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TECHNOLOGY BRIEF

WATER ELECTROLYZER STACK DEGRADATION

THE RESEARCH FRAMING

Electrolysis technology improvements have significantly decreased the stack degradation in the past decade, but more research is needed to understand the effect of dynamic operation on stack degradation, as well as the effect of future electrolyzer cost reduction approaches on system durability.

THE VALUE

Green hydrogen produced by electrolysis with renewables has the potential to be a vital player in economy-wide decarbonization. This potential is dependent upon the capability of electrolysis systems to durably couple with intermittent power sources.

LCRI'S FOCUS

LCRI is performing research to understand the state-of-the-art operational efficiency and durability of electrolysis cells and stacks, developing deployment and operational strategies for energy resource considerations.

INTRODUCTION

This white paper summarizes the importance of water electrolyzer stack degradation and highlights uncertainties and knowledge gaps around the effect of operation on stack lifetime during baseload and dynamic hydrogen production. The paper also summarizes the possible tradeoffs between system durability and stack capital cost reduction, as well as research needs. The objective of this paper is to provide a high-level overview of the current state of knowledge and research on electrolyzer stack degradation and provide thought leadership suggestions on required future steps.

Future deployment of hydrogen production via electrolysis depends heavily on total hydrogen production cost. Currently, other hydrogen production processes (e.g., steam methane reforming) are considerably lower cost compared to electrolysis. Techno-economic assessments on hydrogen production via electrolysis show that the major cost contribution is the total cost of electricity used over the lifetime of the process. Large deployment of renewables is predicted to reduce the cost of electricity. Electrolyzer vendors have significantly improved electrolyzer efficiency in the last decade, resulting in less total electricity use.

However, efficiency reduction over the stack lifetime due to stack degradation is an important area that requires further study [1,2].

Electrolyzer stack lifetime also significantly affects the cost of hydrogen production. The current expected lifetime of 7–10 years—which equates to 60,000–80,000 hours of operation—is projected for both proton exchanging membrane (PEM) and alkaline electrolyzers, with alkaline electrolyzers offering a longer lifetime. Since the stack lifetime is much shorter than the predicted electrolysis plant lifetime of 20 to 40 years, multiple stack replacements are commonly planned during the plant life. Efficiency loss due to stack degradation primarily determines stack lifetime and replacement intervals. The cost of these replacements is 35–45% of the total system capital cost [3]. Historically, electrolyzers are preferred to be operated continuously, and today's electrolyzer stack lifetime is mainly projected for continuous baseload operation. However, studies have shown that flexible operation may lead to shorter stack lifetime. Additionally, flexible operation may decrease operating hours over a given year and may change the timelines on which stack replacements are required. Therefore, flexible operation may lead to more or less frequent stack replacement compared to baseload continuous operation.

To move towards low-cost hydrogen produced via electrolyzers, vendors are taking a variety of approaches to reduce the electrolyzer capital cost. Investigation on system performance impacts of these cost reduction pathways and how they affect stack degradation and stack life is needed.

WHAT IS STACK DEGRADATION?

Stack degradation is measured by a drop in stack efficiency over time. Stack efficiency is reported as kWh/kg H_2, which is calculated using the DC power requirement of the stack to produce one kilogram of hydrogen. Various stack degradation mechanisms can occur during the lifetime of the stack, which increase the power requirement for producing hydrogen. Table 1 lists some of the possible stack degradation mechanisms for alkaline and PEM electrolyzers.

Information collected in a recent EPRI study from industry manufacturers reports that mature alkaline electrolyzer stacks experience 1% annual performance loss in continuous baseload operation. PEM electrolyzers experience 1–1.5% degradation per year at baseload operation [9].

Although most reported stack lifetime data is for continuous baseload operation, manufacturers may establish operation limits or parameters based on the type of operation. Table 2 lists examples of commercial system limitations and considerations with regard to degradation found in the literature.

The electrolyzer system is also highly sensitive to impurities and contamination. In 2016, Proton Onsite (acquired by Nel) reported that during six years of performance, 81% of cell reliability issues were due to customer contamination—mainly water contamination [10].

Table 1. Possible stack degradation mechanisms for PEM and alkaline electrolyzers [4–8]

PEM Electrolyzers	Alkaline Electrolyzers
• Catalyst accumulation, poisoning and/or dilution	• Trapping of product gas bubbles
• Membrane mechanical failure	• Nickel deactivation at cathode by hydrogen permeation
• Membrane degradation, poisoning or decomposition	• Changes in the nickel oxide layer (anode)
• Hotspots	• Catalyst deactivation
• Corrosion	

Table 2. Examples of electrolyzers' operation limitations

Company/Electrolyzer Technology	Operation Limitation
IHT/Alkaline	4–6 hour shut down will not lead to pressure and temperature loss and will not cause operating life loss [11]
Hydrogenic (Cummins)/Alkaline	Electrolyzer start-ups and shutdowns should not exceed 5000 [12]
AccaGen/Alkaline	Frequent on/off operation results in corrosion [11]

EFFECTS OF OPERATION ON STACK DEGRADATION

With increases in renewable energy deployment and consequent power curtailments, electrolyzers need to operate dynamically to take advantage of the lower electricity cost. Some manufacturers have advertised PEM electrolyzers as a flexible electrolyzer technology that can be coupled with intermittent power sources. This is achievable because the high ion conductivity of the PEM enables rapid ramp-up and ramp-down, and the low hydrogen permeability of the membrane enables operation in the range of 5%–120% of nominal design capacity [13].

On the other hand, alkaline electrolyzers operate with lower ion conductivity, which traditionally results in a lower response rate to fluctuating power. While recent technology advancement now enables the newer generation of alkaline electrolyzers to offer a comparable response rate to PEM electrolyzers, increased hydrogen crossover from the cathode side to the anode in alkaline electrolyzer stacks limits low-capacity minimum safe operating loads to be 10–40% of the nominal load (Table 3) [14,15].

Even though PEM electrolyzers are considered a flexible technology that can be coupled directly with renewable power sources, the effect of such operation on system durability needs to be considered. Various studies have focused on developing accelerated stress tests (ASTs) to understand the long-term effect of coupling PEM electrolyzers with intermittent power sources. These ASTs often involve cycling the electrolyzer cell/stack between constant currents or constant voltages [16].

Currently, there is no standard AST, and the results vary from one case to another. A National Renewable Energy Laboratory study showed that the rate, frequency, and severity of these AST conditions lead to various degrees of degradation [2]. Depending on the AST protocols used, various degradation mechanisms (e.g., electrode degradation, and membrane poisoning, thinning, and corrosion, etc.) can also occur [17]. Stack design, materials, and manufacturing methods used to prepare stack components also affect the electrolyzer durability. Similar considerations apply to alkaline electrolyzers, and the degree of degradation and degradation mechanism for

Table 3. Comparison of dynamic operating capabilities of electrolyzers

Electrolyzer Technology	Design Features that Facilitate Dynamic Operation	Dynamic Operating Limitations
PEM	• High ion conductivity of the PEM • Low H_2 permeability of the membrane	• Stack degradation due to voltage fluctuation
Alkaline	• Advanced electrolyzer cell design (e.g., zero gap) • New or improved separators to improve ion conductivity and reduce cell resistance	• Low ion conductivity that leads to a lower response rate • High hydrogen crossover potential at low-capacity factor • Stack degradation due to voltage fluctuation

these systems are a function of the nature and severity of the power fluctuations [18]. Another potential limitation of these stack degradation studies is that many of them have been performed on small-scale and single-cell or half-cell electrolyzers, which may not fully capture the degradation phenomena for commercial systems.

STACK COST REDUCTION AND DEGRADATION

In addition to using future low-cost renewable electricity, reducing stack capital cost is another approach to lower the total cost of hydrogen production. However, for any cost reduction approach, its effect on stack degradation needs to be considered. This section summarizes some of the common approaches used in the alkaline and PEM electrolyzer industry to reduce the stack capital cost.

Increasing Current Density

Current density is the current applied to the cell divided by the active area, which is the area of the membrane between the cathode and anode electrodes where the electrochemical reaction occurs. Since the applied current directly regulates the hydrogen output of the system, increasing current density leads to a more compact system at a similar production rate and significant reduction in the total cost of stack materials.

Today's alkaline water electrolyzers operate at a 0.2–0.8 A/cm^2 current density, which is lower than the 1–2 A/cm^2 for PEM electrolyzers [13]. The lower current density for alkaline electrolyzers is the result of lower membrane and electrolyte ion conductivity, lower electrode activity, and the lower mobility of hydroxyl ions (OH^-) compared to hydrogen ions (H^+).

Increasing the current density can significantly decrease the stack capital cost, especially for PEM electrolyzers, because it reduces the total amount of precious metal used per production unit. However, with the current catalysts and cell design, increasing current density reduces the cell efficiency. In addition, since hydrogen is produced at twice the rate of oxygen, a higher current density causes the membrane to experience a larger differential pressure, which increases the chance of hydrogen crossover. Improving the stack design, employing more active catalysts, and using more robust membranes are research approaches to increase the electrolyzer current density without sacrificing system efficiency and durability.

Operating at Elevated Temperature and Pressure

PEM electrolyzers commonly operate at a temperature of 50–80°C and a pressure of up to 70 bar, and alkaline electrolyzers operate at slightly higher temperature of 70–90°C but a lower pressure of 1–30 bar [13]. A higher operating temperature can reduce the electrolyzer energy requirement to produce hydrogen but can also increase the rate of stack degradation due to material instability. Increasing the stack pressure can also reduce the cost of hydrogen compression associated with the plant but can increase the chance of hydrogen crossover and stack degradation.

Reducing the Amount of Precious Metal Used in PEM Electrolyzers

Reducing the amount of precious metal used in PEM electrolyzers is typically one of the major cost reduction approaches for PEM electrolyzer manufacturers. Today, many commercial PEM electrolyzers are overengineered with regard to materials used [19]. Therefore, reducing the amount of precious metal used for the electrolyzer stack is targeted for new generations of PEM electrolyzers. However, some studies have shown that decreasing the amount of precious metals used in the PEM electrolyzer may increase the rate of stack degradation [20,21].

In addition, the effect of each cost reduction pathway on the system's ability to efficiently and reliably couple with intermittent power sources needs to be investigated. For instance, one study showed that PEM cells with a lower content of iridium in the anode are more vulnerable to power fluctuations and experienced a higher degree of degradation during accelerated testing [2].

Table 4 summarizes possible durability challenges due to cost reduction approaches for PEM and alkaline electrolyzers.

Table 4. Durability challenges of cost reduction approaches for electrolyzers

Cost Reduction Approach	Benefit	Durability/Performance Challenge
Increasing current density	• Reductions in the total cost of stack materials	• Lower efficiency • Higher chance of hydrogen crossover due to increase in pressure differential
Operating at an elevated temperature	• Higher efficiency	• Higher degradation rate due to material instability
Operating at elevated pressure	• Reductions in the cost of hydrogen compression associated with the plant	• Increased chance of hydrogen crossover and stack degradation rate
Reducing the amount of precious metals used in PEM electrolyzer stacks	• Reductions in the cost of stack materials	• Lower efficiency • Higher degradation rate when coupled to intermittent power sources

SUMMARY AND FUTURE RESEARCH NEEDS

Low-carbon hydrogen has the potential to be a vital player in economy-wide decarbonization although this potential will not be fully realized until it can be produced efficiently, durably, and affordably. Lower-cost electricity and electrolyzer production scale-up can significantly decrease the cost of hydrogen production, but the effect of these cost reduction pathways on electrolyzer system durability needs to be examined. Current PEM and alkaline electrolyzer technologies have advanced significantly and are able to durably produce hydrogen at baseload conditions for up to 80,000 hours of operation. However, the ability of these systems to durably operate with intermittent power sources requires more investigation. To further understand and evaluate the durability of new generation electrolyzers, research is needed to:

- Develop standardized AST procedures for electrolyzers that closely mimic the intermittency of renewable power profiles
- Evaluate the stack degradation of larger commercial stack sizes
- Evaluate the effect of cost reduction pathways on stack degradation

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