Chapter 10

Breakthroughs in Electrochemical Innovations Into Scalable Applications

J. Mangaiyarkkarasi
https://orcid.org/0000-0003-1431-9584
Nadar Mahajana Sangam S. Vellaichamy Nadar College, India

J. Shanthalakshmi Revathy
https://orcid.org/0000-0003-1724-7117
Velammal College of Engineering and Technology, India

ABSTRACT

Electrochemical technologies are emerging as pivotal solutions for the global transition to sustainable and scalable energy systems. This chapter bridges recent laboratory breakthroughs with pathways for industrial deployment, emphasizing innovations that extend beyond conventional proof-of-concept studies. Advances in nanostructured electrodes, solid-state electrolytes, and high-performance catalysts have redefined benchmarks of efficiency, stability, and safety. Novel manufacturing strategies including additive manufacturing and roll-to-roll processing are presented as transformative enablers of cost-effective scale-up, while AI-driven optimization accelerates the design-to-application cycle. The chapter also highlights electrochemical routes for green hydrogen production, CO_2 reduction, and nitrogen fixation, which are reshaping sustainable chemical manufacturing. Distinctive case studies in battery storage and hydrogen transport illustrate how scientific progress translates into real-world applications.

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1. INTRODUCTION

Electrochemical technologies have emerged as key enablers in advancing sustainable energy systems, green chemistry, and modern manufacturing. Spanning applications from energy storage and conversion to chemical synthesis and environmental remediation, these processes provide distinctive advantages, including high efficiency, modularity, and seamless integration with renewable energy sources. However, despite significant advancements in laboratory-scale research, translating electrochemical innovations into scalable, real-world applications remains a complex and multifaceted challenge (Ferretti et al., 2025). The journey from breakthrough discovery to large-scale implementation is often hindered by a variety of technical, economic, and regulatory barriers. Materials that perform exceptionally well under controlled lab conditions frequently encounter stability, cost, or manufacturability issues when scaled up. Similarly, reactor designs optimized for fundamental research may not translate seamlessly into commercial systems due to limitations in mass transfer, energy efficiency, or system integration. As a result, the transition from bench to market demands not only scientific excellence but also interdisciplinary collaboration and strategic innovation across engineering, materials science, and systems design. In recent years, however, a new wave of breakthroughs has started to reshape the landscape of electrochemical applications (Buglioni et al., 2022). Advances in nanomaterials, electrode architecture, and electrolyte formulation have led to remarkable improvements in performance, selectivity, and durability. At the same time, innovations in process intensification, additive manufacturing, and artificial intelligence have opened new pathways for the scale-up of electrochemical systems. These developments are enabling researchers and industries to address long-standing limitations and accelerate the deployment of electrochemical technologies in sectors such as energy storage (e.g., batteries and supercapacitors), hydrogen production, carbon dioxide conversion, wastewater treatment, and more (Zheng et al., 2024).

This chapter explores the latest breakthroughs that are propelling electrochemical technologies toward scalable and impactful applications. It highlights key areas of progress, such as the development of robust and earth-abundant catalysts, the design of scalable electrochemical reactors, and the integration of electrochemical systems with digital tools for process optimization. The chapter also examines case studies where innovations have successfully bridged the gap between research and commercialization, offering insights into the critical success factors for scale-up (Olabi, Abbas, et al., 2023). Moreover, the chapter delves into the broader ecosystem that supports electrochemical innovation—policy frameworks, market drivers, and collaborative initiatives that foster technology transfer and industrial adoption. As global tasks like climate change, resource scarcity, and energy insecurity intensify, the demand for scalable, sustainable technologies continues to grow. Electrochem-

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