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Comparison between different electrolysis technologies under varying conditions

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Abstract. The use of renewable hydrogen is becoming increasingly relevance as a sustainable alternative to conventional energy sources, particularly in the transport and industrial sectors. One of its main advantages is that it enables energy use without generating direct pollutant emissions, thus contributing to the reduction of greenhouse gases emissions and the mitigation of climate change. Green hydrogen in these sectors is typically produced through different electrolysis technologies. These processes are often powered by renewable energy sources—such as solar or wind—which are inherently variable over time.
This paper presents a comprehensive comparison of the main electrolysis technologies, including alkaline electrolysis (ALKEL), proton exchange membrane electrolysis (PEMWEL), and anion exchange membrane electrolysis (AEMWEL). It analyzes their respective advantages, limitations, efficiency levels, response times, and adaptability to intermittent energy supplies. The study also explores the technical challenges associated with integrating each technology with renewable power sources, emphasizing key factors to consider when selecting the most suitable method. It is important to note that this analysis does not take cost into account, focusing instead on technical parameters and operational performance. The objective is to provide insights that support informed decision-making for the deployment of hydrogen technologies within sustainable energy systems.

Key words. Renewable Hydrogen, electrolysis, AEMWEL, PEMWEL, AWEL.

1. Introduction

Hydrogen is expected to become one of the main pillars for the decarbonization of the European energy system, as it is widely considered the most promising option for reducing CO2 emissions in key sectors such as transport or industry [1]. In this context, the complementarity between energy carriers, particularly electricity and hydrogen, will play a key role in enhancing the capacity for integrating renewable energy sources, thereby enabling the development of a more flexible, resilient and low-carbon energy system [2][3].

In this scenario, to achieve the goal of a 100% renewable energy system by 2050, the production of hydrogen from renewable sources is seen as a key aspect of the roadmaps and development programs for these technologies in Europe and Spain [1]. Among the various methods available for producing renewable hydrogen, water electrolysis has emerged as the most viable and scalable option in the short-to-medium term, due to its technological maturity, compatibility with variable renewable generation, and potential for rapid deployment [4].

The integration of electrolyzers with renewable energy sources presents both a promising opportunity and a technical challenge. Renewable energy generation from wind and solar—currently most common sources—present high variability and intermittency, influenced by seasonal and meteorological factors [5, 6, 7]. This variability can lead to fluctuating electricity supply, which directly impacts the operational profile of electrolyzers. As such, electrolyzers must be designed to operate dynamically, adapting their performance to real-time changes in energy availability without compromising efficiency or system stability [8]. In this context, the successful integration of electrolyzers with renewable sources requires a comprehensive approach that considers energy storage, grid flexibility, and system balancing strategies to buffer fluctuations and ensure continuous operation, ultimately supporting the scalability and reliability of hydrogen as a clean energy vector.

This study aims to evaluate and compare the performance of different hydrogen production technologies under fluctuating renewable conditions and identify the key factors that must be considered in the selection, sizing and operational strategies of each technology, with particular attention to their technical feasibility, viability and suitability for integration with renewable energy sources.

2. Methodology

The Laboratory of the National Institute of Aerospace Technology (INTA)'s Renewable Energy Area in El Arenosillo (Huelva, Spain) provides facilities equipped with three different electrolysis technologies (PEM, AEM, and Alkaline) enabling the experimental evaluation of hydrogen production under controlled operating conditions. Below is a brief description of the technical specifications of each system:

1) PEM Technology: a Hiat electrolyzer model HYP40 is used. The system features a 1.36 kW electrochemical stack integrated into a balance of plant (BoP) designed for operation at a nominal pressure of 6 bar. Under standard conditions, the stack delivers a hydrogen production rate of 4 Nl/min at an operating current of 62 A.

2) AEM Technology. An Enapter electrolyzer system is currently under evaluation. The system is composed of the electrolyzer EL4.1 model, a water tank (model WT21), and a drying and purification unit (DRY21). This unit is capable of generating 500 Nl/h of high-purity hydrogen at pressures up to 35 bar, with a nominal power consumption of 2.4 kW.

3) Alkaline Technology. The Aquasef electrolyzer developed by Ariema Enerxía is a 5 kW unit operate within a current range of 130 to 235 A and produces between 500 and 860 Nml/h of hydrogen depending on the operating conditions.

To enable a comparative assessment of these three different electrolysis technologies, an experimental procedure has been designed. It consists of a polarization curve test. This protocol yields a set of common performance variables across all systems, facilitating a consistent basis for comparison. Key performance indicators (KPI) include current set point, voltage level, transient response characteristics (settling time and response time), operating temperature, BoP set-up time, and minimum operational power threshold.

The polarization curve is obtained by applying a sequence of constant current steps over defined time intervals. The current is increased step by step to the system's maximum rated current and then symmetrically decreased. Specifically, the test is structured in 10 A steps, each sustained for 10 minutes. The average value of the monitored variables within each step is recorded and used for performance analysis and comparisons. The test aims to characterize the operational efficiency of each electrolyzer under varying power input conditions.

The results from the polarization curve provide insights into the voltage-current relationship, energy consumption profile, and dynamic behavior of the systems. This information is essential for evaluating the compatibility of each technology with fluctuating renewable energy sources, such as photovoltaic or wind power systems.

In this paper, some KPIs are defined to assess every technical aspect.

- "Response time" is defined as the duration required for the electrolyzer to adjust the hydrogen output flow rate following a change in input current.

- "Settling time" refers to the time taken for the cell voltage to reach a stable value after a current change. This period is particularly relevant for evaluating system efficiency, as hydrogen production is considered most effective when the power consumption stabilizes at its minimum level for a given load and operating temperature.

- "Flow rate to power ratio". To enable a comparative assessment in relative terms of hydrogen production across different technologies, the ratio between the volume of hydrogen generated and the amount of power consumed is defined.

This experimental procedure enables the extraction of several KPIs, including response time, settling time, and specific production. Some of these variables will be critical in assessing the suitability of each technology for intermittent power supply scenarios typical of renewable energy sources.

This study also involves a series of tasks that, although not directly related to the main operation, constitute preliminary procedures and recommend practices as outlined by equipment manufacturers and/or technical literature. In assessing the suitability of the technology for the intended application, the following factors should additionally be taken into consideration: the minimum operating power, the preparation time required for inerting and venting procedures prior to operation, the number of operational cycles, preheating requirements, warming up period endurance, etc.

To prepare the equipment and ensure that it operates correctly, efficiently and safely, certain operations are carried out before production begins. In some cases, manufacturers require them to be carried out compulsorily, while in others they recommend certain variations depending on previous use.

It is important to consider these tasks, as they involve a critical consumption of resources—particularly time and electrical energy. During this preparation process, the electrolyzer discards all hydrogen production. This is due to the fact that the hydrogen generated is of low quality and/or present at hazardous concentrations. The evaluation of these tasks will be carried out using the following KPIs and considerations.

- "Minimum power", the minimum operating power divided by the rated power of the electrolyzer.
- "Set-up period", the time it takes for the electrolyzer to start producing hydrogen. At that time, the electrolyzer was considered to have been idle for a long period of time.
- "Wake-up time" refers to the time it takes for the electrolyzer to produce hydrogen again, considering that the electrolyzer has briefly stopped.
- All technologies require an initial start-up period after a complete shutdown.
- Amount of vent and pressurization cycles.
- Number of inerting cycles.
- Preheat needing.
- Preheat period endurance.

Once the preparation tasks have been completed, the electrolyzer is ready to start its operation.

3. Results

This section presents the experimental results obtained from the tests conducted on the three electrolysis technologies. Since the same experimental procedure was applied across all systems, a comparative analysis is presented using a set of graphs for each technology. For each:

- In the first graph (a), the evolution of current setpoints, voltage profiles, and temperature variations throughout the entire test is shown, allowing for the assessment of each system's dynamic behavior under identical operating conditions.

- The second graph (b) displays the temporal evolution of the hydrogen flow rate, along with its stability, evaluated through the moving standard deviation calculated over a statistically significant sampling window. This metric provides a quantitative measure of production regularity during both steady-state and transient phases.

- Finally, the third graph (c) provides a zoomed-in view of the voltage profile during a representative section of the test. This enables a more detailed evaluation of voltage stability under steady-state conditions, reflecting the operational robustness of the system.

The experimental results for the PEMWEL, AEMWEL, and ALKWEL technologies are shown in Figures 1, 2, and 3, respectively.

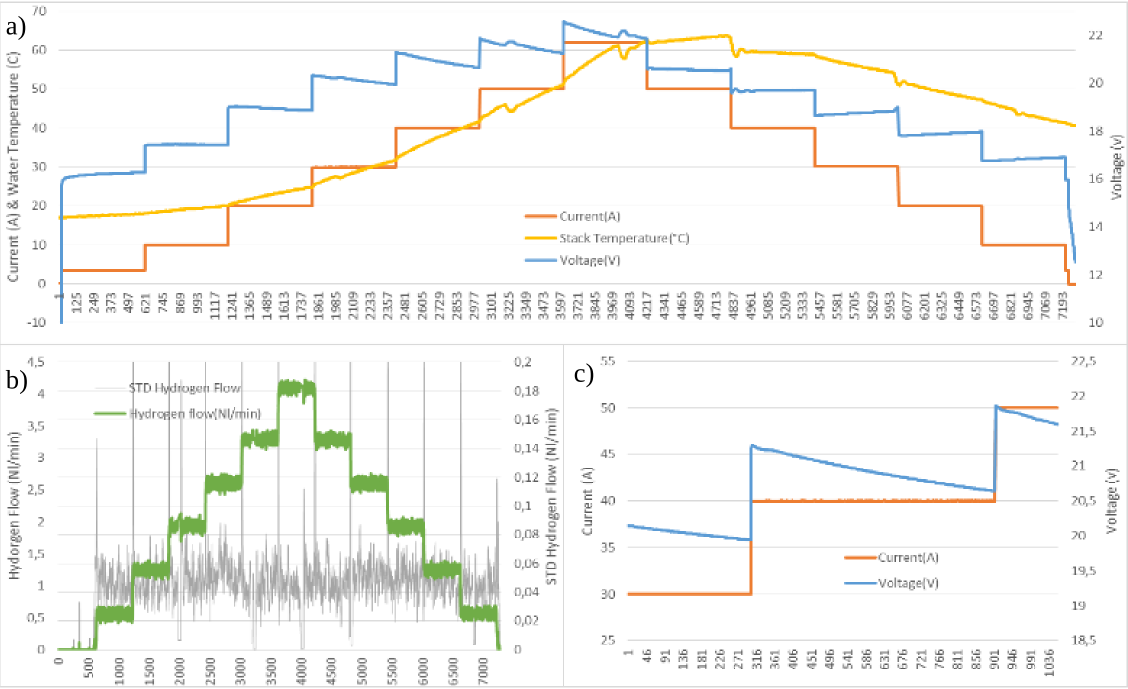

Fig. 1. Polarization curves in PEM electrolyzer

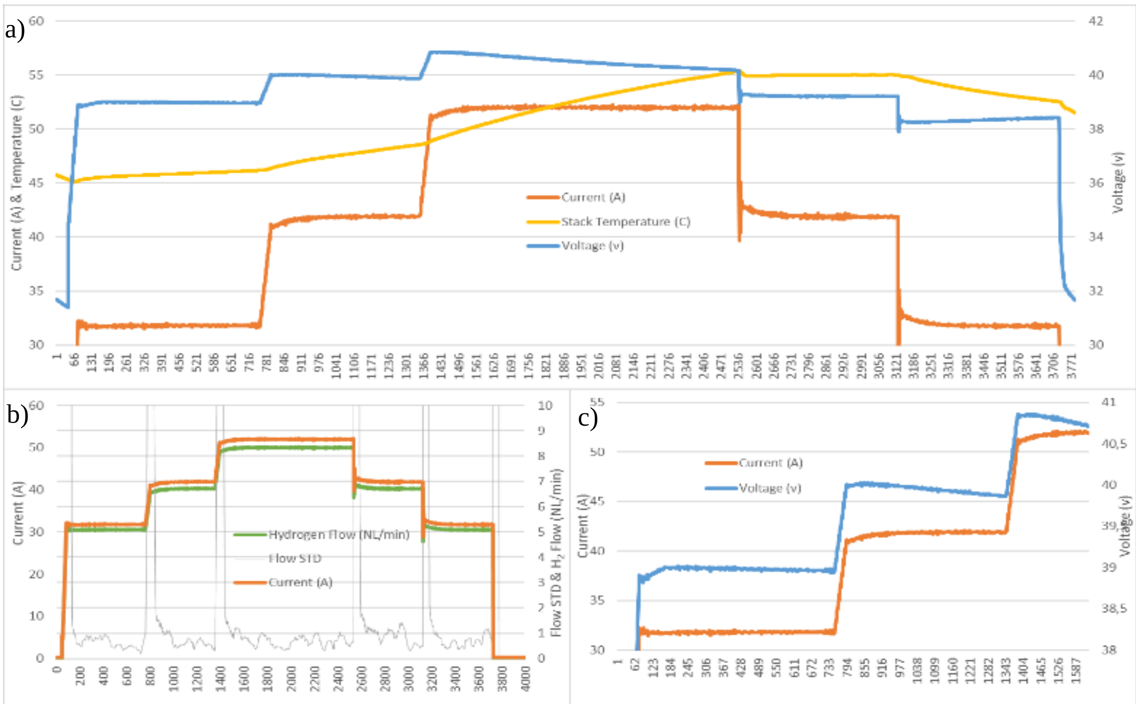

Fig. 2. Polarization curves in AEM electrolyzer

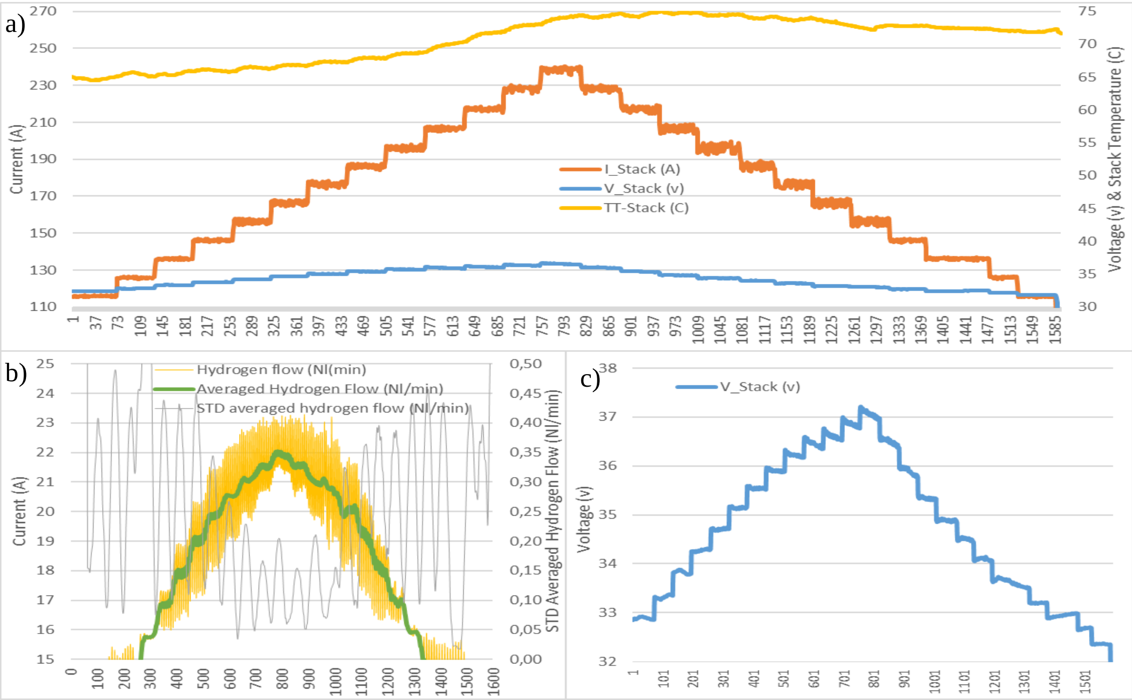

Fig. 3. Polarization curves in Alkaline electrolyzer

Based on these graphs and their analysis, a comparative summary is provided in Table I, highlighting KPIs such as response time, settling time, and specific production (Nl/kW):

Table I. KPIs from test 1

	PEM	AEM	Alkaline
Response time [s]	40	1	240
Settling time [min]	>10	>10	>10
Specific production [Nl /kW]	2.96	3.92	2.51

Table II provides a summary of the KPIs associated with the preparation phase of the electrolyzers, which includes all operations required prior to the onset of stable hydrogen production. These indicators reflect the resource consumption and operational demands involved in initiating each system, offering valuable insight into the practical implications of deploying each technology in real-scale applications.

Table II. Other KPIs

	PEM	AEM	Alkaline
Mínimum power operation ratio (%)	20	60	50
Set-up period from off [min]	10	20	390
Wake up period [min]	<1	8	30
Vent cycles	N/A	3	3
Inerting cycles	N/A	N/A	3
Preheat need (yes/no)	NO	YES (optional)	YES
Preheat time [min]	N/A	46-60	360

4. Conclusions

The experimental evaluation of three electrolysis technologies, PEM, AEM, and alkaline, reveals distinct characteristics that influence their performance in hydrogen production. Based on the results obtained from the conducted tests, the following conclusions can be drawn, highlighting the key findings and providing insights into the optimal application of these technologies.

- Response Time and Adaptability:

Among the technologies tested, AEM technology exhibited the shortest response time. However, none of the technologies achieved steady state conditions within a 10-minute timeframe, as voltage stabilization was not reached within this period.

- Impact of Temperature on Performance:

Temperature is a critical factor that significantly influences the performance of electrolysis stacks. To optimize start-up time and improve operational efficiency, manufacturers of AEM and alkaline electrolyzers incorporate preheating elements into their designs. This feature enables these technologies to achieve a stable production level faster than systems lacking such components. Nevertheless, these technologies require a continuous power supply to maintain the operating temperature, even when solar energy production is insufficient. In contrast, the PEM BoP used in the tests did not include preheating devices, leading to less efficient hydrogen production, particularly during the initial phase when the stack temperature was far from the optimal value.

- Flow-to-Capacity Ratio and Production Efficiency:

In terms of production efficiency, the electrolyzer with the best flow-to-capacity ratio was the AEM technology, achieving a total output of 3.92 NL/h. This indicator highlights the system's capability to produce hydrogen at an optimal rate relative to its installed capacity, thus offering a favorable balance between production and resource utilization.

- Minimum Power Operation

The technology with the best minimum power ratio was the PEM, which is capable of operating at just 20% of its rated power without experiencing performance degradation or operational risks. This feature distinguishes this system from others, as it allows for earlier start-up and more efficient operation at lower power levels, providing greater flexibility in terms of energy availability.

- Start-Up Speed and Temperature Conditioning

The PEM electrolyzer demonstrated the fastest start-up time from a complete stop. The manufacturer recommends implementing pre-conditioning of the stack temperature before initiating hydrogen production to enhance system performance. Despite this, the PEM electrolyzer reached its optimum operating temperature in the shortest period, underscoring its efficiency in thermal management.

- Suitability for Hot Standby Mode

In scenarios where the plant operates in hot standby mode, PEM was found to be the most suitable for rapid return to production. Its operational design facilitates a swift transition from standby to active production, minimizing downtime and enhancing overall system responsiveness.

- Inerting and Purging Cycles

The AEM technology is configured by the manufacturer to automatically perform three inerting and purging cycles, which cannot be modified. In comparison, the alkaline balance of plant recommends conducting between one and six cycles, depending on the system's previous usage. The PEM electrolyzer, however, currently lacks automated inerting and venting cycles, with the control process being fully manual. As a result, hydrogen quality cannot be reliably assured without proper cycle management, posing potential risks in certain operating conditions.

- Technology Selection for Renewable Energy Integration

In conclusion, the selection of the most appropriate technology for coupling with renewable energy sources is not a straightforward process. While technological parameters play a significant role, factors such as operational modes, energy availability, and plant design objectives must also be taken into account. The tests conducted have illustrated the advantages and limitations of each technology through the application of key performance indicators (KPIs).

However, no single technology emerged as the optimal solution across all KPIs. The choice of the best-suited technology will therefore depend on the specific goals and constraints of the plant, including cost considerations, operational conditions, and energy strategies. Future work will explore the hybridization of different electrolysis technologies, combining their strengths to mitigate weaknesses and optimize performance across the identified KPIs. The integration of these technologies in hybrid systems will provide a more robust solution, ensuring complementary operation and improved overall efficiency for hydrogen production in renewable energy applications.

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