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Electrochemical Energy Storage and Conversion Systems – A Short Review

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Abstract

Electrochemical energy production systems – including fuel cells and electrolyzers – are vital technologies to address energy security and environmental demands. Also, their combination for improved performance is essential for future commercial applications. However, their real utilization (and integration with other alternative energy sources) goes beyond efficiency; large-scale penetration of renewable energy in the existing electrical grid systems is challenging due to destabilization possibility. Thus, electrochemical energy storage systems (e.g., electrochemical supercapacitors) are necessary for managing power generation intermittency and grid reliability. Therefore, this ultra-short review provides a brief overview of some of the most promising electrochemical devices for electrochemical energy production and storage for future systems in an engagement scenario.

Introduction

Fossil fuels – oil, coal, and gas – are the global primary energy sources, estimated to be responsible for 85% of the total energy generation [1]. This overdependence on non-renewable fuels has resulted in several environmental issues that are difficult to circumvent, such as climatic variations due to greenhouse gas emissions, poor air quality, and water/soil contamination [2]. Thus, efforts have been directed toward replacing/complementing the global carbon-based energy matrix with alternative sources, e.g., wind, solar or geothermal [3]; however, their unpredictability has considerable effects on grid operations, except when used in small amounts. In this scenario, electrochemical energy conversion technologies have received attention because they are not location-specific as the other sources, delivering higher flexibility [4]. Nevertheless, proper grid integration is required to manage supply energy fluctuations and mismatches. Hence, appropriate storage technologies are essential to reduce the gap between consumption and production, and a myriad of energy storage devices are available, including chemical, mechanical, thermochemical, electrical, and electrochemical systems [5]. The last ones are highlighted due to their simplicity, relatively low cost, speed, and efficiency, and lithium-based batteries are the most popular system. However, although such batteries promise to shift energy in time and store any excess for future utilization, aiming to avoid voltage spikes, their cost, environmental impacts, and safety are severe drawbacks [6,7]. Thus, electrochemical capacitors/Supercapacitors are being improved, and new nanoengineered materials are being studied to overcome their low energy densities [8]. Thus, this ultra-short review will highlight the fundamental principles of alkaline water electrolysis, fuel cells, and Supercapacitors, drawing attention to the main materials for their applications.

Water Electrolysis

Although electrolysis requires electric energy for its functioning, renewable sources are being studied to efficiently provide the power needed for the process as a whole [9]. In the electrolyzer, electric energy is converted into chemical energy; oxygen is produced at the anode, and hydrogen is obtained at the cathode ($2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$), in which the releasing hydroxide ions go through the diaphragm to the anode to form O_2. About 4% of the hydrogen produced worldwide is derived from water electrolysis [9], either in acid or alkaline electrolytes. Although Proton Exchange Membrane, Solid Oxide, and Anion Exchange Membrane Electrolysis are highly studied, alkaline electrolysis achieved a more extensive commercial maturity than the other technologies [10]. It can be noticed that the method requires 1.23 V of potential for the occurrence of both the oxygen (OER) and hydrogen evolution (HER) reactions [3]. However, overpotentials are always needed, and reducing such parameters is essential once they affect the efficiency of alkaline electrolysis. Thus, the efficiency of alkaline electrolysis in this matter is influenced by membrane resistivity, distance between electrodes, bubbles, KOH concentration, and temperature affect such overpotential [10,11]. Such parameters are the most common and easy to circumvent. However, the electrodes' material choice has a significant impact on this matter as well.

One can bear in mind that precious counterparts are studied due to their lower activation energy for H desorption and optimum Gibbs free energy of metal-hydrogen binding [12]. However, due to cost issues and abundancy, Nickel-based materials are usually considered, presenting significant stability; also, their deactivation can be circumvented by using other metals, such as Iron and Vanadium [13,14]. Researchers worldwide are studying non-precious metals for electrolysis catalysts due to their prices, and nanoengineering aspects (controlling shape, size, composition, and structure), doping, and alloying are some strategies for performance improvement [15]. Most studied catalysts for OER are perovskite-type and spinel-type oxides, and layered oxides/(oxy)hydroxides, while HER counts on transition metal oxides, sulfides, and dichalcogenides, and modified carbons, among others [11].

Fuel Cells

The process is based on generating electricity by reducing oxygen in the cathode and oxidizing a fuel (e.g., hydrogen, methanol, ethanol) in the anode [14]. The components of the fuel cell devices are similar to those of the electrolyzer units, i.e., two electrodes (with their surfaces modified with the catalysts) separated by an electrolyte. According to their operating conditions, fuel cells can be classified as Solid Oxide, Proton Exchange Membrane, Molten Carbonate, Alkaline, Phosphoric Acid, Single-layered, and Direct Methanol Fuel Cells [16]. Fuel cells are high-energy density power source devices; thus, future uses can be as backup power for residential, commercial, and industrial areas, but also to power vehicles, buses, and trains. Especially, supply chain developments integrating water electrolyzers and fuel cells are considered to meet future demands for decarbonization goals. Also, Direct Methanol Fuel Cells promise to give us complete flexibility in our daily life once they

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are opportune for portable power sources, with quick methanol refueling, lower gas emissions, and acceptable efficiencies [17,18]. Carbon-based materials have emerged as a promising class of electrocatalysts due to their high surface areas, significant electronic conductivity, and the possibility of functionalization [19]. However, Pt-based materials are the best catalysts for fuel cell reaction, even considering their high cost and limited supply [17,18]. Nowadays, however, alloying processes tend to lower Pt content, and materials engineering focuses on the possibility of replacing this noble metal with non-cost counterparts [19,20]. Thus, industrial and academic researchers are developing new-generation materials for fuel cell applications based on nanoscience concepts.

Supercapacitors

Electrochemical capacitors, known as supercapacitors or ultra-capacitors, are storage devices with energy densities lower than the batteries but higher than electrostatic capacitors. However, they present high power densities, significant capacity retention, and long cycle life [5]. They offer an essential response to power supply fluctuation, necessary for proper grid integration. Depending on the storage mechanism, they can be divided into Electric Double-layer Capacitors, Pseudocapacitors, and Hybrid Capacitors [8]. Although up-and-coming, the synthesis of novel materials for electrodes and electrolytes is needed to improve their performance. Thus, nanoengineering is essential for storage issues, as well as for the other two systems discussed. However, the storage mechanisms of capacitors are entirely different; thus, a deep knowledge of the interfacial reactions at the electrode/electrode interface is required. Also, the most important and cost-effective materials for capacitor electrodes being currently studied are nanostructured carbon-based materials, transition metal oxides (mono, bi-, and trimetallic), conducting polymers, and composites [20], which opens up significant possibilities for development. In the storage field, as well as in the other electrochemical processes presented here, the elucidation of mechanisms is essential; however, to reach this goal, spectroscopic and theoretical approaches are needed to obtain a deep knowledge of the performance of the electrodes.

Future Perspective and Conclusion

Extra fundamental knowledge will be required to achieve major scientific breakthroughs in electrochemical energy storage and production fields. The understanding of the processes has to be coupled with the development of more effective electrode materials. However, one can notice that the discussed systems integration viability, to be successful, requires the massive production of hydrogen, and, apart from technical challenges to reach this scenario, gas storage, safety, and transportation are significant issues to be considered, although not discussed herein. Thus, besides the fundamental understanding needs, energy matrix evolution and adaptation are highly wanted if the world is really committed to developing a society with low-carbon and carbon-free fuels for the future circumvention of the environmental problems we face, with energy security.

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