Desalination 425 (2018) 156–174

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

# Recent developments and future perspectives of reverse electrodialysis technology: A review

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ARTICLE INFO

*Keywords:*
Salinity gradient power (SGP)
Reverse electrodialysis (RED)
Ion exchange membranes
Hybrid membrane process
Desalination

ABSTRACT

Reverse electrodialysis (RED) is an emerging membrane based technology that captures electricity from controlled mixing of two water streams of different salinities. To date, great advancements have been achieved on the development of RED components (e.g., membranes and spacers), optimization of operational conditions, and development of hybrid processes. This review presents an overview on the current achievements in RED membranes and spacers. Meanwhile, the critical operation conditions and their interconnected relationships are highlighted. Moreover, several innovative hybrid systems that show strong synergistic effects are highlighted. The latest development of nano-/micro-fluidic RED and pilot scale tests are also summarized.

## 1. Introduction

Salinity gradient power (SGP) can be harvested from mixing water streams of different salinity. Theoretically, approximately 0.8 kWh is obtainable when 1 $m^3$ of fresh water flow into the sea, which translates into nearly 2 TW of SGP on the basis of the total freshwater flow of the major rivers worldwide (Fig. 1) [1]. The global hydrological cycle makes SGP a renewable energy. Other feed streams, such as treated waste water effluents and desalination brine can further extend the scope of SGP [2–4]. Synthetic high-salinity draw solutions (e.g., ammonium bicarbonate or sodium chloride) have also been investigated for recovering low grade waste heat in a closed-loop osmotic heat engine [5–7] and for energy storage as a concentration battery [8,9].

Reverse electrodialysis (RED) is a mainstream technology for harvesting SGP [11,12]. A typical RED stack comprises of cation exchange membranes (CEMs) and anion exchange membranes (AEMs) assembled in an alternating order to form flow compartments of high salinity streams (HS) and low salinity streams (LS) (Fig. 2). Cations and anions in the HS transport to LS through CEM and AEM in opposite directions under their respective concentration gradients, which can be converted to electricity by redox reaction on the electrodes.

Several review papers on RED are already available in the literature. Progresses up early 2011 have been summarized by Post et al. [12] and Ramon et al. [13]. In a perspective paper published in 2012, Logan and Elimelech [1] provided an overview of different SGP harvesting technologies (e.g., RED, pressure retarded osmosis). Detailed comparisons of these methods were performed by Yip et al. [11,14]. Logan and Elimelech [1] also highlighted the critical challenge of IEMs development for RED. Readers who are interested in the development of IEMs are further referred to Hong et al. [15,16] and Xu [17].

Despite these existing reviews, there is still lack of a comprehensive summary on the latest developments in RED, particularly in view of the exponentially increasing number of publications in the last decade (Fig. 3). These studies can be classified on the basis of their primary focus on RED module optimization [18–23] (including IEMs, spacers and electrodes), stack operation [24–27] (e.g., temperature, feed solution concentrations, flow path, etc.), hybrid process development [5,28–34] (e.g., microbial reverse electrodialysis cells, hybrid RED/reverse osmosis system, RED using thermolytic solutions, etc.) and nano-/micro-fluidic RED development [35,36]. Over the past five years, the RED research scope has been rapidly expanded, and systematic efforts on fouling investigation [37–39], applications for energy storage and pollutants abatement [8,9,40,41] and pilot studies [3,42] have been reported. A comprehensive review is thus warranted to address these recent developments in RED technology.

This review starts with an overview of historical developments in RED, followed by an introduction of basic theory of RED. Subsequently, recent progresses in IEMs and other module components (i.e., spacers and electrodes) and studies on optimization of operational conditions are summarized. Meanwhile, hybrid RED systems (e.g., by combining RED with microbial fuel cell or electrodialysis) as well as some special RED applications (e.g., energy storage, pollutants abatement, and nanofluidic/microfluidic RED devices) are highlighted. Practical considerations such as membrane fouling and pilot testing are also discussed.

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http://dx.doi.org/10.1016/j.desal.2017.10.021
Received 5 September 2017; Received in revised form 12 October 2017; Accepted 12 October 2017

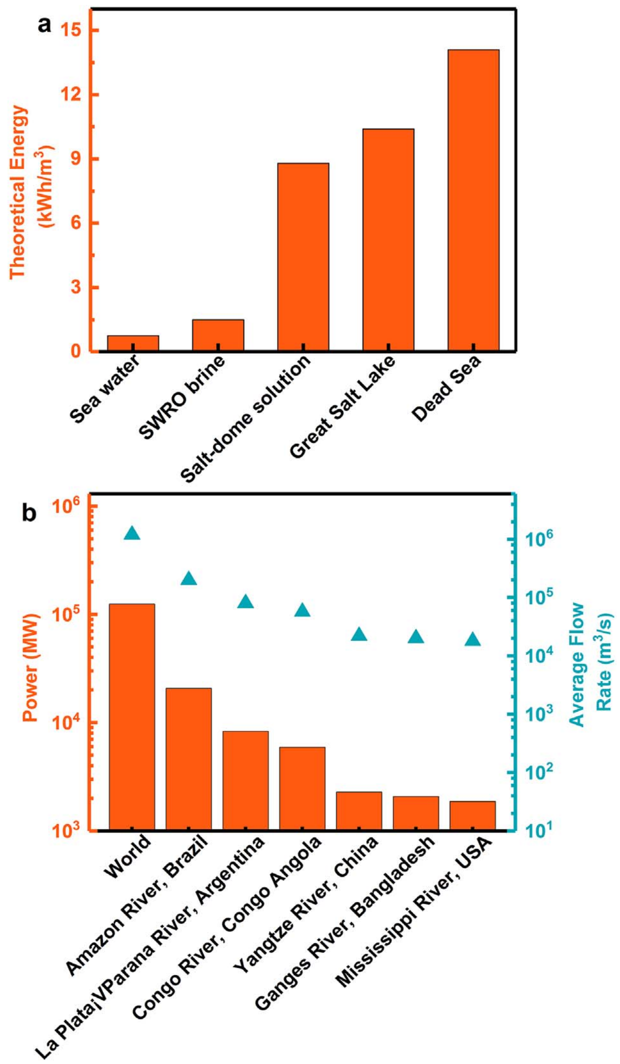


**Fig. 1.** (a) Maximum extractable energy from mixing fresh water with saline water using different high-salinity sources; (b) osmotic power production capacity from selected major rivers across the world. Figure adapted from reference [10] with copyright permission from Elsevier.

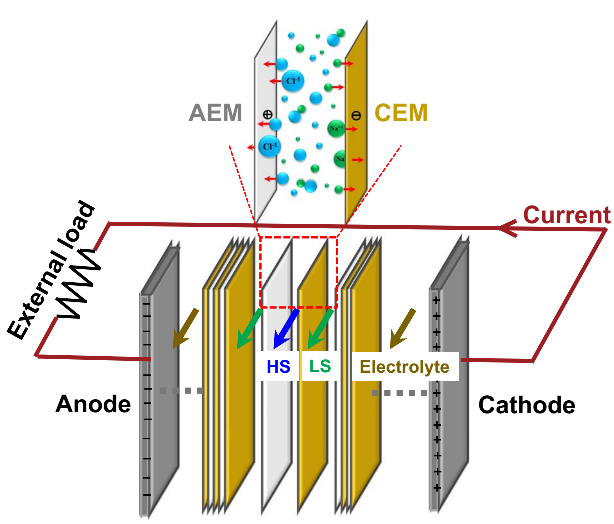


**Fig. 2.** Schematic diagram of an RED stack connected to an external electric load.

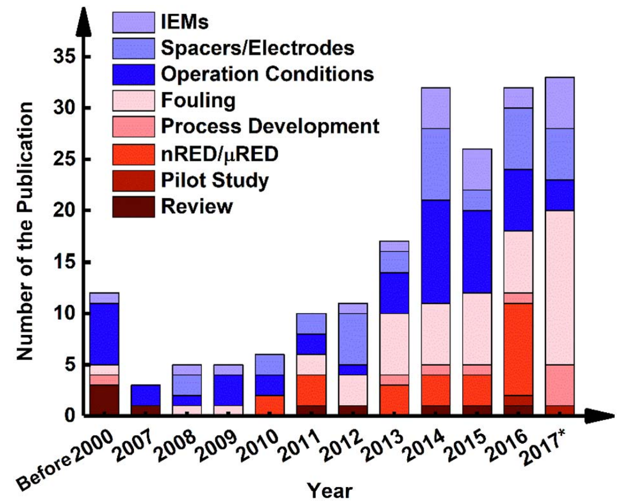


**Fig. 3.** Number of publication on RED since 1954. Publications are categorized based on their main research focus. The data are obtained from Scopus and Google Scholar databases by September 2017. Keyword for searching is ‘reverse electrodialysis’.

## 2. Historical development of RED

### 2.1. Early studies before 2000s

Fig. 4 presents a summary of the historical development of RED technology. In 1954, Pattle [43] first described the concept of salinity gradient power. Using a bench scale ‘hydroelectric pile’ comprised of 47 pairs of alternating acidic and basic membranes of 8 $cm^2$ each, he obtained a power output of 0.2 $W/m^2$ and an electromotive force of 3.1 V from mixing fresh and seawater at 39 °C. Not until two decades later, theoretical models of RED were developed by Fair and Osterle in 1971 for RED in charged capillary membranes [44] and by Weinstein and Leitz [25] in 1976 for IEM stacks. Early theoretical studies revealed that the power production by RED can be potentially competitive against other alternative energy sources [45,46]. However, early experimental works often show impractically low power density (e.g., merely 0.4 $W/m^2$ using a hypersaline NaCl solution of 250 g/L paired to a 1 g/L NaCl [47]) and low energy conversion efficiency (e.g., 1.8%–11.7% [48]). During this early phase of development, we also witness the first report on RED fouling by Ratkje et al. in 1986 [49] and the first hybrid RED/electrolysis system (which was used for simultaneous electricity generation by RED and acid and base production in the electrode compartments [50]).

### 2.2. Studies during early 2000s

Extensive researches on RED emerged in early 2000s (Fig. 4), which coincides with the spike in the cost of fossil fuel energy [53]. During this period, systematic studies on the role of IEMs [54,55], stack configuration [18,54,56,57] and operation conditions [57–61] in RED power generation were performed. With the availability of commercial IEMs and improved stack design, significant improvement in power density was realized (e.g., a maximum value of 0.93 $W/m^2$ was obtained using NaCl of 0.5 M and 0.017 M as feed solutions [55,60]). Meanwhile, hybrid processes of RED/desalination facilities/solar power were proposed by Brauns to realize simultaneous energy production and water purification [51,59].

### 2.3. Studies in 2010s

Tremendous advances in RED performance have been achieved over last decade with the exciting progresses in IEMs and spacer designs. In 2012, the first tailor-made IEM specifically designed for RED showed a