

The Rationale for a Standardized Testing Protocol for Anion Exchange Membrane Water Electrolyzers

Hydrogen production by water electrolysis is an area of growing interest, especially when coupled to intermittent renewable energy generation. The green hydrogen produced is a versatile energy carrier and is essential for industrial decarbonization, playing a critical role in sectors where direct electrification is challenging. Among the different water electrolysis technologies, anion exchange membrane water electrolysis (AEMWE) is seen as especially attractive as it combines many of the positive features from both proton exchange membrane (PEM) and alkaline electrolysis. Specifically, by using an ion-conductive membrane as the electrode separator, AEMWE can be paired with variable renewable energy sources (similar to PEM)¹. Furthermore, as AEMWE operates in alkaline conditions, a much larger variety of catalyst materials can be used, especially non-PGM metal-based catalysts². Despite these advantages, the most critical obstacle for the commercial viability of AEMWEs is their durability or the lifetime of the device³. The degradation of AEMWEs over time leads to increased operating cell voltages, thereby reducing efficiency and increasing hydrogen costs. While measuring the operating voltage before and after a period of operation may indicate the average cell degradation, it does not reveal which mechanism led to the voltage increase or whether the degradation behaviour is linear or non-linear over time. Although there are some excellent reviews detailing AEMWE technology^{4,5,6,7,8,9}, to date, there is limited data highlighting currently achievable stability or cell lifetime.

One issue with AEMWE research is the absence of an accepted standard for testing cell performance or degradation, a well recognized problem in literature^{10,11,12,9,8,13}. When assessing cell performance and stability, factors such as cell materials, catalyst loading, porous transport layers, and MEA preparation techniques are all expected to influence the performance and durability of AEMWEs. Decoupling each effect is complex when no standards are available. For instance, comparing newly developed anode materials across different laboratories would be much easier if a standard membrane and cathode were employed. Furthermore, while exploring the optimization of all parameters is essential for developing high performance AEMWEs, their performance and durability also heavily depend on op-

erational conditions (temperature¹⁴, circulating electrolyte flowrate¹⁵ and concentration¹⁶). Additionally, the electrochemical measurement techniques used in evaluating performance and stability. For example, generating a polarization curve via linear sweep voltammetry may misjudge the electrolyzer's performance if steady-state operation is not reached¹⁷. Consequentially, variability in not only cell parameters but also operating conditions and measurement techniques complicates comparisons between research groups.

In addition to the lack of standardization in cell testing protocols and components, there are few established performance targets for AEMWEs. IRENA has set AEMWE targets for 2050; $> 2 \text{ A cm}^{-2}$ at $< 2 \text{ V}$, with a suggested target lifetime of 100,000 h¹⁸. The first aim was used to establish a thermoneutral voltage efficiency target of $> 75\%$ at 2 A cm^{-2} , and the second to establish a target voltage decay rate of $< 2 \mu\text{V h}^{-1}$. Despite these targets, the majority of AEMWE studies operate at much lower current densities and rarely provide enough evidence that the target lifetime is achievable.

In this paper these issues are addressed and discussed by analyzing recent publications reporting AEMWE cell performance and / or stability. These have been analysed to identify 1) performance trends and 2) stability trends as a function of operating conditions (current density, temperature, membrane etc), to highlight the complexity of comparing studies conducted under different operating or test conditions and to recommend a set of standardized testing protocols.

Although reports exist for non-commercial membranes achieving 5.4 - 14.0 A cm^{-2} at 2 V^{19,20,21,22,23}, they are excluded from this analysis. We chose to focus our comparison on electrolyzers utilizing commercial membranes due to their widespread availability, established performance characteristics, and ease of accessibility, ensuring a comprehensive and reliable assessment of current practices in the field. As a wide range of operating conditions are used when evaluating AEMWE performance, before analyzing trends in stability data, the performance single-cell AEMWEs are compared (Fig. 1).

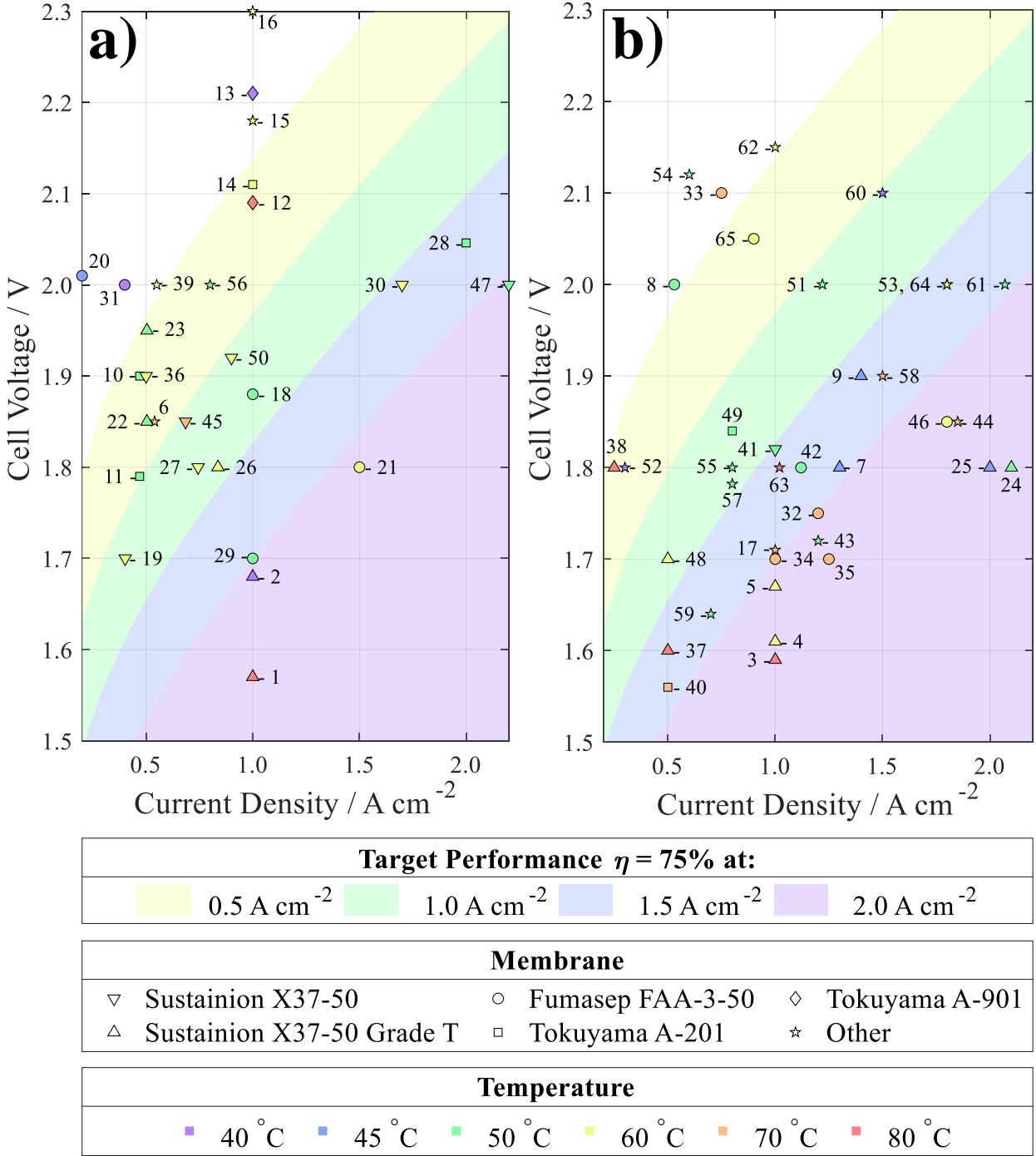


Figure 1: Performances of 65 different single-cell AEMWE set-ups using a) non-PGM-based catalysts, b) PGM-based catalysts. The membrane and operating temperatures of the cell are included. The four shaded regions represent cell performances predicted to achieve the desired efficiency targets, based on a phenomenological model of the Nernst and Tafel relationships (see Supplementary Information).

The goal of this analysis is to highlight any common factors that might be responsible for high cell performance. Unfortunately, no clear trends relating the membrane type or operating conditions to the cell performance are immediately obvious, likely due to the influence of additional variables on cell performance. For example, the initial conditioning of the membrane is a crucial step for determining cell performance. A significant drop in performance occurs within the first few hours, so it is important that a stable cell condition is achieved prior to testing. Karacan *et al.*²⁴ recommended using a time-independent potentiostatic conditioning technique, where the conditioning step runs until the variation in current density decreases to less than 1% per hour. Moreover, some results ascribed to certain membrane types or operating temperature may be misleading if the catalyst material is not considered. For example, those meeting the 75% target at 2.0 A cm^{-2} mainly use the Fumasep FAA-3-50 or Sustainion X37-50 Grade T membrane. However, 69% of these results also utilize PGM-based electrocatalysts (Fig. 1b). Furthermore, while AEMWEs would normally be assumed to perform better at elevated temperatures²⁵, the literature reports which exhibit the best performance are found at a wide range of operating conditions (see Table S7).

The lack of clear relationships between reported performances and operating conditions highlights the complexity of optimizing AEMWE cells. Several studies suggest a positive correlation between rising temperature and performance^{26,27,28,29}. However, upon closer examination of a larger dataset, this apparent relationship fails to hold true (Fig. 2a), despite the notable impact of temperature on cell performance when studied independently. While this does not necessarily call into question the relationship between temperature and AEMWE performance, these findings emphasize the importance of considering the broader research context and the inherent variations in testing conditions. Furthermore, they underscore the pressing need for standardization to decouple the multifaceted factors contributing to improved AEMWE performance.

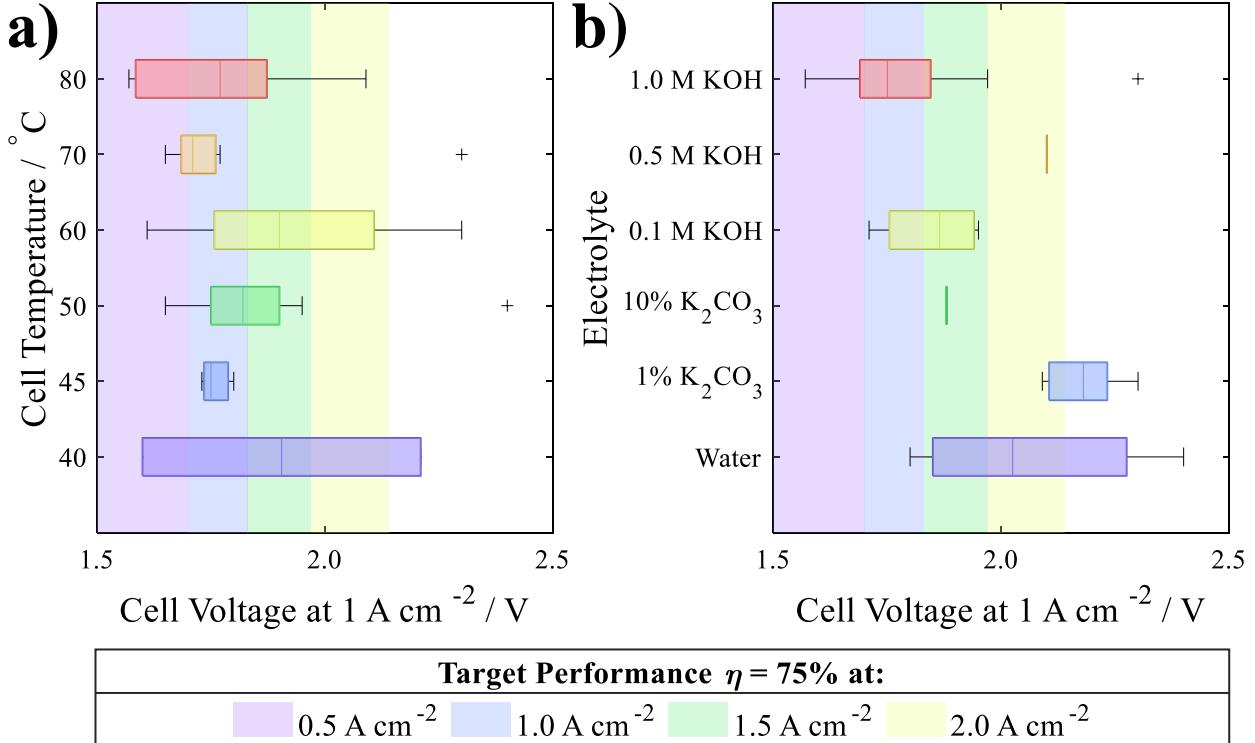


Figure 2: a) Performance of 65 different single-cell AEMWE set-ups at 1 A cm⁻² at various temperatures and, b) electrolytes. The four shaded regions represent cell performances predicted to achieve the desired efficiency targets, based on a phenomenological model of the Nernst and Tafel relationships (see Supplementary Information).

Over half of studies investigating the effect of electrolyte in AEMWEs find that 1 M KOH is most effective in achieving higher efficiency performances^{30,16}. The analysis performed here aligns with this conclusion, with the studies utilizing 1.0 M KOH appearing to show better performance at 1 A cm⁻² compared with other commonly utilized electrolytes (Fig. 2b). Particularly, it is clear that using pure water or K₂CO₃ solutions in the AEM cells generally leads to poor performance. While it is common practice for most cells to circulate 1.0 M KOH electrolyte (18% of studies reviewed here utilize 1.0 M KOH), the substantial variation in flow rates, choice of materials, and device designs suggests that high-efficiency AEMWE outcomes cannot be solely attributed to this electrolyte, as some studies using 0.1 M KOH performed equally well as studies using 1.0 M KOH.

The alkaline electrolyte is a core component of electrolyzer systems, affecting the properties at the electrode interface and the thermodynamic and kinetic properties of electrocatalytic reactions. The presence of metal impurities and inaccurate pH estimations can result in unreliable performance results. Although the inclusion of iron in nickel-based anodes contributes to achieving and sustaining low overpotentials, the presence of iron can lead to deactivation of PGM-based cathode catalysts³¹. To determine if the presence of Fe contributes to the observed inconsistencies, the performance of AEMWE systems with iron supplementing nickel-based anodes and those without are compared (Fig. S1). The analysis found that, on average, nickel-based anodes that included iron achieved lower cell voltages at 1 A cm⁻² than those that were iron-free (Fig. S1a). Furthermore, nickel-based anodes containing iron suffered higher rates of cell degradation when the cathode utilized a PGM-based catalyst when compared to non-PGM cathode catalysts (Fig. S1b). Xu *et al.*³² found there to be a strong correlation between the catalyst's electrical conductivity and AEMWE performance, with iron-containing species achieving higher performances in the AEMWE, attributing the improvement in performance to the increased intrinsic catalytic activity of iron-containing species and only moderately decreased electrical conductivity. Noting the significance of the dry catalyst electrical conductivity on full cell performance, dry conductivity measurements could be an effective technique for screening suitable catalysts for more efficient AEMWE systems. Additionally, in instances where the anolyte and catholyte can potentially mix via a shared electrolyte tank, researchers must decide on the optimal iron content in their system. Marquez *et al.*³³ advocated for the improvement of testing protocols and suggests the best practises for electrolyte preparation, removing Fe impurities, electrolyte standardization, determining composition by ICP-MS analysis, statistical quality control, and electrochemical testing, to validate the quality of alkaline electrolytes used in electrocatalytic systems. Additionally, they provide a general standard protocol for evaluating the electrocatalytic stability of lab-scale alkaline electrolyzers and a guideline for troubleshooting device operation and data acquisition³⁴.

The complexity deepens when attempting systematic comparisons due to the absence of a universally accepted benchmark AEMWE device⁸; instead, many studies propose their own baseline as a starting point for innovation (Tables S3, S4, and Fig. S4). As a potential solution to this issue, the adoption of benchmark AEMWE cells, as proposed by Fafeeh *et al.*³⁵, could become a pivotal component of a standardized testing protocol, facilitating more repeatable and coherent performance evaluations between research groups.

In exploring the performance characteristics of AEMWEs, it becomes evident that the ‘best reported performance’ polarization curves often showcase operations at higher temperatures and electrolyte concentrations along with higher current density ranges, in contrast to the conditions prevalent in durability studies. In fact, 64% of studies use lower current density; and 28% operate at lower temperatures for durability testing compared with the conditions used to determine the cell performance as reported in the studies abstract. While this highlights beneficial conditions for efficient hydrogen production, the translation for the devices suitability as a commercial technology is difficult to decipher. Marquez *et al.*³⁴ emphasized the importance of shifting the focus from achieving high performances, using impractical condition during testing, to understand the physical phenomena influencing cell behaviour under realistic operational conditions. By prioritizing realistic testing conditions, researchers can bridge the intrinsic properties of materials with the electrolyzer’s performance under similar environments representative of industrial usage³⁶. Furthermore, it would foster a more transparent and standardized evaluation framework within the research community.

Standardization has begun to develop for durability studies, with most evaluated at either 0.5 or 1.0 A cm⁻². However, the lack of standard testing times means the degradation rate is typically evaluated across the whole operating period, which is not an accurate representation of the electrolyzer’s stability and degradation behaviour, as it does not account for the variability in the degradation rate over time. For example, if the cell voltage increases > 10% within the first 10 hours but remained stable for 10,000 hours, the system would look

to be unstable if defined by average degradation. Standardizing long-term durability tests is complex, as they require extended periods to complete and can be resource intensive. As a result, some researchers may have limited scope for testing durability and conduct shorter-duration tests, which may not represent real-world operating conditions.

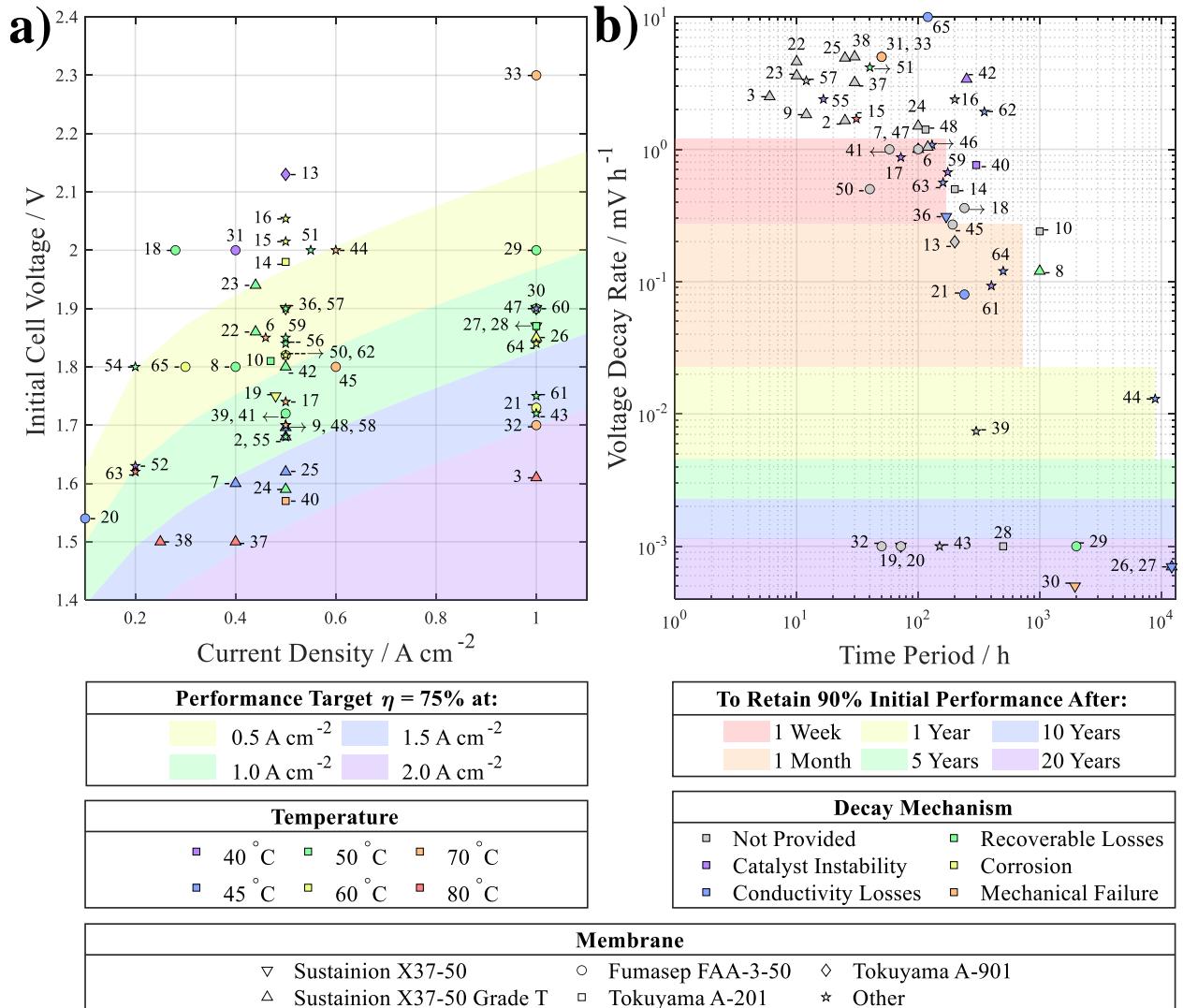


Figure 3: Stability test results from 54 different single-cell AEMWE set-ups. a) current density and initial cell voltage. The four shaded regions represent cell performances predicted to achieve the desired efficiency targets, based on a phenomenological model of the Nernst and Tafel relationships. b) time period used to determine the average voltage decay rate. The six shaded regions represent the decay rate predicted to achieve the desired performance retention targets, based on a first order relationship between cell voltage and time.

The results from durability studies (Fig. 3a) highlights devices to operate at lower effi-

ciencies than those achieved in performance testing, no longer meeting their initial targets. Of the 13 studies that initially achieved 75% efficiency at 2 A cm^{-2} during performance testing (Fig. 1), only 2 achieved that same target in stability measurements. In fact, 47% of results from stability tests no longer meet the efficiency target initially met in performance testing (see Supplementary Information Fig. S3). Additionally, it is worrying to see the majority of stability studies do not achieve an operating lifetime of even 1 week (Fig. 3b). While these results can still be useful to indicate operating conditions or materials that incite higher degradation, unfortunately 45% of studies do not complete post-experiment characterizations or provide a hypothesis for what causes the cell's instability.

Surprisingly, the results show that as the current density used in chronoamperometry studies increases, the cell degradation decreases (Fig. 4a). This seems counter-intuitive, as higher current density operation typically results in extreme bubble evolution on the electrode surface³⁷, which can result in membrane drying³⁸, increasing degradation³⁹. This trend may change at higher current densities; however, stability testing above 1 A cm^{-2} is uncommon. Furthermore, no observable trends were found between degradation and temperature (Fig. 4b and Fig. S2b) or circulating flow rate (Fig. 4c and Fig. S2a). Finally, it is noteworthy to observe that non-PGM catalysts, on average, demonstrate lower cell degradation compared to AEMWE cells using PGM-based catalysts (Fig. 4d). This observation underscores the promising potential of cost-effective non-PGM catalysts for enhancing the longevity of AEMWE devices.

Flow rate is known to impact electrolyzer performance, as higher flow rates effectively help remove product gases⁴⁰, allowing for optimal use of the surface for electrochemical reactions⁴¹ and minimising the possibility of localized 'hot-spots' which are known to damage the membrane. However, when using high electrode flow rates, increased forces acting on the catalyst layer and membrane, may facilitate catalyst particle erosion and mechanical degradation or failure of the membrane respectively. Despite this, the physical, systematic

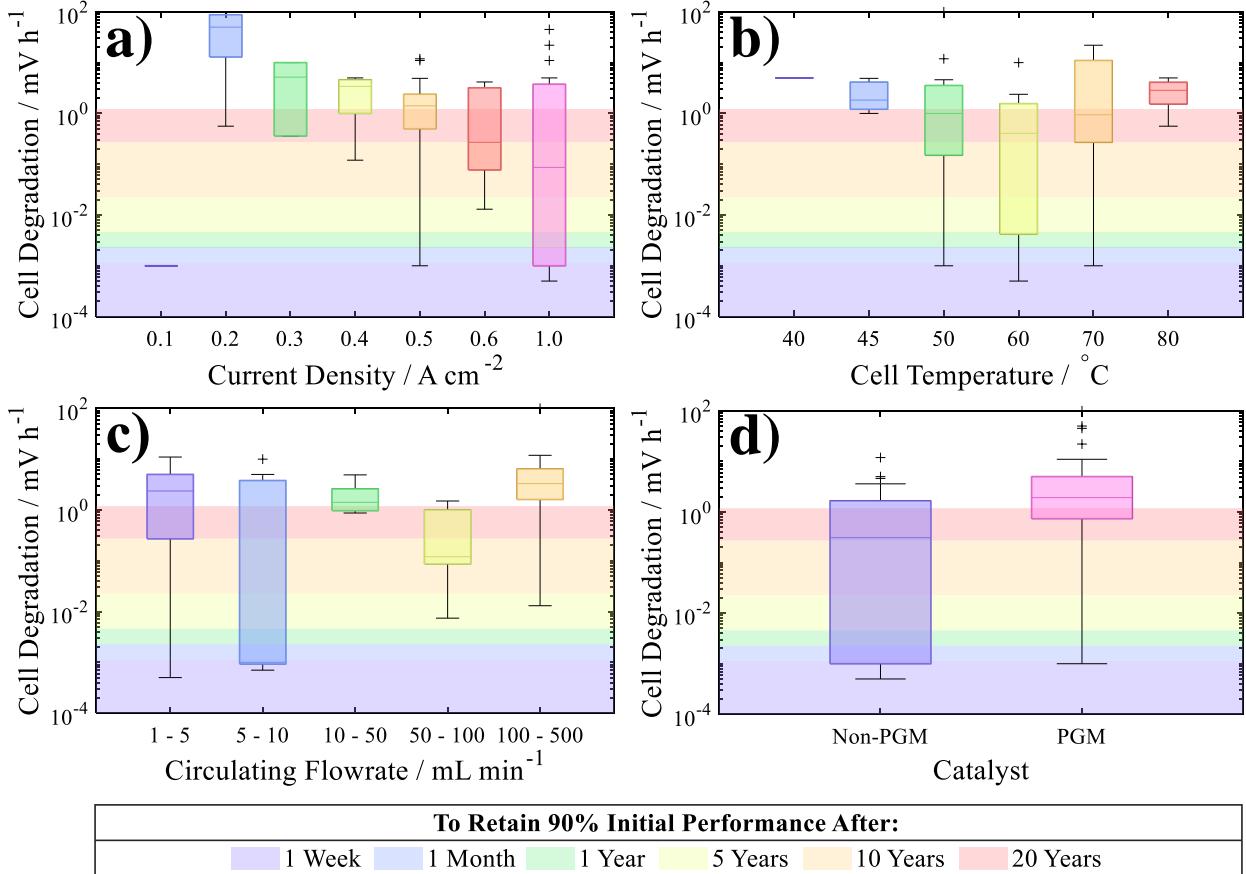


Figure 4: Average degradation rate of 54 different single-cell AEMWE set-ups and their reported a) current density, b) circulating flow rate, and c) cell temperature. The six shaded regions represent the decay rate predicted to achieve the desired performance retention targets, based on a first order relationship between cell voltage and time.

comparison of AEMWE flow rates and durability provides no clear relationship, adding to the complexities of device optimization.

Moreover, the flow rate is an important aspect to consider regarding gas crossover. Specifically, it directly impacts the boundary layer thickness adjacent to the membrane surface. Higher flow rates lead to a thinner boundary layer, thereby reducing the concentration gradient of the gases near the membrane interface. Consequently, this lowers the driving force for gas diffusion across the membrane, ultimately reducing the gas crossover⁴². This reduction in gas crossover not only contributes to safer operation and enhanced performance, as underscored by Barros *et al.*⁴³, but also helps minimize cell degradation. Hydrogen crossover, a

key factor in cell degradation, hampers overall cell efficiency by facilitating the hydrogen oxidation reaction, which generates HO· and HO₂· radicals. These radicals not only contribute toward membrane degradation but can also poison electrode materials, leading to a decline in catalytic activity, compounding the detrimental effects on electrolyzer performance⁴⁴. Aiming to foster the development of efficient, safe, and durable electrolysis systems, Park *et al.*⁴⁵ details three methods to measure gas permeability of ion-exchange membranes, providing the recommended standardized methodology for each.

Furthermore, considering the limited thermal stability of AEMWEs is well known⁹, the lack of a relationship between temperature and durability suggests the variations between testing setups and procedures may be preventing such trends from being observed. Moreover, both porosity and compression have significant effects on fluid transport and resistance. Despite the critical role of porous transport layers in low-temperature water electrolysis technologies, there is notably less research to optimize these components compared to similar studies on gas diffusion layers in fuel cells⁴⁶. To address this gap, Ouimet *et al.*⁴⁷ suggest implementing a set of standardized testing protocols to facilitate meaningful comparisons of porous transport layers between different institutions.

As mentioned above, one notable issue with many long-term AEMWE durability studies is that 45% do not provide any explanation for why the cell is stable or unstable, with only 33% of long-term durability studies conducting electrochemical impedance spectroscopy (EIS). Excluding EIS is a missed opportunity as it provides valuable insight into cell stability, including changes to the charge transfer resistance, double layer capacitance, and other parameters that are indicative of degradation^{27,48}. Furthermore, by combining EIS with other techniques such as XPS⁴⁹, XRD⁵⁰, SEM/TEM, and FTIR⁵¹, researchers can gain a more complex understanding of a cell's degradation mechanism.

The importance of establishing a universal benchmark is underscored by the round robin testing for PEMWE by Bender *et al.*⁵². In this study, five laboratories adopted identical

materials, test cells, and testing frameworks. While the deviation between different laboratories was 2-3 times higher than the lowest deviation observed at a single lab, the highest deviations observed were only one-tenth of those extracted from similar material sets in the literature. The higher deviation in literature values is a result of the inherent heterogeneity of data compiled from various studies, each characterized by unique experimental conditions, methodologies, and reporting practices. This underscores the importance of establishing standard testing frameworks. Recently, the European Union Joint Research Centre called for the standardization of electrolyzer testing protocols, and outlined test procedures and metrics for reporting AEMWE performance and durability⁵³, methodology for obtaining polarization curves⁵⁴, and recording electrochemical impedance spectra⁵⁵. Amador *et al.* supplied a comprehensive assembly, operation, and testing protocol for bipolar membrane water electrolyzers, additionally providing the expected results from the setup. By establishing the expected outcome for a benchmark setup, researchers can effectively identify deviations in their electrolyzer's performance, signalling potential issues or deficiencies. This proactive approach enables researchers to recognize when their device is operating below expectations, prompting them to initiate troubleshooting measures⁵⁶.

The results from this review reveal no considerable relationships between operating conditions, materials, or assembly variables and performance and durability when compared against wider literature. Due to the lack of standardized testing procedures, results of electrolyzer testing vary significantly and cannot be directly compared. To enable reliable comparisons of single-cell AEMWE performances, there is a pressing need to establish and universally adopt a testing protocol and benchmark system configuration. See the supporting information for the standard testing procedure and recommended testing protocols for each step (Table S1), additional standard testing procedures for specific measurements (e.g. dry catalyst conductivity measurements, porous transport layer porosity measurements, gas permeability measurements) (Table S2), a benchmark study recommendation with guidelines for metric reporting (Table S5), and recommended characterization techniques to determine

the degradation mechanism for catalysts, membranes, and ionomers (Table S6).

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Supporting Information Available

Phenomenological model used for establishing performance targets. Fe content effect on AEMWE performance. Stability of 65 different single cell set-ups at various flow rates and temperatures. The variation between performance and stability testing. Recommended testing protocols and benchmark study. Recommended post-experiment characterization techniques. A detailed table of electrolyzer set-ups from literature.

Supporting Information

The Rationale for a Standardized Testing Protocol for Anion Exchange Membrane Water Electrolyzers

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Phenomenological model and electrolyzer set-ups from literature

The phenomenological relationships used to establish the performance and stability targets for anion exchange water electrolyzers, and displayed as shaded regions were found using the following relationships.

Efficiency phenomenological model

Cell potential, E_{cell} , is the sum of the reversible potential, ohmic polarisation, and reaction overpotentials¹.

$$E_{cell} = E_{rev} + E_{ohmic} + \eta_{OER} + \eta_{HER} \quad (1)$$

Where E_{rev} is the reversible potential, E_{ohmic} is the ohmic polarisation, and η_{OER} and η_{HER} are the oxygen and hydrogen evolution reaction overpotentials. The ohmic polarisation is found by²:

$$E_{ohmic} = f(j) = R_{ohmic}(j) \quad (2)$$

Where the current density, j , given in units A cm⁻², and the ohmic resistance, R_{ohmic} , is given in units Ω cm². The oxygen and hydrogen evolution reaction overpotentials, η_{OER} and η_{HER} , are given by Eqs. 3 and 4 and expressed using the Tafel equation³:

$$\eta_{OER} = f(j) = \frac{RT}{(1-\alpha)F} \ln \left(\frac{j}{j_0^{OER}} \right) \quad (3)$$

$$\eta_{HER} = f(j) = \frac{RT}{\alpha F} \ln \left(\frac{j}{j_0^{HER}} \right) \quad (4)$$

Where R is the universal gas constant, 8.314 J mol⁻¹ K⁻¹, T is the temperature given in K, F is Faraday's constant, 96,495 C mol⁻¹, α is the transfer coefficient, and j_0^{OER} and j_0^{HER} are

the exchange current densities for the oxygen and hydrogen evolution reaction. The complete equation, Eq. 5, can be simplified further to Eq. 6, assuming the transfer coefficient is 0.5.

$$E_{cell} = E_{rev} + R_s(j) + \frac{RT}{(1-\alpha)F} \ln \left(\frac{j}{j_0^{OER}} \right) + \frac{RT}{\alpha F} \ln \left(\frac{j}{j_0^{HER}} \right) \quad (5)$$

$$E_{cell} = E_{rev} + R_s(j) + \frac{RT}{\alpha F} \ln \left(\frac{j^2}{j_0^{OER} j_0^{HER}} \right) \quad (6)$$

As the ohmic contributions toward the cell, Eq. 2, the oxygen evolution reaction overpotential, Eq. 3, and hydrogen evolution overpotential, Eq. 4, are a function of current density, j , the phenomenological relationship in Eq. 7 is found as:

$$E_{cell} = E_{rev} + A(j) + B \ln \left(\frac{j^2}{C} \right) \quad (7)$$

Using $E_{rev}^{25^\circ C} = 1.223$ V, $A = 0.2 \Omega cm^{-2}$, $B = 0.051$, ($\alpha = 0.5$, $T = 25$ °C, $R = 8.314$ J mol⁻¹, $F = 96,495$ C mol⁻¹). Solve for C at every known j and E_{cell} combination.

Stability phenomenological model

The following relationship was used establish the stability targets for anion exchange water electrolyzers and estimate the acceptable degradation rate at each time scale:

$$D_{cell} = \frac{\delta E}{\delta t} = \frac{E_{final} - E_{initial}}{t_{final} - t_{initial}} \quad (8)$$

Where E is the cell potential, given in V, and t is the time, given in hours. If the acceptable loss of performance over an electrolyzer lifetime is 90%, the estimated acceptable voltage decay rate of the cell, D_{cell} , to reach the required longevity can be found by Eq. 9:

$$D_{cell} = \frac{E_{initial}}{0.9(t_{requiredlifetime})} \quad (9)$$

Additional figures

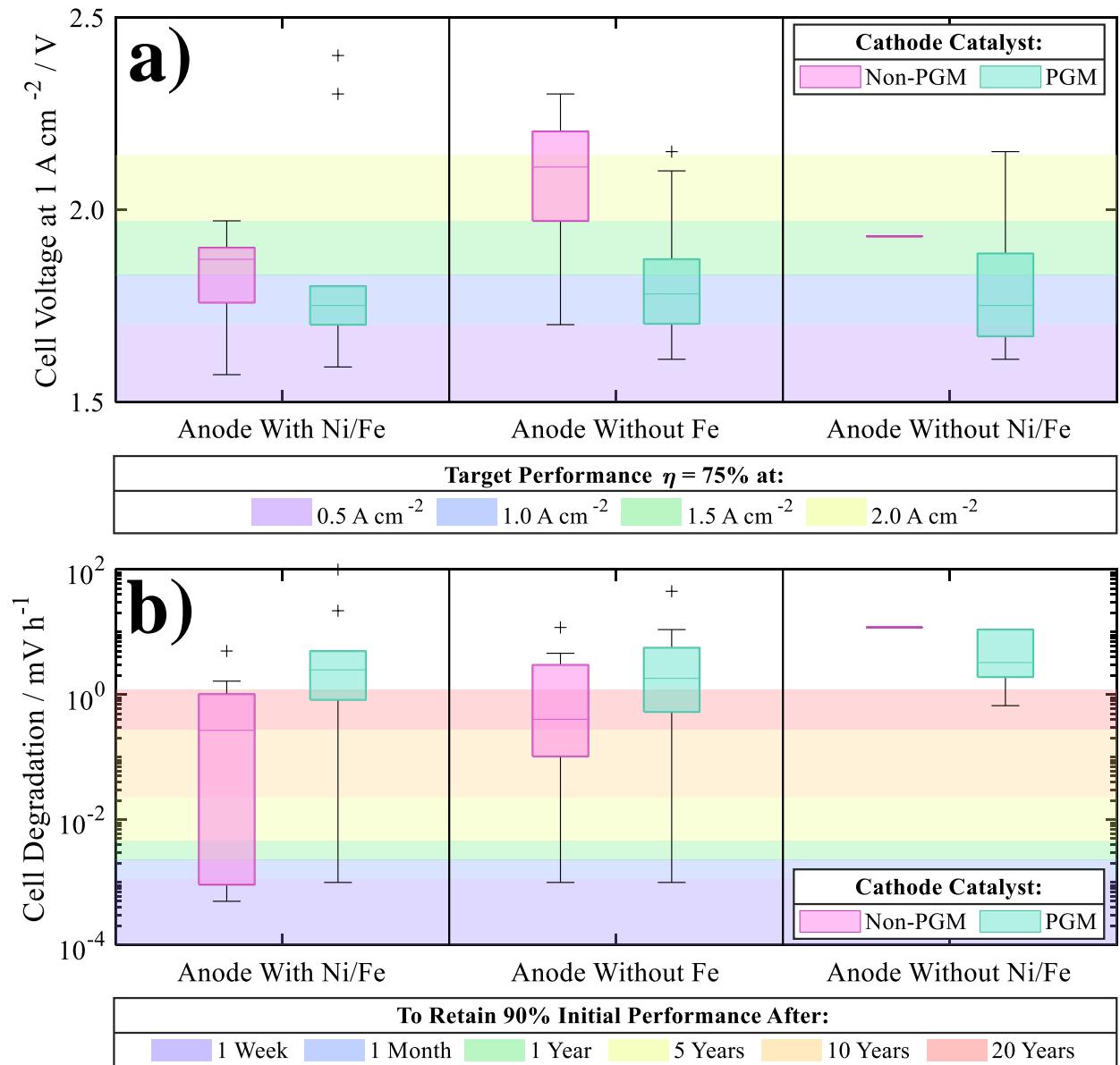
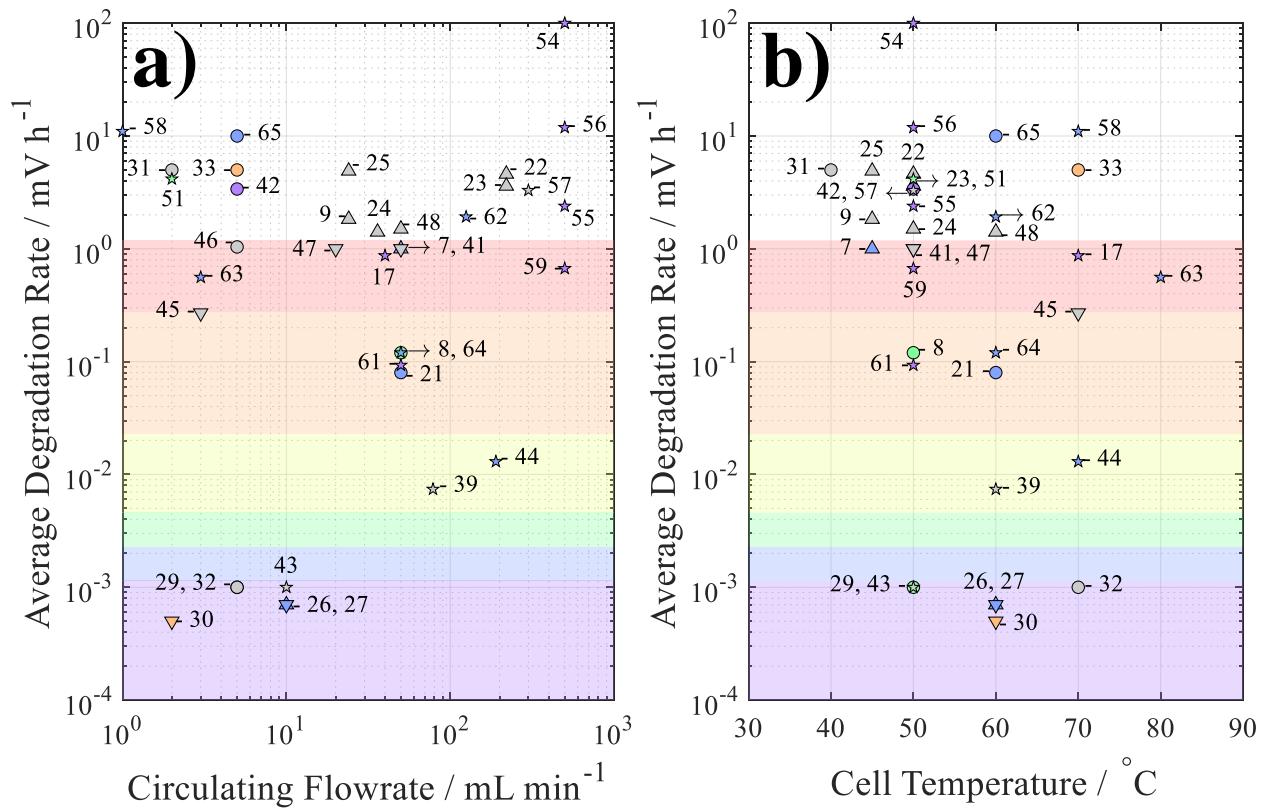


Figure S1: The effect of Fe presence at the anode on PGM and Non-PGM based cathode catalysts. a) performance at 1 A cm^{-2} . The four shaded regions in a) represent cell performances predicted to achieve the desired efficiency targets, based on a phenomenological model of the Nernst and Tafel relationships (Eq. 7). b) cell degradation rate. The six shaded regions represent the decay rate predicted to achieve the desired performance retention targets, based on a first order relationship between cell voltage and time (Eq. 9).



To Retain 90% Initial Performance After:								
 1 Week 1 Month 1 Year 5 Years 10 Years 20 Years								
Membrane								
▽ Sustainion X37-50			○ Fumasep FAA-3-50			◊ Tokuyama A-901		
△ Sustainion X37-50 Grade T			□ Tokuyama A-201			☆ Other		
Decay Mechanism								
□ Not Provided			□ Conductivity Losses			□ Corrosion		
■ Catalyst Instability			■ Recoverable Losses			□ Mechanical Failure		

Figure S2: Stability of 65 different single-cell AEMWE set-ups at various a) circulating flow rates, and b) cell temperatures. The six shaded regions represent the decay rate predicted to achieve the desired performance retention targets, based on a first order relationship between cell voltage and time (Eq. 9).

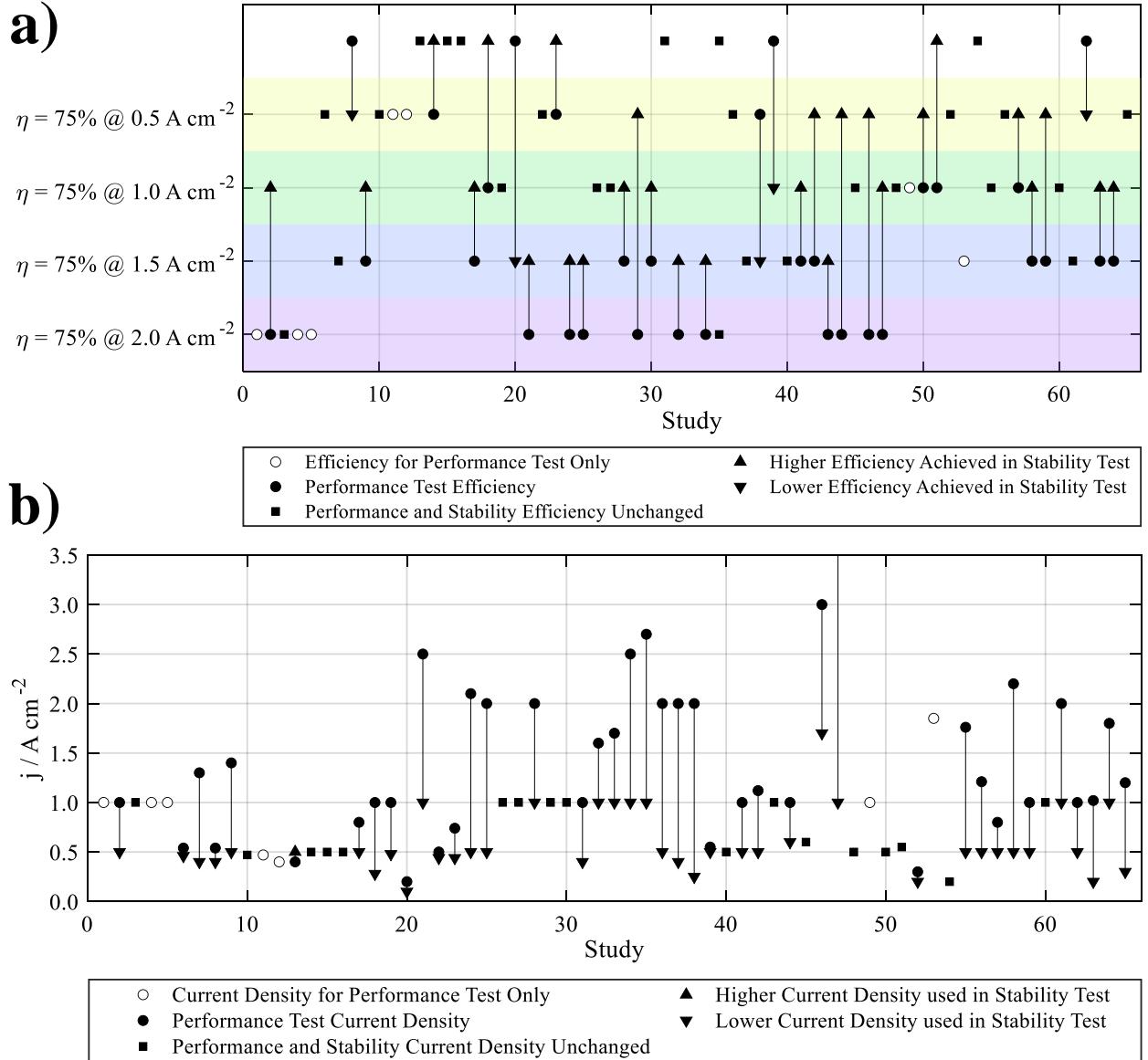


Figure S3: Variation between performance and stability testing. a) Variation between the efficiency target met in the performance test and that in the stability test. The four shaded regions represent cell performances predicted to achieve the desired efficiency targets, based on a phenomenological model of the Nernst and Tafel relationships (Eq. 7). b) The current density used to find the performance of the AEMWE and that used to operate the stability test.

Recommended testing protocols

Table S1: Recommended testing protocols for pre-activation, beginning of test assessment, stability testing, end of test assessment, and reporting for AEMWE.

Pre-activation	Electrolyzer start-up according to benchmark or deviated conditions	See Table S5
	Perform activation / conditioning	4
Beginning of test (BoT)	Perform BoT ex-situ characterization	5,6
	Perform a BoT electrochemical impedance spectra	7
	Perform a BoT polarisation curve	8
Stability test	Perform a BoT electrochemical impedance spectra	7
	Complete chronopotentiometric stability test	9,10
	Gas collection and determination of faradaic efficiency	10
End of test (EoT)	Perform a EoT electrochemical impedance spectra	7
	Perform a EoT polarisation curve	8
	Perform EoT ex-situ characterization	5,6, See Table S6
Reporting results	Report materials, operating conditions, and results	See Table S5

Additional standardized testing protocol recommendations

Table S2: Recommended testing protocols for pre-activation, beginning of test assessment, stability testing, end of test assessment, and reporting for AEMWE.

Pre-experiment	Three-electrode cell testing	11
ex-situ characterization	Dry catalyst electrical conductivity	12
	Ionic conductivity measurements	13
Full-cell testing	Assembling and operation of bipolar membrane water electrolyzers	14
	Resistance, porosity, and water contact angle of porous transport layers	15
	Gas permeability of membranes	16
	Electrochemical characterization and stability testing for AEMWE	9
	Electrochemical characterization of alkaline electrolyzers	17
	Electrolyte preparation and electrochemical testing	18
	Membrane conditioning	4
Post-experiment	Dynamic load testing to determine device suitability for grid services	19
ex-situ characterization	Component specific analysis of membrane electrode assemblies	6

Recommended benchmark study and metric reporting

Numerous studies establish their own individual benchmarks to gauge enhanced performance resulting from material optimization or operational adjustments. However, the absence of standardized benchmark catalysts, membranes, and catalyst/ionomer loading leads to substantial variability among the benchmark cells utilized (Table S3). This variance is further compounded by the use of non-commercial membranes in certain studies, complicating the establishment of a consistent baseline for expected performance. Furthermore, it facilitates progress tracking in the field over time. By comparing current performance against a standardized reference point, researchers can assess advancements, identify trends, and gauge the effectiveness of new developments or methodologies. Finally, the baseline serves as a quality control measure, ensuring the reliability and reproducibility of experimental results.

Table S3: Benchmark studies using various anode catalysts, membranes, ionomers, and cathode catalysts.

Anode		Membrane	Ionomer		Cathode		Electrolyte		Area	E _{cell}	Ref.	
mg cm ⁻²			wt.%	-	mg cm ⁻²	M	mL min ⁻¹	cm ²	V (1 A cm ⁻²)			
IrO ₂	2.0	Sustainion 37-50	Nafion	5	Pt	2.0	KOH	1.0	2	5	1.63	²⁰
IrO ₂	0.8	HTMA-DAPP	HTMA-DAPP	30	PtRu/C	0.4	KOH	1.0	100	5	1.80	²¹
-	-	Sustainion X37-50	PTFE	5	Pt/C	0.5	KOH	1.0	40	13	1.92	⁹
IrO ₂	2.2	Sustainion X37-50 GT	XA-9	5	Pt	2.2	KOH	1.0	-	1	1.85	²²
IrO ₂	3.0	NovaMea-25	XB-7	20	Pt/C	0.5	KOH	1.0	1	4	1.65	²³
Ni-Fe	2.5	FAA-3-50	FAA-3	33	Pt/C	1.0	KOH	1.0	5	5	1.77	²⁴
IrO ₂	2.5	PiperION-50	TP-85	10	Pt	2.5	KOH	1.0	500	1	1.67	²⁵
Ir	3.0	FAA-3PE-30	FAA-3	20	Pt/C	1.0	KOH	1.0	300	25	1.75	²⁶
Ir	3.0	FAA 3-PE	FAA-3	10	Pt	1.0	KOH	1.0	-	25	1.80	²⁷
IrO ₂	3.0	Sustainion X37-50 GT	FAA-3	-	Pt/C	1.0	KOH	1.0	50	5	1.80	²⁸
IrO ₂	1.0	PiperION-40	A5-HCO3	5	PtRu/C	1.0	KOH	0.1	10	5	1.65	²⁹
IrO ₂	5.0	Sustainion X37-50	FAA-3	-	Pt/C	1.0	KOH	1.0	50	3.8	1.77	³⁰
Ir	5.0	Sustainion X37-50	XB-7	-	Pt	5.0	KOH	1.0	-	1	1.60	³¹
Ir	3.0	Fumapem-3-PE-30	FAA-3	16	Pt/C	1.0	KOH	1.0	250	25	1.80	³²
IrO ₂	2.0	XL20-rPNB-LY100	TMA-70	10	PtRu/C	1.4	KOH	1.0	-	5	1.65	³³
IrO ₂	2.0	Sustainion X37-50	Nafion	10	Pt/C	0.4	KOH	1.0	10	5	1.80	³⁴
-	-	FAA-3-50	FAA-3	20	Pt/C	0.5	KOH	1.0	5	5	1.92	³⁵
IrO ₂	2.0	FAA-3-50	Nafion	9	Pt/C	2.0	KOH	1.0	80	5	1.88	³⁶
IrO ₂	2.0	FAA-3-50	QPC-TMA	20	Pt/C	0.4	KOH	1.0	1	5	1.73	³⁷
IrO ₂	3.0	FAA-3-50	Nafion	5	Pt/C	3.0	KOH	1.0	55	1	2.03	³⁸

A standardized performance baseline allows for meaningful comparisons between different studies, materials, or techniques. It enables researchers to evaluate the relative performance improvements achieved through optimizations or innovations accurately. Moreover, it helps researchers validate their findings by providing a reference point against which to verify the accuracy and consistency of their data. For example, if their benchmark performance is much lower than the baseline target, they may expect to find their optimized performance unexpectedly lower than other optimized cells in the literature. This insight allows for better-informed decision-making and interpretation of experimental outcomes.

Table S4: Benchmark studies using IrO_2 at the anode, Fumapem FAA-3-50 as a membrane, FAA as the ionomer, and Pt/C at the cathode.

Anode	Membrane	Ionomer	Cathode		Electrolyte		Area	E_{cell}	Ref.			
			mg cm ⁻²	wt.%	mg cm ⁻²	M						
IrO_2	5.0	FAA-3-50	FAA-3	10	Pt/C	1.5	KOH	1	50	5	1.81	39
IrO_2	3.0	FAA-3-50	FAA-3	20	Pt/C	0.5	KOH	1	5	5	1.90	40
IrO_2	3.0	FAA-3-50	FAA-3	20	Pt/C	0.5	KOH	1	5	5	1.70	41
IrO_2	4.0	FAA-3-50	FAA-3	10	Pt/C	1.0	KOH	1	4.5	5	1.85	42
IrO_2	3.0	FAA-3-50	FAA-3	20	Pt/C	0.5	KOH	1	5	5	1.90	43
IrO_2	2.0	FAA-3-50	FAA-3	20	Pt/C	0.4	KOH	1	1	5	1.80	44
IrO_2	2.0	FAA-3-50	FAA-3	20	Pt/C	0.4	KOH	1	2.5	5	1.90	45
IrO_2	2.0	FAA-3-50	FAA-3	20	Pt/C	0.4	KOH	1	1	5	1.70	46
IrO_2	3.0	FAA-3-50	FAA-3	20	Pt/C	0.5	KOH	1	5	5	1.92	47
IrO_2	2.0	FAA-3-50	FAA-3	15	Pt/C	0.4	KOH	1	1	5	1.65	48
IrO_2	0.5	FAA-3-50	FAA-3	20	Pt/C	0.4	KOH	1	1	5	1.75	49

To determine better determine the effectiveness of establishing a universal benchmark, the results from individual benchmarks using IrO_2 at the anode, Fumapem FAA-3-50 as a membrane, FAA as the ionomer, and Pt/C at the cathode (Table S4) were compared to benchmark studies using a variety of materials (Table S3). The deviation in cell voltage at 1 A cm^{-2} , E_{Cell} , was compared for the two sets of data who established their benchmark at 60°C , an anode catalyst loading of 2.0 mg cm^{-2} , a cathode catalyst loading of 0.5 mg cm^{-2} , or using 20 wt.% ionomer content (Fig. S4).

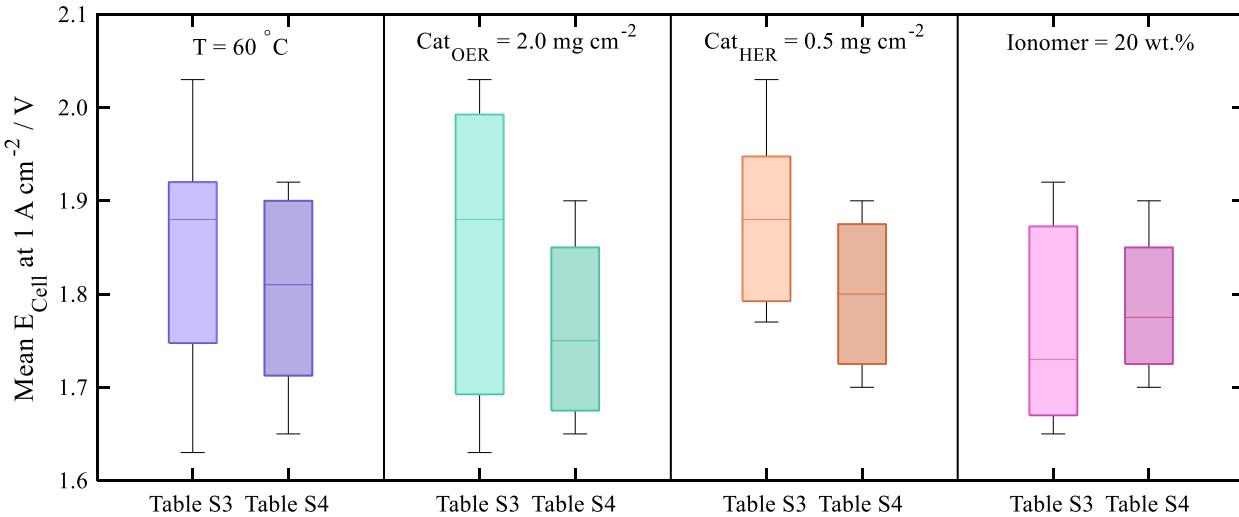


Figure S4: Mean cell voltage for general benchmarks used in literature (Table S3) and similar benchmark studies using IrO₂ at the anode, Fumapem FAA-3-50 as a membrane, FAA as the ionomer, and Pt/C at the cathode (Table S4). Highlighting the deviation in E_{Cell} at 60°C, anode catalyst loading of 2.0 mg cm⁻², cathode catalyst loading of 0.5 mg cm⁻², and 20 wt.% ionomer content.

Overall, studies employing the same set of materials (Table S4) demonstrated a higher level of reproducibility compared to those utilizing diverse materials (Table S3), underscoring the significance of a universal benchmark. While advocating for researchers to adopt a singular membrane, such as the Fumapem FAA-3-50 membrane, could prove effective, challenges related to material accessibility may arise. Thus, as a minimum standard, researchers should aim to utilize a commercially available membrane to approximate a universal reference point. For instance, the IrO₂ || FAA-3-50 || FAA || Pt/C assemblies achieved an average cell voltage of 1.81 V, this provides researchers employing this setup an expected result. In the future, upon adopting the benchmark, similar expected results can be collected for other commercial membranes. Additionally, the establishment of standard reporting metrics is crucial to facilitate easy comparisons among researchers. For instance, reporting cell voltage at 1 A cm⁻² instead of reporting the highest current density achieved, and reporting degradation rates in mV h⁻¹ instead of mA h⁻¹ enhances clarity and consistency across studies. Moreover, presenting all operating conditions and results in a singular table streamlines data compilation for cross-comparisons in the literature, saving readers valuable time. This standardized

approach not only improves accessibility to key information but also fosters collaboration and advances in the field.

The results from Fig. S4 have acted as guideline for the recommendations provided in Table S5 for a benchmark study. The most commonly used materials in existing benchmark studies, such as IrO₂ and Pt/C catalysts, and SS Felt, Ni Felt, and carbon paper porous transport layers have been adopted to allow researchers to utilize materials already in their supply. The most commonly used operational parameters (temperature of 60°C, anode catalyst loading of 2.0 mg cm⁻², cathode catalyst loading of 0.5 mg cm⁻², and 20 wt.% ionomer content) have also adopted.

Table S5: Recommended benchmark study and metric reporting table.

Metric	Units	Benchmark	Study No.
Experimental Setup			
End Plates	-	SS or Ti	
Anode Catalyst	-	IrO ₂	
Anode Catalyst Loading	mg cm ⁻²	2.0	
Anode Porous Transport Layer	-	SS or Ni Felt	
Anode Porous Transport Layer Thickness	mm	0.3	
Membrane	-	Commercial	
Membrane Electrode Assembly Technique	CCM/CCS	CCS	
Cathode Catalyst	-	Pt/C	
Cathode Catalyst Loading	mg cm ⁻²	0.5	
Cathode Porous Transport Layer	-	Carbon Paper	
Cathode Porous Transport Layer Thickness	mm	0.3	
Ionomer	-	Commercial	
Ionomer Concentration	wt.%	20	
Electrolyte	-	KOH	
Electrolyte Concentration	M	1	
Electrolyte Flowrate	mL min ⁻¹	> 2	
Temperature	°C	60	
Performance Results			
Ohmic Resistance	mΩ cm ²		
Cell Voltage at 100 mA cm ⁻²	V		
Cell Voltage at 500 mA cm ⁻²	V		
Cell Voltage at 1 A cm ⁻²	V		
Stability Results			
Ohmic Resistance Before Stability Testing	mΩ cm ²		
Ohmic Resistance After Stability Testing	mΩ cm ²		
Degradation Rate from 0 to X h	mV h ⁻¹		
Degradation Rate from 0 to 12 h	mV h ⁻¹		
Degradation Rate from 12 to X h	mV h ⁻¹		

Recommended post-experiment characterization techniques

Table S6: Recommended characterization techniques to determine degradation mechanisms for catalysts, membranes, and ionomers^{5,6}.

Component	Degradation Mechanism	Characterization	Why
Catalyst	Dissolution	XPS / EDS	Identify changes in elemental composition
		ICP-MS	Quantify dissolved catalyst elements in solution
		SEM / TEM	Visualise morphological changes from catalyst dissolution
	Corrosion	XPS / EDS	Identify elemental changes associated with corrosion products
		ICP-MS	Quantify corrosion products in solution
		SEM / TEM	Visualise morphological features indicative of corrosion
	Chemical Instability	XRD	Detect crystallographic changes in corroded regions
		XPS / EDS	Detect changes in surface chemistry and elemental composition
		XRD	Detect crystallographic changes that may indicate chemical instability
		XPS	Detect changes to surface chemistry from electrochemical processes
Membrane	Electrochemical Instability	EIS	Identify changes to charge transfer resistance
		CV	Assess catalyst stability under applied potentials
		SEM / TEM	Visualise changes in morphology or agglomeration of particles
	Structural Changes	XRD	Detect changes in crystal structure
		XPS / EDS	Identify surface contaminants or adsorbed species causing poisoning
	Poisoning	ICP-MS	Quantify trace contaminants that may be poisoning the catalyst
		FTIR	Detect change in functional groups or membrane / ionomer chemistry
	Chemical Instability	EIS	Provides insight into changes to the membrane's electrical properties
		FTIR	Identify functional group losses causing ion conductivity changes
	Ion-Conducting Group Loss	EIS	Provides insight into changes to membrane / ionomer ion conductivity
Membrane	Mechanical Instability	GC	Identify changes to the gas permeability of the membrane
	Thermal Stability	SEM / TEM	Visualise surface changes or damage to the membrane / ionomer layer
	Thermal Stability	FTIR	Identify structure changes by chain-scission or cross-linking
	Thermal Stability	DMA	Evaluate changes in mechanical properties from thermal degradation

AEMWE setup details from literature

Table S7: Operating specifications and testing conditions for several AEMWE setups.

	Anode	Membrane	Cathode	Electrolyte	Temp.	Ref.
1	Fe-NiMo-NH ₃ /H ₂ /NF	Sustainion® X37-50 Grade T	NiMo-NH ₃ /H ₂ /NF	1 M KOH	80 °C	50
2	Fe-NiMo-NH ₃ /H ₂ /NF	Sustainion® X37-50 Grade T	NiMo-NH ₃ /H ₂ /NF	1 M KOH	40 °C	50
3	NiFe-LDH/CP	Sustainion® X37-50 Grade T	Pt/C/CP	1 M KOH	80 °C	51
4	IrO ₂ /CP	Sustainion® X37-50 Grade T	Pt/C/CP	1 M KOH	60 °C	51
5	NiFe-LDH/CP	Sustainion® X37-50 Grade T	Pt/C/CP	1 M KOH	60 °C	51
6	NiFe-BTC-GNPs/NF	Fumasep® FAA-3-PK-130	NiMO ₄ /MoO ₂ /NF	UPW	70 °C	52
7	Cu _{0.5} Co _{2.5} O ₄ /NF	Sustainion® X37-50 Grade RT	Pt/C/CC	1 M KOH	45 °C	53
8	NiMn ₂ O ₄ /NF	Fumasep® FAA-3-50	Pt/C/CP	1 M KOH	50 °C	54
9	CuCo ₂ O ₄ /NF	Sustainion® X37-50 Grade T	Pt/C/NF	1 M KOH	45 °C	55
10	CuCoO ₃ /NF	Tokuyama A-201	Acta 4030/CC	1% K ₂ CO ₃	50 °C	56
11	CuCoO ₃ /NF	Tokuyama A-201	Acta 4030/CC	1 M KOH	50 °C	56
12	Acta 3030/NF	Tokuyama A-901	Acta 4030/CP	1% K ₂ CO ₃	80 °C	57
13	Acta 3030/NF	Tokuyama A-901	Acta 4030/CP	1% K ₂ CO ₃	40 °C	57
14	Acta 3030/NF	Tokuyama A-201	Acta 4030/CP	1% K ₂ CO ₃	60 °C	58
15	Acta 3030/NF	Fumasep® FAA-3	Acta 4030/CP	1% K ₂ CO ₃	60 °C	58
16	Acta 3030/NF	Fumasep® FAA-3-PP-75	Acta 4030/CP	1% K ₂ CO ₃	60 °C	58
17	Acta 3030/Ni Felt	Aemion™ AP1-HNN8-50	Pt/C/CC	0.1 M KOH	70 °C	59
18	a-NiFeOOH/N-CFP	Fumasep® FAA-3-50	MoNi ₄ /MoO ₂ /NF	UPW	50 °C	60
19	Ni ₂ P@FePOxHy/NF	Sustainion® X37-50	MoNi ₄ /MoO ₂ /NF	1 M KOH	60 °C	61
20	VCoCO _x /NF	Fumasep® FAA-3-50	VCoCO _x /NF	UPW	45 °C	62
21	Fe _x Ni _{1-x} P _{0.5} S _{0.5} /NF	Fumasep® FAA-3-50	Fe _x Ni _{1-x} P _{0.5} S _{0.5} /NF	1 M KOH	60 °C	39
22	Cu _{0.75} Co _{2.25} O ₄ /NF	Sustainion® X37-50 Grade T	NiCoO-NiCo/C/CC	1 M KOH	50 °C	63
23	Cu _{0.75} Co _{2.25} O ₄ /NF	Sustainion® X37-50 Grade T	NiCoO-NiCo/C/CC	0.5 M KOH	50 °C	63
24	NiFeV LDH/NF	Sustainion® X37-50 Grade T	Pt/C/CC	1 M KOH	50 °C	64
25	Ni _{0.75} Fe _{2.25} O ₄ /NF	Sustainion® X37-50 Grade T	Pt/C/NF	1 M KOH	45 °C	65
26	NiFe ₂ O ₄ /SS	Sustainion® X37-50 Grade T	Raney Ni/Ni Fibre	1 M KOH	60 °C	66
27	NiFe ₂ O ₄ /SS	Sustainion® X37-50	Raney Ni/Ni Fibre	1 M KOH	60 °C	66
28	Ni(OH) ₂ -Fe/NF	Tokuyama A-201	Raney Ni/Ni Foam	1 M KOH	50 °C	67
29	NiMo/KB/Ni Felt	Fumasep® FAA-3-50	NiFeO _x /CP	1 M KOH	50 °C	24
30	NiFe/Steel Felt	Sustainion® X37-50	NiFeCo/CP	1 M KOH	60 °C	68
31	10.1-NiFe/CP	Fumasep® FAA-3-50	Ni/CP	1 M KOH	40 °C	69
32	Ni-Fe/NF	Fumasep® FAA-3-50	Pt/C/CP	1 M KOH	70 °C	28
33	Ni-Fe/Ti Felt	Fumasep® FAA-3-50	Pt/C/CP	1 M KOH	70 °C	28
34	NiFe/SS	Fumasep® FAA-3-50	Pt/C/CP	1 M KOH	70 °C	28
35	IrO ₂ /SS	Fumasep® FAA-3-50	Pt/C/CP	1 M KOH	70 °C	28
36	Acta 3030/NF	Sustainion® X37-50	Acta 4030/CP	UPW	60 °C	70
37	Ir-Ni/Mo ₅ N ₆ /NF	Sustainion® X37-50 Grade T	Ir-Ni/Mo ₅ N ₆ /NF	1 M KOH	80 °C	71
38	Ir-Ni/Mo ₅ N ₆ /NF	Sustainion® X37-50 Grade T	Ir-Ni/Mo ₅ N ₆ /NF	UPW	80 °C	71
39	NF	Fumasep® FAA-3-PK-130	MoO ₂ /Ni/NF	1 M KOH	60 °C	72
40	Cu ₂ S@NiFe LDHs/Cu Foam	Tokuyama A-201	Pt/C/CP	1 M KOH	70 °C	73

	Anode	Membrane	Cathode	Electrolyte	Temp.	Ref.
41	NiMoO ₄ /NF	Sustainion® X37-50	Pt/C/CC	1 M KOH	50 °C	74
42	Ni-doped CoP/NF	Fumasep® FAA-3-50	Pt/C/CP	1 M KOH	50 °C	75
43	IrO ₂ /NF	Fumasep® FAA-3-PK-30	NS-Ru@NiHO/Ni ₅ P ₂	1 M KOH	50 °C	76
44	IrO _x /Ni Felt	Aemion+® AF2-HWP8-75-X	Pt/C/Ni Felt	1 M KOH	70 °C	77
45	V-NiFeOOH/Ni ₃ N/NF	Sustainion® X37-50	MoNi ₄ /MoO ₂ @Ni/NF	UPW	70 °C	78
46	NiFe ₂ O ₄ (CCM)/NF	Fumasep® FAA-3-50	Pt/C/CP	1 M KOH	60 °C	47
47	NiFe/TP-4	Sustainion® X37-50	NiMo/TP-4	1 M KOH	50 °C	79
48	TPP-coated NiFe/CP	Sustainion® X37-50 Grade T	Pt/C/CP	1 M KOH	60 °C	80
49	Acta 3030(CCM)/NF	Tokuyama A-201	Pt/C(CCM)/CP	10wt% K ₂ CO ₃	50 °C	81
50	NiFeCr LDH/NF	Sustainion® X37-50	V-Ni ₂ P/Ni ₁₂ P ₅ /NF	1 M KOH	60 °C	82
51	Ir/SS	Sustainion® X37-50 Grade RT	Co _{0.5} Mo _{0.5} S _x /SS	0.1 M KOH	50 °C	83
52	Ce _{0.2} MnFe _{1.8} O ₄ /Pt on Ti	Fumasep® FAA-3-PK-130	Ni/Pt on Ti	UPW	25 °C	84
53	Ir/Ti Felt	Fumasep® FAA-3-PE-30	NiCu MMO/KB/CP	1 M KOH	50 °C	85
54	NiCoO _x :Fe/Pt on Ti	Fumasep® FAA	Pt/C/CP	UPW	50 °C	12
55	Ir/Ti	Aemion™ AF1-HNN8-25-X	Pt/C/CP	0.1 M KOH	50 °C	86
56	Ir/Ti	Aemion™ AF1-HNN5-50-X	Pt/C/CP	0.1 M KOH	50 °C	86
57	Ni ₉₀ Fe ₁₀ /Au on Ti Felt	Fumasep FAA-3-PE-30	Pt/C/CP	0.1 M KOH	50 °C	87
58	IrO ₂ (CCM)/Ti Felt	Orion TM1™	Pt/C(CCM)/CP	1 M KOH	70 °C	46
59	IrO ₂ /SS	PiperION TP-85 50	Pt/C/CP	1 M KOH	50 °C	25
60	IrO ₂ (CCM)/Ni Felt	Aemion™ AF2-HLE7-25-X	Pt/C(CCM)/CP	0.1 M KOH	25 °C	88
61	Ni ₃ Fe LDH/Ni Fibre	DURAION®	Pt/C/CP	1 M KOH	50 °C	89
62	Co ₃ O ₄ /SS	Versogen™ PAP-TP-85	Pt/C/CP	UPW	60 °C	90
63	Fe _x Ni _y OOH-20F/NF	Versogen™ PAP-TP-85	Pt/C/CP	UPW	80 °C	91
64	NiS ₂ /Ni ₃ S ₂ /CP	Aemion™ AF1-HNN8-50-X	Pt/C/CP	1 M KOH	60 °C	92
65	IrO ₂ (CCM)/NF	Fumasep® FAA-3-50	Pt/C(CCM)/NF	0.5 M KOH	60 °C	40

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