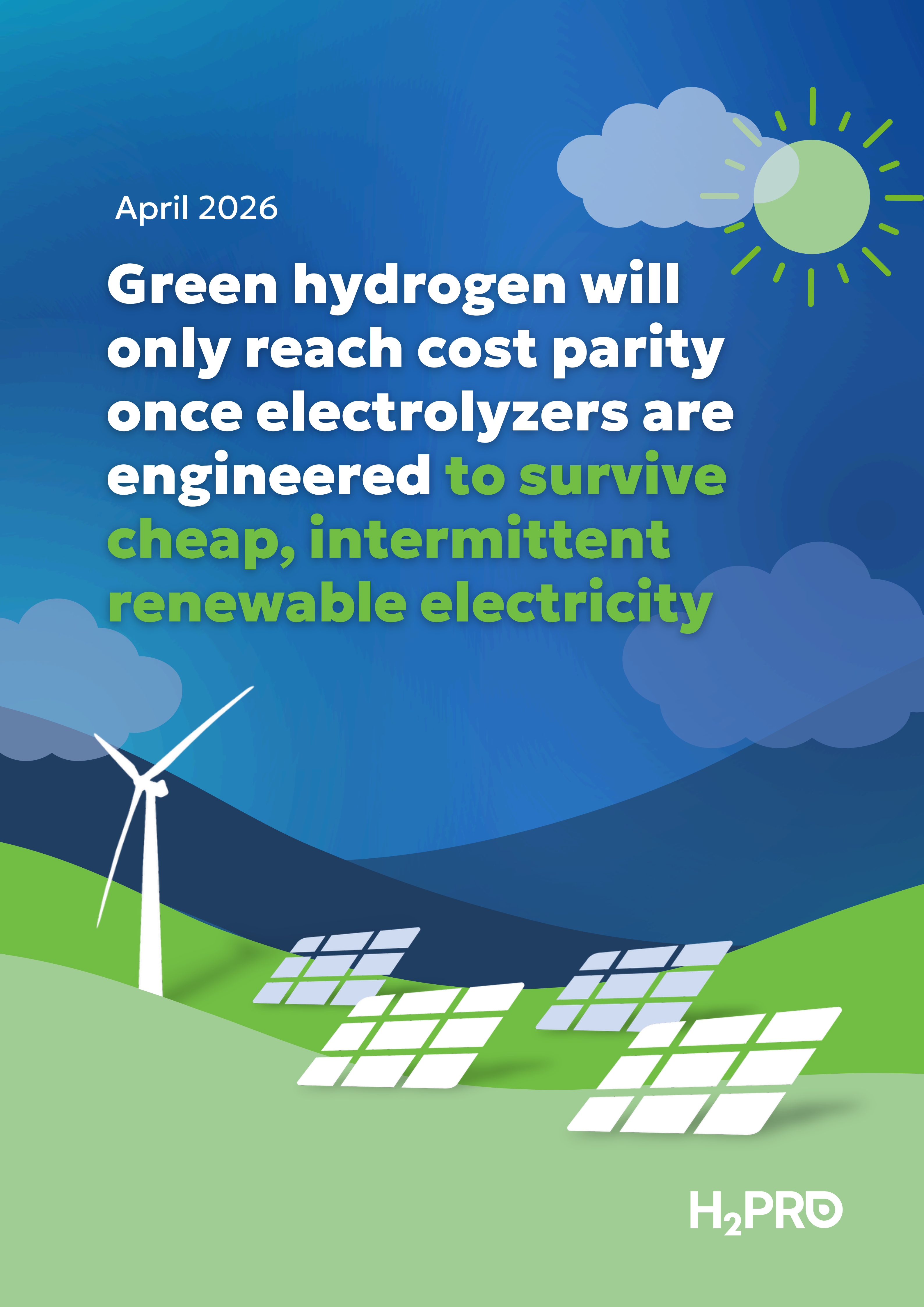
April 2026

Green hydrogen will only reach cost parity once electrolyzers are engineered to survive cheap, intermittent renewable electricity



H$_2$PRO

Key Takeaways

Context

- In a volatile era, green hydrogen is emerging as a key enabler of energy resilience. The challenge is to deliver this lever at a competitive price.
- Renewable electricity is now abundant and low-cost, yet green hydrogen remains prohibitively expensive.
- This is a paradox: electricity accounts for ~60–80% of hydrogen production cost but falling power prices have not translated into lower LCOH.
- The lowest-cost electricity is inherently intermittent (solar, wind, curtailed power), requiring operation **under frequent ON/OFF cycling** and **fluctuating power loads**.
- The core barrier to cost-parity Green Hydrogen is not access to cheap electricity, but the inability of electrolyzers to utilize it without significant tech challenges.

Problem

Conventional electrolyzers were designed for stable baseload electricity. Due to inherent engineering limitations, they struggle under intermittency.

- Under variable load:
  - **AWE** suffers from shunt current losses and gas crossover, severely reducing efficiency and limiting safe operation at low loads
  - **PEM** can follow load, but incurs accelerated catalyst degradation (Ir/Pt dissolution) and membrane degradation (ROS-driven thinning), shortening system lifetime
- Under repeated ON/OFF cycling:
  - **AWE** experiences reverse-current-driven electrode corrosion and phase degradation, rapidly degrading performance
  - **PEM** suffers from small gas crossover during idle periods; unlike during normal operation, these gases are not swept away and can accumulate during shutdown, accelerating corrosion of both the electrocatalysts and the membrane.

Need

Achieving cost-parity green hydrogen requires electrolysis systems designed to follow the exact output profiles of solar and wind, while operating efficiently, safely, and reliably without degradation.

Introduction

Hydrogen as a Strategic Asset for Energy Resilience and Robust Clean Energy Systems

Energy security has emerged as a defining priority for governments and industries worldwide. Recent geopolitical events, including Russia's invasion of Ukraine and current war in the Middle East, have exposed the structural fragility of fossil fuel–dependent energy systems. Supply disruptions, price spikes, and political leverage tied to energy exports have made clear that reliance on globally traded fossil fuels carries inherent risk. The lesson has been internalized: long-term energy resilience requires reducing dependence on volatile, externally controlled fuel sources and shifting toward domestically produced or allied energy supply. In this context, green hydrogen is increasingly recognized as a critical component of national energy security strategy, enabling countries to convert locally available renewable resources into a storable, transportable energy carrier and regain control over energy supply chains.

Figure 1. Oil price volatility driven by geopolitical tensions in the Middle East (2025–2026).[1]

This need is particularly acute given the existing role of hydrogen in the global economy. Hydrogen is already a critical input to refining, fertilizer production, and a range of industrial processes. According to the International Energy Agency (IEA), global hydrogen demand reached nearly 100 million tonnes in 2024.[2] However, the vast majority of this hydrogen (over 99%) is produced from fossil fuels, primarily natural gas (with 60-70% of hydrogen production price a result of natural gas prices), making it subject to the same price volatility, supply constraints, and geopolitical risks that affect broader energy markets. In effect, a critical industrial input remains directly tied to the very system countries are seeking to de-risk.

At the same time, energy systems are undergoing a rapid shift toward renewable electricity. Solar and wind power offer the advantage of domestic generation and declining costs, making them central to energy independence strategies. However, electricity alone does not provide a complete solution. Renewable generation is inherently variable, with production fluctuating across hours, days, and seasons. A robust energy system requires mechanisms to store energy over long durations, balance supply and demand, and transport energy across regions and sectors.

Green Hydrogen provides this missing layer. It enables long-duration energy storage, supports grid balancing during periods of surplus or deficit, and allows energy to be transported in molecular form to sectors that cannot rely solely on direct electrification, including aviation, shipping, and high-temperature industrial processes. Importantly, as electricity demand accelerates due to the rapid expansion of AI infrastructure and data centers, off-grid green hydrogen production offers a way to capture and utilize renewable energy without competing with grid-based electricity demand. In doing so, hydrogen complements renewable electricity and enables the development of energy systems that are not only clean, but fundamentally more dependable and self-reliant.

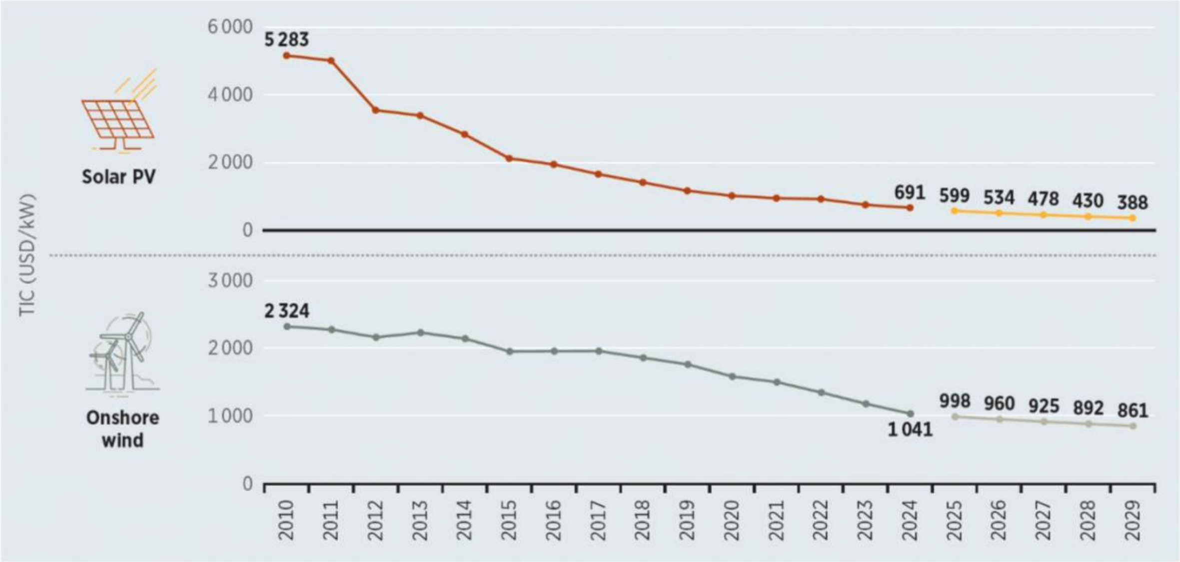
As the role of green hydrogen becomes more clearly defined and its strategic importance comes into focus, regulatory frameworks are becoming more definitive and increasingly stringent. In Europe, for example, policies are evolving to ensure that hydrogen labeled as “green” reflects genuine renewable electricity use. Regulations such as the European Union’s Renewable Fuels of Non-Biological Origin (RFNBO) framework introduce requirements related to additionality, geographic correlation, and temporal matching between renewable electricity generation and hydrogen production. These rules are designed to ensure that hydrogen production supports the development of renewable energy systems rather than relying on fossil-based electricity. However, they also increase the technical demands placed on hydrogen production technologies.

The Green Hydrogen Cost Paradox

Despite its strategic importance, green hydrogen remains prohibitively expensive. This persistent cost barrier reflects a fundamental disconnect between the availability of low-cost renewable electricity and the ability of hydrogen production systems to utilize it effectively.

Indeed, renewable electricity has become the lowest-cost form of energy deployed at scale. The global weighted-average levelized cost of electricity (LCOE) of utility-scale solar photovoltaics declined by approximately 90 percent between 2010 and 2024, while onshore wind fell by roughly 70 percent over the same period.[3] In high-resource markets, utility-scale solar projects have achieved electricity prices well below €25 per megawatt-hour, with record-low auction results falling as low as €11/MWh in Southern Europe[4]. These trends demonstrate that the primary feedstock for green hydrogen production is increasingly abundant and inexpensive.

Figure S5 Global short-term TIC projections for solar PV and onshore wind



Notes: kWh = kilowatt hour; LCOE = levelised cost of electricity; PV = photovoltaic; TIC = total installed cost; USD = United States dollar.

This figure, taken from IRENA's RENEWABLE POWER GENERATION COSTS IN 2024 report, shows declining costs of solar PV and wind. Learning curves and economies of scale are forecast to further reduce LCOE [3].

Notably, the cost of hydrogen produced through electrolysis is dominated by electricity, which in most configurations accounts for approximately 60 to 80 percent of total production cost[5],[6].

Therein lies the cost paradox: if electricity is both inexpensive and the primary cost driver, why have hydrogen costs not declined accordingly?

The answer is that access to low-cost electricity is necessary, but not sufficient; electrolyzers must also be able to use this electricity effectively under real operating conditions.

In practice, the lowest-cost renewable electricity is rarely what electrolyzers consume. When renewable power is procured through the grid, it carries additional cost components, including transmission and distribution fees, balancing costs, contractual premiums, and other system-level charges. These additions increase the effective price of electricity delivered to the electrolyzer. By contrast, the lowest-cost electricity is typically available behind the meter, co-located with generation assets, in off-grid configurations, or during periods of curtailment when supply exceeds demand.

In essence, the lowest cost electricity is inherently intermittent – and conventional electrolyzers were not designed for volatile conditions.

The Hidden Engineering Constraint

Utilization of the lowest cost electricity demands that electrolyzers excel under intermittency. Conventional commercial systems were designed for an entirely different reality. Alkaline and proton exchange membrane (PEM) electrolyzers were engineered for steady-state operation, high utilization rates, and grid-stabilized power input. They were not engineered to withstand frequent shutdowns, extended idle periods, or repeated start-stop cycles.

A direct-to-solar hydrogen facility, for example, must shut down completely every evening and restart each morning. Over the course of its operational lifetime, such a facility will experience thousands of start-stop cycles. Scientific literature and operational experience show that repeated cycling accelerates degradation in conventional electrolyzers. Start-stop operation can expose components to reverse currents, pressure and temperature fluctuations, and membrane hydration changes. Over time, these stresses contribute to catalyst degradation, membrane thinning, increased gas crossover, and overall performance loss in both alkaline and PEM systems, albeit through different mechanisms.

While back-up grid connection or battery buffering can mitigate these challenges, they introduce additional system complexity and cost, undermining the economic advantages of low-cost renewable electricity.

Unlocking use of the lowest-cost renewable electricity therefore requires electrolysis technologies that can operate reliably under intermittent conditions. Such systems must be able to operate safely and efficiently under variable loads, withstand frequent shutdowns and restarts, tolerate extended idle periods, and maintain performance despite the dynamic output profiles of solar and wind generation.

Some small-scale projects are already exploring the possibility of direct connection to renewables. One example is Oort's 250kW off gird electrolyzer which has been powered by solar power for the last two years.[7] Technical information from these projects is not yet open to the public and therefore all the technical information presented in this paper is based on verified peer-reviewed publications.

This paper examines why these capabilities are essential for achieving low-cost hydrogen production. It analyzes the engineering limitations that conventional alkaline and PEM electrolyzers encounter when exposed to intermittent renewable electricity and explains why these limitations affect both system performance and overall hydrogen cost. The paper then explores how electrolysis architectures designed specifically for direct connection to renewables can overcome these constraints and enable hydrogen production that fully leverages the economics of modern renewable energy.

The fundamental/engineering limitations of legacy alkaline and PEM electrolyzer systems

The following paragraphs shed light on the fundamental limitations that last century water electrolyzer technologies face when powered by intermittent sources, such as solar and wind energy. This technical overview explains why alkaline and proton exchange membrane (PEM) electrolyzers struggle to maintain efficiency and durability under variable and stop–start operating conditions. There are two main categories of challenges: (1) problems during variable-load operation and (2) problems from repeated on/off cycling. All findings are supported by recent academic studies, highlighting issues such as shunt currents, gas crossover, and degradation pathways.

Part 1: Problems When Operating Under Variable Loads

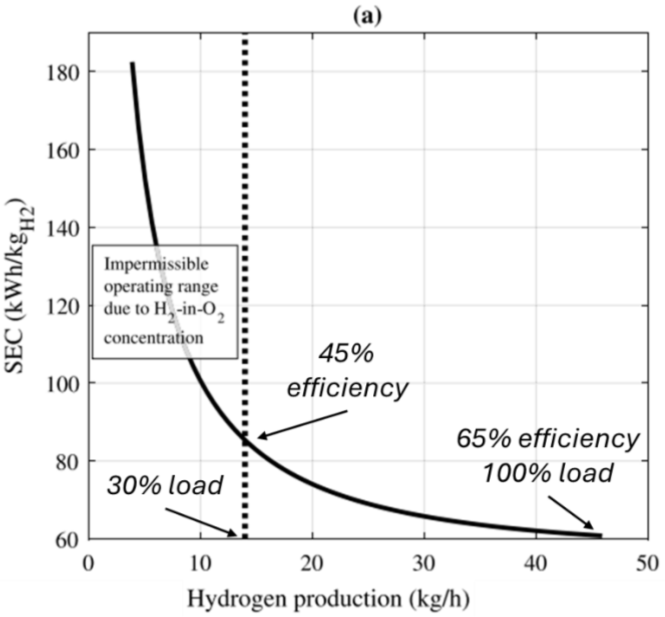
When an electrolyzer is directly coupled to fluctuating renewables, its input power and current density vary with sunlight or wind availability[8]. Such dynamic loading can sharply reduce efficiency and pose safety risks in both alkaline and PEM systems, though the underlying causes differ.

1.1 Alkaline Electrolysis under Dynamic Input Power

Alkaline water electrolyzers (AWE) have historically been designed for steady-state industrial operation. Under partial-load or variable power, they experience two major issues: shunt current losses and excess gas crossover.

Shunt currents are parasitic DC currents that flow through the liquid KOH electrolyte and manifold paths instead of through the intended electrochemical reaction in each cell. At high loads, shunt paths exist but are small relative to the main current; however, at low loads the Faradaic (main reaction path) current drops and the proportion of current that "shunts" through the electrolyte becomes significant[9]. This effect was demonstrated by a combined work of LUT, Stargate Hydrogen Solutions OÜ, ABB Drives Oy, and Aalto University using a 48V small scale alkaline electrolyzer [10]. In practical terms, when solar or wind power dips and the stack runs at a fraction of its capacity, the fraction of input power wasted as shunt current rises sharply, lowering net efficiency. In a 2024 ECS research paper, E. Rasten (Senior Technologist hos Nel Hydrogen) concluded that

"Shunt-currents in the manifold system increase dramatically when going to larger stacks and significantly reduces the energy efficiency at lower and intermediate loads and increases the challenges of electrode stability during intermit operation"[11]. Furthermore, a modeling study of an industrial 3MW, 16 bar alkaline water electrolyzer showed that shunt currents can constitute a large percentage of the total current, "shunt currents were found to be 16.8% at the 100% load and 75.4% at the 30% load", leading to much higher specific energy consumption (kWh per kg H_2) under partial loads[12,13]. The researchers found that at low current densities the energy loss to shunt currents dominated, thus reducing efficiency (down to 45%) and effectively limits the useful dynamic range of operation to a minimum of 30% load (due to high hydrogen concentration in the oxygen stream) as shown in the figure below (Figure 6 in the paper). [12]



A creative approach to reduce these shunt currents is by using an external manifold which can significantly increase the ionic resistance between the electrochemical cells and reduce the shunt currents. Implementing this design is significantly more complex and costly as explained by E. Rasten in the 2024 ECS research paper (page 40)[11], "External manifold system may solve the problem of shunt-currents for larger stacks; however at a cost penalty compared to internal manifold system and even more costly for high pressure operation". Nevertheless, this approach is implemented by some manufacturers.

Compounding this, gas crossover becomes harder to control at low loads. In alkaline cells, hydrogen and oxygen are separated by a porous diaphragm, and some gas permeation or dissolution through the electrolyte is inevitable. At nominal load, vigorous gas evolution helps flush the gases and maintain safe concentrations. But as load decreases, the ratio of gas leakage to gas production increases, so more hydrogen diffuses to the oxygen side (and vice versa) relative to the smaller production rate[14]. One consequence is a higher likelihood of exceeding the acceptable hydrogen-in-oxygen threshold, raising safety concerns. Indeed, multiple comprehensive studies noted that gas crossover can approach critical flammability limits at low current densities during variable operation[15,16]. In other words, when an alkaline stack is idling or operating intermittently (with frequent low-power periods), the passive gas separation may not suffice – hydrogen/oxygen mixtures can accumulate toward explosive levels [15]. Even before reaching a safety limit, increased crossover means lost product (hydrogen that ends up in the wrong stream) and lower Faraday efficiency. In summary, intermittent power causes alkaline electrolyzers to suffer efficiency losses (via shunt currents) and safety/quality issues (via H_2/O_2 cross-contamination). These challenges underscore that traditional alkaline designs are ill-suited to handle highly variable input without significant performance penalties.

1.2 PEM Electrolysis under Dynamic Input Power

PEM electrolyzers are often touted for their rapid response and flexibility. They use a solid polymer membrane (e.g. Nafion) as electrolyte, which enables differential pressure operation and inherently avoids the large liquid electrolyte manifolds of AWE. As a result, PEM technology can ramp output up or down quickly to follow solar/wind fluctuations[17]. Unlike alkaline units, there are no large-scale shunt currents looping through bulk liquid since the ionic current is confined to each cell's membrane. PEM systems can technically operate at partial loads more readily, maintaining stable operation even at low current without the sluggish kinetics of a liquid electrolyte.

However, rapid response and being able to operate at low load does not mean operating indefinitely without damage. Recent reviews emphasize that dynamic and intermittent operation imposes severe stress on PEM electrolyzer components, which accelerates degradation mechanisms, [17] [18] significantly shortening their lifetime and reducing performance. Several coupled factors explain this degradation under variable loads:

- Catalyst dissolution and migration: Iridium and platinum dissolution from catalyst layers, followed by migration into the membrane, permanently reducing electrochemically active surface area and increasing activation overpotentials.[19,20]
- Membrane chemical degradation: Attack by reactive oxygen species (ROS) generated at high potentials or during transient reverse currents, leading to PFSA chain scission and fluoride release, which correlates with membrane thinning.[21],[22]

- Mechanical stress and creep: Variable hydration, differential swelling, and pressure fluctuations generate mechanical stress and creep in the membrane, increasing susceptibility to cracks and pinholes, particularly at elevated pressure. [17]

In summary, PEM electrolyzers can follow variable renewable power more capably than alkaline units, but this flexibility belies an increased rate of component degradation and potential safety concerns. The membrane and catalysts are strained by the dynamic regime: efficiency may remain high initially, yet the lifetime of the system is shortened by continuous load variability. Therefore, the true cost of dynamic operation includes more frequent maintenance or replacement due to these insidious damage mechanisms, even if instantaneous efficiency under variable load is acceptable.

Part 2: Problems Under Repeated On/Off Cycling

Beyond continuous variability, intermittent renewables often force electrolyzers into frequent start-stop cycles (daily shut-down at sunset, cloud-driven cutouts, or wind lulls). Repeated on/off cycling introduces unique stresses not present in steady or even variably-loaded operation. Key issues include electrode material fatigue, reverse current phenomena during shutdown, and exacerbated degradation of membranes and catalysts during each power transition. This section outlines how such cycling affects alkaline and PEM systems.

2.1 Alkaline Electrolysis – Electrode Degradation from Cycling

Alkaline electrolyzers suffer heavily when frequently turned off. An experimental study[23] for connecting an alkaline electrolyzer directly to renewable power concluded that "short-time scale events, i.e., dynamic events on the order of minutes such as those characteristic of a system based on a wind resource, can induce rapid electrolyzer performance degradation compared to steady-state operation". The traditional electrodes (nickel-based for hydrogen evolution and often nickel/iron oxides for oxygen evolution) undergo phase changes and corrosion during idle periods, largely due to a phenomenon called reverse current. When an AWE stack is suddenly powered down, the cells do not instantaneously stop all electrochemical activity. Upon shutdown, the external power is removed, but the cell stack still contains reactant gases (hydrogen in the cathode side and oxygen in the anode side) and remains at elevated temperature. This can create a galvanic cell condition: hydrogen and oxygen begin to spontaneously recombine across the cells, effectively driving a current in the reverse direction through the stack (each cell acting momentarily like a fuel cell rather than an electrolyzer)[9]

Indeed, field data shows that long idle periods allow significant reverse currents to flow in industrial alkaline stacks, and these currents directly correlate with accelerated electrode degradation. In his 2024 ECS research paper, E. Rasten (Senior Technologist hos Nel Hydrogen) explains why the stack does not rest quietly when off – it self-discharges chemically, eating away at the electrode integrity unless preventative measures are taken [11]. The deleterious effects of this process center on electrode corrosion due to role-switching. In an alkaline cell, the nickel-based cathode is engineered to reduce water to hydrogen (a reducing environment), and the anode (often nickel or nickel-coated with catalytic oxides) is engineered to oxidize OH^- to oxygen (an oxidizing environment). During a reverse current event, these roles flip: the cathode becomes a local anode, and the anode becomes a cathode. Nickel that was formerly cathodically protected now corrodes aggressively under anodic potential and likewise, any catalytic coatings on the original anode (e.g. metal oxides used to improve OER kinetics) may be physically undermined when that electrode suddenly sees a cathodic potential [24]. A 2025 research study demonstrated that the nickel anode undergoes "mechanical stress during phase transitions, eventually causing fracturing" [25] and that this process led to significant electrode degradation: "Under those conditions, pure nickel, which often represents benchmark stability in alkaline environments, suffers substantial mass loss, up towards 1 % of the anode (O_2 electrode) material corresponding to ~0.95 μm of the surface, during 120 prolonged shutdown cycles at elevated temperatures." In addition, A 2024 deep electrochemical study [24]explicitly showed that periodic power-off (mimicking renewable intermittency) causes reverse currents that alter the crystal structure and composition of Ni-based electrodes in real time. Using multiple analytical tools Marquez et al. showed "that reverse currents during simulated shutdowns expose catalytic films to deep discharge conditions, which severely degrade catalytic films."

In summary, alkaline electrolyzers experience pronounced electrode degradation under repeated cycling. The reverse-current during each shutdown acts like a self-inflicted corrosion test, degrading the catalysts and significantly damaging their performance. Over time this leads to poorer kinetics and efficiency (e.g. higher voltage required to drive the same current) and can dramatically shorten electrode life.

2.2 PEM Electrolysis – Membrane and Catalyst Failure Mechanisms on Cycling

PEM electrolyzers are not immune to the damaging impact of on/off cycles. In fact, A comprehensive review on PEM electrolyzer degradation states that "Frequent ON/OFF cycling accelerates degradation, causing platinum dissolution, catalyst layer delamination, and membrane damage." [17] An experimental study from 2024 focusing on the impact of intermittent operation on photovoltaic-PEM electrolyzer systems[26] revealed that zero current periods cause significant degradation where "catalyst layer detachment and membrane thinning (is) especially pronounced". An additional study that tested the effects of ON/OFF cycles verses variable loads operation "demonstrate(s) a significant increase in durability losses when simulating start-stop operation, well beyond the performance losses associated with low catalyst loading and load input[27]

The two primary causes for this fast degradation are membrane degradation [21] (thinning, cracking, or perforation) and electrocatalyst degradation. [20] Both phenomena are directly correlated to small amounts of gas crossover through the membrane. Both oxygen and hydrogen are able to slowly pass through the membrane. Under normal conditions this small amount is negligible and is immediately removed by the main gas stream. By contrast, during and after shutdown there is no main gas stream, and hydrogen and oxygen, which are both highly reactive, start to corrode the electrocatalysts and the membrane.

Membrane chemical degradation is led by oxygen crossover to the cathode which reacts with hydrogen at the cathode and forms hydrogen peroxides. Hydrogen peroxides decompose to form free radicals attacking the polymer membrane thereby releasing fluoride. As fluoride is released, the polymer membrane begins to degrade and becomes thinner. As the membrane becomes thinner the crossover accelerate and degradation rate accelerate as well. Simulation research [21] demonstrated that a 200 µm thick membrane will loss about 11% of its thickness during one year of continuous operation (8760 continuous working hours), but under intermittent power the degradation significantly accelerates and the membrane will lose more than 50% of its thickness within only one year of intermittent power (8760 working hours, 8760 Off hours, 4380 On-Off cycles), as shown in the following figure (Fig 8 in the paper[21]).

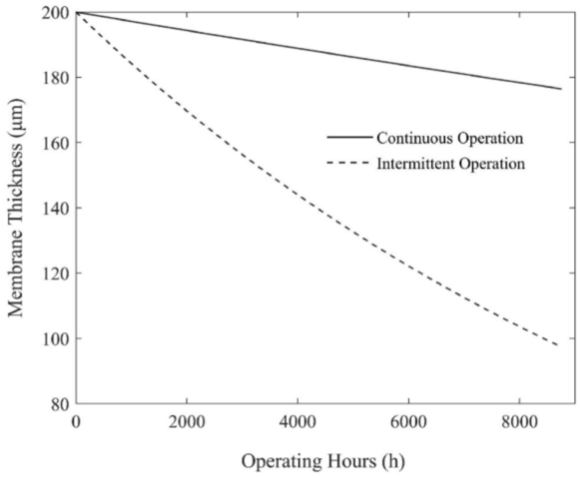
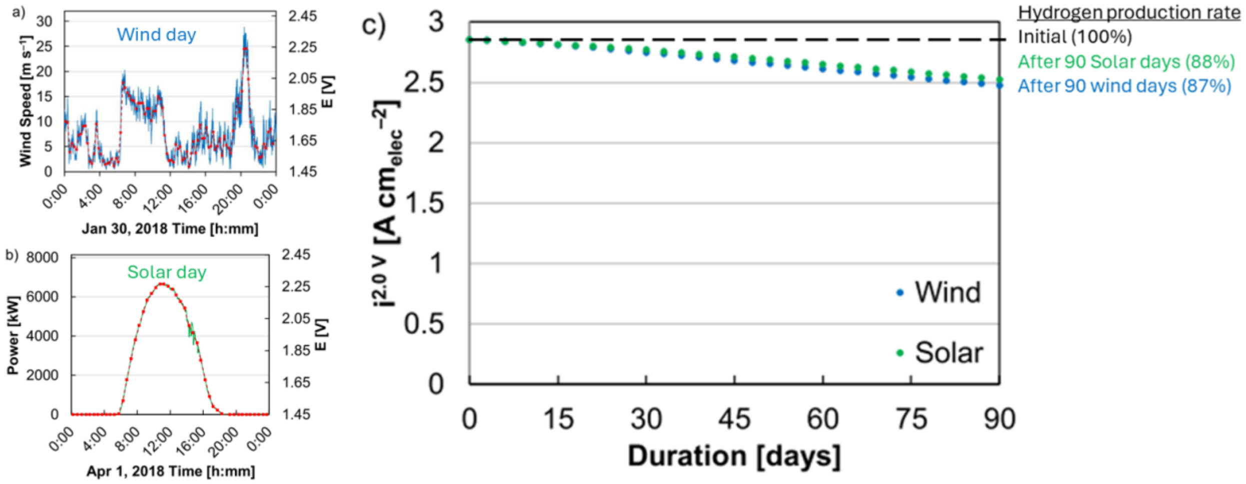


Fig. 8. Comparison of membrane degradation for both intermittent and continuous operations (both operational for 1 year).

This phenomenon can be misleading, as PEM electrolyzer efficiency may improve initially due to the decreased ohmic overvoltage losses as a result of the increased ionic conductivity of a thinner membrane. However, eventually the thickness of the membrane will reach a critical value where transport of hydrogen to the anode increases to unsafe levels, leading to catastrophic failure of the device. Periodic membrane replacement as part of preventive maintenance can address this issue, but it is a complex and costly procedure that most operators prefer to avoid.[28]

Both the Platinum (the HER catalyst) and Iridium oxide (the OER catalyst) degrade during and after shutdown, but it seems that the performance loss results from Iridium oxide dissolution. The iridium oxide (the OER catalyst and the anode) is chemically attacked by hydrogen crossing from the cathode to the anode where it accumulates and reduces the iridium oxide to iridium metal. During operation, iridium is oxidized again into an amorphous structure instead of the original crystalline one. Although the amorphous iridium oxide catalyst has a higher activity, it also exhibits a lower stability. This improves the performance initially, but leads to a quicker degradation, because of the increased dissolution rate of iridium [22]. As a result, whenever commercial electrolyzers use low iridium concentrations on the anode they may encounter fast performance degradation caused mainly by the ON/OFF cycles induced by solar and wind power profiles. Comprehensive research which studied this effect found that after only 90 days of simulating wind and solar power, the electrolyzer production was reduced by 13% for wind and 12% for solar, as shown in the following figure (Figure 7 in the paper [29])



In aggregate, the picture that emerges is that repeated ON/OFF cycles undermine PEM electrolyzer longevity through multiple interconnected mechanisms. Membrane chemical degradation (tracked by fluoride release and thinning) is significantly accelerated by frequent OFF periods. Catalyst and electrode degradation is likewise worsened by iridium dissolution and structural changes in the anode catalyst, while the cathode catalyst/support can suffer oxidation and particle growth. These processes ultimately limit the stack lifespan and reliability. A PEM electrolyzer running on a highly intermittent power profile will show faster performance decay. **The "hidden" damage during each OFF cycle adds up, even if the electrolyzer is not producing hydrogen at that time.** This is why most manufacturers advise avoiding excessive on/off cycling of PEM systems.

Different engineering solutions are considered to overcome these difficulties. One solution considered is applying minimum power. This approach was investigated by Kuhnert et al. [30] they applied minimum power of 12% and demonstrated significant reduction in degradation rate. On the other hand, Núnez et al.[31] applied a reduced current of 15% from the maximum current, but this led to enhanced degradation. Another electrical solution is applying a shielding voltage during idle hours. A comprehensive electrochemical study by Weiß et al.[32][1] and by Kornherr, et al [33], applied 1.3V during idle time at the cell level and demonstrated stable electrochemical performance compered to pure idle (OCV) which shows reduced performance. The researchers concluded that degradation of catalyst (mostly Iridium) as the main reason for the degradation during idle without shielding voltage. On the other hand, different study done by Milosevic, et al [34] which perform similar tests show that applying 1.3V during idle time did improve the performance at high currents but at low currents the performance degrade more compared to pure idle (OCV). In addition, they looked on the iridium catalyst loss to the electrolyte and concluded that applying 1.3V during idle time might even promote iridium dissolution, as they found iridium concentration in the anode electrolyte line to be the highest under these working conditions. All three papers clearly demonstrated that shielding voltage helps preserve performance during the first hundreds of on/off cycles, but long-term stability (thousands of cycles) is still unproven. Preventing iridium oxide catalyst degradation by precise control of the catalyst potential is thetically possible but it is not trivial. The Iridium in the electrocatalyst has multiple oxidation stats Ir^0, Ir^{+3}, Ir^{+4}, Ir^{+5},[35] and $Ir^{+4}O_2$ is considered to be the most stable form iridium oxide catalysts. The Iridium oxidation state is dictated by PH, temperature and electrode potential. Applying too low voltage during idle may promote dissolution of Ir^{+3} while applying too high might generate gas or form less stable Ir^{+5} . One example of such non-trivial effects was demonstrated by Voronova et al [36] which studied the effect of lower voltage limit (LVL) under dynamic PEM operation. They found that LVL of 1.4 V resulted in fast performance decay, while LVL of 1.5V showed a negative degradation slope. (which might result from membrane thinning and/or structural improvements on the catalyst-membrane interface). However, when they test high LVL (1.7,1.9 V) this led to the fastest degradation. Applying voltage shielding as an engineering solution to mitigate rapid degradation in large-scale PEM systems may be more difficult than it initially appears. Unlike voltage shielding in a single laboratory cell, large-scale PEM stacks contain hundreds of cells connected in series, each of which may differ in temperature and pressure, making the voltage distribution across the stack during standby both non-uniform and difficult to control.

In addition to direct stack degradation, operating a PEM electrolyzer with daily on/off cycles is difficult because the system does **not transition quickly or smoothly between states** and exhibits **unstable gas composition during every start-up and shutdown**. A recent publication which examines a large PEM stack (190Nm^3/h , 215V, 3800A) [37] shows that a cold start requires ~6340 s and shutdown ~855 s, meaning a significant portion of each day would be spent in transient operation rather than steady production. More critically, during these transients the concentrations of hydrogen and oxygen **fluctuate significantly**, including spikes and non-monotonic behavior in H_2-in-O_2 and O_2-in-H_2, which “can easily lead to a decrease in system performance”. Since these unstable conditions occur every time the system is turned on or off, frequent daily cycling would repeatedly expose the electrolyzer to long, inefficient, and compositionally unstable operating periods, making reliable and efficient operation inherently challenging.

In conclusion, the evidence reviewed here shows that PEM electrolyzers are highly sensitive to repeated shutdown and restart cycle. These cycles accelerate membrane degradation, catalyst dissolution, gas crossover, and transient instability, all of which shorten stack lifetime and reduce reliability. Although several mitigation strategies have shown promise, none has yet fully resolved the long-term durability challenges associated with highly variable renewable power. As a result, improving PEM electrolyzer resilience to cycling remains a central requirement for the large-scale integration of PEM electrolyzers with solar and wind energy systems.

Bottom line

Both alkaline and PEM electrolyzers face significant challenges when required to operate under the variable and intermittent power profiles characteristic of solar and wind energy. A comprehensive academic review published in 2024 summarized this clearly: "we provided a review of 130 publications covering the impacts of intermittent operation on alkaline and PEM electrolyzers from the year 2000–2023. The review encompassed issues related to efficiency, gas quality and durability arising at all operational scales, from the cell to the system level. The key points from reviewed publications can be summarized as follows: i) performance and durability of electrolyzers at all levels of the system operation, are significantly influenced by the variation of temperature and electrical load conditions, ii) both the performance and durability of electrolyzers are impacted by the frequency of intermittent cycles during intermittent operation, iii) short current interruption or decrease promote partial performance recovery, iv) the stiffness of ramp-up and ramp-down events typically encountered in intermittent operation has an impact on the efficiency, gas purity and degradation rate, v) the frequency and waveform of ripple factors encountered in power conversion units impact the efficiency and degradation rate of electrolyzers."[38] In practical engineering terms, alkaline systems are constrained by intrinsic gas-separation limitations that make low-load operation inefficient and, at sufficiently low currents, unsafe, while PEM systems, although more operationally flexible, pay for that flexibility through accelerated degradation under repeated cycling. **As a result, neither technology can directly absorb highly intermittent renewable electricity without compromise; effective integration will require not only connecting electrolyzers to renewable power, but doing so in a way that preserves safety, efficiency, and long-term durability.**

DWE is designed for intermittent power

Conventional alkaline and PEM electrolyzers evolve H_2 and O_2 simultaneously, so they rely on a separator (membrane/diaphragm) and tight operating constraints to prevent gas crossover and maintain safety and efficiency - constraints that worsen at low/variable power. H2Pro's Decoupled Water Electrolysis (DWE) addresses these shortcomings by separating hydrogen evolution and oxygen evolution into two distinct stages that occur at different times and can run at different rates, enabling practical membraneless operation with minimal shunt currents and no gas crossover.

The DWE core architecture: Two electrodes without a membrane.

- **BFE (Bi-Functional Electrode):** performs either HER (Hydrogen evolution reaction) or OER (Oxygen evolution reaction) depending on current direction, so it must be catalytic under alternating cathodic/anodic polarization. In addition, it has minimal parasitic reactions and preserves performance for over 100K cycles.

- **ChE (Chargeable electrode):** based on the Nickel hydroxide / nickel oxyhydroxide couple, $Ni(OH)_2 \rightleftarrows NiOOH$, acting as a solid redox mediator
  that exchanges OH^- between stages (in alkaline electrolyte). This is inspired by reversible Ni-based alkaline battery chemistry. The ChE temporarily consumes/generates charged hydroxide ions and preserves performance for over 100K cycles.

Figure 2. Illustration of H2Pro's unique DWE process (right) in comparison to a generic conventional electrolysis process (left)

The two-phase electrochemical cycle:

Phase 1 — Hydrogen production + “charging” the ChE

At the BFE (cathodic), water is reduced (HER) to produce hydrogen:

- HER: $4H_2O + 4e^- \rightarrow 2H_2 + 4OH^-$

The OH^- ions generated at the BFE are consumed at the ChE and transform $Ni(OH)_2$ to NiOOH (charging the electrode):

- ChE charge: $4Ni(OH)_2 + 4OH^- \rightarrow 4NiOOH + 4H_2O + 4e^-$

Phase 2 — Oxygen production + “discharging” the ChE

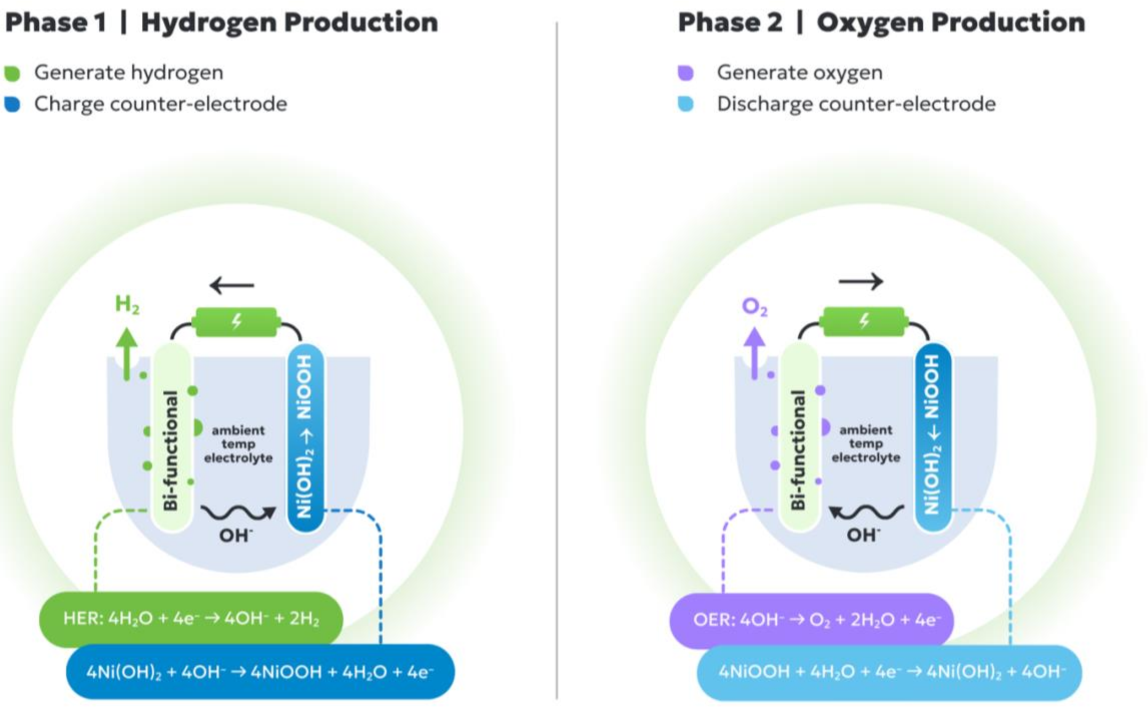
When the ChE reaches its operational capacity, the current is reversed and the BFE becomes anodic and the OER consumes OH^- ions while generating oxygen:

- OER: $4OH^- \rightarrow O_2 + 2H_2O + 4e^-$

Meanwhile the ChE discharges (NiOOH is reduced back to $Ni(OH)_2$) and generates OH^- ions:

- ChE discharge: $4NiOOH + 4H_2O + 4e^- \rightarrow 4Ni(OH)_2 + 4OH^-$

The two phases are presented in figure 3.



Phase 1 | Hydrogen Production

Phase 2 | Oxygen Production

Figure 3. Schematic illustrations of H2Pro unique DWE process. Left / Hydrogen production phase. Right / Oxygen production phase

The process starts at phase 1 in which Hydrogen is produced at the BFE while the ChE charges. The hydrogen gas is routed to its separation tank. Once the ChE reaches its operational capacity, phase 1 ends, the current is reversed, and Oxygen is produced at the BFE and routed to its separation tank, while the ChE discharges. Once fully discharged, the cycle is repeated starting again at phase 1. As only one gas is produced at a time (H_2 or O_2), the need for a membrane to keep the gases apart is eliminated.

DWE cycles holds two main engineering challenges:

- BFE durability/activity under polarity reversal which requires exceptional materials stability with high catalytic performance in both directions.
- Capacity–rate tradeoff / overcharge avoidance: pushing current density too hard can overcharge NiOOH and trigger oxygen generation during the H_2 step, wasting energy and breaking the "no-simultaneous-gas" premise.

Both challenges were overcome via novel and proprietary H2Pro electrodes developed by the R&D team.

Nickel hydroxide ChE reliability: $Ni(OH)_2$/ NiOOH redox couple is known for being stable and reliable even in harsh environments, and H2pro demonstrated endurance over tens of thousands of charge/discharge cycles, consistent with long-lived Ni-based battery use cases.

Earth-abundant BFE catalysts: H2pro achieved a high bifunctional performance by identifying a novel catalytic combination of an HER alloyed catalyst and an OER alloyed catalyst, while precisely controlling multi-element alloying to reduce parasitic reactions that waste electrons. Overall, H2Pro's novel BFE electrodes are based on a multiphase structure with multiple elements that provide the unique properties needed. The unique microstructure of the electrode is presented in the figure below, where A, B and C are different multi-element phases. Further information can be found in H2pro's recent publication PCT/IL 2026/050244

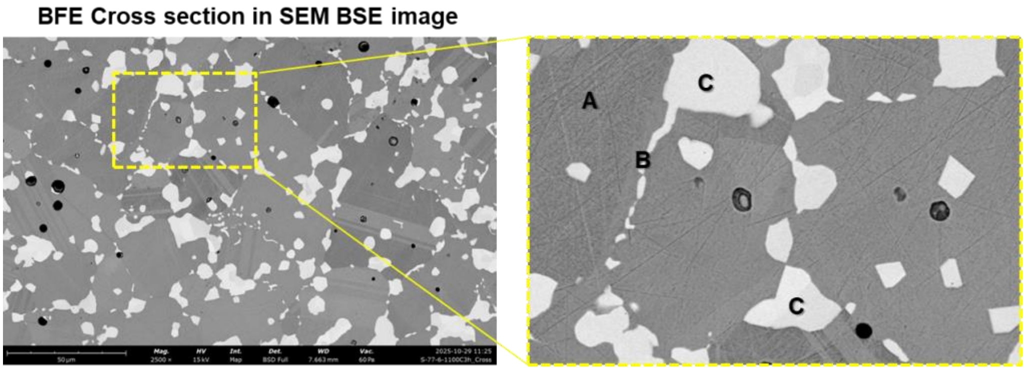

BFE Cross section in SEM BSE image

Figure 4

As shown in the figure below, H2pro demonstrated more than 10K DWE cycles – an amount equivalent to more than one year of solar operation, including thousands of on/off events and reverse currents. The cycles resulted in no significant performance degradation, while maintaining the high efficiency of about ~50 kWh/kg.

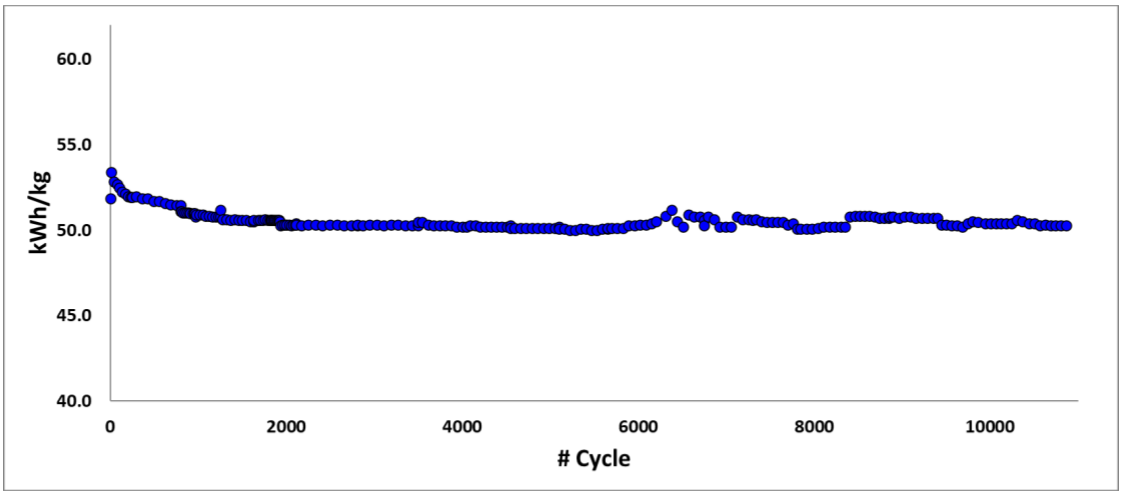


Figure 5

Furthermore, under accelerated testing protocol, these electrodes demonstrated a lifetime of more than 50K on-off cycles, including forward and reverse currents, under accelerated degradation conditions, representing at least 10 years of solar operation.

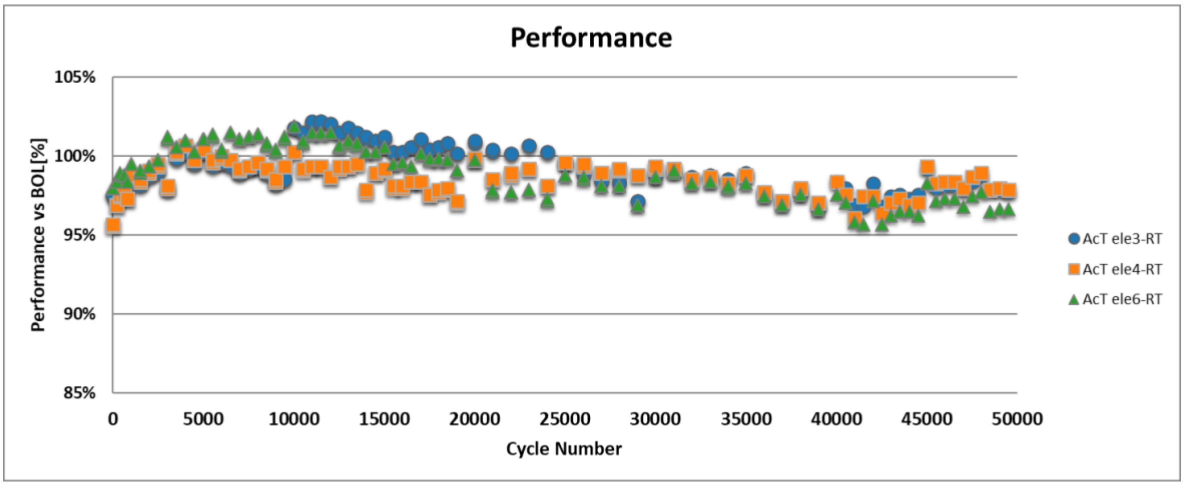


Figure 6

In addition to the unique performance stability of H2pro electrodes under thousands of on/off cycles, the electrodes and unique electrochemical reactor architecture maintains high efficiency at variable loads, as explained in the next paragraph.

The DWE multi electrochemical cells architecture:

Overview

To scale this electrochemical process to practical hydrogen production systems, the technology is implemented in modular electrochemical cell packs. Each cell pack comprises multiple electrochemical cells connected in series both electrically and hydraulically. Adjacent cells are separated by ionic shunt current eliminators that allow directional electrolyte flow between cells while preventing parasitic ionic current leakage. Multiple cell packs are integrated to form a larger scalable set. The cell packs are connected electrically in series to build the system voltage, while hydraulically they are connected in parallel through common inlet and outlet manifolds. This modular architecture enables scalable electrolyzer systems suitable for large-scale hydrogen production.

The electrode unit

The smallest modular building block of the system is the electrode unit presented in the figure below. Each unit consists of two electrodes: on one side the chargeable electrode, and on the opposite side H2Pro's state-of-the-art bi-functional electrode (BFE).

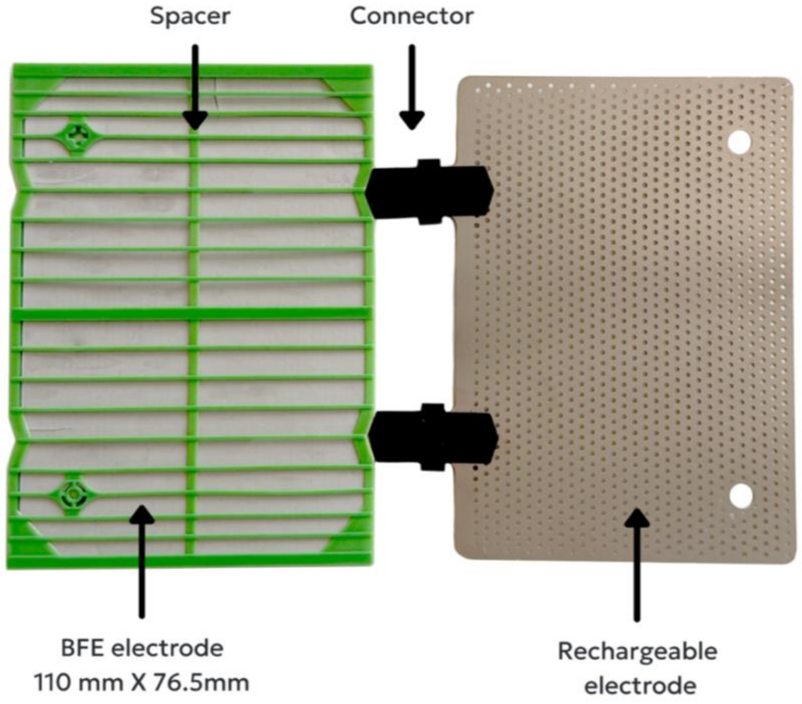
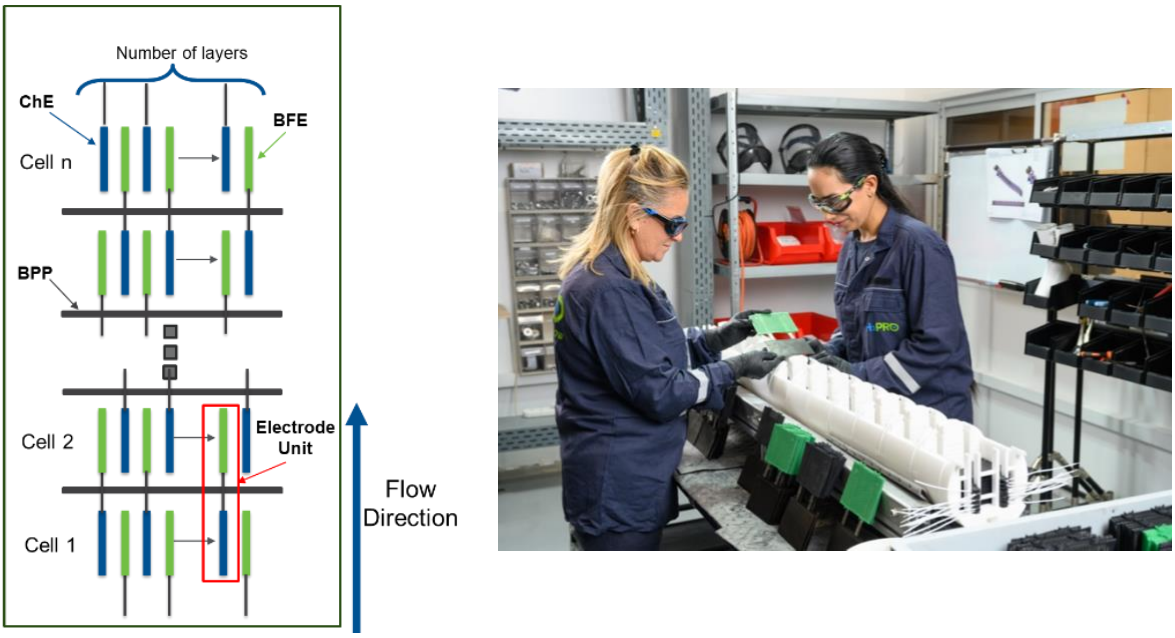


Figure 7

The Cell-Pack

Using H2Pro's proprietary layering technique, individual electrode units are assembled into larger functional modules called Cell-Packs (CPs) (see Figure 8). Multiple electrode units are arranged in a stacked configuration such that each half-electrode unit participates in a different electrochemical cell within the stack. Each cell-pack therefore consists of multiple electrochemical cells connected both electrically and hydraulically in series, forming a repeating electrochemical structure composed of multiple stacked layers. Adjacent cells are separated by a shunt current suppression component known as the Bipolar Plate (BPP).

The BPP is a simple plastic plate, with precisely designed holes, that performs two critical functions. First, it manages electrolyte flow by providing optimized flow channels that distribute the electrolyte across the cell while maintaining minimal pressure drop. Second, it provides electrical isolation between adjacent cells to suppress parasitic shunt currents. The BPP introduces a controlled ohmic resistance of several ohms between neighboring cells. This electrical separation is essential for maintaining high system efficiency by limiting shunt currents. This cell-pack architecture enables the system voltage to be built internally while preventing the accumulation of shunt currents. Because the cells are connected both electrically and hydraulically in series, shunt current accumulation does not occur, unlike configurations where cells are connected hydraulically in parallel as commonly found in conventional alkaline electrolyzers.



(a) (b)

Figure 8. Cell-pack configuration. (a) A schematic of the layers stacking of the electrode units showing the multiple cells and full cell-pack. (b) an image showing the layering process of assembling the cell-pack.

The Set

At a higher level of integration, multiple cell-packs are connected electrically in series while sharing common inlet and outlet hydraulic manifolds (see Figure 9). The parallel hydraulic connection introduces additional potential shunt current paths between cell-packs, which may be at higher voltage differences depending on the number of connected CPs. To mitigate these currents, Passive Shunt Protection (PSP) elements are integrated between each cell-pack and the hydraulic manifolds in the form of spiral tubes. These spiral tubes increase the effective electrolyte conduction path length between cell-packs, thereby increasing the electrical resistance of the pathway to hundreds of ohms and reducing the resulting shunt currents. This modular architecture enables the construction of high-voltage electrolyzer units operating at approximately 800 V, while maintaining minimal parasitic current losses. As a result, the technology can be scaled to large industrial installations suitable for GW-scale hydrogen production using multiple electrolyzer units.

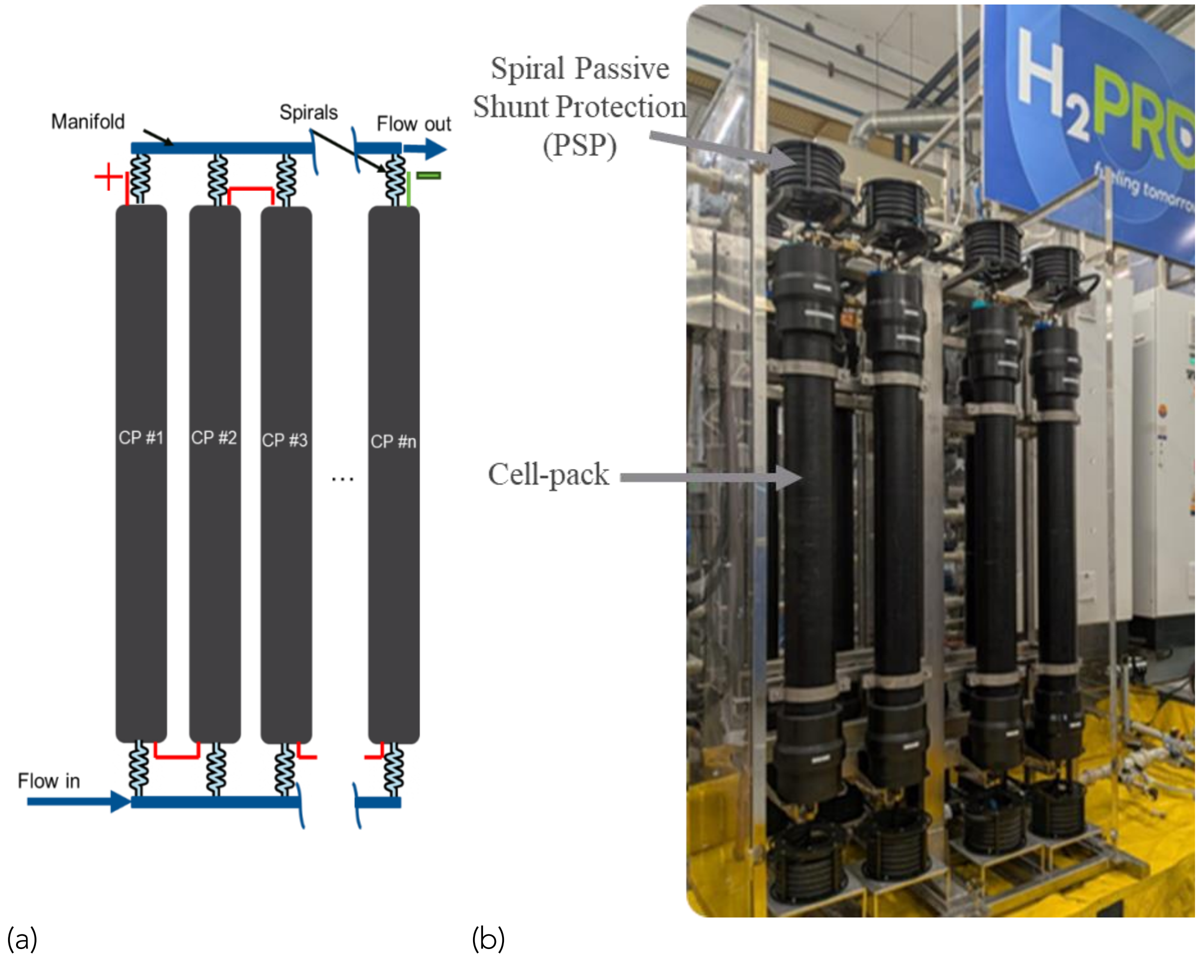


Figure 9. A scalable set, (a) A schematic showing the unit architecture where the CPs are connected in series electrically and in parallel hydraulically. (b) a a 200 [V] Set unit comprising of 8 CP.

H2Pro's electrolyzer set architecture is specifically designed to suppress shunt currents both within individual cell-packs and between cell-packs. This enables the construction of high-voltage electrolyzer sets while maintaining very low parasitic shunt current losses. Figure 10 illustrates the performance of a ~200 V H2Pro electrolyzer set, comprising 8 cell-packs (CPs), each containing 13 cells (104 cells total) with 54 layers per cell. Figure 10(a) presents both model predictions and experimental measurements of the current efficiency of the set. The graph shows that the electrical current efficiency remains high across a wide range of loads, reflecting the effective suppression of shunt currents in the system. The high electrical current efficiency translates into low specific energy consumption (SEC) over the same operating range. Figure 10(b) shows the measured SEC of a single electrode together with the calculated SEC of the full system, based on the electrode measurements and the measured electrical current efficiency.

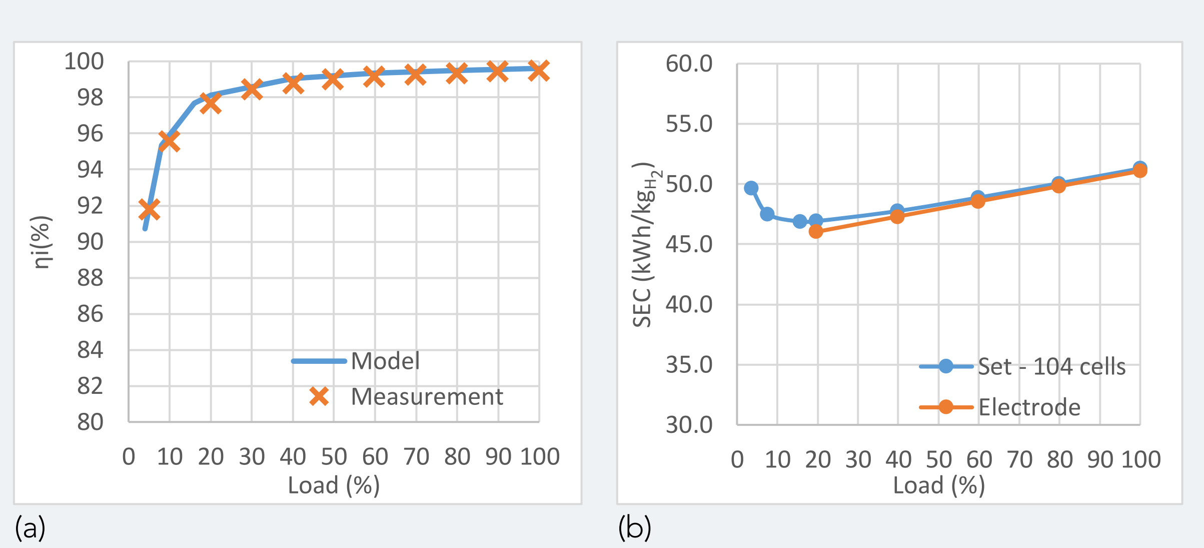


Figure 10. (a) Shows the electrical current efficiency both a model calculation and a measurement on the set for different loads. (b) shows the measured SEC of a single electrode and a expected SEC of H2pro pilot system based on SEC electrode measurements and measured current efficiency.

This multi-level architecture, which combines shunt-current mitigation at both the cell-pack and system levels, enables stable electrolyzer operation across a wide range of operating conditions. By minimizing shunt current losses, the system maintains high efficiency even under variable and partial-load operation. As demonstrated in Figure 10, the electrolyzer unit can operate efficiently down to approximately 10% of nominal load while maintaining high overall system efficiency. Further information about the unique DWE architecture can be found in H2pro's recent publication: PCT/IL2026/050246.

H2Pro’s DWE: A Renewable-Native Alternative to Legacy Electrolyzers

The analysis presented in this paper leads to a clear conclusion: the primary constraint on cost-competitive green hydrogen is no longer the cost of renewable electricity, but the ability of electrolysis systems to utilize it effectively. As long as electrolyzers are designed for steady-state operation, they will systematically fail to capture the lowest-cost renewable energy, incur degradation under intermittent conditions, and carry structural cost penalties that cannot be resolved through incremental improvements alone.

Achieving cost parity therefore requires a fundamental shift in system design. Rather than adapting legacy technologies to accommodate intermittency, electrolysis systems must be engineered from the outset to operate under it. Architectures capable of frequent start-stop operation, efficient performance across a wide load range, and resilience to dynamic operating conditions are not incremental improvements; they are foundational requirements for aligning hydrogen production with the realities of modern renewable energy systems.

H2Pro’s Decoupled Water Electrolysis (DWE) was designed to meet the needs of this new energy reality. Its membraneless architecture separates hydrogen evolution and oxygen evolution into two distinct stages, inherently avoiding both gas crossover and membrane degradation. Its unique bi-functional and chargeable electrodes (BFE and ChE) are designed to operate under both forward and reverse currents, making the system resilient to on/off cycling and reverse-current events. In addition, its electrochemical architecture intrinsically suppresses shunt currents, enabling efficient performance under variable load conditions. For these reasons, unlike legacy alkaline and PEM systems, H2Pro’s DWE is natively compatible with renewable energy sources and intentionally designed for intermittent operation.

The technology is now at TRL 7, with a field pilot system currently under construction and expected to be in full operation in the coming months, followed by a multi-megawatt off-grid demonstration system directly connected to solar PV. These deployments are intended to directly demonstrate the capabilities outlined in this paper, including hyper-flexible operation that can follow the exact output profile of the sun - efficient, safe, and reliable operation without degradation.

Ultimately, unlocking the lowest-cost renewable electricity is essential to reducing the levelized cost of hydrogen. Electrolysis technologies that can operate reliably under intermittent conditions will be critical to closing the cost gap with fossil-based hydrogen. Achieving this threshold will enable hydrogen to fulfill its role as a scalable energy carrier, strengthening energy resilience and supporting the development of robust, self-reliant energy systems.

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H$_2$PRO

April 2026 | White Paper Version 1

Green hydrogen will only reach cost parity once electrolyzers are engineered to survive cheap, intermittent renewable electricity

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