Technical report – Hydrogen Innovation Initiative

Wind turbine - electrolyser literature review

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Date: 14/01/2025

In partnership with:

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DOCUMENT HISTORY

Revision	Date	Prepared by	Checked by	Approved by	Revision History
Rev 1					
Draft 1	10/01/25	Michael Walsh	Shahrouz Nayesbossadri		
Draft 2					

Field	**Detail**
Report Title	
Status	
Document Reference	

1.1 Introduction

The transition to renewable energy sources is a critical step in addressing global climate change and reducing dependence on fossil fuels. Among the various renewable energy technologies, offshore wind power has emerged as a promising solution due to its high energy yield and minimal land use. However, the intermittent nature of wind power poses challenges for its integration into the energy grid. One innovative approach to mitigate this issue is the direct integration of electrolyser technologies with offshore wind turbines to produce green hydrogen.

Electrolysis is a process that uses electrical energy to split water into hydrogen and oxygen. When powered by renewable energy sources, such as wind or solar, this process produces green hydrogen, a clean and sustainable fuel. Green hydrogen has the potential to play a significant role in decarbonising various sectors, including transportation, industry, and energy storage.

The integration of electrolysers with offshore wind turbines offers several advantages. It provides a means to store excess wind energy in the form of hydrogen, which can be used when wind power generation is low, or demand is high. This integration can enhance the overall efficiency and reliability of renewable energy systems. However, the direct coupling of electrolysers with wind turbines introduces technical challenges, particularly related to the variable and intermittent nature of wind power.

To better understand the integration challenges that restrict the immediate rollout of wind turbine-electrolyser systems we have completed a literature review of existing and proposed industry projects, electrolyser technologies and their feasibility/limitations when deployed directly with wind turbines. Following the review, it was deemed that one of the most significant risks associated with direct electrolyser integration is the degradation of electrolysers when operated under variable power conditions. Electrolysers are typically designed to operate under steady-state conditions, and frequent power fluctuations can lead to accelerated wear, decreased system efficiency and reduced lifespan. Understanding the degradation mechanisms of different electrolyser types under variable power conditions is crucial for developing robust and reliable systems.

A second literature review was conducted to investigate the failure modes and degradation mechanics of various electrolyser technologies, including Alkaline (AEL), Proton Exchange Membrane (PEM), and Solid Oxide Electrolysers (SOEC). The findings from this review highlight the susceptibility of each electrolyser type to different degradation pathways when subjected to variable power inputs.

In addition to the literature review, a model was developed to analyse wind power data and assess the frequency and duration of accelerated power ramping events. This model aims to provide insights into the operational challenges and potential mitigation strategies for electrolysers directly coupled with wind turbines. A description of the model and some of the key results will be summarised in a separate technical report titled ‘Technical report – Hydrogen Innovation Initiative: Wind turbine - electrolyser power variance model analysis’.

1.2 Literature review of electrolyser-turbine projects, technologies and their feasibility

From the research conducted it is clear that hydrogen production from wind power is being seriously considered in industry today with demonstration systems planned for the coming years. There is not currently any consensus as to the exact role hydrogen will play in these systems. Some demonstrations focus on purely balancing wind turbine output using hydrogen electrolysis. Others are interested in creating systems with no grid connection at all and purely producing hydrogen. Some pursue a hybrid approach of selling power when demand and price is high and switching to hydrogen generation when demand is low.

For all of these approaches there are several sub-system arrangements to be explored, such as wind farm scale vs. turbine scale systems, energy storage system requirements and technology selection for a chemistry that copes with the demands of wind power best. AEL , PEM and Anion Exchange Membrane (AEM) technologies are all potential candidates.

From a technological perspective PEM and AEM systems are advised for direct integration with renewables due to their accelerated response time when compared with AEL technologies. Accelerated response times facilitate direct load following and subsequently improve the total (turbine-electrolyser) system efficiency by reducing the amount of unused power generated while the electrolyser responds to power variations. However, although there is a mature presence of hydrogen electrolysers on the market for use in hydrogen production plants and even beginning to be marketed for solar powered hydrogen farms - no commercial system today is specifically designed or verified for use with wind power.

Although the focus of this study was to assess the feasibility of direct integration with wind turbines. Several alternative layouts can be considered, typically described as on-shore and off-shore centralised layouts. In each case the electrolyser capacity serving an entire wind farm will be located in one central location. This design has many benefits when compared with the decentralised or direct integration considered, such as easier access for on-going maintenance and power control schemes that leverage the granularity of a whole fleet of systems to reduce power losses and the impact of degradation. Conversely, a centralised design requires a larger initial investment, has a greater complexity and limits the learning rate cost reduction associated with multiple smaller systems.

Creating high-level performance models of different electrolyser technologies for wind would enable virtual testing of any number of system configurations. It would bring the ability to demonstrate if a system is economically beneficial today and later to test potential design improvements to new or existing systems in future. This review has identified degradation and system performance as a significant risk to the deployment of wind integrated electrolyser systems, and as such system models should aim to integrate degradation mechanics to accurately capture long-term performance.

1.3 Literature review of electrolyser technologies operation and degradation

The degradation within electrochemical system significantly influences their longevity, efficiency, and overall performance. Understanding these phenomena from an academic perspective, is crucial for the development of more durable and reliable technologies.

Failure Modes

Failure modes in water electrolysers vary based on electrolyser type, operational conditions, and environmental factors, impacting performance and efficiency. Key failure modes include electrode degradation due to electrochemical corrosion, catalyst poisoning, or mechanical damage, leading to loss of catalytic activity and compromised electrode integrity. Membrane failure, caused by chemical attack, mechanical stress, or ion contamination, results in increased resistance and reduced gas separation efficiency. Catalyst degradation at the electrode-electrolyte interface, due to dissolution, poisoning, or structural changes, impairs catalytic performance and hydrogen evolution kinetics. Gas crossover, caused by membrane defects or incomplete sealing, decreases product purity and electrolyser efficiency.

Failure Mechanisms

The primary failure mechanisms associated with electrolysers encompass electrochemical degradation, mechanical stress, membrane degradation, catalyst degradation, and gas crossover.

Electrochemical degradation arises from the harsh operating conditions within electrolysers, including high temperatures, acidic or alkaline environments, and high current densities. This degradation mechanism primarily affects electrode materials, leading to corrosion, dissolution, and loss of catalytic activity. The corrosion of electrode materials compromises their structural integrity and electrochemical performance, resulting in reduced electrolyser efficiency and lifespan.

Mechanical stress represents another significant failure mechanism in water electrolysers, particularly in PEM systems where mechanical forces exerted during operation can lead to membrane deformation, electrode delamination, and electrode-membrane detachment. Mechanical stress may result from thermal expansion and contraction, differential swelling of electrodes and membranes, and hydraulic pressure variations. These mechanical forces can cause irreversible damage to electrolyser components, impairing their functionality and compromising overall system performance. Additionally, mechanical stress-induced deformation can lead to reduced electrode-membrane contact area, hindering proton transport and exacerbating degradation.

Membrane degradation can occur due to chemical attack, mechanical stress, and electrochemical degradation, leading to reduced ion conductivity, increased gas crossover, and decreased membrane mechanical strength.

Catalyst degradation can occur due to catalyst dissolution, poisoning, and structural changes, leading to reduced catalytic activity and hydrogen evolution kinetics. Structural changes in catalyst particles, such as agglomeration, sintering, and particle growth, can also impair catalytic performance and efficiency.

Gas crossover may occur due to membrane defects, electrode-membrane gaps, and incomplete sealing of electrolyser components, allowing hydrogen and oxygen to mix and react internally. Gas crossover leads to loss of reactants, decreased Faradaic efficiency, and potential safety hazards, such as gas accumulation and explosion risks. Moreover, gas crossover exacerbates membrane degradation by exposing the membrane to oxidative species and reactive intermediates, accelerating degradation.

Mitigation Strategies

Effective mitigation strategies encompass various approaches, including material selection, operating condition optimization, design improvements, and proactive maintenance practices. By implementing these strategies, researchers and operators can mitigate degradation mechanisms and improve electrolyser performance and reliability.

Choosing materials with superior corrosion resistance, mechanical strength, and chemical stability is essential for enhancing electrolyser durability. For alkaline water electrolysers, materials such as nickel-based alloys, titanium, and stainless steel are commonly used for electrodes and current collectors due to their resistance to corrosion in alkaline environments. Additionally, selecting robust ion-conducting membranes and housing materials can help mitigate membrane degradation and structural damage, ensuring long-term electrolyser performance.

Operating condition optimisation is another critical mitigation strategy for addressing degradation in water electrolysers. By optimising parameters such as temperature, pressure, electrolyte concentration, and flow rate, researchers can minimise degradation mechanisms and improve electrolyser efficiency. For alkaline water electrolysers, optimising electrolyte pH and composition can mitigate electrode corrosion and catalyst degradation, while controlling temperature and pressure can reduce mechanical stress and membrane deformation.

Design improvements offer opportunities to enhance electrolyser durability and reliability. Incorporating features such as electrode coatings, membrane additives, flow field optimization, and electrode geometry modifications can mitigate degradation mechanisms and improve performance.

Proactive maintenance practices are essential for identifying and mitigating degradation in water electrolysers, ensuring optimal system performance and reliability over time. Regular inspection, cleaning, and component replacement can help prevent degradation from progressing and restore electrolyser performance. Monitoring operating parameters such as cell voltage, current density, and gas composition can provide early warning signs of degradation and facilitate timely intervention.

1.4 Conclusion

In conclusion, the integration of electrolyser technologies with offshore wind turbines presents a promising solution for addressing the intermittency of wind power and enhancing the efficiency and reliability of renewable energy systems. The production of green hydrogen through electrolysis, powered by wind energy, offers a sustainable and clean fuel alternative that can significantly contribute to the decarbonisation of various sectors. However, the direct coupling of electrolysers with wind turbines introduces technical challenges, particularly related to the variable and intermittent nature of wind power.

Our comprehensive literature review and subsequent analysis have identified the degradation of electrolysers under variable power conditions as a significant risk. Electrolysers, typically designed for steady-state operation, experience accelerated wear, decreased efficiency, and reduced lifespan when subjected to frequent power fluctuations. Understanding the degradation mechanisms of different electrolyser types under these conditions is crucial for developing robust and reliable systems.

Additionally, our research highlights the need for high-level performance models to virtually test various system configurations and assess their economic viability. These models should integrate degradation mechanics to accurately capture long-term performance and identify potential design improvements. While hydrogen production from wind power is gaining traction in the industry, with several demonstration systems planned, there is no consensus on the exact role hydrogen will play. Various approaches, including balancing wind turbine output, creating off-grid hydrogen production systems, and hybrid systems, are being explored.

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