1 milligram Pt/cm^2 without influencing the cell performance, since the HER kinetics of Pt in an acidic cathodic electrode is fast, [50]. Molybdenum disulphide (MoS_2) has moreover shown an effective catalyst for HER [51]. MoS_2 is less costly than Pt and is around 104 times more abundant than Pt. It may be a dichalcogenide metal that shows semiconductor behavior comparable to silicon and high chemical stability, leading to significant performance in PEM water electrolysis [52].

3.3. Gas diffusion layer (GDL)

To improve the PEM infrastructure the basic component added to the water electrolysis process with proton exchange membranes (PEM) is the diffusion layer of gas . It's important for water management and gas diffusion of the reactants [53]. The GDL is responsible for developing the supporting framework of the fuel cell [54,55], collecting the current and distributing the reactant gas through flow channels over the surface of the electrodes. Typically, a thin layer of carbon black and a hydrophobic polymer are applied to a porous carbon fibre paper or fabric to form the GDL. The hydrophobic polymer is used to repel water and prevent flooding of the electrode, while the carbon black provides electrical conductivity [56].

3.4. Separator plates (catalyst layers (CLs)

The separator plate divides the cathode and anode electrodes, allowing the reaction gases to pass through the GDL film into the catalyst layer (CLs). In addition, separator plate supports the cell mechanically and facilitates the eliminate the water and heat from the cell. It consists of conductive materials such as metal, carbon fiber and graphite. The required mechanical properties, corrosion resistance and electrical conductivity are some of the variables that influence the choice of material. Graphite plates offer high electrical conductivity and light in weight but may need to be coated to prevent corrosion. Metal plates have a higher contact resistance and are heavier, but they are also more resistant to corrosion,[57].

4. PEM thermodynamics

The innovation UN goal related the engineering principle to application to exhibit smart solution for energy sector. To understand the energy efficiency of current and voltage generated from PEM cell , the minimum Gibbs free energy (ΔG)
required for water splitting can be calculated from equation 2:

$$\Delta G = n*F*Erev \quad (2)$$

n = number of electrons, F = Faraday's constant= 96500 and Erev = Reversible voltage
Applying the numeric values from equation 1, the energy (ΔG) = 237.22 kJ mol^{-1} , and the heat (ΔH) = 285.84 kJ mol^{-1} , the reversible energy from equation 3 is :

$$Erev = (\Delta G/ n*F) =1.23 \text{ V} \quad (3)$$

Also from the energy conversion, its more applicable to replace ΔH with ΔG in water spit calculation, so the minimum thermal voltage (V min), can be found from equation 4.

$$V min = (\Delta H/ n*F) = (\Delta G/ n*F) +(T\Delta S/n*F) = 1.48 \text{ V} \quad (4)$$

Vmin = minimum thermal voltage , ΔS = Entropy change ,T = temperature

In the practical application the voltage is higher than Vmin, minimum thermal voltage . So, the efficiency can be calculated from equation 5.

Cell efficiency = (Vmin /Vcell)

5. Opportunities and challenges of PEM water electrolysis

5.1. Water to water production

Water electrolysis is a strategy of changing over renewable energy sources into chemical energy that can be stored in hydrogen (H_2) [58]. On the other hand, fuel cells can create power by electrochemical recombination of hydrogen atoms with water, so, hydrogen serves as an energy carrier in this system, [59 - 62]. To discharge the stored energy, the hydrogen must first be collected, then changed over back into water [60]. To attain this objective, fuel cells and water electrolysis must be combined. (HER) hydrogen revolution reaction and (OER) oxygen evaluation reaction control the water electrolysis cell and the (ORR) oxygen reduction reaction and hydrogen oxidation response (HOR) governate the fuel cells electrochemical reactions for energy generation and transformation, [63-64]]. Figure 3 and Table 3 show the two innovations of water electrolysis and fuel cells and their differences.

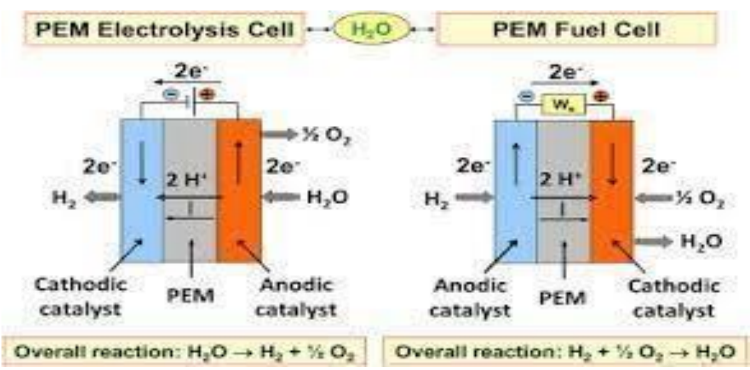

Fig. 3: Hydrogen Water Electrolysis and Hydrogen Fuel Cells, [65].

Table 3: Comparison Between Water Electrolysis (PEM) and Fuel Cell (FC) ,[66], [67]

Water electrolysis Parameters	Water electrolysis (PEM)	Fuel Cell (PEM)
Electrode reactions	Cathode: $4H^{+} + 4e^{-} \rightarrow 2H2$ Anode: $2H2O \rightarrow 4H+ + 4e^{-} + O2$	Cathode: $4H+ + O_2 +$ $4e^{-} \rightarrow 2\ H2O$ Anode:$2H2 + 4H2O \rightarrow 4H+{\cdot}4H2O + 4e^{-}$
Current density (A/cm2)	1 – 3	0.4-0.9
Efficiency (%)	67 – 82	40 – 60
Operating temperature (oC)	≤ 80	60- 100
Operation Pressure (bar)	30-50	3-4
Electrolysis energy consumption (kWh/Nm3)	4.0 – 5.0	50-60
Response time	Seconds	< 1 seconds
Electrolyser life (h)	80,000	40,000-80,000
Applicability	commercial application	commercial application
Disadvantages and challenges	high cost of catalyst and the PEM	Expensive, sensitive to impurities in the fuel, require a pure hydrogen resource

5.2. PEM challenges

Hydrogen production with high purity can be achieved by the promising technique of proton exchange membrane (PEM). However, several challenges require resolution of the financial issues and efficiency improvement of PEM technology. The development of efficient electrocatalysts is an important requirement for the approach,[68]. The ability of the membrane assembly (MEA) to withstand extreme conditions such as high temperature and pressure , which can lead to membrane degradation and reduced performance,[66], needs to develop.

PEM water electrolysis has restrict utilization due to the platinum group metals (PGMs) high cost, which used in the catalyst layers (CLs) [69]. Researchers are looking for new materials and structures that can increase the durability and efficiency of the catalysts. Commercial PGM catalysts with higher loading have not performed as well as dendritic platinum nanoparticles (dend-Pt NPs), [68] which have been fabricated. Also, industrial use of non-PGM catalysts such as chalcogenides and metal oxides are being investigated,[70], [71]. These new catalyst designs and materials can reduce the PGMS cost .Also, Pt alloy catalysts was developed to improve performance and moderate the use of PGMs. The application of non-PGM catalysts such as nickel and cobalt phosphide gave well improvement and acceptable durability, [72 - 75].

For polymeric membranes cost decline, the composite techniques can be applied to improve the cell mechanical properties. Membrane thickness reduction will raise the performance and reduce the cost.

CCS, Catalyst coating substrate and CCM, catalyst coating membrane are the two types of membrane electrode manufacturing techniques applied for resistance decreasing. In the CCS method, the active catalyst components coated on the diffusion layer, while in the CCM method, the active catalyst components coated on both sides of the proton membrane [76], [77]. In CCM method, the catalyst is better utilized and the transfer of proton resistance between the catalyst layer and the membrane is significantly reduced compared to the catalyst coating substrate method. For CCM method, the membrane is coated with a homogeneous catalyst slurry produced by solubilization of catalysts, ionomer solution and solvent combination, then it's hot pressed under high pressure [78]. Also, the membrane ionic conductivity will increase, resulting in low membrane resistance and electrolytic energy, which subsequent upgrades the overall performance of the electrolysis.

Another challenge with PEM is enhancing the pressure to extend efficiency. The hydrogen created within the cell shall be stored under high pressure. It is controversial whether the gas is compressed electrochemically by electrolysis or in downstream gas compressors. The electrochemical compression with no moving parts and hydrogen purification function, is more sustainable for PEM technology. The perfect pressure of cathode is a function of film thickness and current density by presenting pressure-optimized cell operation. Concurring to this strategy, thick layers increment the safety and efficiency of the PEM. Also, utilizing Nafion212- rather than Nafion117 with a compressor produces twice as much hydrogen ass Nafion 117, [79], [80].

6. Conclusions

In sustainable green hydrogen generation utilizing PEM, proton exchange membrane , for water split into hydrogen and oxygen employing selective membrane barrier. This framework could be a promising innovative development for economical energy arrangements because it is characterized by great productivity, quick load change times and modular stability. The MEA, membrane exchange assembly , the gas diffusion layers and the separator plates (catalytic layers) are the fundamental parts of the PEM . As ionomer arrangement quickens the proton exchange and decreases the ohmic misfortune of the cell, it increments the effectiveness of the cell. These parts, with functional shift, can be applied for both hydrogen water electrolysis and fuel cell as energy storage and power supply.

The improvement of viable electrocatalysts, film degradation and the high cost of platinum group metals (PGMs) are among the challenges that limit the viability of this approach. To extend the proficiency and durability of catalysts, researchers are exploring novel materials and structural configuration non-PGM catalysts for research and development. PEM can be a promising sustainable approach for energy sectors all over the globe.

7. Recommendations

Green hydrogen is an innovated energy source, align with UNs goal 9, that can replace carbon fuels in several commercial sectors. It is formed through renewable energy resources and water. to convince the increasing demand, and environmental sustainability, which is one of UN development goal (UN 7) . However, the operating green hydrogen generation techniques are either too costly or low efficient. Thus, advanced technologies that can recover efficiency and sustainability are required. Proton exchange membrane electrolysis which moves protons from oxidation pole to reduction pole, is one of the most promising electrolysis cells. Compared to others, PEM offers additional advantages, including high current density, low operating temperature, quick response time, and high hydrogen purity. But PEM has various disadvantages, such as expensive material costs, durability, and hydrogen embrittlement. To address these issues, many procedures were recommended. Production of novel membranes and catalysts with different fabrication procedures that can lessen platinum loading and improve the stability of PEM cells. Also, enhance the efficiency and reliability of the hydrogen production process by optimizing the PEM systems' design and performance. By implementing these actions, PEM can become a competitive technology for green hydrogen manufacture and contribute to comprehensive energy modification and climate change mitigation.

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