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VIEWPOINT

Technology Landscape of Anion Exchange Membrane Water Electrolyzers: Where Are We Today?

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The production cost of green hydrogen using mature technologies, such as alkaline water electrolyzers (AWEs) and proton exchange membrane water electrolyzers (PEMWEs), is higher than gray and blue hydrogen, making green hydrogen less competitive.[1] Among emerging electrolyzer technologies, anion exchange membrane water electrolyzers (AEMWEs) have gained attention due to their lower operational expenditures (OPEX) compared to AWEs and reduced capital expenditures (CAPEX) relative to PEMWEs.[2−4] Despite rapid advancements from 2016 to 2024 (Figure S1), AEMWEs still face challenges in performance, stability, and scalability compared to AWEs and PEMWEs. To advance AEMWE technology toward commercial viability, it is crucial to understand its status and identify efficient directions. This involves not only monitoring key performance indicators (KPIs) across various reports, but also identifying key parameters driving developmental trends, understanding their relationships with performance and stability, and recognizing the gap between current status and commercial deployment.

However, various combinations of cell and operating parameters in AEMWE make it difficult to decouple their effects on performance and stability, complicating fair evaluation and direct comparison of results in AEMWE reports. Additionally, as the field is advancing rapidly, even the same cell component or operating condition can yield different results depending on its combination with new parameters introduced by recent innovations. Consequently, statistical analysis of extensive AEMWE data often results in statistically insignificant correlation between key parameters and KPIs.[5]

Despite these challenges, this Viewpoint analyzes the impact of cell and operating parameters on AEMWE performance and stability. This is achieved by focusing on promising results (i.e., potential) of parameters that meet U.S. Department of Energy (DOE)'s target KPIs: current density >2 A/cm^2 at 1.8 V for performance and voltage degradation rate (dE/dt) < 4 μV/h for stability.[6] We identify distinct characteristics of high-performance and high-stability systems, compare the status of academia and industry, reveal gaps in AEMWE development, and propose research directions to bridge these gaps (Figure S2).

We collected data that demonstrated promising performance or stability comparable to the DOE targets (Table S1). For detailed information on performance and stability metrics, as well as performance unit conversion, see Supporting Notes 1 and 2. Among the many parameters, we focused on six key cell parameters: anode catalyst, cathode catalyst, anion exchange membrane (AEM), membrane electrode assembly (MEA), anode porous transport layer (PTL), and cathode gas diffusion layer (GDL), and three key operating parameters: electrolyte OH^- concentration ($[OH^-]$), temperature, and operating current density. Other parameters were excluded due to insignificant qualitative correlation with performance and stability or insufficient data to observe trends.

High-Performance System. We investigated how operating conditions, such as electrolyte OH^- concentration and temperature, affect AEMWE performance. Figure S3a shows that using 1 M $[OH^-]$ leads to better performance than lower $[OH^-]$ like 0.1 or 0 M (i.e., pure water). Based on this, we further examined the impact of temperature using 1 M $[OH^-]$ electrolyte. Figure S3b indicates that higher temperatures lead to better performance, with the highest performance at 80 °C. However, temperatures of 50, 60 and 70 °C also achieved sufficiently high performance above 2 A/cm^2 at 1.8 V.

We compared the impact of six cell parameters on AEMWE performance in 1 M $[OH^-]$ electrolyte at two common operating temperatures (60 and 80 °C), as shown in Figure 1 and Figure S4. To simplify the analysis, each cell component was categorized based on its type.

For anode and cathode catalysts, we categorized them into platinum group metal (PGM) and non-PGM. Figure 1a shows that PGM anode catalysts (i.e., Ir-based) generally outperform non-PGM anode catalysts (e.g., Ni, NiFe-based) at both 60 and 80 °C. However, both PGM and non-PGM anode catalysts can achieve current densities above the DOE target of 2 A/cm^2 at 1.8 V. This result indicates that non-PGM anode catalysts can eventually replace PGM anode catalysts like IrO_2, which are still commonly used to achieve high performance in many reports.[7,8]

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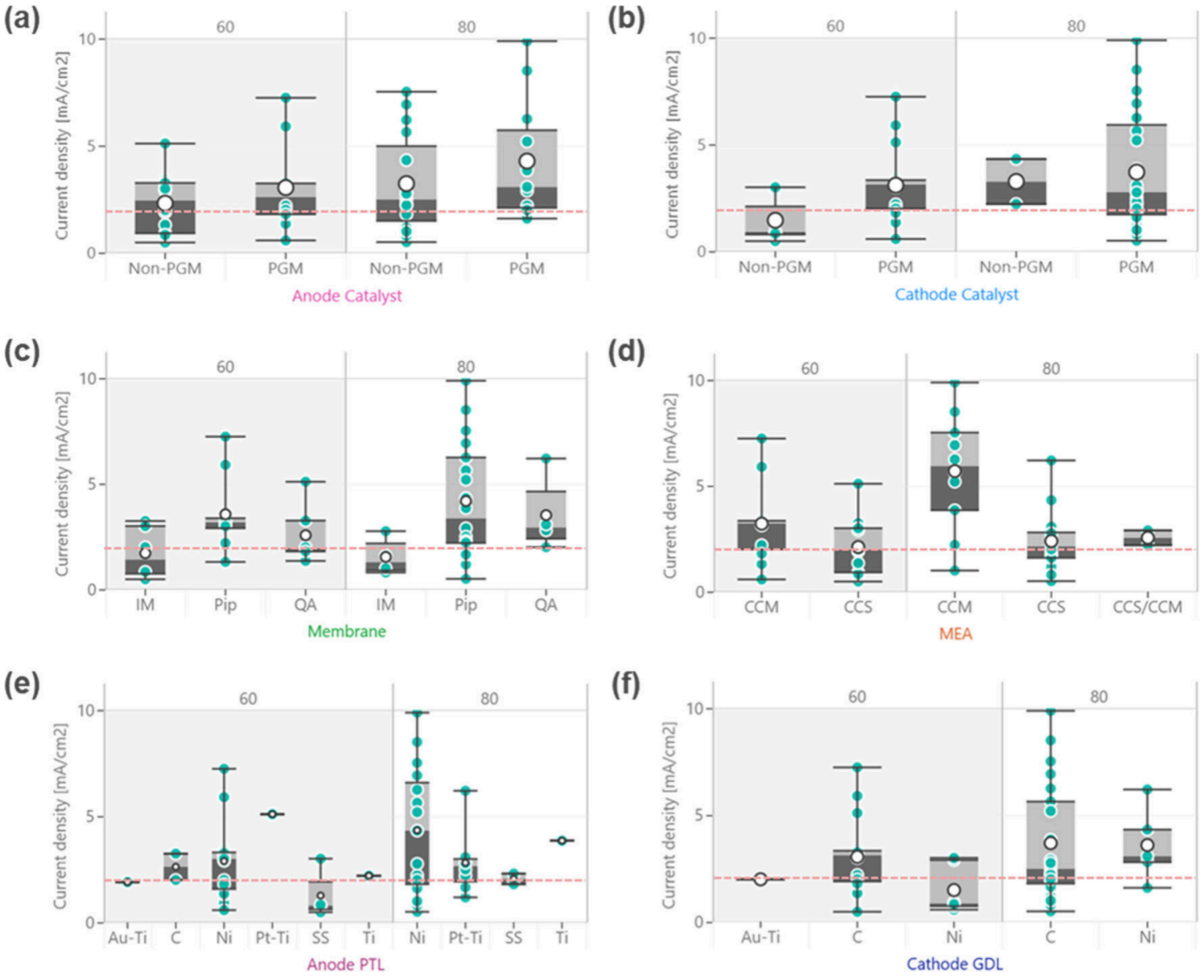

Figure 1. Impact of six key cell parameters on AEMWE performance at 1.8 V at temperatures of 60 and 80 °C. (a) Anode catalyst, (b) cathode catalyst, (c) membrane, (d) MEA configuration, (e) anode PTL, and (f) cathode GDL. The red dashed line represents the DOE's target performance of 2 A/cm^2 at 1.8 V.

Figure 1b indicates that PGM cathode catalysts (e.g., Pt, PtRu-based) typically outperform non-PGM cathode catalysts (e.g., Ni, Co, NiFeCo, NiMo-based) more substantially than anode catalysts. There are fewer reports on AEMWE using non-PGM cathode catalysts, likely due to their lower performance, suggesting that PGM cathode catalysts will likely remain the primary choice for the foreseeable future. However, two recent reports show that non-PGM cathode catalysts can achieve sufficiently high performance (around and above 2 A/cm^2 at 1.8 V),[9,10] indicating potential for further development.

The AEMs were categorized into three subgroups by their functional groups: imidazolium (IM), piperidinium (Pip), and quaternary ammonium (QA). All AEMs in this study used ether-free polymer backbones, which exhibit higher oxidative stability for AEMWE applications.[11] See Supporting Note 3 for commercial AEMs under each category. Figure 1c shows that Pip-based AEMs typically exhibits the highest performance, followed by QA and IM-based AEMs at both 60 and 80 °C. However, all three types of AEMs can achieve sufficiently high performance above 2 A/cm^2 at 1.8 V. Additionally, as opposed to positive effect of high temperature on performance in Figure S3b, IM-based AEMs did not exhibit noticeable performance enhancement at 80 °C compared to 60 °C.

MEA configurations were classified into catalyst-coated membrane (CCM), catalyst-coated substrate (CCS), and a combination of CCS for one electrode and CCM for the other (CCS/CCM). Figure 1d shows that CCM generally performs better than CCS and CCS/CCM, but all three configurations can achieve performance above 2 A/cm^2 at 1.8 V. This result suggests that although CCM is preferred over CCS for PEMWE due to lower contact resistance and PGM catalyst loadings,[12−14] both CCM and CCS could be viable MEA configurations for advanced AEMWE.

Anode PTLs were categorized into six types based on materials: carbon (C), nickel (Ni), stainless steel (SS), titanium (Ti), Au-coated Ti (Au−Ti), and Pt-sintered (or platinized) Ti (Pt−Ti). For cathode GDLs, three types (C, Ni, Au−Ti) were used. The structures of anode PTLs and cathode GDLs includes foam, felt, mesh, and paper. Figure 1 panels e and f show that all types of anode PTLs and cathode GDLs have the potential to achieve performance above 2 A/cm^2 at 1.8 V.

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Table 1 summarizes the characteristics of a high-performance system. Most combinations of cell components can achieve high performance above 2 A/cm^2 at 1.8 V, even for non-PGM cathode catalysts. The optimal combination for the best performance could include PGM or non-PGM for anode catalyst, PGM for cathode catalyst, Pip for AEM, CCM for MEA, Ni or Pt−Ti for anode PTL, and C for cathode GDL.

Table 1. Summary of Distinct Characteristics of High-Performance and High-Stability Systems[a]

	High-Performance System	High-Stability System
Anode Catalyst	PGM, Non-PGM	PGM, Non-PGM
Cathode Catalyst	PGM > Non-PGM	PGM, Non-PGM
AEM	Pip > QA > IM	QA, IM
MEA	CCM > CCS	CCS
Anode PTL	Ni, Pt−Ti > Ti, Au−Ti, C, SS	Ni, SS
Cathode GDL	C Ni, Au−Ti	C, Ni
Temperature	80 °C > 70 °C > 60 °C > 50 °C	50−70 °C
Electrolyte [OH$^-$]	1 M > 0.1 M, 0 M	0.1−1 M
Current Density		0.2−1 A/cm^2

[a]The inequality sign indicates the order of performance.

High-Stability System. We investigated the stability of AEMWEs using the plot of dE/dt versus stability testing time, as shown in Figure S5 and Figure 3. Here, stability testing time represents the reliability of the measured dE/dt. The high stability region is defined by dE/dt values lower than 10 μV/h and stability testing time longer than 1000 h, highlighted in yellow. Given the early stage of AEMWE development and its lower stability compared to AWE and PEMWE, we evaluated the potential of parameters for promising stability by identifying those within the high stability region, rather than employing statistical comparisons. The threshold of 10 μV/h was chosen because it is in the same order as the target dE/dt of 4 μV/h. The 1000 h standard was selected to avoid initial abrupt degradation or electrochemical activation, which typically occurs within this period[4,15]

The impact of operating conditions (electrolyte [OH$^-$], temperature, and current density) on stability was examined (Figure S5). Note that stability test conditions often differ from performance test conditions (Table S1), complicating the understanding of relationship between performance and stability, which will be discussed in the Supporting Note 4.

Figure S5a shows that 0.1−1 M [OH$^-$] (i.e., alkaline electrolyte) demonstrates stable operation, while 0 M [OH$^-$] (i.e., pure water). Although using pure water in AEMWE, like in PEMWE, avoids caustic electrolyte handling and reduces costs,[16] it results in reduced stability and needs further research and development. Figure S5b shows that the operating temperatures between 50 and 70 °C fall within the high stability region. No high stability reports exist for 80 °C operation, although 80 °C offers the highest performance, suggesting an important trade-off. Figure S5c shows that the high stability region includes current densities from 0.2 to 1 A/cm^2. Higher current densities above 1 A/cm^2 fall outside this region and are rarely used for stability tests, possibly due to accelerated electrochemical dissolution and detachment of catalysts and membrane degradation.[3,17] This suggests that high-performance reports exceeding the DOE target performance may not be durable at these high current densities.

Figure 2 compares the impact of six key cell parameters on AEMWE stability. Regarding catalysts, both PGM and Non-PGM catalysts for the anode and cathode are reported in the high stability region, indicating their potential for high stability (Figure 2a,b). For AEM, IM and QA-based AEMs are reported in the high stability region, while Pip-based AEMs, despite their best performance, are not yet observed in the high stability region to the best of our knowledge (Figure 2c). Regarding MEA configuration, high stability was reported only with CCS, not CCM, which contrasts with the performance trend favoring CCM for higher performance (Figure 2d).

For anode PTL, only Ni and SS are in the high stability region, while Ti, Pt−Ti, Au−Ti, and C generally show poor stability (Figure 2e). For cathode GDL, C and Ni fall into the high stability region, while Au−Ti exhibits poor stability (Figure 2f). These trends differ from performance trends in Figure 1e,f, where all types can achieve high performance (>2 A/cm^2 at 1.8 V). Ti-based anode PTLs and cathode GDLs, adopted from PEMWE technology, requires caution due to differences in electrolyte type (e.g., water vs. KOH) and pH levels (acidic vs alkaline). Ti-based anode PTLs with protective Pt and Au coatings (i.e., Pt−Ti, and Au−Ti), which are relatively stable in PEMWE's acidic environment,[18] tend to exhibit poor stability in AEMWE's alkaline condition. Carbon should be avoided for anode PTLs as it can dissolve into carbonate under harsh oxidative conditions at the anode.[19]

Table 1 summarizes the characteristics of a high-stability system, which includes PGM or non-PGM catalysts for both anode and cathode, IM and QA for AEM, CCS for MEA, Ni or SS for anode PTL, and C or Ni for cathode GDL.

Industry vs Academia. Despite recent publications highlighting AEMWE's outstanding performance, most advancements have not transitioned to commercial application, similar to trends in AWE and PEMWE.[20−23] Comparing academic and industrial research outcomes, identifying key differences, and bridging these gaps is crucial.

Figure 3 illustrates the performance and stability status of AEMWEs from major original equipment manufacturers (OEMs). Figure 3a indicates that OEMs typically operate AEMWE at a current density of 0.5−1 A/cm^2 with a voltage of 1.8−2 V, higher than AWE (<0.5 A/cm^2),[24] but below the DOE target (2 A/cm^2 at 1.8 V) and recent academic performance (>2 A/cm^2 at 1.8 V). The high stability region in Figure 3b is mainly occupied by OEM reports except for two recent academic reports.[25,26] This suggests that OEMs demonstrated promising degradation rates near or below 10 μV/h over 1000 h In contrast, most academic reports do not achieve this level of stability.

In summary, industry OEMs generally exhibit lower performance but higher stability, whereas state-of-the-art academic results show higher performance but lower stability. This discrepancy arises from differing priorities: industry focuses on feasibility of AEMWE technology for commercial applications, comparing it with AWE and PEMWE technologies. Therefore, it is more critical for the industry to demonstrate (i) stable operation of AEMWE, (ii) at a reasonable cost, and (iii) at scale.[27]

Due to differing priorities, different operating conditions and cell parameters are chosen. OEMs operate AEMWEs under milder conditions such as lower temperatures (45−70 °C) and current densities (<1 A/cm^2) compared to academia (60−80 °C, >2 A/cm^2).

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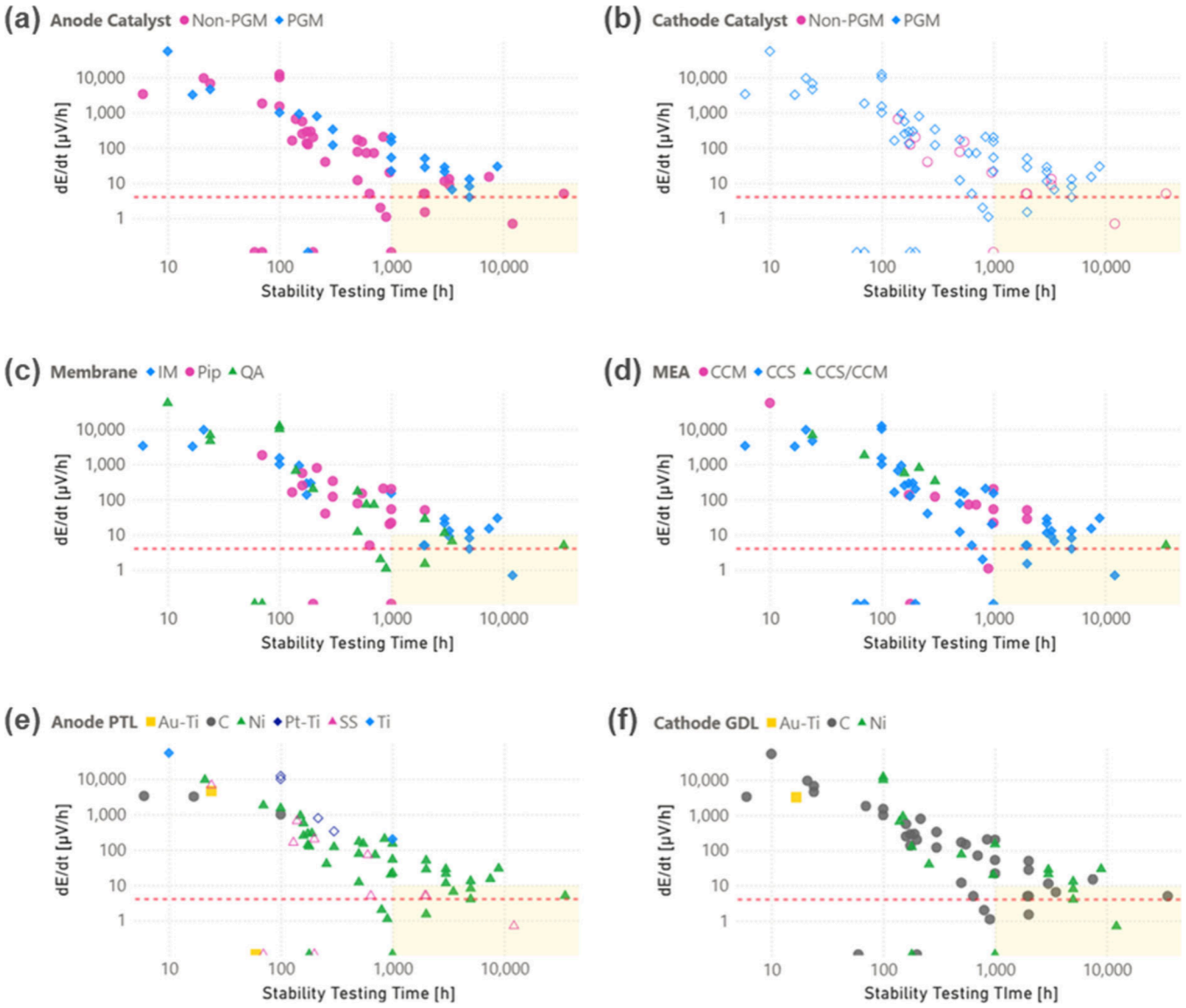

Figure 2. Impact of six cell parameters on the stability of AEMWE, shown using the plot of dE/dt versus stability testing time: (a) anode catalyst, (b) cathode catalyst, (c) membrane, (d) MEA configuration, (e) anode PTL, and (f) cathode GDL. The yellow shaded region indicates the high-stability region with dE/dt < 10 μV/h and stability testing time >1000 h. The red dashed line represents the DOE's target dE/dt of 4 μV/h.

Regarding cell parameters, many academic reports rely on PGM catalysts, especially for the cathode. OEMs, however, use non-PGM for both anode and cathode catalysts, maximizing cost and supply chain advantages. OEMs have used IM or QA-based AEMs for high-stability AEMWE instead of Pip-based AEMs, which were only invented in 2019 and may not yet be optimized for deployment at 80 °C.[28]

For MEA configuration, OEMs often employ CCS instead of CCM, likely due to higher stability (Figure 2d). CCS can also be advantageous for scaling up, because fabricating CCM with AEM for large active areas is challenging due to relatively poor mechanical stability of AEMs compared to robust PFSA membranes in PEMWE.[12,17,29] Additionally, CCS, requiring higher catalyst loadings compared to CCM, is feasible for AEMWE with non-PGM catalysts, whereas PEMWE, using PGM catalysts, would be more costly with CCS.

Gaps and Future Research Directions. The optimal combination of cell components and operating conditions varies between achieving the best performance and the best stability. For instance, Pip-based AEM and CCM combination excel in performance, while IM-based AEM and CCS offer superior stability. Table 1 reveals some common parameters shared by both high-performance and high-stability systems. However, no report has simultaneously achieved the target performance (>2 A/cm^2 at 1.8 V) and stability (dE/dt < 4−10 μV/h, stability testing time >1000 h). High-performance systems lacks stability, and high-stability systems fall short in performance (Figure S6).

To make AEMWE competitive with AWE and PEMWE technologies, future research should prioritize bridging the gap between performance and stability. Instead of solely aiming for higher performance, efforts should focus on either enhancing the performance of stable systems or boosting the stability of high-performance systems.

One strategy is to combine components from high-performance and high-stability systems. For example, since

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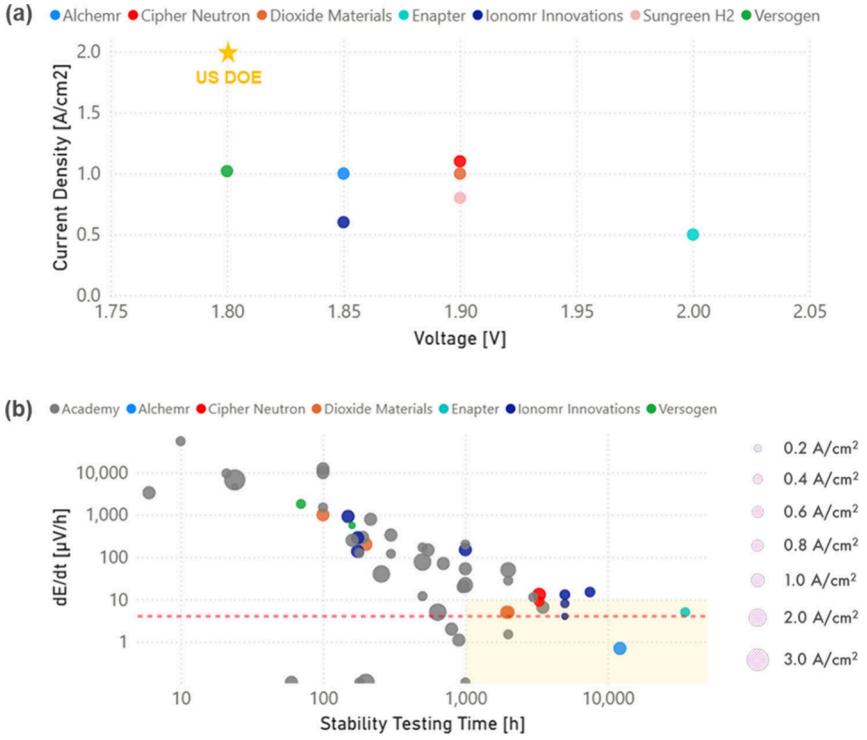

Figure 3. (a) Current status of industry OEMs' AEMWE performance. (b) Comparison of OEMs' AEMWE stability with academia using the plot of dE/dt versus stability testing time, with bubble size representing current density in stability tests. The red dashed line represents the DOE's target dE/dt of 4 μV/h. Performance data from OEMs, validated through long-term stability tests, were selected in (a). Note that Enapter's performance in (a) represents the system efficiency, whereas other OEMs' performance is based on cell or stack efficiency.

the invention of Pip-based AEM, many high KPI AEMWE reports have used this membrane. Given its early optimization stage compared to IM and QA-based AEMs, focusing on improving AEMWE stability with Pip-based AEM could be a viable strategy. Specifically, combining Pip-based AEM with CCS and operating at 60 °C instead of 80 °C could enhance stability. Promising results have already been observed with Pip-based AEM and CCS, bringing it closer to the ideal KPI targets (Figure S6).[4]

Additionally, optimizing the design and manufacturing process of cells and stacks beyond the six key cell parameters can improve the performance of high-stability system. For example, Cipher Neutron recently announced that their AEMWE, classified as a high-stability system using IM for AEM and CCS for MEA configuration, reduced the cell voltage at 1.1 A/cm^2 from 1.9 to 1.56 V through advanced flow field design and optimization of catalyst coating and cell compression.[30]

Concluding Remarks. In this Viewpoint, we examined the relationship of cell parameters and operating conditions with AEMWE performance and stability. Evaluating and comparing reported results is challenging due to multifaceted factors and inconsistent procedures.[5] See Supporting Note 4 for challenges and recommendations for AEMWE research protocol. Despite these challenges, our analysis of promising results meeting DOE targets suggests distinct combinations of cell parameters and operating conditions for high-performance and high-stability systems, particularly between academia and industry due to differing priorities. Although the AEMWE field has made significant progress, there remains a gap between performance and stability that must be addressed to meet DOE target KPIs for competitive commercial deployment. The insights presented here could improve the accurate evaluation and comparison of AEMWE technologies and guide future research and advancements.

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■ ASSOCIATED CONTENT

Supporting Information

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Table S1 (list of references for AEMWE technology analysis and their cell and operating parameters); Figures S1−S6 (AEMWE technology analyses); Supporting Notes 1−4 (performance and stability metrics, performance unit conversion, commercial AEMs, and challenges and recommendations for AEMWE research protocol) (PDF)

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Notes

Views expressed in this Viewpoint are those of the authors and not necessarily the views of the ACS.

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