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Review

# Potential ion exchange membranes and system performance in reverse electrodialysis for power generation: A review

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ABSTRACT

Reverse electrodialysis (RED) is an emerging membrane-based energy conversion process used to extract electricity by mixing two water streams of different salinities. This technique utilizes transport of cations and anions during controlled mixing of saltwater and freshwater through selective ion exchange membranes. The development of ion exchange membranes and optimization of system performance are crucial for sustainable energy capture from salinity gradients using RED. Recently, increased attention has been given to the preparation of ion exchange membranes and to understanding the factors that determine the RED power performance. This review evaluates potential ion exchange membrane materials, currently available state-of-the-art RED membranes, and their key properties. Discussion will focus on the electrochemical and physical properties of these membranes (e.g., resistance, permselectivity, and swelling) because of their significant role in RED performance throughout the system. Although an interconnected relationship exists between membrane properties, RED requires high quality membranes that are uniquely tailored to have a low resistance and high permselectivity. Moreover, harnessing this potential technology demands not only carefully optimized components but also a novel RED stack design and system optimization. The key findings and advancements needed to assure proper stack design and optimization are also described. This review paper's goal is to elucidate effective energy conversion from salinity gradients and expedite implementation of RED as the next promising renewable source of power for large-scale energy generation.



**Contents**



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## 1. Introduction

The development of renewable and sustainable energy conversion technology is widely recognized as an important strategy for global energy security and is becoming extremely important due to growing environmental concerns, such as pollution and global warming. The ocean is a largely untapped renewable and clean energy resource. Mixing ocean water with freshwater creates free energy. More specifically, the chemical potential of sea and river water can be converted into electrical energy. The amount of available energy due to the salinity gradient of seawater mixed with river water is equivalent to the energy obtained from a waterfall that is ~270 m high [1–3]. Salinity gradient energy has become recognized as a nonpolluting and sustainable energy source, and its viability is further assured by the abundance of river and seawater. The two most promising approaches in capturing salinity gradient energy are (1) pressured-retarded osmosis (PRO), a membrane technology using semi-permeable membranes and (2) reverse electrodialysis (RED), which uses ion exchange membranes (IEMs). Each of these technologies is used in different salinity conditions. For example, mixing concentrated brines is suitable for PRO, and mixing sea and river water is favorable for RED [4]. Another possible salinity gradient energy source is obtainable by incorporating wastewater effluent with brines discharged from desalination plants; however, this technology needs more membrane and system optimization. The successful application of PRO and RED are often limited by the cost of membranes. Also, the performance deterioration of membranes is an obstacle for commercialization. The membranes used in PRO and RED are in various stages of development. Compared to the availability of semi-permeable membranes used in PRO, the access to RED ion exchange membranes is relatively low. In addition, commercially developed and optimized membranes for RED application are rare primarily because the currently available IEMs were developed specifically for electrodialysis (ED). Fig. 1 shows how ED converts salt water to fresh water whereas RED uses both salt water and fresh water to create energy or voltage. Hence, RED is the inverse process of ED.

Both ED and RED use the ion exchange process to achieve their goals, and they both consist of an alternating series of anion exchange membranes (AEMs) and cation exchange membranes (CEMs) as shown in Fig. 2.

The principle of ED was first demonstrated in 1890 by Maigrot and Sabates with the initial aim of demineralizing sugar syrup [5]. The principle of RED was first developed in 1954 by Pattle [2], who proved that mixing river water with seawater can be used as a power source. Weinstein et al. [6] proved RED power generation feasible by using a simple mathematical model that emphasized the importance of manufacturing RED IEMs and optimizing their operating conditions to advance RED technology for large-scale energy conversion. In 1980, Lacey [7] concluded that membranes with low electrical resistance and high selectivity are necessary to maximize the net output voltage from RED cells. Lacey also stated that RED membranes should be durable, physically strong, and dimensionally stable for the lowest possible cost. Jagur-Grodzinski et al. [8] investigated the role of flow control using spacer patterns to generate higher power. In 2007, Turek and Bandura [9] noted that the membrane size with shorter length, but wider width (i.e., shorter ionic flow path) results in more effective energy production in the industrial unit.

Daniilidis et al. [10] also emphasized that affordable membrane cost in combination with power performance is the key to successful RED commercialization. The current cost of IEMs is 2–3 times higher than that of reverse osmosis (RO) membranes used in desalination processes [1,11]; however, cost reduction is possible as global demand increases. In the last decade, RO membranes have had a notable cost reduction owing to significant development in membrane materials and fabrication methods, resulting in an increased use of RO for water desalination application. Likewise, proper IEM development for RED is necessary to promote stable power generation in an RED cell.

Recently, some efforts have been reported on designing RED IEMs that show the potential of IEM development for viable energy production [12–15]. These studies focus on investigating the core electrochemical and physical properties of IEMs that directly influence RED performance. Even though this research has provided key performance-determining membrane properties in an RED stack, further physico- and electrochemical property analyses are needed. Research on exchange capacity, permselectivity, and resistance is needed to provide a greater variety of membranes prepared with different methods and materials to improve real power density generation.

Since RED membrane development and optimization are rapidly transitioning and becoming more common for practical application, it is worthwhile to present an overview of IEMs for RED. This includes a review of emerging membrane materials, preparation methods, properties, and other relevant components of an RED stack. Other topics include potential RED IEM materials and current state-of-the-art membranes for RED application. The final focus will be on the authors' investigation of key physical and electrochemical properties of ideal RED membranes essential to system performance based on experimentally determined results and theoretical modeling approaches.

## 2. Key membrane properties and performance in RED

The study of IEM properties examines how they affect IEM performance under different circumstances [16,17]. The durability of membrane material and fine physicochemical characteristics are of great importance in many applications. Thermal and chemical stabilities are good indicators of the durability of membranes. Transport-related properties, such as swelling degree, permselectivity, ion exchange capacity (IEC), and ionic conductivity influence the electrochemical characteristics. Most of these properties can