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Economic consequences of undefined durability in water electrolysis: on extending use beyond the performance drop threshold

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ABSTRACT

Electrolyzer durability remains undefined by international standards, despite its importance in the techno-economic viability of hydrogen production. Existing benchmarks define end-of-life (EoL) through a performance threshold (PT), typically based on voltage degradation. These thresholds often trigger stack replacement, although stacks may continue operating beyond such limits at a reduced efficiency. This work estimates the economic lifetime of an electrolyzer, defined as the operational period that minimizes the levelized cost of hydrogen (LCOH), comparing it with conventional PT-based lifetimes. Two stack management strategies are evaluated using an LCOH model that incorporates degradation rates, electricity costs, and capacity factors (CF): replacing the entire stack, or extending its operation while supplementing production losses with smaller stacks to maintain hydrogen production. Results show that the economically optimal lifetime often diverges from PT lifetimes, particularly in low CF and low-cost energy contexts, where lifetime extension proves advantageous. The economically optimal strategy is highly context dependent.

1. Introduction

While no universally adopted standard currently exists, international standardization bodies have yet to converge on a harmonized definition of "durability" or "lifetime" for water electrolysis systems used in hydrogen production [1]. As a result, comparing technologies remains challenging: in the absence of a standardized procedure to define and assess this metric, durability values reported by manufacturers often rely on differing assumptions and cannot be directly compared [2].

A fundamental prerequisite for defining durability is the identification of an End-of-Life (EoL) criterion [3]. EoL criteria can take different forms: for instance, it is not the same to assume that after the set hours of lifetime given by the manufacturers the electrolysis voltage has increased by a relative amount at a given current density, than to assume that the equipment just stops functioning at the designated lifetime, as it happens for instance with lightbulbs. While the first EoL type would enable extending the operational lifetime of the electrolysis stack at a reduced efficiency, and supplement the missing hydrogen production rate with a new smaller electrolysis stack, the second EoL type would only allow for the substitution of the full stack, which could lead to higher costs of hydrogen production.

Once an EoL criterion is selected, defining durability also requires harmonized testing procedures [4]. Even if the EoL criteria match between manufacturers, failing to harmonize testing conditions could lead to practical differences between different electrolyzers that estimate similar durability on paper. Important parameters like current density, on/off cycling, operating temperatures, quality of input water, etc. Could have an effect in the degradation rate of the electrolyzer [5]. Considering the long operational lifetimes of these systems, standardized accelerated testing protocols and extrapolation models are also essential to ensure meaningful durability metrics [6].

A unified definition of electrolyzer durability would also facilitate a more accurate understanding of how degradation affects key performance indicators, such as specific energy consumption per unit mass of hydrogen, and would strengthen the reliability of techno-economic assessments [1]. The current lack of such a standard definition of

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durability burdens all techno-economic analyses by increasing uncertainty and risk, or by forcing to make more pessimistic and safer assumptions, hindering the deployment of hydrogen production projects using water electrolysis [7]. At present, it is not possible to set a trustworthy framework of assumptions and degradation models to predict accurately the economic performance of electrolyzers, without very likely overestimating the levelized cost of hydrogen (*LCOH*) production to remain on the safe side [8].

Although no standard definition of durability exists, the most common interpretation in the electrolysis field refers to the time required for a performance metric, typically the cell voltage, to deteriorate to a predefined threshold at constant current density [9]. This sets a performance threshold (PT) type EoL criterion. For instance, the US Department of Energy (DOE) defines the PT EoL requirement as a voltage increase of 10% with respect to the initial one at the same current density [10–12], but the Joint Research Centre (JRC) of the European Comission (EC) fixes this requirement to a 20% of degradation with respect to the initial state [13]. Although the PT EoL criterion does not imply a complete failure of the electrolyzer, it is common practice in scientific literature to assume full replacement of the system or stack at that point. However, there is no explicit indication that the system becomes non-functional at that point.

This opens the door to a broader interpretation of EoL, including:

- Functional EoL, when the system becomes physically inoperable;
- Safety EoL, such as when membrane degradation causes hydrogen crossover to exceed flammability limits;
- Economic EoL, defined as the point where the *LCOH* reaches its minimum before rising again [14].

Regarding the safety EoL criterion, there is scientific evidence that at least PEM water electrolysis increases hydrogen crossover over lifetime due to the degradation of the membrane [15,16]. Crossover entails the diffusion of hydrogen to the anode channels where the oxygen evolution reaction (OER) takes place. Crossover, apart from leading to a performance loss, can cause safety issues. This occurs when the molar concentration of H_2 in H_2–O_2 mixtures reaches the lower flammability limit (LFL) concentration in the anode side of the electrolyzer, or when the molar concentration of O_2 in the cathode side reduces the H_2 concentration to the higher flammability limit (HFL) [17]. At either threshold, the resulting H_2–O_2 mixture becomes flammable, compromising the safe operation of the electrolyzer and necessitating a shutdown. While the progressive increase of H_2 or O_2 crossover over time could also affect other electrolysis technologies, this phenomenon has been comparatively less studied [18].

The economic EoL is conceptually aligned with varying the replacement time to optimize *LCOH*, as explored in prior studies [19]. As long as functional and safety thresholds are not reached, extending operation beyond the PT-based EoL becomes a feasible and potentially profitable strategy.

From an industrial standpoint, adopting an economically driven EoL provides a compelling alternative [20]. If the system remains functional, safe, and compliant with regulations, continuing operation up to the *LCOH* minimum, rather than replacing equipment at a fixed performance loss, can enhance project economics. By synchronizing replacement or supplementation decisions with the economic EoL instead of fixed degradation markers, operators may achieve higher financial returns and longer asset lifetimes.

Nevertheless, it is important to acknowledge that such economically justified lifetime extensions may not always be viable in the future. Regulatory bodies may impose stricter efficiency-based operational limits, turning today's voluntary guidelines into mandatory constraints – analogous to how aging but functional vehicles are phased out due to emissions regulations [21]. Future energy policies could prioritize efficiency enforcement over asset preservation, driven by sustainability targets or market dynamics. For now, however, these restrictions do not exist, and lifetime extension beyond PT EoL remains an open and critical topic for the hydrogen industry, bounded only by safety and functionality.

1.1. *Aim of the study*

The goal of this study is to critically examine how the concept of electrolyzer lifetime should be defined and managed from an economic perspective. In particular, it investigates how degradation over time – modeled through a simple yet consistent framework – impacts hydrogen production cost, and how different stack management strategies may extend lifetime and improve techno-economic performance.

To date, the literature lacks a comprehensive and critical analysis of the lifetime concept as applied to electrolyzers. There is limited understanding of how systems evolve over time under realistic operating conditions, and how replacement or supplementation policies influence long-term costs. While advanced degradation models exist, they are often too specific or complex to inform generalized economic reasoning. In contrast, this work adopts a streamlined but robust modeling approach, isolating key variables – degradation, capacity factor, and electricity cost – to assess their effect on the economically optimal lifetime and on the viability of alternative stack strategies. Specifically, it aims to answer the following questions:

- What is the “economic durability” of an electrolyzer, under simplified assumptions of linear degradation? How does this optimal lifetime compare to the standard PT-based EoL criteria (DOE and JRC), across different operational contexts – namely, low-capacity factor (CF) renewable-based systems with cheap electricity and high-CF grid-connected systems with higher energy prices?
- Can alternative stack management strategies, which avoid premature replacement and instead preserve the initial stack through the addition of spare capacity during the system's life, deliver lower *LCOH* or extended lifetime benefits? Under which scenarios (in terms of CF and electricity cost) do such strategies become preferable to conventional replacements?

By systematically addressing these questions, the study seeks to provide a reasoned basis for evolving the definition of electrolyzer durability beyond fixed technical limits, toward context-dependent and cost-optimized criteria.

The remainder of this article is structured as follows: Section 2 presents the methodology adopted to estimate the economic lifetime of an electrolyzer and describes the alternative stack management strategies, while Section 3 discusses the results. Finally, Section 4 draws the main conclusions and outlines implications for future definitions of durability.

2. Methods

The methodological framework adopted in this study is structured as follows. First, the degradation model and performance thresholds used to characterize electrolyzer aging are defined (Section 2.1). Then, the procedure for estimating the economically optimal operational lifetime is described, based on the evolution of hydrogen production and cost over time (Section 2.2). Lastly, four alternative stack management strategies are presented (Section 2.3), two involving full stack replacement and two based on partial supplementation, along with the corresponding cost formulations and operating scenarios used for the comparative analysis.

2.1. *Degradation framework and end-of-life (EoL) criteria*

This study adopts a degradation framework based on performance thresholds established by recognized institutions. Specifically, two performance thresholds are considered:

- U.S. Department of Energy (DOE) criterion, which defines the EoL of an electrolyzer as the point at which the cell voltage increases by 10% compared to its initial value under constant current density [10–12].
- The European Commission's Joint Research Centre (JRC) criterion, which extends this threshold to 20% [13].

These voltage-based metrics are widely used as proxies for system degradation and are supported by multiple modeling efforts in the literature which typically assume a linear increase in cell voltage U_{cell} over time [22–24]. While actual degradation mechanisms may follow nonlinear trajectories [1], this study assumes a first-order linear approximation to simplify the analysis and to be in line with the previous references.

It should be noted, however, that the evolution of operating voltage during degradation may differ between alkaline and PEM electrolyzers [25]. In alkaline systems, degradation is generally associated with a gradual increase in operating voltage over time due to catalyst deactivation, electrode aging, and increases in internal resistance [26]. In PEM electrolyzers, the behavior can be more complex. Certain degradation mechanisms affecting the membrane electrode assembly (MEA), such as membrane thinning or microstructural changes within the catalyst layers, may reduce the measured ohmic resistance in early phases of MEA activation or under specific operating conditions [27–29]. As a result, a thinner membrane may exhibit a lower apparent ohmic resistance even if the intrinsic proton conductivity of the material remains unchanged, but this may increase gas crossover which may exacerbate thermal degradation. Nevertheless, most durability studies report that the cumulative impact of degradation mechanisms in PEM electrolyzers ultimately results in a progressive increase in operating voltage due to catalyst degradation, interfacial resistances, and transport limitations [18,30]. Consequently, the increase in operating voltage remains a practical and widely adopted indicator of electrolyzer degradation and end-of-life conditions for both alkaline and PEM technologies.

As said in the previous paragraph, for the purposes of techno-economic analysis and to remain consistent with commonly adopted modeling approaches in the literature, this work employs a first-order linear approximation of voltage increase over time. While this simplification is suitable for the scope of the present analysis, more detailed models accounting for non-linear degradation phenomena may further improve the accuracy of long-term performance and cost predictions.

From a practical perspective, given that electrolyzer manufacturers typically report specific energy consumption $w^0_{H_2}$ (kWh/kg H_2) rather than cell or stack voltage, and considering that $w^0_{H_2}$ is proportional to the voltage under constant current operation, any relative increase in voltage over time translates proportionally into an increase in specific energy consumption. Therefore, because voltage and specific energy consumption are directly proportional under constant current, the degradation rate defined as a relative voltage increase (%/kh) can be effectively reinterpreted as a degradation of $w^0_{H_2}$. This enables its direct integration into long-term techno-economic models, aligning performance-based EoL criteria with economic analysis.

To evaluate electrolyzer durability from an economic perspective, the model combines both technical and economic parameters, summarized in Tables 1 and 2, respectively. Among these, the electricity cost c_E and the degradation rate $rdgr$ represent the most uncertain variables. A sensitivity analysis is therefore performed by discretely varying both parameters within plausible ranges.

Table 1
Economic parameters for the estimation of the economic durability of a 1-MW AWE.

Parameter	Description	Value	Units	Ref.
inv	Specific investment cost	1000	€/kW	[31]
$OPEX_{fix}$	Fix annual OPEX	3	% INV	[31]
r	Discount rate	0.04		
c_E	Electricity cost	0.01-0.19	€/kWh	

Table 2
Technical parameters for the estimation of the economic durability of a 1-MW AWE.

Parameter	Description	Value	Units	Ref.
$\dot{W}_{nom}$	Nominal power of the electrolysis system	1000	kW	
$w^0_{H_2}$	Specific electricity consumption at time 0	55	kWh/kg	[31]
$rdgr$	Relative degradation rate of w_0	0.13-0.25	%/kh	[10, 11]
CF	Capacity factor	0.25 or 0.95		

To reflect real-world use cases, two operating scenarios are considered based on the capacity factor (CF), defined as the ratio of actual annual operation to full-load hours:

- $CF = 0.25$, representing systems powered by intermittent renewables (e.g., solar PV)
- $CF = 0.95$, corresponding to grid-connected systems with continuous operation.

Degradation is referenced to calendar time rather than cumulative hours of operation. While this assumption may penalize low-CF systems, it aligns with literature suggesting that frequent start/stop cycling – typical of renewable-powered systems – may exacerbate degradation [32]. A calendar-based approach thus provides a neutral and conservative basis for comparing durability across configurations.

All input values in Tables 1 and 2 are selected to reflect a 1 MW of alkaline water electrolysis (AWE). Regarding the electricity cost, c_E, this study assumes a fixed-price Power Purchase Agreement (PPA) throughout the system's lifetime. While other contractual models exist (e.g., indexed or variable-rate PPAs), the fixed-price approach offers key advantages: budget stability, modeling simplicity, and transparency for long-term financial planning. Although it may lead to higher costs in cases of declining market prices, it avoids the uncertainty associated with price volatility and hedging complexity. Since the primary aim is to isolate the impact of technical parameters such as $rdrg$ and CF on the $LCOH$, the fixed-price scheme serves as a robust and widely adopted baseline assumption [33].

2.2. Optimal economic lifetime estimation

To assess the optimal economic lifetime of the electrolyzer, the $LCOH$ is computed assuming continuous operation beyond the conventional performance thresholds defined by DOE (10%) and JRC (20%). This allows the evaluation of whether extended operation – despite performance degradation – can still yield competitive hydrogen production costs.

The instantaneous hydrogen production rate is modeled as:

$$\dot{m}_{H_2}(t) = \frac{\dot{W}_{nom} \cdot CF}{w_{H_2}(t)} \tag{1}$$

where $\dot{W}_{nom}$ is the nominal power of the system, CF is the capacity factor and $w_{H_2}(t)$ is the instantaneous specific consumption of the electrolysis system. This last term is defined as follows:

$$w_{H_2}(t) = w^0_{H_2} \cdot (1 + rdgr \cdot t) \tag{2}$$

In Eq. (2), $w^0_{H_2}$ is the initial specific consumption (kWh/kg), $rdgr$ is the degradation rate (%/kh) and t is the time (h).

The mass of hydrogen produced in the i-th year, denoted as m_i, is obtained by integrating Eq. (1) over the corresponding yearly time interval:

$$m_i = \frac{\dot{W}_{nom}\cdot CF}{w^0_{H_2}\cdot rdgr}\cdot \ln\left[\frac{1+rdgr\cdot 8760\cdot i}{1+rdgr\cdot 8760\cdot (i-1)}\right] \tag{3}$$

The levelized cost of hydrogen, $LCOH_k$, is calculated as a function of the time horizon, considering all discounted costs and hydrogen production from the start of operation up to year k:

$$LCOH_k = \frac{INV + \sum_{i=1}^{k}\frac{OPEX_i}{(1+r)^i}}{\sum_{i=1}^{k}\frac{m_i}{(1+r)^i}} \tag{4}$$

where:

$$INV = inv\cdot \dot{W}_{nom} \tag{5}$$

$$OPEX_i = OPEX_{fix_i} + OPEX_{var_i} \tag{6}$$

$$OPEX_{var_i} = c_E\cdot \dot{W}_{nom}\cdot CF\cdot 8760 \tag{7}$$

The optimal economic lifetime is evaluated as the the year k for which $LCOH_k$ reaches its minimum value before increasing thereafter.

To better understand the impact of degradation on system economics, $LCOH_k$ is decomposed into two components:

- $LCOH_{stack,k}$ representing the contribution of the electrolysis stack
- $LCOH_{BoP,k}$, associated with the Balance of Plant (BoP).

These contributions are calculated as:

$$LCOH_{stack,k} = \frac{sc\cdot inv\cdot \dot{W}_{nom} + \sum_{i=1}^{k}\frac{OPEX_{var_i} + sc\cdot OPEX_{fix_i}}{(1+r)^i}}{\sum_{i=1}^{k}\frac{m_i}{(1+r)^i}} \tag{8}$$

$$LCOH_{BoP,k} = \frac{(1-sc)\cdot inv\cdot \dot{W}_{nom} + \sum_{i=1}^{k}\frac{(1-sc)\cdot OPEX_{fix_i}}{(1+r)^i}}{\sum_{i=1}^{k}\frac{m_i}{(1+r)^i}} \tag{9}$$

where sc represents the stack contribution fraction in the total investment cost inv of the electrolysis system. In this work $sc = 0.3$, consistent with reported values for 1 MW-scale alkaline systems [34]. It can be noted that through this approximation, the electricity cost is attributed to the stack alone, since it is the main consumer and the component affected by degradation.

Importantly, this analysis assumes that performance degradation does not increase energy input but instead reduces hydrogen output per unit of input power over time. Hence, the impact of degradation is captured as a loss in annual hydrogen production, not as an increase in electricity consumption.

2.3. *Stack management strategies*

To evaluate the impact of stack management on the levelized cost of hydrogen, four alternative operational strategies are defined (see Table 3). These are grouped into two primary categories:

Table 3

Overview of operational strategies considered in the study.

Alternative	Description
A1	Replacement at 10% degradation (DOE)
A2	Replacement at 20% degradation (JRC)
B1	Additional stack capacity added instead of replacement at A1's time
B2	Additional stack capacity added instead of replacement at A2's time

- Type A: full stack replacement upon reaching a predefined degradation threshold;
- Type B: no replacement, but supplementation with additional stack capacity at specific points in time.

In type A alternatives, the electrolyzer stack is fully replaced when it reaches a predefined degradation threshold. Two sub-cases are modeled: A1, with replacement at a 10% degradation level, consistent with the DOE's EoL definition [10]; and A2, with replacement at a 20% degradation level, aligned with the JRC criterion [13].

In type B alternatives, the initial electrolyzer is not replaced at any point. Instead, the BoP is slightly oversized at installation to allow for future integration of supplementary stack capacity. This added capacity is intended to compensate for performance degradation over time and to restore hydrogen production to its original level in the defined supplementation years. The supplementation years coincide with the replacement years defined in alternatives A1 (for B1) and A2 (for B2).

All B strategies assume that the BoP infrastructure is appropriately sized to host the supplementary stack capacity without major retrofitting. Although permanently operating the original stack beyond typical EoL could be unrealistic – due to functional, safety, or auxiliary system limitations – it is adopted here as a limiting academic case. This idealized assumption serves as a benchmark to assess the potential economic value of partial supplementation over traditional replacement policies.

For both replacement (type A) and supplementation (type B) strategies, the specific cost of the stack is assumed to represent 30% ($sc = 0.3$) of the total system investment cost [34]:

$$inv_{stack} = sc\cdot inv \tag{10}$$

Only for type B alternatives, the initial capital investment of the electrolyzer system is updated to reflect both the cost of the stack and the oversized BoP. To compute the oversized BoP investment, the six-tenths rule is applied [35]:

$$inv_{BoP,B} = (inv - inv_{stack})\cdot \left(\frac{\dot{W}_{nom} + \Sigma \dot{W}_{supp_j}}{\dot{W}_{nom}}\right)^{0.6} \tag{11}$$

The total initial investment for type B configurations is then the sum of the oversized BoP and the original stack:

$$inv_B = inv_{BoP,B} + inv_{stack} \tag{12}$$

At each supplementation year j, the additional stack power $\dot{W}_{supp_j}$ is calculated to compensate the hydrogen production deficit $\dot{m}_{deficit_j}$, so as to match the initial production level m_1:

$$\dot{W}_{supp_j} = \frac{\dot{m}_{deficit_j}\cdot w^0_{H_2}\cdot rdgr}{\ln(1+rdgr\cdot 8760)\cdot CF} \tag{13}$$

From an economic perspective, both stack replacements (type A) and supplementations (type B) are assumed to occur at the beginning of the year closest to the respective degradation threshold, 10% for A1/B1 and 20% for A2/B2.

In all cases, the degradation rate is fixed at $rdrg = 0.17$ %/kh [10]. To account for varying energy supply profiles, two operational regimes are evaluated [36,37]:

- $CF = 0.25$ and $c_E = 0.05$ €/kWh, representing renewable-powered systems (e.g., PV or wind)
- $CF = 0.95$ and $c_E = 0.11$ €/kWh, indicative of grid-connected operation.

For each scenario, the $LCOH$ is evaluated over a fixed time horizon of 30 years for all four strategies (A1–B2). This common time horizon allows a consistent comparison between replacement and supplementation strategies. A sensitivity analysis across a broad range of CF and electricity costs c_E is then performed to determine which strategy minimizes $LCOH$ under different boundary conditions over a fixed 30-year time horizon.

3. Results and discussion

This section presents and discusses the results of the study. First, the economically optimal operational lifetime of the electrolyzer is identified and compared with conventional EoL criteria under different operating conditions (Section 3.1). Then, the impact of alternative stack management strategies is evaluated with respect to their influence on *LCOH* (Section 3.2). Finally, the broader implications of these results on the definition of electrolyzer durability are discussed (Section 3.3).

3.1. Economically optimal lifetime beyond fixed EoL criteria

Fig. 1 presents the evolution of the $LCOH_k$ as a function of the electrolyzer's retirement year (k)) for a fixed degradation rate. $rdrg = 0.17\ \%/\text{kh}$. This implies that the PT EoL is achieved for the DOE (10%) at 58.8 kh or 6.71 years of operation, while for the JRC (20%) at 115.6 kh or 13.43 years of operation.

The left graph of Fig. 1 represents a low-utilization scenario ($CF = 0.25$ and$c_E = 0.05$ €/kWh), typical of systems coupled to intermittent renewables, while the right graph refers to a high-utilization scenario ($CF = 0.95$ and $c_E = 0,\ 11$ €/kWh) representative of grid-connected operation.

In both scenarios, the $LCOH_k$ curves exhibit distinct minimums for the overall system as well as for the stack component alone. These points define the economically optimal lifetime, i.e. the value of k that minimizes $LCOH_k$, enabling a direct comparison with the DOE and JRC EoL thresholds. A notable feature is the relative flatness of the $LCOH_k$ curves beyond the minimums, implying that continuing operation beyond the optimal lifetime would have a smaller impact than decommissioning earlier. This flat region suggests some flexibility in lifetime extension decisions, particularly relevant in the context of high capital expenditure assets such as electrolyzers.

In the grid-connected case (right panel), the economically optimal lifetime of the stack (7 years) and of system (13 years) align closely with the DOE and JRC EoL criteria, reinforcing their adequacy for typical grid-connected settings.

In contrast, in the low-CF scenario (left panel), the stack reaches its minimum at 21 years while the system reaches its minimum *LCOH* at 38 years, well beyond both institutional EoL thresholds, even when degradation is considered cumulatively over calendar time as done in this study, which may penalize degradation in low *CF* settings. This divergence highlights how traditional PT EoL limits may lead to premature decommissioning in low-utilization contexts, where stack degradation accumulates more slowly in absolute terms. These findings motivate the exploration of alternative strategies that allow continued operation of the original stack beyond conventional EoL boundaries without compromising economic performance.

Fig. 2 further expands the analysis by showing bidimensional maps of *LCOH* and optimal economic lifetime across wide ranges of *rdgr* and c_E, for the two capacity factor settings. The *LCOH* shown in panels A and C corresponds to the minimum value of $LCOH_k$, while panels B and D report the corresponding economic lifetime. Panels A and B correspond to a low-utilization case ($CF = 0.25$), representative of electrolyzers coupled to variable renewable sources, while panels C and D represent high-utilization systems ($CF = 0.95$), typically connected to the electrical grid.

It can be noted that for degradation rates aligned with DOE benchmarks and reported values in the literature (e.g., 0.17 %/kh), the optimal economic lifetime of the 1-MW system extends over 21 years for $CF = 0.25$ and 10 years in the case of $CF = 0.95$. This suggests that rigidly enforcing a fixed EoL criterion, such as the 10% voltage increase adopted by the DOE, may result in premature decommissioning from a cost-efficiency perspective.

Interestingly, while increasing the *CF* leads to a lower *LCOH* due to better asset utilization (as seen in Panels C vs A), it concurrently reduces the optimal economic lifetime (Panel D vs B). The observed increase in economic lifetime at lower *CF* values may appear counter-intuitive, given that Eq. (2) does not inherently favor reduced degradation under low *CF* conditions. Additionally, the maps reveal that lifetime sensitivity is strongly dependent on c_E and *rdrg* in both low and high *CF* scenarios. This underlines the importance of co-optimizing operational strategy and component replacement scheduling to minimize hydrogen production costs under varying energy supply conditions.

3.2. Evaluation of stack replacement strategies

Building upon the insights from the previous section, this part explores alternative stack management strategies that intentionally extend system operation beyond the conventional EoL timeframes. Rather than replacing the stack at fixed degradation thresholds, two categories of approaches are investigated: full replacement (type A) and partial supplementation strategies (type B). The latter are specifically designed to preserve the original stack while compensating for its degradation through the incremental addition of new stack capacity. This enables a near-constant hydrogen production rate over time, while testing whether such flexible configurations can offer further cost advantages under varying operational conditions. Four stack strategies were compared:

- A1 – replacement at 10% degradation (DOE)
- A2 – replacement at 20% degradation (JRC)
- B1 – no replacement, stack supplementation at A1's time

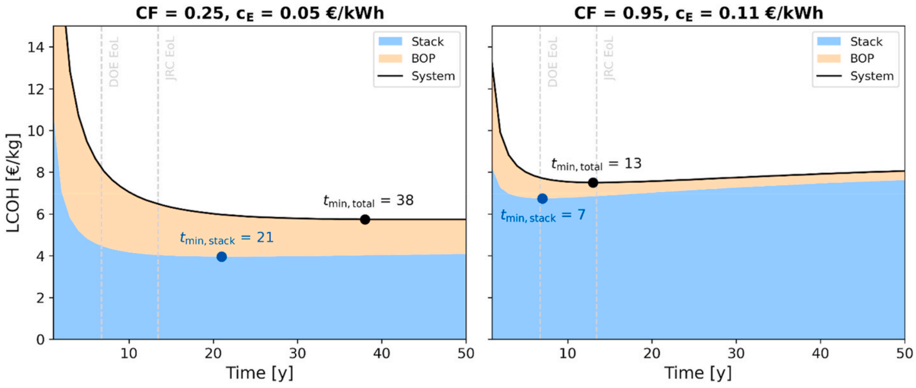


Fig. 1. Levelized cost of hydrogen ($LCOH_k$) as a function of the electrolyzer's retirement time (k) under a fixed degradation rate of 0.17 %/kh. Left figure corresponds to CF = 0.25 and $c_E = 0.05$ €/kWh (Renewable-coupled scenario), while right figure shows results for CF = 0.95 and $c_E = 0.11$ €/kWh (grid-connected scenario). In both cases, a distinct minimum is observed for both the stack-only and the system LCOH. The definition of the LCOH contributions is shown in Eqs. (8) and (9).

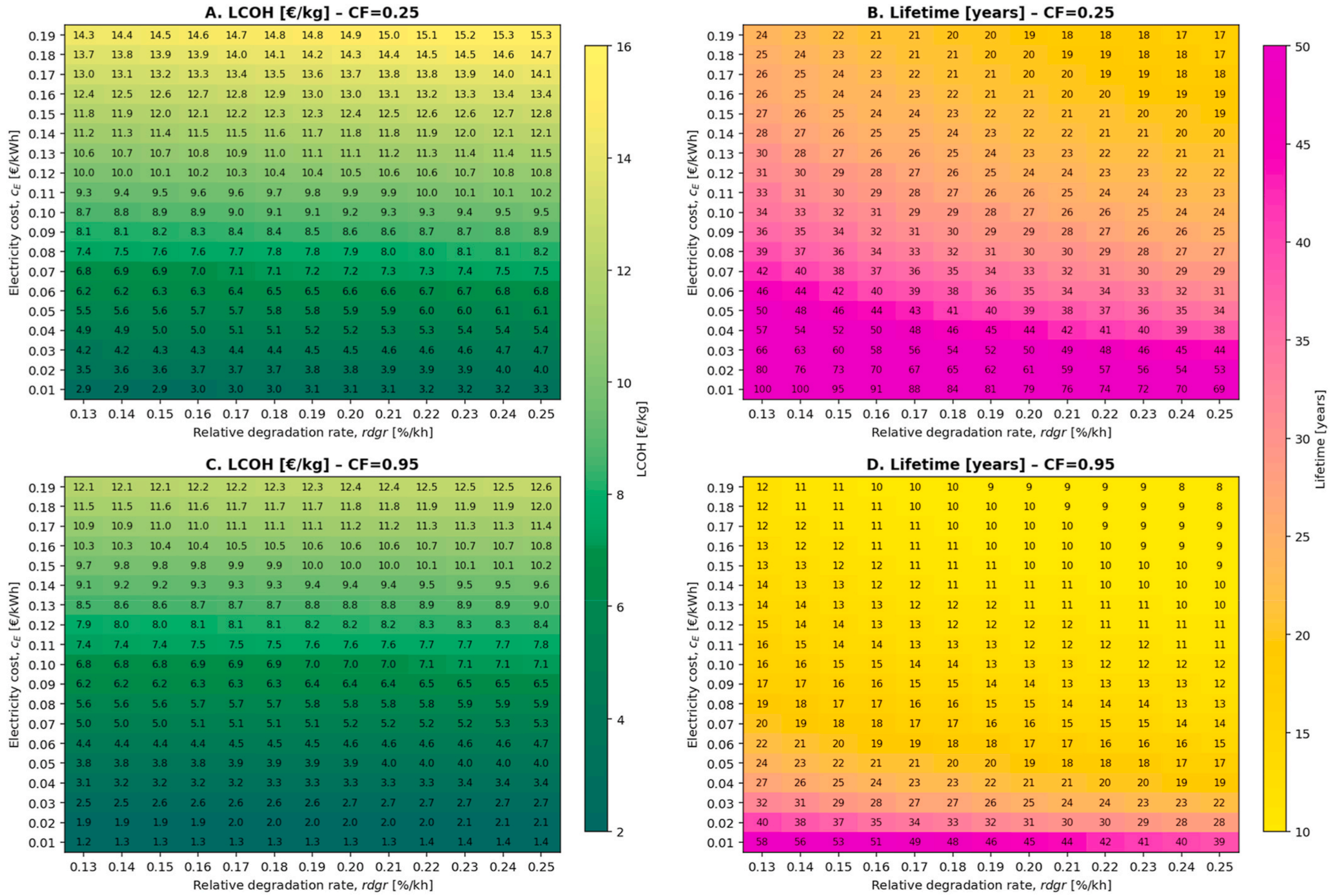


Fig. 2. Bidimensional maps showing the variation of levelized cost of hydrogen (*LCOH*, panels A and C) and the optimal economic lifetime (panels B and D) as a function of the degradation rate (rdgr, horizontal axis) and electricity cost (c_E, vertical axis). Panels A and B correspond to $CF = 0.25$, representative of a PV-coupled electrolyzer system. Panels C and D correspond to $CF = 0.95$, representative of a grid-connected electrolyzer with high annual utilization. All other technical and economic parameters are specified in Tables 1 and 2

- B2 – no replacement, stack supplementation at A2's time

Table 4 summarizes the *LCOH* obtained under the four stack management strategies for two contrasting operating scenarios. The reported *LCOH* values are calculated over a fixed 30-year time horizon. In the low utilization case ($CF = 0.25$, $c_E = 0.05$ €/kWh), strategy B1 yields the lowest *LCOH*, closely followed by A2 and A1, indicating that avoiding replacement and opting for limited supplementation can be economically advantageous when energy is inexpensive and the system operates intermittently. Potentially, B1 management strategy will achieve a *LCOH* reduction of 6% taking A1 alternative as a basis, considering that degradation has been modeled through calendar time rather than through operational time, meaning that with refined degradation models this reduction in *LCOH* could be even higher. In contrast, under high-utilization case ($CF = 0.95$, $c_E = 0.11$ €/kWh), the replacement strategies, particularly A1, outperform B-type alternatives, emphasizing the increasing economic relevance of maintaining efficiency when operational intensity is high. These findings further reinforce the context dependence of the economically optimal lifetime and challenge the validity of fixed performance thresholds as universally applicable EoL criteria.

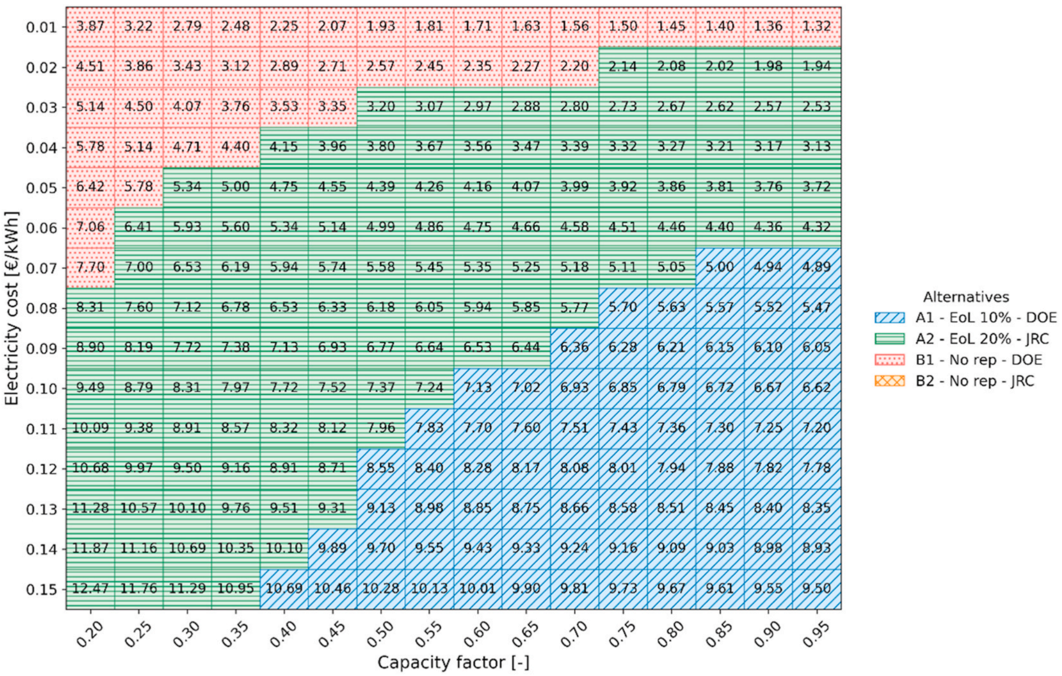
Table 4
Levelized Cost of Hydrogen (*LCOH*) [€/kg] for each replacement strategy under two contrasting scenarios over a time horizon of 30 years. The first row corresponds to a low-utilization case ($CF = 0.25, c_E = 0.05$ €/kWh), representative of renewable-powered systems (e.g., wind or solar). The second row corresponds to a high-utilization case ($CF = 0.95, c_E = 0.11$ €/kWh), typical of grid-connected operation.

	A1	A2	B1	B2
$CF = 0.25$ and $c_E = 0.05$ €/kWh	6.15	5.81	5.78	5.83
$CF = 0.95$ and $c_E = 0.11$ €/kWh	7.20	7.29	7.71	7.72

Fig. 3 presents a decision map showing the optimal replacement strategy, among A1, A2, B1 and B2, alongside the corresponding *LCOH*, as a function of c_E and *CF*. Each cell indicates the most economically favorable strategy and the resulting *LCOH* value in €/kg.

The analysis confirms a strong dependence of the optimal approach on the operating regime. At low *CF* and low c_E, the B1 alternative, based on lifetime extension without replacement and partial supplementation using as reference the *DOE* time, emerges as the most cost-effective among the four assessed alternatives. As *CF* increases, the LCOH-minimizing strategy transitions toward A2, suggesting that under high utilization, the economics favor stack replacement under a more lenient performance threshold (20% degradation). Interestingly, A1 becomes preferable only within a band of high c_E at relatively high *CF*, where early replacement (at 10% degradation) allows improved cost-effectiveness. Across the entire parameter space, the B2 strategy, which represents delayed supplementation without replacement, is never optimal in the c_E and *CF* intervals considered.

These findings highlight the sensitivity of long-term electrolyzer economics to both electricity procurement and asset management strategies, reinforcing the value of flexible system design that



	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95
0.01	3.87	3.22	2.79	2.48	2.25	2.07	1.93	1.81	1.71	1.63	1.56	1.50	1.45	1.40	1.36	1.32
0.02	4.51	3.86	3.43	3.12	2.89	2.71	2.57	2.45	2.35	2.27	2.20	2.14	2.08	2.02	1.98	1.94
0.03	5.14	4.50	4.07	3.76	3.53	3.35	3.20	3.07	2.97	2.88	2.80	2.73	2.67	2.62	2.57	2.53
0.04	5.78	5.14	4.71	4.40	4.15	3.96	3.80	3.67	3.56	3.47	3.39	3.32	3.27	3.21	3.17	3.13
0.05	6.42	5.78	5.34	5.00	4.75	4.55	4.39	4.26	4.16	4.07	3.99	3.92	3.86	3.81	3.76	3.72
0.06	7.06	6.41	5.93	5.60	5.34	5.14	4.99	4.86	4.75	4.66	4.58	4.51	4.46	4.40	4.36	4.32
0.07	7.70	7.00	6.53	6.19	5.94	5.74	5.58	5.45	5.35	5.25	5.18	5.11	5.05	5.00	4.94	4.89
0.08	8.31	7.60	7.12	6.78	6.53	6.33	6.18	6.05	5.94	5.85	5.77	5.70	5.63	5.57	5.52	5.47
0.09	8.90	8.19	7.72	7.38	7.13	6.93	6.77	6.64	6.53	6.44	6.36	6.28	6.21	6.15	6.10	6.05
0.10	9.49	8.79	8.31	7.97	7.72	7.52	7.37	7.24	7.13	7.02	6.93	6.85	6.79	6.72	6.67	6.62
0.11	10.09	9.38	8.91	8.57	8.32	8.12	7.96	7.83	7.70	7.60	7.51	7.43	7.36	7.30	7.25	7.20
0.12	10.68	9.97	9.50	9.16	8.91	8.71	8.55	8.40	8.28	8.17	8.08	8.01	7.94	7.88	7.82	7.78
0.13	11.28	10.57	10.10	9.76	9.51	9.31	9.13	8.98	8.85	8.75	8.66	8.58	8.51	8.45	8.40	8.35
0.14	11.87	11.16	10.69	10.35	10.10	9.89	9.70	9.55	9.43	9.33	9.24	9.16	9.09	9.03	8.98	8.93
0.15	12.47	11.76	11.29	10.95	10.69	10.46	10.28	10.13	10.01	9.90	9.81	9.73	9.67	9.61	9.55	9.50

Fig. 3. Bidimensional decision map of the economically optimal stack management strategy (A1, A2, B1, B2) and its associated *LCOH* (in €/kg) as a function of electricity cost c_E [€/kWh] (vertical) and capacity factor *CF* (horizontal). Each cell contains a number that corresponds to the *LCOH* (€/kg).

accommodates context-specific optimization.

3.3. Discussion on electrolyzer durability metrics

One of the central motivations of this study lies in the absence of a standardized definition of electrolyzer durability. As discussed in the Introduction Section, current institutional benchmarks – such as the DOE's 10% voltage increase threshold or the JRC's 20% analogue – are primarily technical in nature. While useful for performance classification, these thresholds do not necessarily capture the economic rationale behind long-term electrolyzer operation.

The framework developed in this work addresses this disconnect by introducing a techno-economic approach to define electrolyzer lifetime. The economically optimal point for retirement or supplementation is determined based on *LCOH* minimization, as a function of electricity cost, degradation rate, and system utilization. This approach allows for a more integrated and economically grounded interpretation of durability.

Results from the bidimensional maps and scenario comparisons demonstrate that the optimal operational strategy and lifetime are highly context-dependent. For instance, the DOE's 10% threshold may lead to premature replacement in low-CF, low-cost scenarios, where the B1 alternative outperforms both A1 and A2 in terms of *LCOH*. Conversely, under high utilization and elevated electricity costs, even the JRC's more relaxed criterion may fall short of capturing the optimal replacement horizon, which in some cases aligns with lifetimes shorter than 20 years.

These results reinforce the idea that “durability” should not be treated as a fixed or intrinsic parameter, but rather as a function of system economics, particularly energy cost, degradation rates, and operational patterns. In doing so, this work advocates for a shift in durability metrics: from rigid technical thresholds toward performance-aware, cost-optimized criteria that can better guide system design and policy frameworks.

In any case, these results should be interpreted with caution, as the methods used may have limitations. This study presumes a constant degradation rate throughout the electrolyzer's operational lifetime, independent of capacity factor or dynamic operating conditions. However, available literature suggests that degradation mechanisms may be affected by load cycling, idle times, and start-stop sequences, which increase at low *CF*, but on the other hand, degradation over accumulated effective time of use is reduced at low *CF*. This knowledge gap, that we attribute to the lack of durability and degradation testing protocols standards, made us model *rdrg* to be neutral, which could penalize low-CF scenarios. Another possible limitation in this study is that, while the economic lifetime is derived based on cost optimization criteria, it does not explicitly account for other potential EoL triggers such as safety limits (e.g., increased hydrogen crossover) or functional failures (e.g., stack inoperability).

To improve future durability modeling and economic projections, standardized testing procedures, particularly in the form of accelerated degradation protocols, are essential. These would enable a better understanding of stack aging under real-world conditions and support the development of more accurate, condition-dependent degradation models.

4. Conclusions

This study examined the concept of electrolyzer durability from a techno-economic perspective, focusing on how different EoL criteria affect hydrogen production costs. While electrolyzer lifetime is commonly interpreted through performance-threshold (PT) definitions based on voltage increase, these criteria do not necessarily reflect the economically optimal point at which a stack should be replaced, supplemented, or retired. In addition to PT-based definitions, broader interpretations of EoL can be considered, including functional EoL (when the system becomes physically inoperable), safety EoL (when degradation causes conditions such as hydrogen crossover beyond flammability limits), and economic EoL, defined as the point where LCOH reaches its minimum before increasing again.

A key motivation for this work lies in the absence of a harmonized definition of electrolyzer durability in international standards. This lack of standardization introduces uncertainty in techno-economic analyses and may lead to conservative assumptions regarding stack lifetime and replacement strategies, potentially increasing the estimated cost of hydrogen production.

To investigate these aspects, a techno-economic framework was developed to evaluate four stack lifetime management strategies: two based on full stack replacement at predefined degradation thresholds (A1 at 10% degradation and A2 at 20%), and two based on lifetime extension through stack supplementation without replacement (B1 and B2). The levelized cost of hydrogen was used as the central metric, and sensitivity analyses were performed across a wide range of degradation rates, electricity costs, and capacity factors.

The results show that the PT EoL criteria currently used as practical benchmarks for stack replacement are not economically optimal in all contexts. Replacement at a 10% degradation threshold, consistent with the DOE criterion, may lead to premature decommissioning when electricity costs are low or capacity factors are modest. Under these conditions, lifetime extension strategies based on partial stack supplementation, particularly B1, can result in lower LCOH values than conventional replacement approaches. Conversely, in operating regimes characterized by high capacity factor and higher electricity cost, replacement strategies become economically preferable, with A2 and in some cases A1 emerging as the most cost-effective options. These findings highlight that no single stack management strategy or EoL threshold is universally optimal. Instead, the economically optimal lifetime of an electrolyzer depends strongly on the operational context, particularly electricity price and system utilization.

While the proposed framework provides useful insights into the economic implications of different stack management strategies, some simplifying assumptions should be noted. The degradation model assumes a linear increase in voltage over time, which may not fully capture the complex degradation behavior observed in real systems, particularly over long term operation. In addition, degradation is assumed to be independent of capacity factor, which may penalize low-CF scenarios. Moreover, specific assumptions regarding cost structure and plant configuration may affect the general applicability of the results.

Future work should focus on experimental validation of long-term degradation under variable operating profiles, including the effects of load cycling, start–stop operation, and partial-load conditions. Such studies would help clarify the relationship between safety EoL, functional EoL, and economic EoL, and would allow a more realistic evaluation of extended stack lifetime strategies such as the B-type management alternatives explored in this work. Finally, given the central role of durability in determining the levelized cost of hydrogen, further efforts toward the standardization of durability metrics and testing protocols are essential. Harmonized testing procedures and accelerated degradation protocols would improve the comparability of durability results and support the development of more reliable techno-economic assessments for electrolysis systems. In this context, the development of consistent durability definitions and testing standards by international organizations such as IEC, ISO, and CENELEC could play a key role in improving the reliability of lifetime predictions and facilitating the large-scale deployment of hydrogen electrolysis technologies.

CRediT authorship contribution statement

Rafael d'Amore-Domenech: Writing – review & editing, Writing – original draft, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Paolo Marocco:** Writing – review & editing, Validation, Methodology, Investigation, Data curation, Conceptualization. **Vladimir L. Meca:** Writing – review & editing, Validation, Conceptualization. **Marta Gandiglio:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Large Language Model (LLM) tools in order to improve readability and English language. After using these tools, the authors reviewed and edited the content as needed, and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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