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Review Article

Evaluating the Viability of Electrolyzer Technologies for Integration with Diverse Renewable Energy Sources

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ABSTRACT

As the demand for renewable energy grows, efficient methods for storing excess energy are crucial to ensuring reliable and sustainable power systems. Hydrogen production through water electrolysis provides a promising solution for long-term energy storage. This paper explores the integration of electrolyzers with renewable energy sources, focusing on the advantages and limitations of three key electrolyzer technologies: Proton Exchange Membrane (PEM), Anion Exchange Membrane (AEM), and Alkaline Water Electrolyzers. While PEM and AEM electrolyzers offer high efficiency, rapid response times, and compatibility with intermittent renewables, they face challenges in scaling and cost. Alkaline electrolyzers, the most established technology, excel in large-scale industrial applications but struggle with dynamic operations and hydrogen crossover. The analysis highlights the need for continued advancements in electrolyzer technology to maximize the potential of green hydrogen in grid balancing, decarbonizing industry, sustainable transportation, and distributed hydrogen production. Recommendations for improving electrolyzer performance, reducing costs, and enabling seamless integration with renewable energy are provided to support a cleaner, hydrogen-powered future. Advancing these technologies will be pivotal in unlocking hydrogen's role as a cornerstone of a resilient, low-carbon energy economy.

Keywords: Proton Exchange Membrane (PEM) Electrolyzer; Anion Exchange Membrane (AEM) Electrolyzer; Alkaline Water Electrolyzer; Green Hydrogen Production; Intermittent Renewables; Energy Storage; Water Electrolysis; Renewable Energy

INTRODUCTION

Renewable resources are becoming increasingly popular as the demand for green energy rises over fossil fuels. However, the energy that these resources, such as hydropower, solar power, and wind power, produce must be stored for long-term use. One method for storing this excess energy is to use it to produce hydrogen. The United States Government has invested over seven billion dollars in hydrogen development and infrastructure due to its potential in green energy storage applications (1).

Currently, hydrogen production can be mainly classified into three categories- green (renewable energy-based), blue (coal gasification and natural gas/steam

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reformation-based with carbon capture technology), and grey (coal gasification and natural gas/steam reformation-based) (2). As shown in Figure 1, blue and grey hydrogen produced through steam methane reformation (SMR) and autothermal reformation (ATR) are responsible for over 95% of hydrogen production. Still, because blue and grey hydrogen are produced using fossil fuels, they yield high carbon dioxide emissions, a greenhouse gas contributing to global warming. Despite blue hydrogen utilizing carbon capture technology, it involves using methane, a climate pollutant with a high global warming potential, which decreases its overall environmental sustainability (3) (4). Green hydrogen, however, utilizes energy created by renewable resources and should be the main focus of future hydrogen production because of its minimal carbon intensity, despite making up less than 1% of 2022's hydrogen production (Figure 1).

Green hydrogen can be produced using electrolyzers integrated with renewable energy resources. Electrolyzers do not output carbon dioxide, making them a cleaner alternative among hydrogen production processes. The energy required to run an electrolyzer can come from renewable sources, making the overall process environmentally friendly. Electrolyzers use electricity to split water (H2O) into hydrogen (H2) and Oxygen (½ O2). This hydrogen can then be used for many purposes, but can also be converted back to electricity (6). Green hydrogen produced by electrolyzers powered by renewable resources creates an environmentally sustainable cycle that solves the energy storage problem for excess energy from renewable resources.

This paper will cover the potential of electrolyzers to be integrated with renewable energy resources; it will discuss the function of PEM, AEM, and alkaline electrolyzers, comparing them against each other under several criteria such as safety, durability, and cost, and provide the ideal situation for each electrolyzer to be used in and suggestions for further research to improve these technologies.

ELECTROLYZER UTILIZATION

Electrolyzers have many applications within society because of the green hydrogen they can produce. As shown in Figure 2, there are many ways of producing and utilizing hydrogen. Some areas where electrolyzers can bring about environmentally conscious changes include balancing the energy grid, storing energy, decarbonizing industry, green transportation, and distributed hydrogen production (Figure 2).

Grid Balancing and Energy Storage

There have been many recent advances in renewable energy technology, enabling a greater extraction of energy from these resources. However, as our resources have grown, excess energy produced from intermittent resources has as well, creating moments of excess that the grid cannot handle and deficits of energy, resulting in an unbalanced energy grid (8). Sources such as wind and solar power are highly intermittent, producing significant amounts of energy under one condition and virtually none during another condition, because of their dependence on weather conditions, but are expected to make up a

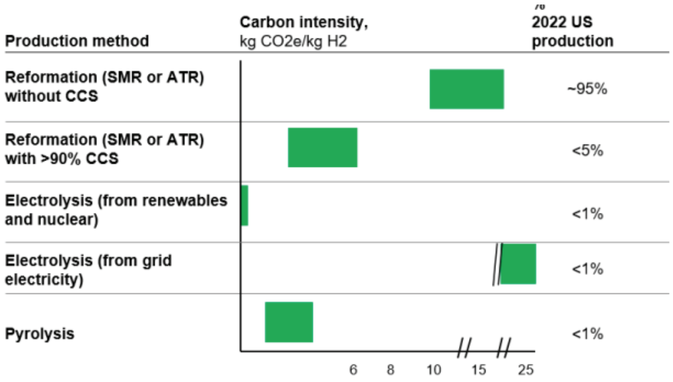

Figure 1. Percentage of hydrogen produced by different hydrogen production methods and the carbon output of each method. Figure credited to the U.S Department of Energy, 2023 (5).

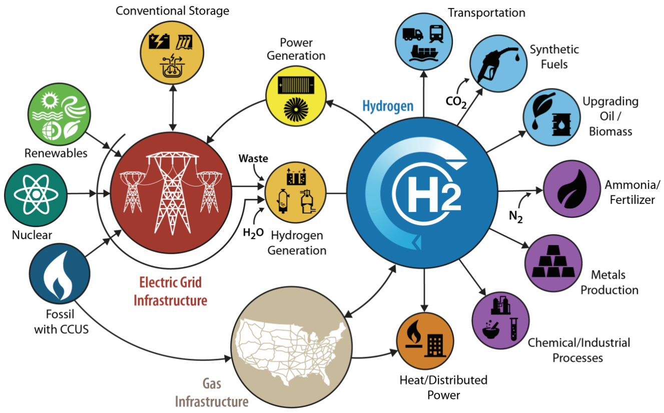

Figure 2. Mapping of different hydrogen production methods and their uses. Figure credited to the U.S Department of Energy, n.d. (7).

significant portion of energy demand in the future (9). Coupling electrolyzers with renewable resources in times of excess energy can help balance the grid by utilizing the excess energy to create hydrogen. This hydrogen may then be converted to electricity and fed back into the grid in times of low supply and high demand, or it can be used as fuel for fuel cells or powering factories (10). A benefit of hydrogen as opposed to other forms of renewable energy storage, such as batteries, is that hydrogen can be stored for long periods without degrading (11). Electricity used to create hydrogen can also be supplied by nonintermittent renewable resources as the shift is made from fossil fuels to renewable sources, making hydrogen an optimal solution for future energy storage needs.

Decarbonizing Industry

Many industrial processes, such as iron and steelmaking, chemical production, petroleum refining, and ammonia synthesis, require high amounts of energy; this energy is provided through non-renewable resources such as fossil fuels. Combusted fossil fuels contribute to greenhouse gases and carbon dioxide emissions (12). In fact, the industry sector contributes to over 30% of greenhouse gas emissions in the United States, making it one of the top three contributors to CO2 emissions (13). An alternative to this would be hydrogen. While maintaining a similar level of efficiency, hydrogen proves to be a more environmentally friendly and flexible option compared to fossil fuels (14). Ideally, hydrogen, because it is produced by electricity, can be converted back into electricity using fuel cells, so it would provide power for factories in place of coal or natural gas, emitting high pollution levels. Green hydrogen can prevent over 80 gigatons of carbon dioxide from entering the air and reduce industrial carbon dioxide emissions by over 95% if it replaces traditional, polluting forms of energy production (15). Renewably sourced hydrogen can also substitute for hydrogen produced from current, polluting hydrogen production methods in industrial chemical processes, such as ammonia synthesis (16). Green hydrogen, as produced by electrolyzers utilizing renewable energy resources, can be integrated into industrial processes and be used in the production of numerous chemicals themselves, such as ammonia and methanol, to lower the overall carbon footprint of many industries compared to current methods and resources.

Transportation

Transportation contributes to over 29% of total greenhouse gas emissions in the United States, making it one of the top three contributors of greenhouse gases (13). The majority of current vehicles rely on fossil fuels to combust, but a significant negative side effect of this process is that it releases greenhouse gases in the form of air pollution. An alternative solution to powering vehicles would be using a hydrogen fuel cell instead of a combustion engine. In this technology, hydrogen is stored in a tank and flows into the fuel cell; the hydrogen then reacts with oxygen from the air and generates electricity to power the motors and move the vehicle. When this whole process occurs, it only releases heat and water as byproducts (17). Fuel cells, as opposed to combustion engines, are more efficient and quieter and travel farther with less energy due to the energy-dense properties of hydrogen compared to gasoline (18). Electrolyzers can provide the hydrogen required for fuel cells because of an electrolyzer's ability to create high-purity hydrogen, which enables fuel cells to operate at their peak performance and degrade at a slower rate. (19) Additionally, using an electrolyzer that converts energy from renewable resources ensures a green cycle from the start- extracting energy from renewable resources- to the finish- powering vehicles with a fuel cell that does not emit any greenhouse gases (20).

Distributed Hydrogen Production

Currently, hydrogen production is very centralized, and because of limited hydrogen transportation and distribution infrastructure, it is difficult and expensive to move large amounts of hydrogen (21). One way to combat the challenges of limited infrastructure is to utilize electrolyzers. Electrolyzers can range from small, appliance-sized equipment well suited for small-scale distributed hydrogen production to large-scale factories tied directly to the energy grid (22). Focusing on the smaller electrolyzers, utilizing this technology would allow hydrogen production to become more decentralized and would help reduce and potentially eliminate significant costs and dangers involved with transporting hydrogen over long distances (23). Delocalized hydrogen production would also enable local industries that utilize hydrogen and fuel cell-powered vehicles to gain easy access to hydrogen across the board, and areas with abundant renewable resources would also be able to directly transfer that energy gained into hydrogen.

ELECTROLYZER TECHNOLOGIES

Water electrolyzers use water, heat, and electricity to produce hydrogen and oxygen. They contain a positive and negative electrode — the anode and cathode, respectively. Two half-cell reactions make up the overall reaction. The cathode undergoes a hydrogen evolution reaction (HER) and oxidation, while the anode undergoes an oxygen evolution reaction (OER) and reduction. Both electrodes are separated by an electrolyte that allows electric current and ions to move between the two electrodes. They are also connected by an external circuit to allow electrons to move from the anode to the cathode. Overall, the cell equation is water (H_2O) → hydrogen (H_2) + oxygen (½ O_2) (24). This paper will discuss three different types of electrolyzers: proton-exchange membrane, anion-exchange membrane, and alkaline electrolyzers.

Proton Exchange Membrane Water Electrolysis

In proton-exchange membrane (PEM) water electrolyzers, a solid polymer electrolyte is the proton exchange membrane. As shown in Figure 3, in the anode, water (H_2O) is split into oxygen (½ O_2), protons ($2H^+$), and electrons ($2e^-$). The oxygen gets released while the protons travel through the membrane, and the electrons travel through an external circuit towards the cathode. In the cathode, the protons and electrons recombine to produce hydrogen (H_2), which is then released (19).

There are many advantages of PEM electrolyzers, making them a popular choice for hydrogen production. PEM electrolyzers have high efficiency rates, between 70%-80%. They also have a fast response time of less than 10 seconds when running and 5-10 minutes when turning on, allowing them to quickly adjust for changes in hydrogen demand (26). PEM electrolyzers are suitable for areas in high demand because they are smaller and more compact compared to other electrolyzers. They also operate at relatively lower temperatures, between 5°C and 80°C, lowering their operation costs. One of the most important aspects of PEM electrolyzers is that they produce high-purity hydrogen. With a purity of around 99.9995% and the main impurity being water vapor, the hydrogen produced from PEM electrolyzers helps increase efficiency in industrial processes when used (27).

Despite the many advantages of PEM electrolyzers, there are some limitations. They are only capable of producing very limited amounts of hydrogen, making them unsuitable for large-scale hydrogen production. PEM electrolyzers are expensive to produce, purchase, install, and maintain, partly because they rely on rare-earth precious metal catalysts such as iridium and platinum, which lowers their cost-efficiency in the long run due to the need to replace the catalysts (27).

Anion Exchange Membrane Water Electrolysis

In an anion exchange membrane (AEM) electrolyzer, the electrodes are separated by a membrane that allows negatively charged ions, called anions, to move from the cathode to the anode. As shown in Figure 4, in the cathode, water ($4H_2O$) is reduced to produce hydrogen ($2H_2$) and hydroxyl ions ($4OH^-$) using electrons ($4e^-$). The hydroxyl ions travel through the AEM towards the anode. There, the hydroxyl ions recombine to form water ($2H_2O$) and oxygen (O_2) by losing electrons ($4e^-$) (28).

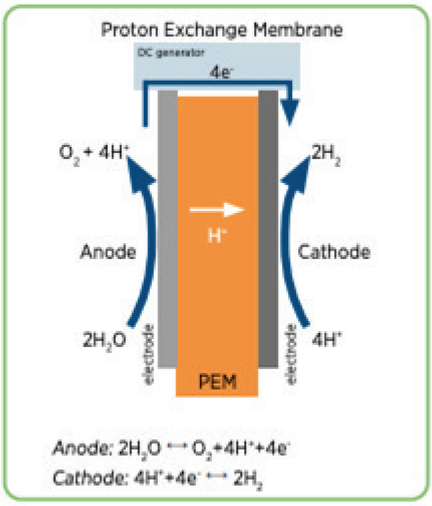

Figure 3. Diagram of a proton-exchange membrane electrolyzer cell with half-cell reactions. Figure credited to the International Renewable Energy Agency, 2020 (25).

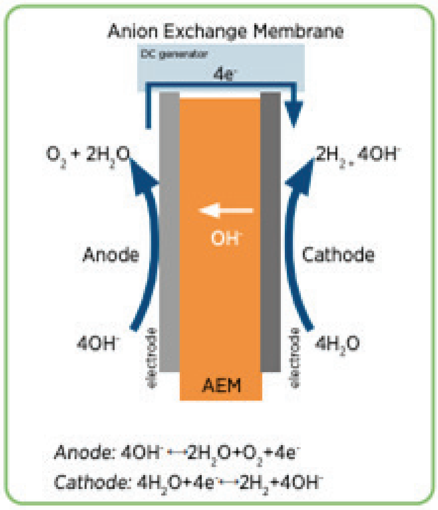

Figure 4. Diagram of anion exchange membrane electrolyzer cell with half-cell reactions. Figure credited to the International Renewable Energy Agency, 2020 (25).

Despite being a relatively new technology, there are foreseeable advantages to AEM electrolyzers. AEM electrolyzers can use cost-effective catalysts such as nickel rather than the noble metals required in PEM electrolyzers, which makes them promising in the long term (29). AEM electrolyzers also produce high-purity hydrogen of 99.9-99.999%, making them suitable for many applications (24).

Because AEM electrolyzers are a relatively new technology and are still under research, several drawbacks are being investigated. Due to their limited durability, AEM electrolyzers must be operated at a lower temperature range of 40-60°C, which creates lower efficiencies of 50-60% within the cell (24). This means that the durability and stability of AEM electrolyzers must be improved to maintain efficient performance in the long run. Currently, AEMs have lower ionic conductivity and face challenges with chemical stability, which can degrade the optimized performance of the technology over time and must be improved before being used on an industrial scale (29).

Alkaline Water Electrolysis

In alkaline electrolyzers, two electrodes sit in an alkaline solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH) with a concentration of 25-30%. They are separated by a diaphragm, which is a porous barrier that separates the anode and cathode and prevents their products from mixing. As shown in Figure 5, in the cathode, water ($2H_2O$) and electrons ($2e^-$) are split into hydrogen (H_2) and hydroxide ions ($2OH^-$). The hydroxide ions then travel through the porous diaphragm under the influence of an electric circuit to the anode. Here, in the anode, the hydroxide ions become water (H_2O), oxygen (½ O_2), and electrons ($2e^-$) (30).

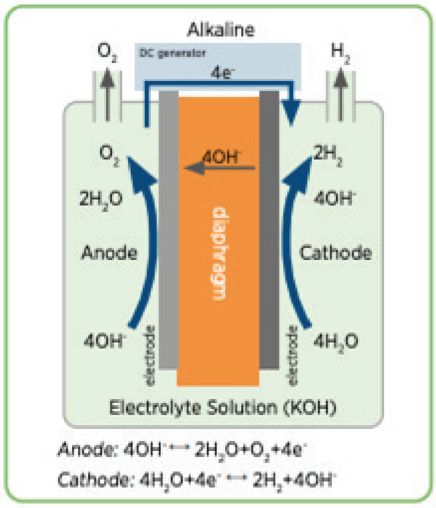

Figure 5. Diagram of alkaline water electrolyzer cell with half-cell reactions. Figure credited to the International Renewable Energy Agency, 2020 (25).

Alkaline electrolyzers have several advantages and are more mature compared to other electrolyzers, establishing them as a more prominently used technology. Alkaline electrolyzers can use non-rare-earth metals such as nickel as catalysts, which reduces the long-term costs of these electrolyzers. They can also produce large quantities of hydrogen, which makes them suitable for industrial hydrogen production purposes. Alkaline electrolyzers have a higher tolerance for impurities and still operate effectively (27).

Despite being a long-used technology, alkaline electrolyzers have their limitations. Alkaline electrolyzers have lower efficiencies of about 60-75%. The alkaline solution present in the electrolyzer is also corrosive, which can increase maintenance costs for electrolyzer parts in the long run. While not on the same level as PEM electrolyzers, alkaline electrolyzers produce 99.98% pure hydrogen, with the impurities being water vapor and some corrosive gases (27). They can also experience a crossover of gases and have a slower response time of 1-5 minutes when already running and 1-2 hours when starting up (26). Alkaline electrolyzers also have lower current densities, so they require large systems to make up for the lower power densities (24).

Applicability of Electrolyzer Technologies to Meet Integration

The electrolyzer with the largest scale of use is currently the alkaline water electrolyzer. It has been the most commercialized and has been used in many industrial applications such as ammonia synthesis and the chloro-alkaline process for the production of chlorine since the early 1900s (31). Currently, only 4% of global hydrogen is produced by electrolyzers as green hydrogen (19). Of this 4%, 58% of the hydrogen produced by electrolyzers is produced by alkaline water electrolysis, totaling about 11.6 billion cubic meters of hydrogen produced by alkaline water electrolyzers each year (32). Alkaline electrolyzers, while currently prominent, are less suitable for integration with renewable sources due to challenges in handling dynamic operations.

Many renewable resources are intermittent, meaning they are not always available or predictable. This subjects them to variable energy outputs depending on the conditions they are in. Intermittent renewable resources include solar, wind, wave, and tidal. Solar energy relies on the sun to generate power, so when it is dark or cloudy, power generation drastically decreases and fluctuates as shown in Figure 6a. Wind power similarly fluctuates throughout the day as shown in Figure 6b. Wave power relies on the winds' interaction with water, so the power output will be variable based on the strength of the waves. Finally, while tidal power is predictable on a day-to-day basis, its output varies throughout the day based on the movement of the tides. All of these renewable resources either produce different power output levels throughout the day or are unpredictable and condition-dependent, making them intermittent rather than constant sources. As shown in Figures 6a and 6b, solar energy does not have a constant power output throughout the day and fluctuates on cloudy days, and wind speed changes throughout the day, causing differences in power generation. Electrolyzers powered by intermittent renewables must be dynamic and able to handle the fluctuations that they experience.

Even though alkaline water electrolyzers have been the popular choice for hydrogen production via electrolyzers so far, they are not suitable for intermittent renewable resources. Alkaline water electrolyzers are not dynamic, meaning they struggle to adjust their hydrogen production rate rapidly, taking a long time to ramp up and down when faced with changes or fluctuations in the electricity supply. Because of the size of alkaline water electrolyzers, with medium-sized systems around 9.4 × 5.8 × 2 m, they take longer to heat up and cool down, making efficient load changes difficult (36) (37). Additionally, the slow process of ramping up and down can create safety hazards because

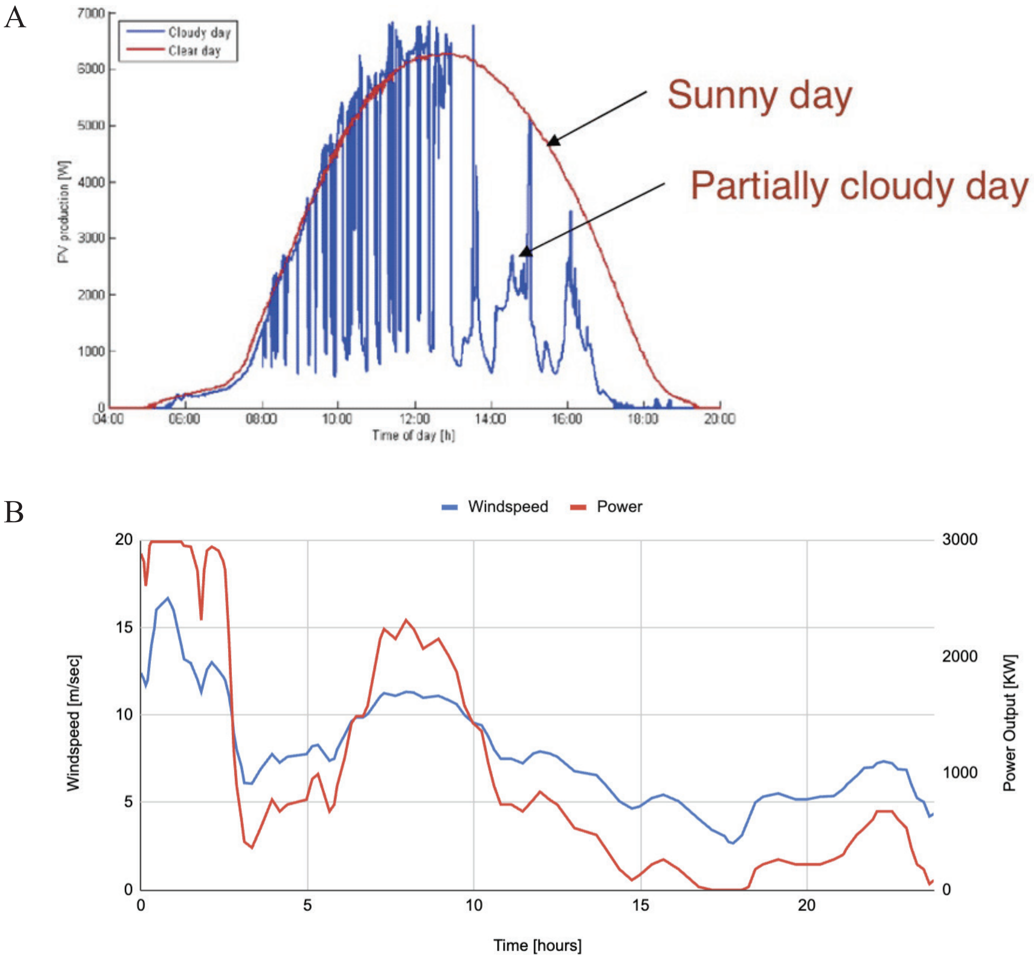

Figure 6. A) Line graph showing time vs power output of solar energy under different weather conditions. Figure credited to Lahaye et al., 2012 (33), with permission from TU Delft. **B)** Dual y-axis graph showcasing time vs windspeed and time vs power output of wind energy. Figure credited to Lebsir et al., 2015 (34) and Shaltout et al, 2012 (35), with permission from ASME.

of the delayed gas separation coupled with pressure imbalances. Because the alkaline electrolyzer has a porous gas separator, this can result in gas crossover between the two sides of the diaphragm under low current densities, creating explosive mixtures within the electrolyzer (38).

For many reasons, PEM and AEM electrolyzers are more suitable for intermittent renewable resources. Because of their smaller sizes, they can ramp up and down efficiently and adjust to load changes better. Electrolytes in the cathode of alkaline electrolytes are saturated with dissolved hydrogen. When electrolyte from the cathode and anode is mixed and recycled to the cell, the electrolyte fed to the anode, where oxygen is produced, has appreciable dissolved hydrogen, creating safety concerns like flammability risks, particularly at low current densities. The content of hydrogen gas present in the electrolyte at different operational current densities creates flammability hazards within the cell. Alkaline electrolyzers are generally run where the electrolyte gets mixed between the anode and the cathode. At the same time, PEM generally has higher rates of hydrogen crossover between the cathode and the anode because of its thin membrane. The alkaline electrolyzer experiences higher rates of hydrogen crossover under lower current densities when operating under high pressure to produce high-pressure hydrogen (39). This means that when alkaline electrolyzers are experiencing lower current densities from periods of low power production from intermittent renewable resources, producing high-pressure hydrogen will involve a high crossover rate between gases, posing many safety risks.

Because of the size of alkaline electrolyzers, they also take a long time to heat up and cool down. This means that under periods of intermittency when there are fluctuating current densities, the alkaline electrolyzer will not be able to change in temperature fast enough to efficiently produce hydrogen (40). Because PEM and AEM electrolyzers are much smaller, they can quickly adapt to this change in current densities and heat up and cool down faster. AEM electrolyzers run under a wider variety of current densities, encompassing the current density ranges of the PEM and alkaline electrolyzers, allowing them to operate efficiently under periods of high and low energy production from intermittent renewables, as shown in Table 1.

While still sparse, some places are already utilizing PEM electrolyzers powered by renewables for hydrogen production. For example, a PEM electrolyzer in Canada is powered by renewables and produces over 8.2 tons of green hydrogen a day (41). For now, AEM electrolyzers have been mostly limited to research facilities due to their novel nature, but many companies are partnering with manufacturers to begin implementing AEM electrolyzers on the industrial level (42).

LIMITATIONS AND FUTURE DIRECTIONS

While each electrolyzer has its benefits, some characteristics need to be improved for them to be optimally integrated with renewable resources. Alkaline electrolyzers are well established, but they lack safety features for integration with intermittent

Table 1. Comparison of operational characteristics in PEM, AEM, and alkaline electrolyzers

	Alkaline	**AEM**	**PEM**
Developmental Stage	Mature	R&D	Commercialized
Lifetime (Stack)	60,000 h	>30,000 h	50,000-80,000 h
Electrode Area	10,000-30,000 cm^2	<300 cm^2	1500 cm^2
Operating Temperature	70-90°C	40-60°C	50-80°C
Current Density	0.2-0.8 A/cm^2	0.2-2 A/cm^2	1-2 A/cm^2
Voltage Range	1.4-3 V	1.4-2.0 V	1.4-2.5 V
Efficiency	50%-78%	57%-59%	50%-83%
Cell Pressure	<30 bar	<35 bar	<70 bar
H2 Purity	99.5-99.9998%	99.9-99.9999%	99.9-99.9999%
Capital Costs (Stack) Minimum 1 MW	$270/kW	Unknown	$400/kW

Table adapted from Kumar & Lim, 2022 (24).

renewable resources. PEM electrolyzers are efficient and relatively new, but they are very costly due to the materials, especially the catalysts, that they require. AEM electrolyzers are a very novel technology with lots of promise for adaptability, but preliminary testing has shown that they lack the durability needed to sustain for a long time. Currently, research is being conducted on improving these aspects of these electrolyzers to facilitate safe, cost-effective electrolysis from renewable resources.

For alkaline electrolyzers, research is being conducted to manually control the temperature and pressure of the electrolyzer. Being able to efficiently control the temperature of the electrolyzer will help reduce the time it takes to ramp up and down, helping the alkaline electrolyzer quickly adapt to fluctuations in power in a safer manner (43). Additionally, being able to control the pressure will allow for higher-purity hydrogen to be efficiently produced while minimizing gas crossover during periods where low current densities are present (44).

PEM electrolyzers show lots of promise for intermittent renewable energy integration. However, they are very costly due to the expensive nature of their platinum and iridium catalysts. Many researchers are looking at cheaper alternatives for this rare earth metal. Some promising catalysts include iron, nickel, cobalt phosphide, and some carbon-based catalysts (45). However, the main challenge with these catalysts is that they degrade at a faster rate than platinum, resulting in frequent replacement and driving up costs. Researchers and industry will need to find the correct balance between cost and efficiency (46).

Due to its novelty, researchers have been working to optimize the AEM electrolyzer for large-scale applications. One of the main drawbacks of this technology is its long-term durability. To improve the durability of AEM electrolyzers, researchers are looking into several factors that influence this, such as catalyst stability and membrane robustness. The catalysts within AEM electrolyzers corrode easily and affect the stability and function of the cell. Ways to improve catalyst stability and increase corrosion resistance include forming protective layers on the surface of the catalyst while using strong adhesion between the membrane, catalyst, and electrode to reduce degradation (47).

CONCLUSION

Electrolyzers offer a promising solution for sustainable hydrogen production, enabling the efficient storage of renewable energy and supporting the transition to a low-carbon economy. The government has been working to implement financial incentives and tax credits for hydrogen produced by electrolysis, along with frameworks and support programs to unify hydrogen and electrolysis standards across the country (48). These overarching actions will continue to facilitate the growth of green hydrogen from water electrolysis on a higher level as improvements to the technologies themselves are made. While each type of electrolyzer- PEM, AEM, and Alkaline- has unique advantages and limitations, their integration with renewable energy resources can address challenges in energy storage, grid balancing, industrial decarbonization, transportation, and distributed hydrogen production.

Alkaline electrolyzers, the most mature technology, excel in large-scale hydrogen production but struggle with intermittent renewable sources due to their slower response times and safety hazards under periods of lower energy production, making them better suited for continuous resources like geothermal or hydroelectric power. On the other hand, PEM and AEM electrolyzers are better suited for dynamic operation because of their safer and more compact nature, allowing them to efficiently change hydrogen production, making them ideal for coupling with intermittent renewables. Continued research and development are needed to enhance the performance, durability, and cost-effectiveness of AEM and PEM electrolyzers while reducing reliance on rare earth metals. Such research and government action will better enable widespread adoption of green hydrogen production to facilitate a cleaner, more resilient energy future, where hydrogen can play a central role in meeting the world's energy demands sustainably.

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DECLARATION OF CONFLICT OF INTEREST

The author declares that there are no conflicts of interest regarding the publication of this article.

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