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Michael D. Guiver,
Tianjin University, China

*CORRESPONDENCE
Dario R. Dekel,
dario@technion.ac.il

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Grand challenges in anion exchange membrane energy applications

Karam Yassin[1,2] and Dario R. Dekel[1,2,3]*

[1]The Wolfson Department of Chemical Engineering, Technion – Israel Institute of Technology, Haifa, Israel, [2]The Nancy & Stephen Grand Technion Energy Program (GTEP), Technion – Israel Institute of Technology, Haifa, Israel, [3]Israel National Institute of Energy Storage (INIES), Technion – Israel Institute of Technology, Haifa, Israel

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1 Introduction

Ion exchange membranes are essential components in electrochemical systems, playing a crucial role in energy and environmental applications. These membranes are broadly classified into proton exchange membranes (PEMs) and anion exchange membranes (AEMs). Despite being a relatively young technology, AEMs have attracted considerable attention for energy applications due to their potential to achieve a significant reduction in materials and device costs thanks to their alkaline character. This cost reduction facilitates mass production and commercialization, thereby expanding the applicability of electrochemical energy technologies.

AEMs serve as barriers between the electrochemical device's anode and cathode, enabling selective anion transport between the electrodes, while preventing the undesired crossover of reactants and gases. Since the first energy-related application was demonstrated about a decade ago for fuel cells (Dekel, 2013), AEM-based technologies have expanded their applications to water electrolysis, redox flow batteries, CO_2 electrolysis, CO_2 separation, and, very recently, electrochemical oxygen separation. Figures 1, 2 show different AEM-based electrochemical systems and their schematic representations, respectively. Intensive research efforts have recently been dedicated to developing innovative AEMs for specific targeted activities to meet the diverse needs of both established and emerging AEM-based electrochemical systems.

Structurally, AEMs consist of a polymeric backbone embedded with fixed positively charged functional groups (Dekel, 2017). Various polymer backbones such as polysulfone (Parrondo et al., 2014), poly (phenylene oxide) (Parrondo and Ramani, 2014; Willdorf-Cohen et al., 2018; Chu et al., 2019), fluoropolymers (Ponce-González et al., 2018; Adhikari et al., 2020; Soni et al., 2021), polystyrene (Vengatesan et al., 2015), and polybenzimidazole (Aili et al., 2017), have been developed, along with different cationic functional group chemistries including piperidinium (Lu et al., 2020; Xiao et al., 2021), trimethyl ammonium (Arges et al., 2012; Li et al., 2012; Cha et al., 2020), spirocyclic (Xue et al., 2020; Qiao et al., 2021), imidazolium (Fan et al., 2019; Park et al., 2020) and carbazolium (Gjineci et al., 2020) groups to optimize ion conductivity and chemical stability.

Each electrochemical system has different specific requirements for AEM properties, and a thorough understanding of these requirements is crucial for determining optimal membrane performance. Understanding their impact on overall system performance is essential for advancing AEM technology. Numerous studies have explored and developed new approaches to tailor and improve the properties of AEMs (You et al., 2020; Clemens et al., 2023; Zhang et al., 2025) and evaluated their performance in different AEM-based

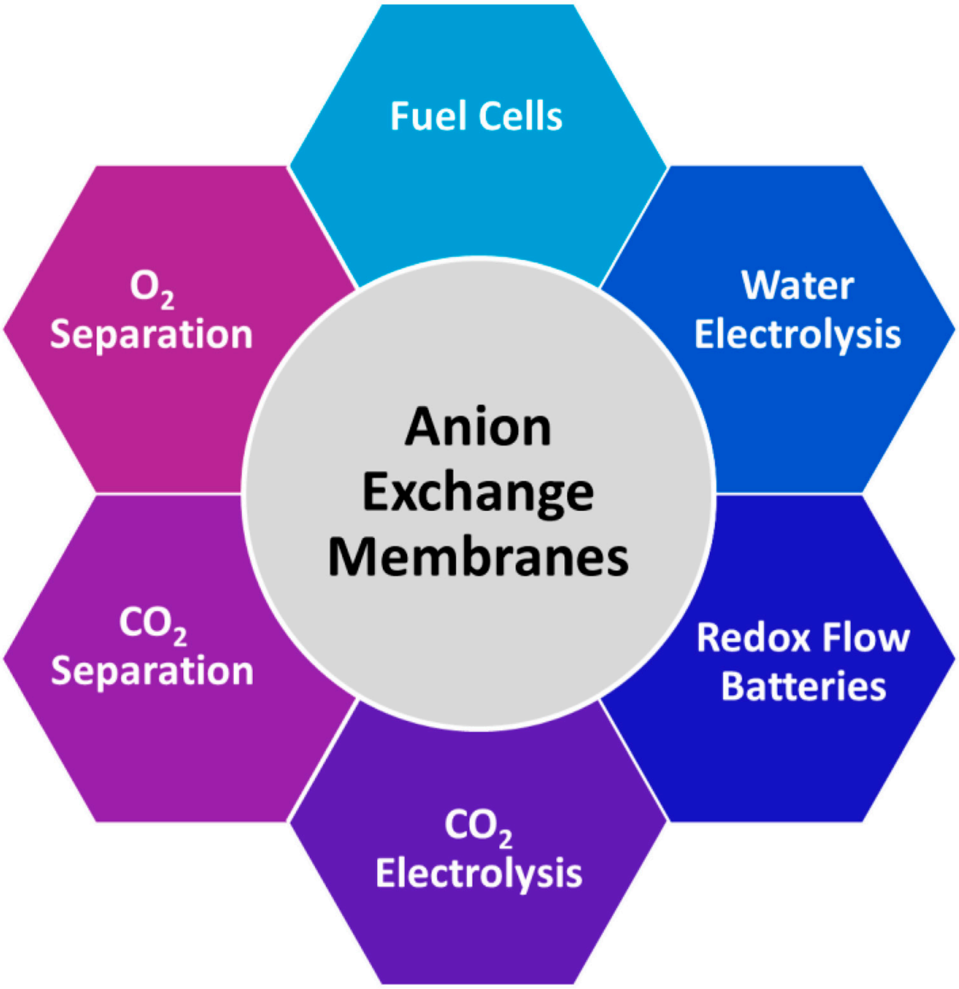

FIGURE 1
Anion-exchange membrane-based electrochemical systems.

systems. Yet, significant gaps remain in understanding the interactions between AEM properties and the specific demands of diverse electrochemical systems. Addressing these challenges will provide insights to drive further research and innovation in AEM technology, ultimately advancing both scientific understanding and practical implementation of AEMs in electrochemical systems.

2 Challenges in anion exchange membranes across different energy-related applications

2.1 AEM fuel cells (AEMFCs)

AEMFCs (Figure 2a) have gained considerable attention in recent years as a promising technology for sustainable energy production due to their ability to utilize a wide range of affordable and abundant precious-metal-free catalysts and cost-effective fluorine-free hydrocarbon AEMs (Dekel, 2017). As the core component of the AEMFC, AEMs allow the transport of hydroxide anions and water between the electrodes and prevent fuel, usually H_2, crossover.

Remarkable progress has been reported in AEMFCs in the past few years, including the development of highly active platinum group metal (PGM)-free catalysts (Lilloja et al., 2020; Santori et al., 2020; Hossen et al., 2023) and critical raw material (CRM)-free AEMFCs (Biemolt et al., 2021). An AEMFC lifetime of 5,000-15,000 h was theoretically demonstrated (Yassin et al., 2020), and a cell lifetime of 2,000 h was experimentally proven (Ul Hassan et al., 2020). Altogether, the research community has made very impressive progress in such a short time. Despite these significant advances in AEMFCs, certain AEM-specific challenges still need to be addressed to bring the performance and stability of this technology closer to practical levels. A recent study identified key parameters and ideal properties required to design future advanced AEMs for AEMFC technology (Yassin et al., 2024). This provides a framework for developing highly stable membranes capable of long-term operation of AEMFCs.

Water management poses a significant challenge during AEMFC operations, particularly at high current densities. The anode produces excess water while the cathode consumes it,

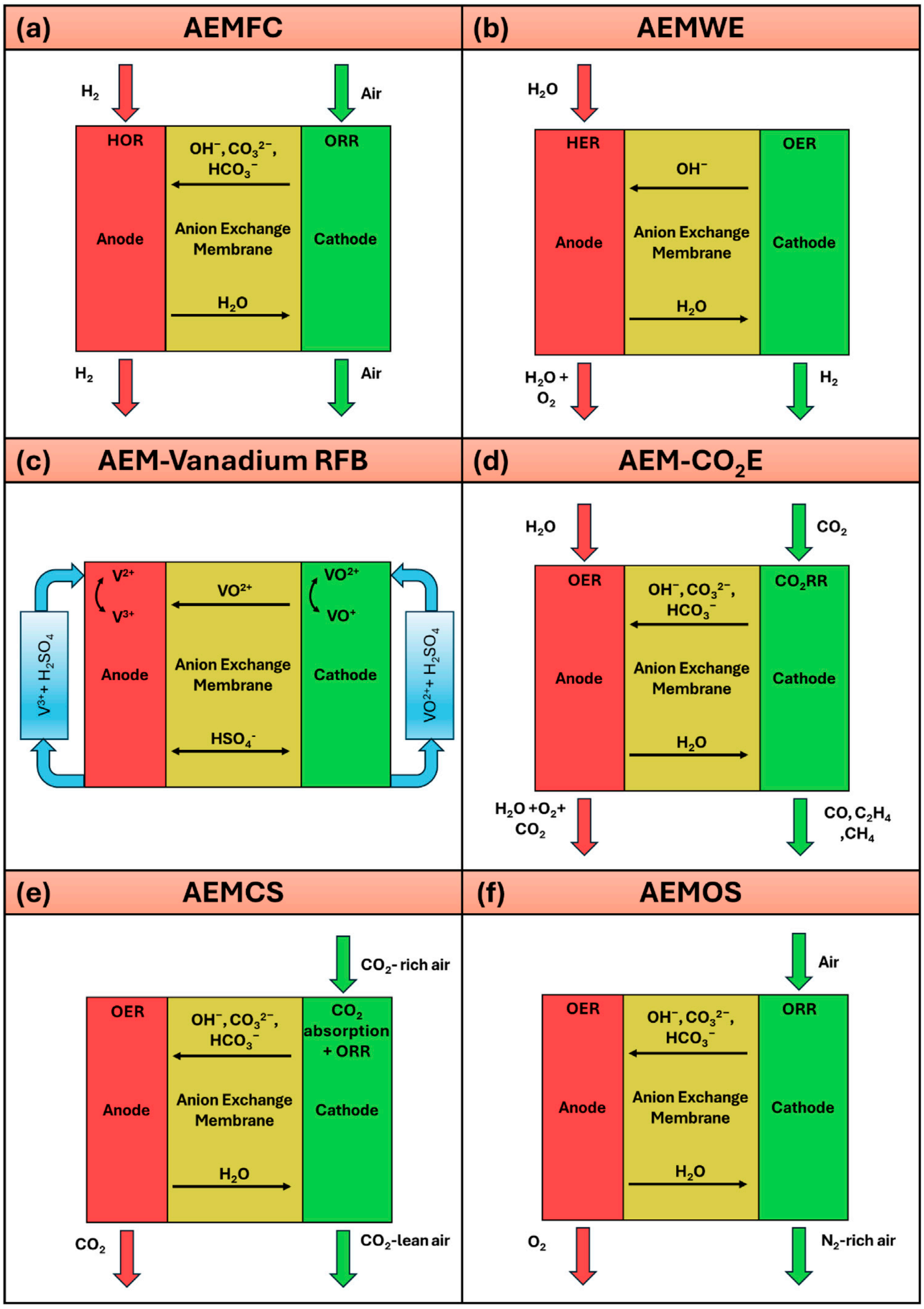

FIGURE 2
Schematic representation of different electrochemical systems based on Anion-Exchange Membranes (AEMs). **(a)** AEM fuel cell (AEMFC); **(b)** AEM water electrolyzer (AEMWE); **(c)** Redox flow battery (RFB); **(d)** CO_2 electrolysis (CO_2E); **(e)** AEM CO_2 separator (AEMCS); **(f)** AEM oxygen separator (AEMOS). Hydrogen oxidation reaction (HOR); Oxygen reduction reaction (ORR); Hydrogen evolution reaction (HER); Oxygen evolution reaction (OER); CO_2 reduction reaction (CO_2RR).

leading to an imbalance that can cause flooding at the anode and dehydration at the cathode (Omasta et al., 2018; Eriksson et al., 2023). This decrease in hydration reduces the hydroxide conductivity of the ionomeric materials, resulting in increased ohmic losses and resulting in poorer cell performance and stability (Dekel et al., 2019). Strategies to enhance water transport include developing AEMs with higher water diffusivity and thinner thickness (Leonard et al., 2020; Yassin et al., 2020) and increasing operating temperature to facilitate water redistribution in the cell (Douglin et al., 2020; Yassin et al., 2021).

The cathode dehydration also affects the AEM chemical stability, which remains a critical challenge for achieving long-term AEMFC operation (Dekel et al., 2019). Under high pH and low hydration conditions, the cationic functional groups become susceptible to severe chemical attack by poorly solvated and highly reactive hydroxide anions (Dekel et al., 2018). The cation degradation causes a reduction of the polymer ion exchange capacity and, in turn, a reduction in membrane ionic conductivity, resulting in a rapid decline in cell performance (Dekel et al., 2019; Adabi et al., 2021; Lorenz et al., 2022). Therefore, developing chemically stable AEMs capable of long-term exposure to alkaline conditions at low hydration levels is crucial for advancing AEMFC technology.

Another key issue in AEMFCs is the carbonation of the AEM when ambient air containing CO_2 is introduced to the cathode (Ziv et al., 2018). The literature highlights the lack of experimental studies examining the impact of carbonation on AEMFCs and the underlying factors responsible for the marked deterioration in performance in the presence of CO_2 (Ziv et al., 2018). The OH^- anions generated in the cathode react with CO_2 to form (bi) carbonate anions. The impact of CO_2 on AEMFCs is very complex, involving multi-anion transport phenomena, concentration polarization, and back diffusion, as well as changes in water distribution, cation stability, and local pH. These interconnected processes alter the behavior of the electrocatalysts and ionomeric materials, significantly reducing the performance and durability of the cell. Enhancing our understanding of the transport mechanisms and electrochemical effects of CO_2 will assist in addressing the challenges associated with carbonation and evaluating the feasibility of operating AEMFCs using ambient air. The challenge also calls for the design and development of AEMs that can adsorb less CO_2 as well as AEMs with higher (bi)carbonate anion conductivity (Yassin et al., 2025).

Fuel versatility in AEMFCs also presents a unique avenue of research. In addition to hydrogen, AEMFCs can utilize other fuels such as methanol (Vecchio et al., 2023), ethanol (Roschger et al., 2023), urea (Kim et al., 2021), hydrazine (Sakamoto et al., 2018), and ammonia (Dekel et al., 2023), offering advantages in terms of higher energy density and simplified storage and handling. However, operating with liquid fuels presents unique issues for AEMs, such as fuel crossover and probable chemical degradation due to reaction intermediates. Tailoring AEM features like selectivity, fuel crossover, and chemical stability against fuels is critical for ensuring long-term performance and durability in liquid-fuel-based AEMFCs.

2.2 AEM water electrolysis (AEMWE)

Water electrolysis is a promising technology for producing high-purity, pressurized hydrogen through electrochemical conversion, which involves breaking down water into hydrogen and oxygen using electricity (Chatenet et al., 2022). AEMWE technology (Figure 2b) has recently attracted significant attention, mainly due to the ability to remove the expensive and scarce iridium and other precious metal catalysts from the cells, significantly alleviating the bill of materials (López-Fernández et al., 2021). Despite the numerous reports demonstrating AEMWE performance data, most studies present AEMWE operation with liquid electrolytes, commonly with concentrated KOH solution. This highly alkaline environment enhances the ionic conductivity of the ionomeric materials and improves oxygen evolution reaction (OER) kinetics (Liu et al., 2021); however, it also introduces challenges related to material durability, safety, and hydrogen purity.

Pure water operation has emerged as a goal for high-performance AEMWE offering safer and more flexible operation (Santoro et al., 2022). However, this shift poses issues in ensuring appropriate ionic conductivity and water transport for OER. When pure water substitutes alkaline electrolytes, membranes must be capable of efficiently transporting hydroxide anions throughout the cell. This emphasizes the need for AEMs with higher hydroxide conductivity and superior water diffusivity to maintain optimal hydration across the membrane and the cathode catalyst layer (Muhyuddin et al., 2025).

Efficient water management within AEMWE cells operating in dry-cathode mode (Wang et al., 2022) is crucial to prevent cathode dehydration and ensure adequate water delivery to the anode. Although water management strategies are frequently studied in AEMFCs, this research topic on AEMWE is scarce. Improving water transport from the anode to the cathode is critical, especially when the cathode is operated under dry conditions (Koch et al., 2022). Potential approaches include designing AEMs with increased water diffusivity and/or developing cell designs that encourage water back-diffusion.

2.3 AEM redox flow batteries (AEM-RFBs)

In recent years, a pronounced focus has been placed on researching and developing low-cost hydrocarbon AEMs, demonstrating a promising substitute for the PEMs in RFB technologies such as organic and vanadium RFBs (Figure 2c) (Yang et al., 2024). AEMs play a vital role in all types of RFBs by acting as physical separators between the anode and the cathode electrodes, allowing ion passage to maintain electrical neutrality and preventing internal short circuits in the system. Key properties of ideal AEMs include high ion selectivity, low electrical resistance, mechanical strength, and chemical stability. Despite advancements, challenges remain, especially related to membrane properties that affect efficiency and durability.

In AEM-RFBs, the membrane must conduct selected anions while preventing the crossover of active redox anions/cations between the anolyte and catholyte chambers. The AEM selectivity is essential for maintaining charge balance and avoiding self-discharge, which can dramatically lower battery efficiency and cycle life. Furthermore, the anion transport behavior in AEMs is complex and poorly understood since various anions with variable valences coexist in the system. For example, preventing vanadium ion crossover in vanadium AEM-RFB is particularly challenging due to the small ionic radii and high diffusivity of vanadium species, leading to efficiency losses and capacity fade (Zhao et al., 2023). However, achieving great selectivity frequently comes at the expense of ionic conductivity, resulting in a difficult balance between performance and durability.

The chemical stability of the AEM is another major concern due to the highly alkaline environment and the high concentrations of metal ions and oxidative species like VO_2^+, Ce^{4+}, and Br_2. These harsh conditions can break down the polymer backbone and functional groups of the AEM (Herrmann et al., 2021; Hao et al., 2022). This degradation affects the ionic conductivity of the membrane, causes structural weakness, and increases ion crossover, resulting in worse battery efficiency and capacity decline (Herrmann et al., 2021; Hao et al., 2022). Developing robust AEMs capable of withstanding these harsh alkaline oxidative media is critical for maintaining long-term stability in operando AEM-RFBs.

Mechanical robustness is especially important for AEMs in RFB applications. The physicochemical characteristics and ion accumulation significantly influence tensile strength and elongation at break. Metal ion fouling can further reduce mechanical stability; however, research into these issues is limited (Gao et al., 2022). This emphasizes the significance of developing mechanically and chemically stable AEM to ensure long-term stability. Overall, the chemical stability and mechanical integrity of the AEM are controlled by the polymer matrix, while its functionality determines properties such as physicochemical, electrochemical, and ion selectivity. Consequently, innovative design approaches and advanced synthesis strategies are crucial for driving progress in the development of high-performance AEMs for RFB applications.

2.4 AEM CO_2 electrolysis (AEM-CO_2E)

Electrochemical CO_2 reduction (Figure 2d) has been achieved in several cell architectures, including the zero-gap reactor (or membrane-electrode assembly) originally developed for low-temperature water electrolysis and fuel cell systems. The AEM-CO_2E offers a sustainable method to convert CO_2 into high-value chemicals (Salvatore et al., 2021), producing carbon monoxide and multi-carbon products like ethylene, methane, and ethanol. Gaseous products exit through the cathode, while liquid products diffuse through the AEM to the anode, where they are collected. The anode, typically supplied with an aqueous electrolyte (e.g., KOH, $HKCO_3$), facilitates the OER to complete the electrochemical circuit. Despite the promise of this configuration, AEM-CO_2E systems face numerous operational and material challenges. AEMs have been extensively studied in the context of fuel cells and water electrolysis, but established performance metrics for CO_2 electrolyzers remain unavailable.

Water management seems to be a critical factor affecting the performance of the AEM-CO_2E, as observed in other AEM-based technologies such as fuel cells and water electrolyzers (Weng et al., 2019). Water acts as a reactant in the conversion of CO_2, but excess water can hinder the diffusion of CO_2 to the catalyst and shift the reaction preference toward OER. Water transport within the system–via diffusion, electro-osmotic drag, or convection–is influenced by the microstructure and chemical composition of the membrane and operating conditions. This underscores the need for AEMs with improved water transport properties to balance water availability for CO_2 reduction while minimizing flooding and unwanted side reactions (Reyes et al., 2020).

Product and reactant crossover further complicates the operation. Negatively charged products (e.g., formate) migrate across the positively charged AEM while neutral molecules (e.g., ethanol) can diffuse through the AEM, reducing efficiency. Moreover, the reaction of CO_2 with the produced OH^- in the CO_2 reduction reaction generates CO_3^{2-} and HCO_3^-, further reducing the free CO_2 available to the catalyst in the cathode. The produced HCO_3^- and CO_3^{2-} ions are transported through the AEM to the anode electrolyte, where they are reconverted to a significant amount of CO_2, often surpassing the CO_2 converted into the desired product (with up to 60% of the total CO_2 being neutralized) (Larrazábal et al., 2019). These effects highlight the need for AEMs with enhanced selectivity for the transport of desirable anions (such as carbonate and bicarbonate) over undesirable negatively charged products (e.g., formate), reducing crossover and improving system efficiency (Banerjee et al., 2022).

Additionally, AEMs used in CO_2 electrolysis face mechanical and chemical stability issues. The high pH and harsh conditions (high temperature and high pressure) at the cathode degrade AEMs, limiting cell longevity. Combined with interfacial and ohmic losses that contribute to high operating voltages (Salvatore and Berlinguette, 2020), these challenges demonstrate the need for innovative membrane materials tailored to AEM-CO_2E systems. Recent advances in AEMs have shown promise for gas-phase CO_2 electrolysis, but substantial innovation is required to overcome these barriers and achieve commercially viable AEM-CO_2E technologies.

2.5 AEM CO_2 separator (AEMCS)

Electrochemical processes offer promising alternatives for CO_2 separation, achieving energy requirements up to 80% lower than traditional chemical absorption methods (Rigdon et al., 2017). Despite the promising aspects of AEMCSs (Figure 2e), the technology is in its very early stages, and its potential remains largely unexplored due to limited research carried out until now. In an AEMCS, the AEM plays a crucial role by selectively transporting carbonate or bicarbonate anions from the cathode to the anode, where they are electrolyzed back into CO_2 and O_2. This process enables the capture and separation of CO_2 from ambient air in a more energy-efficient manner, with the membrane ensuring both the selective transport and effective separation of CO_2 from other gases (e.g., N_2, O_2).

Carbonate species have long been recognized and addressed as a significant challenge in AEMFCs as they impart thermodynamic, kinetic, and ohmic overpotentials. Selectivity for carbonate species is a significant difficulty in AEMCS applications, especially in mixed-gas settings. To efficiently separate CO_2, AEMs must transport carbonate or bicarbonate anions to the anode. Increasing selectivity for CO_2-derived anions may affect the total conductivity of the AEM by limiting ionic mobility. Finding the right balance between ion selectivity and conductivity is thus a major challenge.

CO_2 separation requires chemical stability due to prolonged exposure to alkaline environments that produce carbonate and bicarbonate ions. Under these conditions, the polymer backbone and functional groups of the AEM are expected to degrade, reducing membrane durability and decreasing separation efficiency. Having said that, initial research recently suggested that the presence of (bi) carbonate anions in the AEM helps to stabilize the cationic functional groups, and therefore, increases the AEM durability in alkaline medium (Willdorf-Cohen et al., 2025). This requires further research to confirm initial findings.

Mechanical stress or vibrations can also contribute to membrane degradation, as they can cause cracks or other defects in the membrane structure. This can be exacerbated by the presence of reactive species and high temperatures, which can make the membrane more susceptible to mechanical damage. Therefore, AEMs with high mechanical resilience are essential.

2.6 AEM oxygen separator (AEMOS)

In the realm of electrochemical oxygen separation technologies in alkaline media, a few studies have contributed to the understanding and advancement of the feasibility of using an electrochemical driving force to efficiently separate oxygen from nitrogen (Arishige et al., 2014; Tian et al., 2022; Zhang et al., 2022). However, these studies relied on high concentrations of corrosive KOH solutions as a liquid electrolyte, which introduces safety risks and requires additional purification steps for oxygen. Therefore, there is a clear need for all-solid-state-based technology that eliminates these risks and enables pure oxygen generation through a safe, reliable, and affordable technology.

Recently, a novel technology based on an electrochemical AEM-oxygen separator (Figure 2f) device, achieving >96% oxygen purity from synthetic air, was proposed (Faour et al., 2024). This technology offers a promising solution to generate oxygen on-site from the air using an efficient electrochemical driving force and suitable solid-state AEM polymer electrolytes. This design provides the necessary alkaline environment while eliminating the need for corrosive liquid electrolytes. In AEMOS operation, the cathode is fed with air, and a low potential difference (0.7–1.2 V) is applied between the cathode and anode electrodes. The OH^-anions generated during the oxygen reduction reaction at the cathode transport through the AEM to the anode, where oxygen is produced by OER. This results in the net selective transport of oxygen from the cathode to the anode, potentially producing pure oxygen gas at the anode.

A significant challenge for this technology is its ability to operate in the presence of carbon dioxide from ambient air. Previous studies on AEMFCs show that even low levels of CO_2 can lead to carbonation of the AEM (Krewer et al., 2018; Ziv et al., 2018), which reduces anion conductivity and hinders overall performance. Thus, further research is needed to assess the impact of CO_2 on the alkaline stability of AEMs and to evaluate AEMOS performance with CO_2-containing gas mixtures.

Since AEMOS technology is still in its very early stages, there is limited information on the specific requirements for the AEMs used or the challenges of this technology. Thus, the investigation of AEM properties and their impact on AEMOS performance remains a critical area of study. Studying the key material properties of AEMs and ionomers and their impact on the performance and stability of AEMOS is critical to optimizing the AEMs and the technology and enhancing their durability.

3 Concluding remarks

AEMs are pivotal to advancing electrochemical energy systems, driving efforts to enhance their performance, efficiency, and scalability. As a critical component in various electrochemical devices, including fuel cells, water electrolysis, redox flow batteries, CO_2 electrolysis, CO_2 separators, and oxygen separators, AEMs enable efficient ion transport, supporting more sustainable and cost-effective energy conversion and storage technologies. Optimizing these membranes not only improves device operation but also contributes to addressing global energy challenges, aiding the transition to cleaner energy systems. Ongoing development of AEMs, particularly improvements in chemical stability, anion conductivity and selectivity, water diffusivity, and mechanical robustness, is essential for their integration into next-generation energy systems.

In this section on "Energy" within the *Frontiers in Membrane Science and Technology* journal, high-quality original research articles and comprehensive review articles are encouraged and welcomed. Such contributions are expected to make significant strides in membrane development, particularly in the context of energy applications. The section aims to highlight studies that address practical challenges, propose innovative solutions, and provide insights that help bridge the gap between laboratory-scale membrane development and industrial-scale manufacturing.

Author contributions

KY: Conceptualization, Writing – original draft. DD: Resources, Funding acquisition, Conceptualization, Writing – review and editing, Supervision.

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