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Solid-State-Electrolyte Reactor: New Opportunity for Electrifying Manufacture

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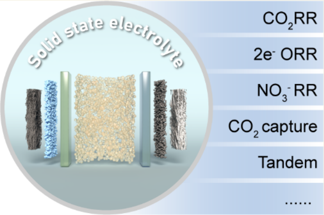

ABSTRACT: Electrocatalysis, which leverages renewable electricity, has emerged as a cornerstone technology in the transition toward sustainable energy and chemical production. However, traditional electrocatalytic systems often produce mixed, impure products, necessitating costly purification. Solid-state electrolyte (SSE) reactors represent a transformative advancement by enabling the direct production of high-purity chemicals, significantly reducing purification costs and energy consumption. The versatility of SSE reactors extends to applications such as CO_2 capture and tandem reactions, aligning with the green and decentralized production paradigm. This Perspective provides a comprehensive overview of SSE reactors, discussing their principles, design innovations, and applications in producing pure chemicals—such as liquid carbon fuels, hydrogen peroxide, and ammonia—directly from CO_2 and other sources. We further explore the potential of SSE reactors in applications such as CO_2 capture and tandem reactions, highlighting their compatibility with versatile production systems. Finally, we outline future research directions for SSE reactors, underscoring their role in advancing sustainable chemical manufacturing.

KEYWORDS: *Solid-State Electrolyte Reactor, CO_2 Reduction Reaction, 2e⁻ O_2 Reduction, Nitrate Reduction, CO_2 Capture, Tandem Reaction, Electrochemical Reactor*

1. INTRODUCTION

Chemical manufacturing has long been the backbone of modern civilization, underpinning critical industries such as agriculture, healthcare, energy, and materials.[1−4] However, this sector remains one of the most energy-intensive and carbon-emitting, heavily reliant on fossil fuels as both feedstocks and energy sources.[5,6] This has spurred the emergence of electrocatalysis, a revolutionary platform that bridges the gap between renewable energy and chemical manufacturing.[7] By leveraging electricity—especially from solar, wind, and hydropower—electrocatalysis enables the conversion of simple, abundant molecules into high-value chemicals and fuels, such as hydrogen, ammonia, formic acid, and hydrogen peroxide.[8−11] These products are essential as both energy carriers and feedstocks for a wide range of industries. Importantly, the declining costs of renewable energy have made the electrochemical route increasingly competitive, with electricity prices projected to fall below $0.03 per kWh in the near future.[12] This economic shift underscores the potential of electrocatalysis to replace fossil-derived processes, aligning with global efforts to achieve net-zero emissions. In an increasingly decentralized and intermittent energy landscape, electrocatalysis plays a pivotal role by transforming variable renewable energy inputs into stable, storable chemical outputs, which provides a scalable and sustainable solution for industrial production.[13,14]

Despite their vast potential, traditional electrocatalytic processes grapple with a fundamental challenge: the generation of impure product streams. In electrocatalysis, complex reaction pathways often lead to the simultaneous formation of multiple products, complicating the separation and purification processes. For example, in the carbon dioxide electroreduction reaction (CO_2RR), diverse products, such as formic acid, carbon monoxide, ethylene, and ethanol, are generated depending on the catalyst and operating conditions.[15,16] This product diversity, while showcasing the versatility of electrocatalysis, necessitates energy-intensive and costly downstream separation methods. The reliance on liquid-phase electrolytes in conventional systems further compounds this issue. These electrolytes, typically aqueous salt solutions such as $KHCO_3$ or KOH, are indispensable for maintaining ionic conductivity but inevitably introduce ionic impurities into the liquid products. As a result, the liquid chemicals produced in these systems are often contaminated with salts, requiring additional purification steps such as distillation, ion exchange, or electrodialysis.[17,18] These processes can account for a substantial fraction of the total production cost, posing a major barrier to the widespread industrial adoption of electrocatalysis.

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Table 1. Merits and Limitations of Different Electrolyzer Configurations

Electrolyzer types	Merits	Limitations
Single-chamber membrane-free reactor	simple design; avoid the use of ion exchange membrane and gaskets; allow the synergy of cathodic and anodic processes	mixed catholyte and anolyte; product consumption or unwanted side reactions occurring at the opposite electrode
H-cell	avoid the interference between cathodic and anodic compartments; convenient for mechanism study	limited electrode surface area; large interelectrode distance; accumulation of liquid products; restricted mass transport of gaseous feedstock
Gas diffusion flow cell	improve the mass transport of gaseous feedstock by facilitating a triple-phase interface; avoid the accumulation of liquid products by flowing the electrolyte	poor stability of the triple-phase interface because of water flooding and salt deposition
Membrane electrode assembly	with catalyst layers integrated with the ion exchange membrane; minimize the distance for ion transport and reduce the ohmic losses	lower efficiency toward liquid products due to crossover; severer salt deposition
Solid-state electrolyte reactor	with a solid-electrolyte layer for the collection of pure products; avoid the energy-intensive postreaction purification processes; prevent the product crossover; more stable reaction interface, avoid the water flooding	larger ohmic loss and energy consumption; suboptimal performance under industrially relevant conditions

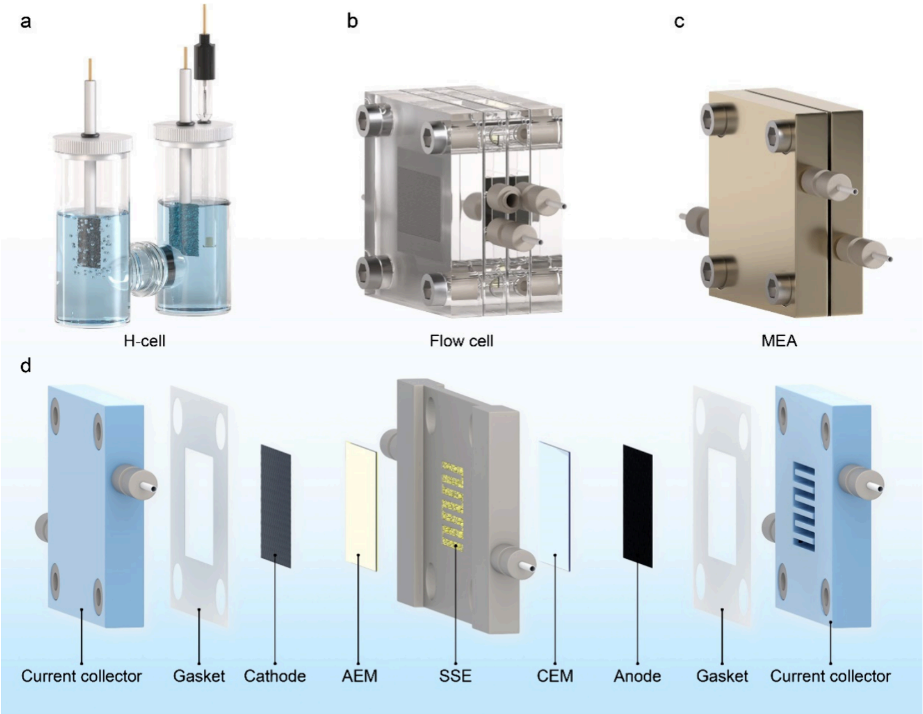

Figure 1. Configurations of the electrolyzer design commonly utilized in CO_2 electrolysis. (a) H-cell. (b) Gas diffusion flow cell. (c) Membrane electrode assembly. (d) Solid-state electrolyte reactor. To obtain pure liquid products, ions/molecules electrochemically generated from the cathode, such as $HCOO^-$, move across the AEM toward the middle solid electrolyte layer, and protons generated from anodic reactions (water or hydrogen oxidation) move across the CEM into the middle chamber to compensate for the charge. The target molecules (such as HCOOH) are thus formed within the middle layer via ionic recombination, and carried out via the deionized water stream that flows through this porous layer.

In addressing these limitations, while the optimization of electrocatalysts is crucial, innovation in reactor design is equally imperative. Recent advances have given rise to the development of solid-state electrolyte (SSE) reactors, a breakthrough in electrochemical technology that fundamentally redefines the boundaries of product purity and process efficiency.[10,19,20] By replacing traditional liquid electrolytes with solid ionic conductors, SSE reactors decouple ion transport from product collection. This innovative architecture prevents the contamination of liquid products with electrolyte salts, enabling the direct synthesis of high-purity chemicals. By eliminating the need for postreaction purification, SSE reactors drastically reduce both operational costs and energy consumption, positioning electrocatalysis as a competitive alternative to conventional chemical manufacturing routes.

The versatility of SSE reactors is further demonstrated by their applicability across a wide range of electrocatalytic reactions.[9,11,21,22] Beyond CO_2RR, SSE reactors have been successfully employed in the production of pure hydrogen peroxide via the oxygen reduction reaction (ORR), offering a sustainable and efficient alternative to conventional hydrogen peroxide (H_2O_2) synthesis.[11,21] Additionally, they have shown promise in electrocatalytic ammonia synthesis through nitrate reduction, addressing both environmental and agricultural needs.[9,22] Recent advancements have also expanded the scope of SSE technology to CO_2 capture and tandem reactions, where intermediate products from one reaction seamlessly feed into subsequent processes without the need for separation.[23−25] This capability holds immense potential for the integrated production of complex chemicals, reducing energy inputs and streamlining the overall process.

Beyond economic and technical advantages, the ability of SSE reactors to produce pure products unlocks new paradigms in chemical production, particularly in decentralized manufacturing. This capability challenges the conventional model of large-scale, centralized production facilities by enabling localized, on-demand synthesis of critical chemicals. Such flexibility is invaluable in remote or resource-constrained regions, where centralized industrial infrastructure may be inaccessible or insufficient. The COVID-19 pandemic underscored the importance of decentralized production, as supply chain disruptions highlighted vulnerabilities in the availability of essential chemicals such as disinfectants and medical oxygen. In these scenarios, onsite electrocatalytic production of pure products such as hydrogen peroxide could provide rapid, localized solutions, enhancing resilience and self-sufficiency.[26,27]

In this perspective, we delve into the principles, advancements, and diverse applications of SSE reactors. We examine their role in overcoming the limitations of traditional electrocatalytic systems, particularly in achieving high-purity product synthesis. Recent breakthroughs in SSE reactor design and their extended application in CO_2 capture and integration with downstream reactions will be highlighted, highlighting their potential to revolutionize chemical manufacturing. Finally, we discuss the current challenges and broader implications of SSE technology in enabling decentralized and sustainable production models, offering a transformative vision for the future of the chemical industry.

2. PRINCIPLE AND DESIGN OF A SOLID-STATE ELECTROLYTE REACTOR

The evolution of electrochemical reactor technologies has led to the development of several configurations, including single-chamber membrane-free reactors, H-cells, flow cells, and membrane electrode assemblies (MEAs), each tailored to optimize the reaction environment and efficiency for specific applications.[28] However, while these designs offer distinct advantages, they also have inherent limitations, particularly when employed in gas-involved reactions (Table 1). For example, single-chamber reactors can facilitate synergistic interactions between cathodic and anodic processes,[29,30] but have limited applications in aqueous electrolysis. Therefore, we will focus primarily on other types of electrolyzer configurations that are more relevant to the scope of discussion.

H-cells are among the simplest and most widely used reactor designs in laboratory research (Figure 1a). They offer a straightforward setup for studying fundamental reaction mechanisms and catalyst performance within the kinetically controlled region. For example, the Jaramillo group investigated the CO_2RR pathways over copper across a range of potentials in the H-cell, revealing the formation of multicarbon products (including aldehydes, ketones, alcohols, and carboxylic acids) involving enol-like surface intermediates as a possible pathway.[31] However, H-cells are significantly limited by the low solubility of gaseous feedstock (*e.g.*, CO_2) in aqueous electrolytes, which is approximately 33 mM for CO_2 under ambient conditions (1 atm, 25 °C).[32] This solubility constraint, combined with the limited diffusion coefficients of CO_2, leads to insufficient reactant delivery to the catalyst surface, resulting in low reaction rates, diminished product yields, and poor energy efficiency.[33] Attempts to increase CO_2 solubility through increased pressure or decreased temperature have yielded only marginal improvements and have failed to address the underlying mass transport bottleneck.[34,35] For example, the Dai group reported a $Cu(OH)_2$-derived Cu/CuO_x catalyst achieving 87% Faradaic efficiency for CO_2-to-acetate in borate-containing electrolytes under 58 atm $CO_2(g)$. However, the current densities are still not promising (<100 mA cm^{-2}) under constrained mass transfer conditions.[36] Moreover, the limited electrode area and large interelectrode distance would lead to increased ohmic polarization, thus restricting the current density in the H-cell.[37] Moreover, the accumulation of liquid products also accelerates product crossover[38] or affects the membrane.[39]

To overcome these limitations, flow cells incorporating gas diffusion electrodes (GDEs) have been introduced to facilitate a triple-phase interface where gaseous CO_2, liquid electrolytes, and solid catalysts converge (Figure 1b). This design significantly improves mass transport, allowing for higher reaction kinetics and increased current densities.[40,41] Xing et al. reported an order of magnitude increase in the current density over that of a Cu catalyst from ∼6 mA cm^{-2} in a H-cell to ∼250 mA cm^{-2} in a flow cell under the same potential, indicating the vital role of mass transport.[42] However, flow cells are prone to performance degradation because of "water flooding" at high current densities. This occurs when the liquid electrolyte infiltrates the porous GDE, disrupting the delicate balance of the triple-phase interface and reducing the available catalytic surface area.[43] As a result, long-term stability and operational efficiency are compromised. For instance, the Jiao group reported a slight decrease in the total C_{2+} Faradaic efficiency after 30 min of CO electrolysis at 500 mA cm^{-2} in a flow cell owing to flooding caused by the condensation of water vapor.[44]

Membrane electrode assemblies (MEAs) represent a further advancement, integrating the catalyst layer directly with an ion exchange membrane (Figure 1c). This design minimizes the distance for ion transport, reduces ohmic losses, and enhances the overall reaction efficiency, which is more convenient for scaling production.[45] For example, Zheng et al. realized practical 3.34-L-h^{-1}-CO production in a 10 × 10 cm^2 MEA at more than 8 A with a low cell voltage of only 2.8 V.[46] Despite these benefits, MEAs face critical challenges, particularly with respect to liquid product handling. Under the influence of concentration gradients and electric fields, liquid products such as formic acid and acetic acid tend to permeate through the ion exchange membrane to the anode, where they are oxidized. This product crossover results in substantial efficiency losses and undermines the benefits offered by the MEA configuration.[47] Additionally, ion transport limitations across the membrane can result in salt deposition in the cathodic GDE and flow channels, further exacerbating system performance degradation.[48] Endrődi et al. observed that although lowering the anolyte concentration could improve stability, the crossover and consequent precipitation of alkali metal cations still occur, leading to performance degradation.[49]

In response to these challenges, SSE reactors have emerged as transformative innovations, addressing key limitations of conventional reactor designs. SSE reactors are specifically engineered to prevent product crossover and enable the direct synthesis of pure liquid products that are free from electrolyte contamination. Their advanced architecture comprises a structured assembly of catalyst-coated gas diffusion layers, ion-selective membranes, and a crucial middle layer—the porous solid electrolyte (Figure 1d). This middle layer serves dual functions: as an ionic conductor, facilitating the selective transport of ions such as protons (H^+) or formate ions ($HCOO^-$), and as a product separator, ensuring that liquid products remain isolated from the bulk electrolyte and do not migrate to the anode compartment. This design not only prevents product loss but also allows the generation of pure, concentrated liquid products. The choice of materials for the porous solid electrolyte is critical to the performance of SSE reactors.

Based on the working mechanism of the SSE reactor, the adopted solid electrolyte needs to satisfy the following three properties: high ionic conductivity for efficient ion transfer, proper geometric factors (such as surface area and porosity), and sufficient chemical stability. Generally, polymer-based ion conductors, such as sulfonic acid-functionalized styrene-divinylbenzene copolymers, are commonly employed because of their high ionic conductivity and stability under mild operating conditions. Moreover, the current carrier of polymer ion conductors also changes when modified with different functional groups on the surface. For example, sulfonic acid groups lead to efficient proton transportation, whereas quaternary amino groups lead to migration of anions. Xia et al. compared the CO_2RR performance when a H^+-conductor and a $HCOO^-$-conductor were used in the SSE reactor. As a result, the H^+-conductor SSE achieved a distinctly higher current density (100 mA cm^{-2} vs. 50 mA cm^{-2}) at a lower cell voltage (3.27 V vs. 3.47 V) than did the $HCOO^-$-conductor owing to the higher electromobility of the protons. Furthermore, they also analyzed the electrochemical impedance spectra of SSE powders of different sizes. These authors reported that the 50-μm-SSE exhibited greater ionic conductivity (0.018 S cm^{-1}) and lower charge transfer (12.5 Ω cm^2) resistivity than did the 300-μm-SSE (0.0064 S cm^{-1} and 24.5 Ω cm^2) because of the improved surface area and porosity. For more demanding environments, such as high temperatures or chemically aggressive settings, inorganic ion conductors such as cesium-substituted heteropolyacids ($Cs_xH_{3-x}PW_{12}O_{40}$) offer superior thermal and chemical stability.[50]

Compared with traditional systems, SSE reactors demonstrate significant advantages. By eliminating the crossover of liquid products and achieving high product purity, they reduce the need for energy-intensive postreaction purification processes. This improves the overall sustainability and economic viability of the system. The inherent stability of the SSE reactor's reaction interface prevents flooding, allowing for consistent performance even at industrially relevant current densities. For example, in hydrogen peroxide production via the two-electron oxygen reduction reaction ($2e^-$ ORR), SSE reactors achieve Faradaic efficiencies exceeding 90% at current densities up to 400 mA cm^{-2}, with stable operation over extended periods.[21] However, SSE reactors are not without challenges. The assembly of these systems is more complex than traditional designs are, and the increased internal resistance due to the SSE layer can limit energy efficiency. Scaling SSE reactors for industrial applications remains a significant hurdle, requiring further advances in material science and reactor engineering to optimize performance and reduce costs.[18]

Despite these challenges, the unique advantages of SSE reactors make them highly promising platforms for a wide range of electrocatalytic applications. Their ability to produce high-purity liquid products, prevent product loss, and maintain stable operation under demanding conditions positions them as a key technology in the drive toward sustainable chemical manufacturing. As research continues to refine these reactors and expand their compatibility with diverse reaction systems, their role in sustainable chemical manufacturing is expected to grow, driving innovations in areas ranging from CO_2 reduction to synthetic fuel and chemical production.

3. APPLICATIONS IN PURE CHEMICAL PRODUCTION

3.1. Liquid Carbon Fuels from the CO_2RR

Facing the challenge of achieving a carbon-neutral energy cycle, the electrochemical CO_2RR has emerged as a transformative technology, capable of converting CO_2 into valuable fuels and chemicals using renewable electricity.[51,52]

Liquid fuels such as formic acid, ethanol, and acetic acid are particularly promising products of the CO_2RR because of their high energy densities, ease of transport, and compatibility with existing infrastructure. These fuels can serve as both energy carriers and feedstocks for various industrial processes, contributing to a circular carbon economy.[52] Despite these advantages, the production of liquid fuels from traditional CO_2 electrolysis faces significant challenges. The main factor is the purity of the liquid fuel, which is often mixed with ionic impurities from the aqueous electrolyte.

Technoeconomic analysis (TEA) provides a comprehensive framework for assessing the economic feasibility of CO_2RR technologies. On the basis of an existing calculation model for evaluating the cost of the CO_2RR process, we investigated the distribution of the operating cost of common CO_2RR-derived liquid products under different electricity unit costs (Figure 2).[17] The operating cost of CO_2RR-derived liquid fuels is influenced by three primary factors: electricity input, separation costs, other cost containing materials and system maintenance. Among these, electricity expenses represent a significant portion of the overall operation cost. For simple products such as formic acid, the operating cost can already be competitive with market prices (~0.73 USD kg^{-1}) under optimal conditions. For more complex products such as ethanol or acetic acid, which require multiple electron transfers and exhibit lower Faradaic efficiencies, electricity costs dominate the overall expenses.

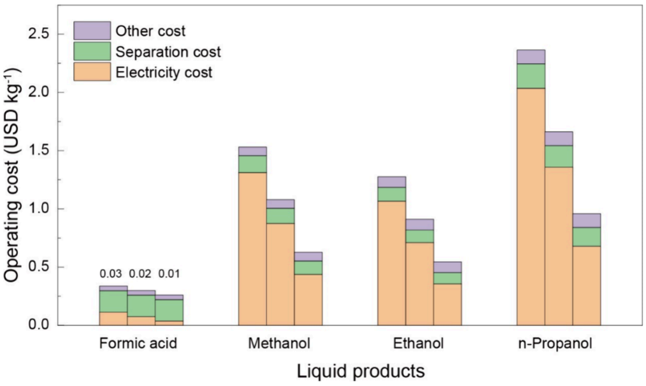

Figure 2. Technoeconomic analysis of the operating cost of the production of common liquid products (formic acid, methanol, ethanol, and n-propanol) in the CO_2RR under different unit costs of electricity (0.03, 0.02, and 0.01 USD kWh^{-1}, respectively).

However, the separation cost incurred during downstream purification should not be ignored. In conventional CO_2 electrolysis systems, liquid products are typically mixed with ions such as K^+ or Na^+ from the electrolyte. Separating these impurities to achieve commercial-grade purity levels involves

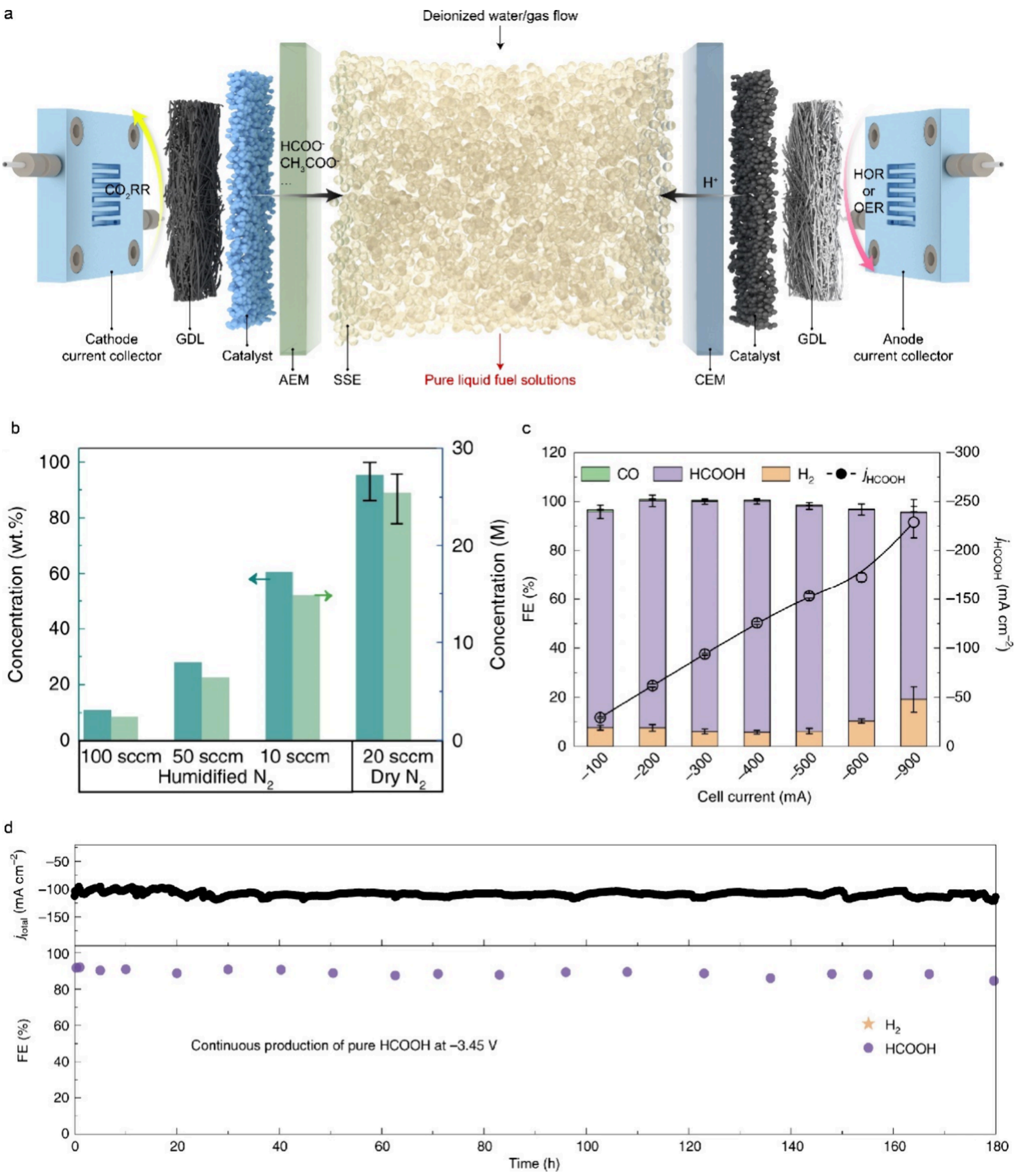

Figure 3. SSE reactors utilized for liquid carbon fuel production in the CO_2RR. (a) Schematic illustration of the CO_2 reduction cell with a solid electrolyte. (b) Dependence of formic acid product concentration on the N_2 gas flow rate at a fixed overall current density of 200 mA cm^{-2}. Reproduced from ref 19. Available under a CC-BY 4.0 license. Copyright 2020 The Authors. (c) FEs of all the products under different cell currents, along with the corresponding HCOOH partial current density over Pb_1Cu SAAs in an SSE reactor. Reproduced with permission from ref 20. Copyright 2021 Springer Nature. (d) Long-term operation of the SSE reactor over Pb_1Cu SAAs for pure HCOOH solution production at −3.45 V. Reproduced with permission from ref 20. Copyright 2021 Springer Nature.

energy-intensive processes that significantly increase the final cost of the product. For example, the purification of formic acid requires multiple steps, including ion exchange and distillation, to remove residual salts and concentrate the product. These steps can increase the overall cost by 50% or more, undermining the economic benefits of electrochemical production (Figure 2).[18]

As above, TEA highlights that the costs associated with downstream purification significantly impair the economic viability of CO_2RR products. While the falling costs of renewable electricity offer a favorable outlook for CO_2 electrolysis, the economic viability of this technology depends heavily on the purity and concentration of the resulting products. The global market for liquid fuels and chemicals is vast, with formic acid alone resulting in an annual demand of over 800,000 t.[53] High-purity, high-concentration products are critical for tapping into this market, ensuring that CO_2RR technologies can scale to meet industrial demand without sacrificing competitiveness. In this context, solid electrolyte reactors represent a key advancement in this direction, offering

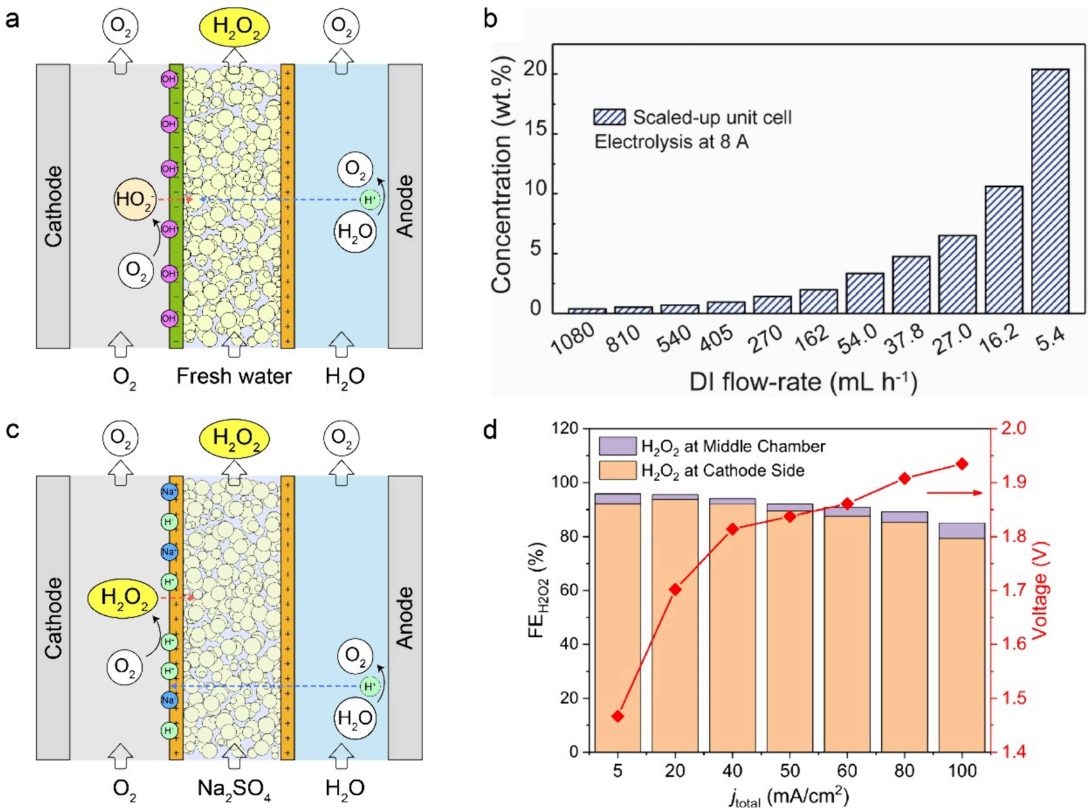

Figure 4. SSE reactors utilized for pure H_2O_2 production via the $2e^-$-ORR. (a) Schematic illustration of the O_2 reduction cell with a solid electrolyte. (b) Dependence of the H_2O_2 concentration (up to ~20 wt %) on the DI water flow rate at a constant overall current of 8 A in an SSE reactor. Reproduced with permission from ref 11. Copyright 2019 The American Association for the Advancement of Science. (c) Schematic illustration of the $2e^-$-ORR SSE reactor with a double-PEM configuration. (d) The I−V curve and corresponding FEs for the production of H_2O_2 using the SSE reactor with a double-PEM configuration through the flow of 0.03 M Na_2SO_4 in the middle chamber. Reproduced from ref 21. Available under a CC-BY 4.0 license. Copyright 2022 The Authors.

a viable route to produce high-value liquid fuels directly from CO_2.

In the initial study, Xia et al. demonstrated the feasibility of continuous pure liquid carbon fuel production from CO_2 conversion using a solid electrolyte reactor (Figure 3a).[10] By employing a solid ion conductor layer, the system decouples the functions of ion transport and product collection, enabling the generation of concentrated formic acid solutions. This design achieved an impressive 12 M concentration of formic acid and demonstrated operational stability for over 100 h with minimal degradation. The authors compared several types of solid electrolytes with different current carriers (H^+ and $HCOO^-$), sizes (50 and 300 μm), and compositions (functionalized polymers and inorganic $Cs_xH_{3-x}PW_{12}O_{40}$). The use of a 50-μm-styrene-divinylbenzenesulfonated copolymer as a proton conductor was demonstrated to be the best option due to its high porosity and fast ion conduction. These parameters are significant for achieving better HCOOH selectivity, fewer hydrogen evolution side reactions, lower cell voltages, and higher energy efficiency. However, owing to the limited ion conduction in solid electrolytes and the contact resistance between the solid electrolyte and the ion exchange membrane, the cell voltage was still higher than that of general MEA reactors. The authors further improved the energy efficiency by replacing the oxygen evolution anodic reaction with hydrogen oxidation, largely reducing the cell voltage below 2 V. Building on this foundation, further efforts have refined solid electrolyte reactors for higher product concentrations and efficiencies. The incorporation of an inert gas carrier system not only facilitated the efficient removal of formic acid vapors but also allowed their flexible condensation into concentrated liquid fuels. Coupled with a high activity grain boundary-enriched bismuth catalyst, this SSE reactor demonstrated ultrahigh concentrations of pure formic acid solutions (up to nearly 100 wt %) condensed from generated vapors (Figure 3b).[19] In addition, further engineering over bismuth catalysts to promote the efficiency of pure formic acid production has been fully researched.[54−57] However, the larger overpotential of the main group of metal catalysts in the CO_2RR still limits the enhancement of performance.

Further advances were made with the introduction of a single-atom alloy catalyst designed to increase the C_1 selectivity and efficiency in the SSE reactor. A Pb single-atom alloyed Cu catalyst (Pb_1Cu) was developed to optimize the CO_2-to-formate conversion pathway.[20] The Pb atoms effectively modulated the electronic structure of the Cu matrix, favoring the formation of HCOO* intermediates and suppressing competing reaction pathways, such as C−C coupling and hydrogen evolution. This catalyst achieved near-unity Faradaic efficiency toward formic acid and high current densities exceeding 1 A cm^{-2}. When integrated into an SSE reactor, the system continuously produced pure formic acid solutions (0.1 M, 8 L in total) for 180 h with minimal performance decay (Figure 3c,d).

Expanding beyond C_1 products, this technology was also extended to the electrochemical reduction of carbon monoxide

(CO) into C_{2+} products, notably acetic acid. By optimizing the edge to (100) surface ratio of Cu nanocube catalysts by controlling their size, researchers achieved an unprecedented acetic acid Faradaic efficiency of 43%, with relative product purities exceeding 98 wt %.[58] The reactor continuously produced pure acetic acid solutions with concentrations up to 2 wt % (0.33 M) and an operational stability exceeding 150 h. This outcome demonstrates the ability of SSE systems to produce a diverse range of liquid fuels directly from CO_2 or CO, positioning them as versatile platforms for sustainable chemical production.

The development of SSE reactors represents a transformative milestone in the CO_2RR, enabling the direct production of high-purity, high-concentration liquid carbon fuels. With ongoing improvements in reactor design and catalyst efficiency, the pathway to commercial deployment appears increasingly viable.

3.2. Hydrogen Peroxide from the $2e^-$ ORR

The current production of H_2O_2, a widely used and green oxidant, relies on energy- and resource-intensive anthraquinone processes.[59,60] The electrochemical synthesis of H_2O_2 via two-electron oxygen reduction ($2e^-$ ORR) provides a promising energy-efficient and low-waste alternative.[61] However, both traditional and electrocatalytic methods typically yield H_2O_2 at low concentrations, requiring additional concentration and purification steps to avoid self-decomposition during storage and transportation, raising both economic and safety concerns. Therefore, the development of a scalable, safe, and environmentally friendly method for producing high-purity H_2O_2 could revolutionize its industrial applications and supply chain.

The method based on SSE reactor represents a significant departure from conventional H_2O_2 production. Traditional processes require mixing H_2 and O_2 gases under high pressure—a risky setup due to the flammability of H_2 and the reactivity of both gases. To mitigate these risks, H_2 is often diluted with inert gases, which limits the achievable H_2O_2 concentration. Additionally, the reactions are usually conducted in organic solvents such as methanol, adding post-reaction purification steps to yield usable aqueous H_2O_2.[62] In contrast, Xia et al. proposed an electrosynthesis method that innovatively splits the reaction into two separate half-reactions, eliminating the need for high-pressure mixing and hazardous solvents.[11] At the anode, H_2 is oxidized to release protons (H^+), whereas at the cathode, O_2 undergoes a $2e^-$ ORR to generate hydroperoxide ions (HO_2^-). These ions then combine in an SSE layer to form H_2O_2, which dissolves directly into flowing deionized (DI) water, producing a pure, aqueous H_2O_2 solution without further purification (Figure 4a).

In this system, carbon black was chosen for its high surface area, which enhances the catalytic activity and facilitates gas diffusion. To further improve H_2O_2 selectivity, Xia et al. treated carbon black with nitric acid to introduce oxygen-containing functional groups, which help direct the reaction toward H_2O_2 generation rather than complete reduction of O_2 to water, achieving selectivity levels above 90%.[11] With this optimized reactor and catalyst design, the SSE reactor delivered sustained performance over 100 h of continuous operation, achieving high-purity H_2O_2 concentrations of up to 20% by weight (Figure 4b). In this work, styrene-divinylbenzene copolymer microspheres functionalized with sulfonic acid groups were utilized as a proton-conducting solid electrolyte. The inorganic SSE ($Cs_xH_{3-x}PW_{12}O_{40}$) and HO_2^--conducting SSE were also tested. However, the inorganic $Cs_xH_{3-x}PW_{12}O_{40}$ proton conductor-equipped cell exhibited a relatively high voltage at the same current density, perhaps due to its poor ion conductivity. Moreover, the anion-conducting SSE-equipped reactor presented a relatively low H_2O_2 FE owing to the self-decomposition of the product in a highly local alkaline environment in the HO_2^--conducting SSE. Notably, in the long term stability test, a reinforced AEM (AMI-7001, Membranes International Inc.) was used for its robust mechanical properties, resulting in better interfacial contact between the SSE and AEM. Moreover, the chemical stability of polymer-based ion conductors and membranes in the oxidative environment of the $2e^-$ ORR should also be considered.

Despite progress in solid electrolyte reactors for pure H_2O_2 production, challenges still remain in optimizing the catalyst and operating environment. In systems with anion exchange membranes (AEMs), catalysts struggle in alkaline conditions where H_2O_2 easily deprotonates ($pK_a > 11$) and degrades, reducing stability.[21] Additionally, AEMs are typically less durable than proton exchange membranes (PEMs), such as Nafion, especially when exposed to air. Acidic H_2O_2 solutions, which are more versatile and in demand because of their stronger oxidative properties, motivate research on efficient H_2O_2 generation in acidic media. While noble metal catalysts (*e.g.*, Pt- and Pd-based) are effective and stable in acidic environments, their high cost and toxicity limit their scalability. In acidic media, carbon-based catalysts offer a nontoxic alternative but generally require high overpotentials (>300 mV) owing to slow ORR kinetics.[21] The development of efficient and stable carbon catalysts for H_2O_2 production in acidic environments could unlock practical applications.[63]

To address this issue, Zhang et al. first explored whether alkali metal cations could migrate across PEMs to regulate the catalyst/membrane interface, enhancing H_2O_2 selectivity.[21] Initial tests using a PEM-MEA setup with a carbon black and H_2SO_4 anolyte showed limited H_2O_2 selectivity, as proton flux interfered with cation migration. Using Na_2SO_4 as an anolyte was also ineffective because of proton transport from the anode to the cathode. In light of this, Zhang et al. developed a new SSE reactor with two PEMs (Nafion-117) to harness cation effects for improved H_2O_2 production (Figure 4c). The SSE layer between the cathode and anode facilitated ion transfer and maintained low resistance. Oxygen and water flowed continuously at the cathode to drive the $2e^-$ ORR, whereas the anode oxidized water. A dilute cation solution flows through the SSE layer, enhancing H_2O_2 selectivity by optimizing the local catalyst/PEM interfacial environment. Continuous H_2O_2 production was achieved with high Faradaic efficiency (~90%) and stability (>500 h) when only 0.03 M Na_2SO_4 was used as the cation source, demonstrating a robust approach to sustainable H_2O_2 synthesis (Figure 4d).

To enable a continuous supply of cation solution in the SSE layer, Zhang et al. further developed a closed-loop system where the cation solution of the SSE layer circulates through the cathode and returns, allowing H_2O_2 accumulation. In this configuration, the cation mixture mixes with oxygen, flows to the cathode for H_2O_2 production, and cycles back to the solid electrolyte layer. This design enables cation reuse, eliminates constant resupply, and neutralizes OH^- ions at the cathode with SE layer protons, maintaining stability. This setup achieved a steady H_2O_2 concentration, reaching ~5,000 ppm in 13 h, and operated stably for over 200 h, producing 3.7 L of 5,000 ppm of H_2O_2.[21] The closed-loop solid electrolyte design exemplifies a practical approach to cation tuning, presenting an efficient, scalable method for H_2O_2 production in acidic media.

The design of the SSE reactor for the $2e^-$ ORR promises to bring H_2O_2 synthesis closer to end users, potentially eliminating the need for bulk transportation and allowing localized production in facilities such as water treatment plants, hospitals, or industrial sites. By enabling safe, on-demand H_2O_2 generation, SSE technology is promising for enhancing both environmental sustainability and economic efficiency, setting a new standard for decentralized H_2O_2 production.

3.3. Ammonia from Nitrate Reduction

Ammonia (NH_3), a vital chemical with wide applications, is traditionally produced via the Haber-Bosch process. This process is energy-intensive with high carbon emissions, spurring interest in sustainable alternatives that could leverage renewable energy.[9] The electrochemical nitrate reduction reaction (NO_3RR) offers a promising pathway for the mild conversion of nitrate (NO_3^-) to ammonia while managing waste by targeting nitrate contaminants in industrial and agricultural wastewater.[64] However, the NO_3RR typically requires high-concentration supporting electrolytes to achieve efficiency and selectivity, which are costly and unsustainable for large-scale use, especially in low-salinity wastewater. Achieving efficient NO_3RR in low-electrolyte environments remains a critical challenge because of competition from the HER, which reduces the ammonia yield.[9]

A recent study by the Wang group presented a solution to this problem through an innovative SSE reactor design.[9] This SSE reactor introduces a cation shielding mechanism that enables efficient NO_3RR without the need for added electrolytes. The authors first evaluated the performance of a conventional MEA setup using a Ru-dispersed Cu nanowire (Ru-CuNW) catalyst for the NO_3RR. Although the MEA was capable of operating without extra electrolytes, it yielded low ammonia selectivity (FE < 20%) because of high proton flux at the catalytic interface. This influx of protons lowered the local pH, favoring the HER over the NO_3RR. When the authors switched to an anion exchange membrane, they reported that it relieved the low pH issue but led to nitrate ion loss to the anode side, which hindered complete nitrate conversion to ammonia. These results demonstrated the limitations of conventional MEA systems in achieving both high selectivity and efficient nitrate utilization.

To overcome these limitations, an SSE reactor structure was proposed that incorporates two cation exchange membranes with an additional middle SSE layer between the cathode and anode.[9] With sodium ions flowing through the SSE layer, the authors were able to investigate and optimize the effect of cation shielding, inspired by its role in suppressing the HER in CO_2 reduction processes. Sodium ions, which are abundant in wastewater, effectively maintain a high local pH near the catalyst and improve NO_3RR selectivity, resulting in a notable FE increase from 25% to 92% at a current density of 100 mA cm^{-2}. Considering the demand for Na^+ conduction, the solid electrolyte should conduct cations efficiently. Therefore, the authors continued to use the styrene-divinylbenzenesulfonated copolymer, minimizing the ohmic drop between the cathode and anode.

Following these promising results, the authors developed a complete process design for the SSE system (Figure 5a).[9] First, the nitrate stream flows into the cathode chamber where the NO_3RR begins, while sodium ions migrate from the middle SSE layer into the cathode, creating a favorable environment for ammonia production. After the NO_3RR, ammonia gas was separated from the catholyte via an air-stripping process. The remaining solution, still containing Na^+ ions, was then recirculated into the SSE layer to sustain the cation flow. In the final step, the OH^- ions produced from the NO_3RR neutralize H^+ ions generated in the oxygen evolution reaction (OER) at the anode, maintaining a balance across the reactor chambers and supporting consistent NO_3RR performance. This closed-loop design minimizes cation and pH imbalances and eliminates the need for supplemental electrolytes, using only the nitrate solution as the input for ammonia synthesis.

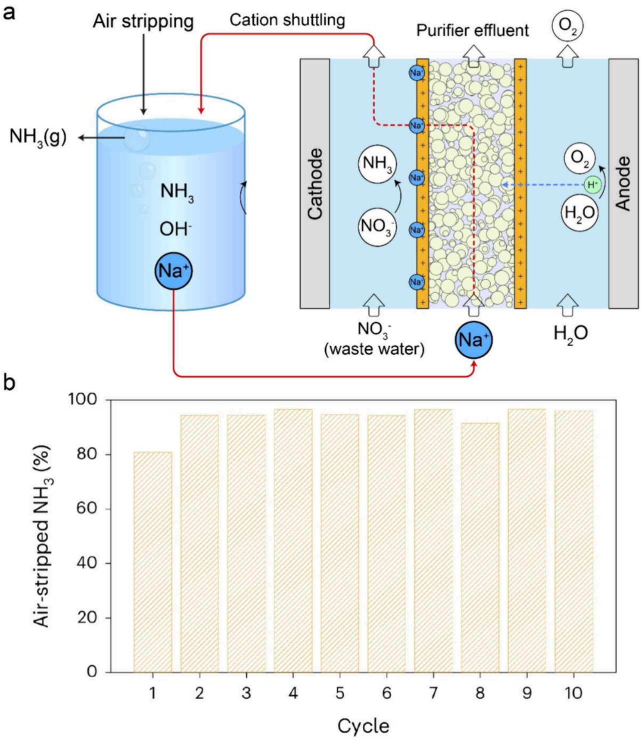

Figure 5. SSE reactors utilized for ammonia production from nitrate reduction. (a) Schematic illustration of the nitrate reduction setup with a solid electrolyte. (b) The air-stripping efficiency of purifying the NH_3 product out from the catholyte after each cycle of reactions in the above ten cycles of the stability test. Reproduced with permission from ref 9. Copyright 2024 Springer Nature.

By fine-tuning several operational parameters, including the flow rate, current density, and nitrate concentration, this system can be further optimized in a single-pass flow configuration.[9] These adjustments helped establish optimal conditions for achieving the highest FE of ammonia, which exceeded 90% in batch conversion tests for 100 mL of 2,000 ppm nitrate solution, meeting the World Health Organization's nitrate limits for drinking water. Furthermore, the system demonstrated excellent long-term stability; it effectively converted 10 sequential batches of nitrate solution with residual nitrate concentrations under 0.001 M and sodium levels below 0.05 M (Figure 5b).

In addition to its technical achievements, this new SSE reactor design holds substantial promise for industrial and environmental applications. A TEA assessment revealed the potential of the SSE reactor for industrial applications in both waste treatment and sustainable ammonia production.[9] Although the cost is currently above that of the Haber-Bosch process, the dual functionality of nitrate removal and ammonia production offers substantial environmental and operational benefits, underscoring the viability of SSE reactors in decentralized, renewable-powered setups.

While this study provides a compelling blueprint for electrochemical ammonia production, challenges still remain. Although the SSE reactor reduces the need for supporting electrolytes, the cation loop requires a sufficient source of cations, which may limit its application in low-salinity water bodies. Future research should focus on optimizing the cation shuttle mechanism to improve ion transfer without compromising reactor durability. Experimentation with cation selection and the SSE reactor architecture could unlock further improvements in efficiency, yield, and stability, enhancing the suitability for a broader range of water sources and nitrate concentrations.

4. EXTENDED APPLICATIONS

4.1. Electrocatalytic CO_2 Capture

As climate change concerns grow, efficient carbon capture technologies are increasingly essential. Traditional methods such as amine scrubbing and $CaCO_3$ cycling are effective but highly energy-intensive, requiring high temperatures for CO_2 desorption, which makes them costly and challenging to scale. For example, thermal cycling often requires temperatures above 900 °C, which consumes large amounts of fossil fuel-derived energy and offsets CO_2 emission reductions.[65]

Emerging electrochemical carbon capture technologies offer promising, energy-efficient alternatives.[66] These systems utilize electricity to drive CO_2 capture and release reactions under ambient conditions, making them well-suited for decentralized applications and renewable energy integration. Typically, these methods rely on redox reactions or pH-switching processes: redox-active systems use molecules such as quinones to bind and release CO_2 but are often limited by low capture rates and sensitivity to O_2, whereas pH-swing methods use electrolytic processes to create localized acid and alkaline conditions for CO_2 capture and release. In this context, SSE reactors were further developed to simplify this process by integrating continuous capture and release without additional chemicals, offering a streamlined and efficient solution.

In the conventional CO_2RR, carbonate ions formed on the cathode side can migrate toward the anode, where they mix with generated O_2, leading to carbon losses and decreased efficiency. SSE reactors mitigate this issue by employing a buffer layer that recombines carbonate ions with protons, converting them back to high-purity CO_2 gas within the reactor before any O_2 exposure occurs. The modified SSE reactors use a CO_2RR at the cathode and an OER at the anode to establish a pH gradient that captures CO_2 at the cathode and releases it as high-purity CO_2 gas in the middle solid-electrolyte layer (Figure 6a).[23] This electrochemical setup involves a cathode where CO_2 is absorbed, forming carbonate or bicarbonate ions. These ions then migrate through the reactor and combine with protons at the central SSE layer, where a styrene-divinylbenzenesulfonated copolymer is used for proton conduction. In the middle chamber, CO_2 gas is regenerated and expelled in pure form. This configuration enables the device to achieve high CO_2 purity without O_2 contamination, as the regenerated CO_2 is completely separated from O_2. Impressively, this SSE reactor achieved high-purity CO_2 recovery (up to 99%) and a continuous CO_2 conversion efficiency of over 90%, even at high current densities.

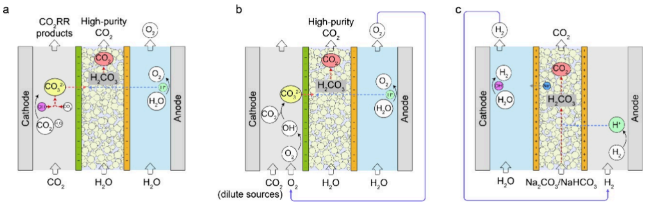

Figure 6. SSE reactors utilized for CO_2 capture. (a) Schematic illustration of the SSE reactor with a CO_2RR/OER redox configuration for CO_2 capture. CO_2 is captured by OH^- generated *in situ* at the reaction interface of the CO_2RR and forms carbonate ions. These ions then migrate across the AEM to the middle SSE chamber. SSE conducts protons from anodic water oxidation and releases CO_2 from carbonate. (b) Schematic illustration of the SSE reactor with an ORR/OER redox configuration for CO_2 capture in dilute sources. CO_2 is converted into carbonate ions by the high-alkaline environment of the ORR reacting interface. The SSE conducts anode-generated protons and regenerates CO_2. (c) Schematic illustration of the SSE reactor with a HER/HOR redox configuration for CO_2 capture. The carbonate or bicarbonate solution directly flows through the SSE chamber. SSE conducts protons from anodic hydrogen oxidation to combine with carbonate or bicarbonate, releasing CO_2. Moreover, SSE conducts sodium ions to the cathode, leading to the regeneration of NaOH for further CO_2 capture.

Further work by Zhu et al. shifted the focus from CO_2 recovery in CO_2 electrolysis to broader application for continuous CO_2 capture from dilute sources, such as flue gases.[24] This SSE reactor design combines ORR/OER redox electrolysis to enable high-efficiency, continuous CO_2 capture without the need for additional chemicals or complex processing. In this design, the SSE reactor captured CO_2 at the cathode by converting it into carbonate ions under a high-alkaline environment created by the ORR. These carbonate ions were then driven by the electric field across an anion-exchange membrane into the SSE layer. The SSE adopted a styrene-divinylbenzenesulfonated copolymer for proton conduction supplied by the OER at the anode, where carbonate ions recombined with protons to release high-purity CO_2 in the middle layer (Figure 6b). Notably, by reducing the SSE layer thickness from 2.5 mm to 1.5 mm, the authors conserve approximately 200 mV of cell voltage under 100 mA cm^{-2} at similar carbon-capture FEs. This result indicates a promising strategy for the development of energy-efficient SSE reactors. This device delivered a CO_2 capture rate of 86.7 kg_{CO2} per day per square meter at 500 mA cm^{-2} and a Faradaic efficiency exceeding 90%. The reactor was operated with minimal energy input (approximately 150 kJ mol^{-1} CO_2), demonstrating the potential of SSE reactors for decentralized carbon capture applications.

The most recent advancement further refined SSE reactor technology by focusing on the efficient regeneration of high-purity CO_2 from carbon-containing solutions, specifically (bi)carbonates, in a modular SSE reactor. This study addressed two key issues in carbon capture loops: the energy-intensive regeneration process and capture capacity retention. In this system, the SSE reactor uses hydrogen evolution and oxidation

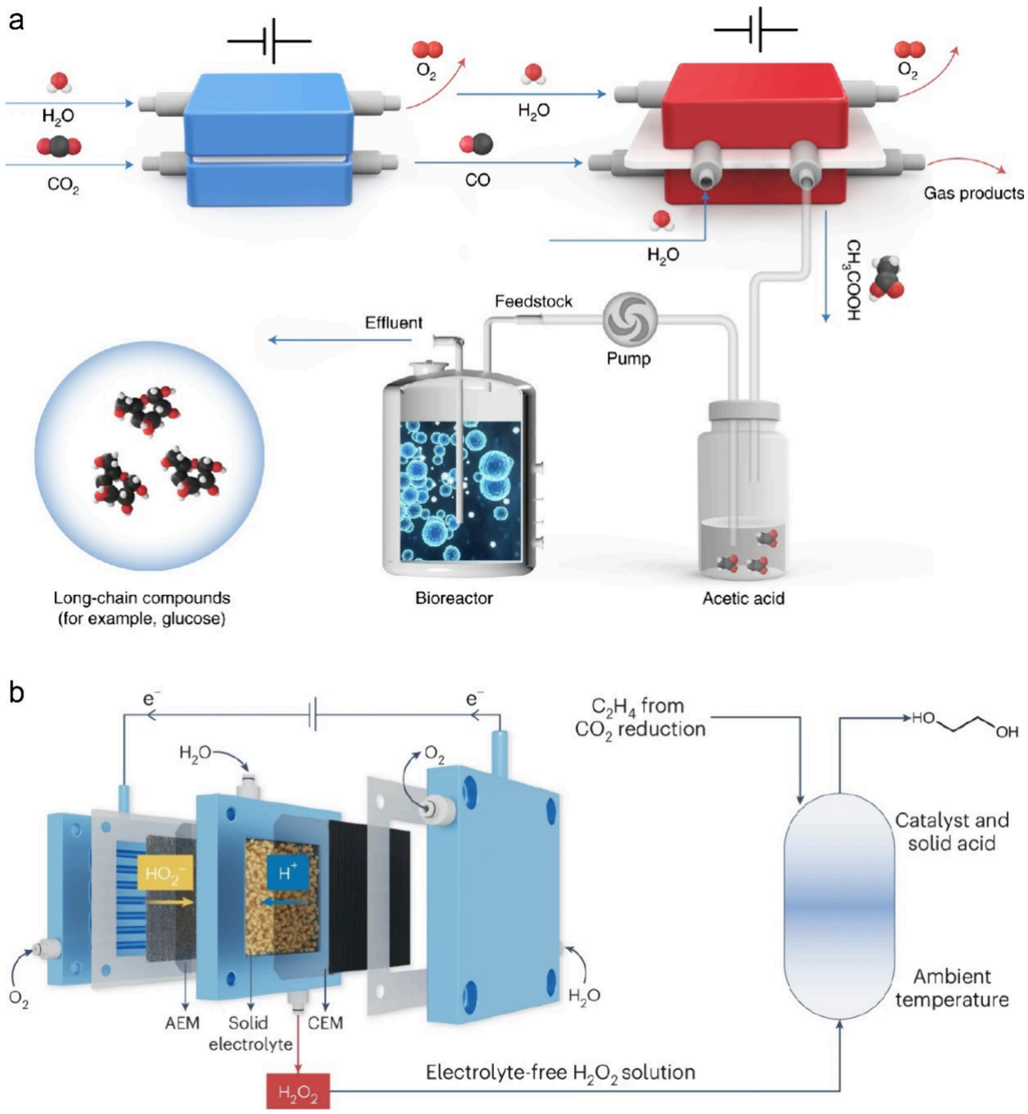

Figure 7. SSE reactors utilized for tandem reactions. (a) Schematic illustration of the *in vitro* artificial sugar synthesis system with spatial decoupling of the electrochemical and biological modules. Reproduced with permission from ref 67. Copyright 2022 Springer Nature. (b) The present cascade catalytic system coupling electrogenerated hydrogen peroxide with ethylene oxidation. Reproduced with permission from ref 73. Copyright 2023 Springer Nature.

redox reactions to selectively split bicarbonate ($NaHCO_3$) and carbonate (Na_2CO_3) solutions, regenerating the NaOH absorbent in the catholyte and releasing pure CO_2 in the SSE layer (Figure 6c).[25] The sodium form styrene-divinylbenzenesulfonated copolymer is used as the SSE, undertaking dual tasks to conduct both Na^+ (from the SSE layer to the cathode for NaOH regeneration) and protons (from the anode to the SSE layer for releasing CO_2). The authors also suggest the prospect of further improving the energy efficiency by improving the SSE ionic conductivity and reducing the thickness of the SSE layer. This process, which avoids chemical consumption and byproducts, results in high Na^+ transport numbers (~90%) and demonstrates both high capture capacity retention (~90%) and low energy consumption (50 kJ mol^{-1} CO_2 at 1 mA cm^{-2} and 118 kJ mol^{-1} CO_2 at 100 mA cm^{-2}).

These advancements in SSE technology underscore its potential to play a crucial role in future carbon management, offering an efficient, scalable, and sustainable pathway for both CO_2 capture and conversion. Expanding SSE reactor functionality to handle a variety of CO_2 sources, including low-concentration CO_2 from ambient air, will further broaden their application scope and make them viable for direct air capture.

4.2. Tandem Reactions

The increasing global demand for sustainable chemical processes has spurred the development of tandem reaction systems, where intermediate products from one reaction are directly utilized in subsequent processes. These systems are particularly promising when powered by renewable electricity and integrated with solid electrolyte reactors, which offer the advantage of producing high-purity, concentrated liquid products. These intermediates serve as critical reactants in a wide array of chemical and biological processes.[67−75] The seamless transition between electrocatalysis and downstream reactions not only simplifies the overall production workflow but also enhances the sustainability and efficiency of chemical manufacturing.

The success of tandem systems hinges on the availability of high-purity intermediates. Traditional electrocatalytic methods often yield products mixed with ionic impurities, which complicates the integration of downstream processes.[76] Pure liquid products, however, provide a game-changing solution. In addition to their intrinsic chemical value, the compatibility of pure intermediates with downstream reactions makes them ideal for integrated production platforms. For example, pure hydrogen peroxide is essential for oxidation reactions,[59] whereas pure acetic acid is a key substrate in biosynthetic processes.[77] Direct integration of these intermediates eliminates extensive purification, lowering operational costs and improving system efficiency. Producing and utilizing pure intermediates also enhances the overall sustainability of tandem systems. By minimizing energy-intensive purification and improving downstream efficiency, these systems align with the principles of green chemistry and sustainable development. High-purity intermediates act as the nexus of electrocatalysis and downstream reactions, which maximizes resource utilization while minimizing the environmental impact.[73]

Recent advances in tandem reaction systems underscore the vast potential of integrating pure liquid products from solid electrolyte reactors into downstream processes. Among these systems, the tandem electro-biocatalysis system stands out.[67−69] Electrocatalysis, despite its scalability and efficiency, is inherently limited in its ability to propagate carbon−carbon bonds, restricting its product range to C_1−C_3 species. On the other hand, biological carbon utilization, which leverages sophisticated metabolic pathways, excels in synthesizing long-chain compounds but suffers from slow reaction rates and limited substrate flexibility. By combining the strengths of both approaches, hybrid systems have emerged as a powerful solution, leveraging the speed and precision of electrocatalysis to generate key intermediates, which are then biologically upgraded into complex, long-chain products.

The work by Zheng et al. exemplified this integration through a hybrid system that bridges electrochemical and biological processes.[67] In their setup, an SSE reactor equipped with a grain-boundary-rich Cu catalyst converted CO_2 to pure acetic acid with a Faradaic efficiency of 46% and a partial current density of 413 mA cm^{-2}. This ultrapure acetic acid, with a relative purity of ~97 wt %, is directly utilized in the fermentation of genetically engineered *Saccharomyces cerevisiae* to produce glucose (Figure 7a). A key innovation here is the spatial decoupling of the electrochemical and biological modules, allowing each to operate under optimal conditions: the SSE reactor maximizes acetic acid purity at precise potentials, whereas the bioreactor operates at a specific pH and temperature ideal for yeast metabolism. This independent optimization minimizes cross-module interference, ensuring high efficiencies in the respective operations. Building on this concept, a similar system uses SSE reactors to produce pure acetic and formic acids, which serve as the carbon source and reducing equivalents, respectively. Formic acid plays a crucial role as a reducing agent, driving anabolic pathways in engineered microbes and regenerating essential cofactors such as NAD(P)H. This enables efficient production of β-farnesene, a valuable biofuel precursor, significantly enhancing the system's capacity to synthesize long-chain hydrocarbons.[68]

This approach further extends to Bioplastic production, as demonstrated by Wi et al., who developed an integrated platform combining an SSE reactor with a bioreactor for polyhydroxybutyrate (PHB) synthesis.[70] Unlike systems relying on pure acetic acid, this method generates an optimized biocompatible electrolyte medium containing acetate and biocompatible salts, enabling direct microbial fermentation without additional processing. The SSE reactor, which employs a silver-doped Cu_2O nanocube catalyst, electrochemically converts CO into acetate with a Faradaic efficiency of 55% and acetate concentrations exceeding 150 mM. The biocompatible acetate solution is fed into a bioreactor containing *Ralstonia eutropha*, a microorganism engineered to convert acetate into PHB.

The concept also applies to a tandem electro-thermal catalytic system. For example, Fan et al. reported ethylene glycol production by coupling electrogenerated hydrogen peroxide with ethylene oxidation.[71] Traditionally, ethylene glycol synthesis relies on energy-intensive thermocatalytic routes with high CO_2 emissions. This system uses an SSE reactor to produce pure H_2O_2 via a two-electron oxygen reduction reaction, achieving a Faradaic efficiency of over 90% at current densities up to 500 mA cm^{-2}. The pure H_2O_2 stream is then fed into a catalytic reactor, where it oxidizes ethylene over a titanium silicalite-1 (TS-1) catalyst under ambient conditions, achieving near-complete selectivity for ethylene glycol (Figure 7b). Similarly, a study by the Wang group explored interfacial electrochemical-chemical coupling for efficient olefin oxidation.[72] This demonstrates an SSE reactor design that uses a high local concentration of H_2O_2 at the membrane interface to drive ethylene oxidation to ethylene glycol. By integrating this interfacial reaction within the reactor, the system achieves a 3-fold improvement in ethylene glycol production rates compared with traditional tandem systems.

With the advancement of SSE reactors producing pure intermediates as a central intermediate, the versatility of tandem reaction systems extends far beyond examples of food, biofuels and bioplastics. By optimizing the compatibility between electrocatalytic and downstream processes, these systems can be tailored to produce a wide range of valuable compounds. For example, the production of olefins and other hydrocarbons through the coupling of electrocatalytic hydrogenation and chemical synthesis represents a significant opportunity for the petrochemical industry. Similarly, the synthesis of specialty chemicals, such as pharmaceutical precursors, can be enhanced by using pure intermediates generated through electrocatalysis.

5. FUTURE PERSPECTIVES

The advent of SSE reactors marked a significant milestone in electrocatalysis, addressing several critical challenges in modern chemical manufacturing. By enabling the direct production of high-purity chemical products, SSE reactors bypass costly and energy-intensive purification processes associated with traditional systems, thus reshaping the landscape of chemical production. The versatility of SSE reactors extends beyond CO_2 reduction and hydrogen peroxide synthesis. Future applications could target more chemical reactions, sustainable production of specialty chemicals, and even direct air capture and conversion of CO_2. One particularly promising avenue is the deployment of SSE reactors in tandem reactions, where intermediate products from one reaction serve as feedstock for subsequent processes. However, realizing their transformative potential requires overcoming key scientific, technological, and industrial challenges.

A fundamental component of SSE reactors is the solid electrolyte, which facilitates ion transport while simultaneously acting as a product separator. Current solid electrolyte materials, including polymer-based ion conductors and inorganic oxides, have shown impressive ionic conductivities and chemical stabilities. However, their performance under industrially relevant conditions, such as high temperatures, extreme pH environments, and elevated current densities, remains suboptimal. Future research should prioritize the development of next-generation solid electrolytes with ultra-high ionic conductivity, tailored ion selectivity, and long-term stability in harsh operating environments. Hybrid materials, which combine the flexibility and processability of polymers with the structural stability and conductivity of inorganic components, offer promising options for achieving these goals. Moreover, the exploration of multifunctional solid electrolytes capable of modulating local reaction environments or participating directly in catalytic processes could redefine the role of solid electrolytes, enhancing overall reactor performance.

Compared with traditional liquid electrolyte systems, SSE reactors inherently experience greater internal resistance. This increased resistance stems from the inherent properties of solid electrolytes and the complex interfaces between different reactor components. As a result, the systems exhibit greater ohmic losses, leading to higher energy consumption and reduced efficiency. Addressing this issue will require innovations in the design and engineering of low-resistance solid electrolytes and advanced interfacial structures.

For the optimization of solid electrolytes, both charge transfer and mass transport are important. Previous reports have demonstrated the greater efficiency of functionalized-polymer-based proton conductors, which use mainly sulfonic groups. Charge conducting could be further improved by trying more types of functional groups, such as phosphonic groups, which are also widely used in proton conductors at room temperature. Moreover, the types of polymer backbone could also be further screened to increase the chemical and mechanical stability of SSE powders. Doping with organic proton conductors such as heteropolyacid or protonated montmorillonite also promises to tune the physicochemical properties of SSE. As for the geometric aspects, small and high porosity powders can efficiently accelerate mass transport. The thinner and more compact packing of the SSE powders would also present an enhanced charge transfer. However, dense integration would also result in greater flow resistance in the SSE chamber, affecting the collection efficiency of pure products, which is expected to be balanced with proton conduction.

Enhanced interfacial engineering could also minimize resistance at critical junctions, especially for SSE-ion exchange membrane interfaces, improve overall energy efficiency and reduce operational costs. From chemical aspects, strategies to increase the affinity between SSE and the membrane should be developed. For example, specific chemical modifications of the main chain of the SSE or the surface of an ion exchange membrane with similar functional groups may increase the degree of charge transfer at these interfaces. Novel preparation processes could also be developed to realize the epitaxial growth of solid-electrolyte-components on the unilateral surface of ion exchange membranes, achieving efficient integration of the SSE and the membrane. From engineering aspects, increasing the contact area at the interface may have an effect. Both improving the roughness of the membrane surface and hybrid packing of SSE powders of different sizes improved the degree of contact. Moreover, advanced hot-pressing techniques are expected to be developed to enhance the interfacial contact, with sufficient moisture remaining for charge conduction.

Moreover, the energy efficiency of SSE reactors could be further optimized by matching proper anodic reactions for proton supply. Although the hydrogen oxidation reaction has been reported to lower the cell voltage effectively, potential security issues in the transportation, storage, and flow control of H_2 still limit its large-scale application. Therefore, exploring safe, environmentally friendly, less energy-intensive, and economical anodes as highly efficient proton sources would become a vital research direction for developing energy-efficient SSE reactors. The electro-oxidation of organic molecules such as alcohol and aldehyde, with lower anodic potential, safe operation conditions, and higher value-added products, would become ideal options for the anode of the SSE reactor.

The assembly of SSE reactors poses another technical challenge. Key components such as GDEs and ion exchange membranes must be precisely integrated to ensure optimal performance. However, these components often degrade under continuous operation, leading to decreased efficiency and reliability over time. Advances in GDE design, focusing on enhanced hydrophobicity and optimized pore structures, could prevent flooding and improve gas transport. Similarly, ion exchange membranes need to be tailored for greater durability and selectivity, ensuring consistent performance during long-term operation.

The scale-up of the SSE reactor increases the demand for component consistency, flatness, and assembling precision. The geometric structure of the current collector, gas/liquid flow field, pipelines, and connection mode of circuits should be rationally designed to guarantee the uniform distribution of key factors such as current, mass, temperature, and moisture. Multiphysics simulations with the finite element method could also offer guidance for component design by revealing the parts-structure-dependent field distribution. Moreover, the automation and intelligentization of the SSE reactor assembly process has become a developing tendency toward industrial application. Several strategies could be adopted in the future to further standardize assembly technology, largely to reduce difficulties and risks in cell construction. For example, intelligent sensors could be introduced to monitor the compactness of assembled components and offer feedback in real time. Setting attachments for assisted location would further improve the accuracy of assembly. Exploring the preintegration techniques of solid electrolyte powder, ion exchange membranes, and electrodes would also simplify the assembly process. For example, the mold of SSE powders into sheets and hot-pressed with ion exchange membranes as an individual component would be more convenient and flexible for the building and maintaining of SSE stacks.

A deeper understanding of the reaction mechanisms at the catalytic interface within SSE reactors is also imperative. Unlike traditional systems, SSE reactors create highly localized and dynamic microenvironments that are influenced by ionic gradients and the accumulation of reaction products. These unique conditions can alter the catalytic behavior and reaction pathways, making them difficult to predict and optimize. However, the limited accessibility of *in situ* and *operando* characterization techniques currently hinders the detailed exploration of these mechanisms. Solid electrolyte layers restrict direct observation of catalytic processes, complicating efforts to identify active sites, intermediate species, and reaction pathways. To address this, advancements in emerging *in situ* characterization methods, such as X-ray absorption spectroscopy, neutron scattering, and advanced electron microscopy, are urgently needed to provide deeper insights into the catalytic processes within SSE reactors.

The successful deployment of SSE reactors will also rely on interdisciplinary collaboration across material science, catalysis, engineering, and policy. Governments, industries, and research institutions must work together to establish supportive policies, including incentives for sustainable technologies and increased funding for research and development. Conducting life cycle assessments is essential for evaluating the environmental impact of SSE reactors and ensuring that their deployment aligns with sustainability goals.

Looking ahead, SSE reactors hold immense potential to revolutionize chemical manufacturing, offering a flexible and sustainable solution to some of the most pressing challenges in industry. Their ability to produce high-purity chemicals efficiently and on demand could decentralize production, reduce reliance on centralized facilities, and increase the resilience of supply chains. As the technology matures, SSE reactors could become the cornerstone of a decentralized, resilient, and environmentally friendly industrial ecosystem, empowering communities and industries to adapt to the evolving demands of the future. Through continued innovation and collaboration, SSE reactor technology offers a transformative vision for a greener, more sustainable future.

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Notes

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