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Performance of the first reverse electrodialysis pilot plant for power production from saline waters and concentrated brines

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ABSTRACT

This work reports experimental data collected for the first time on a full-scale RED pilot plant operated with natural streams in a real environment. The plant – located in the South of Italy – represents the final accomplishment of the REAPower project (www.reapower.eu). A RED unit equipped with almost 50 m^2 of IEMs (125 cell pairs, 44x44 cm^2) was tested, using both artificial and natural feed solutions, these latter corresponding to brackish water ($\approx$ 0.03 M $NaCl_{equivalent}$) and saturated brine (4–5 M $NaCl_{equivalent}$). A power output up to around 40 W (i.e. 1.6 W/m^2 of cell pair) was reached using natural solutions, while an increase of 60% was observed when testing the system with artificial NaCl solutions, reaching up to $\approx$ 65 W (2.7 W/m^2 of cell pair). The unit performance was monitored over a period of five months under, and no significant performance losses were observed due to scaling, fouling or ageing phenomena. Such results are of paramount importance to assess the potential of the technology, towards the successful development on the industrial scale.

A scale-up of the pilot plant is planned through the installation of two additional RED modules, with an expected power output in the order of 1 kW.

1. Introduction

Salinity gradient power (SGP) technologies aim at the exploitation of the energy available when two natural streams with different concentration are mixed together. A number of processes have been proposed so far to capture such renewable energy source: among these, reverse electrodialysis (RED) represents a promising option that might be brought to industrial implementation as soon as new stack components and suitable ion exchange membranes will be available at competitive costs [1,2].

In the RED process, the mixing of concentrated and dilute streams is regulated by a pile of ion exchange membranes (IEMs), which selectively allow the passage of cations and anions, thus generating a net ionic current. This latter is then converted into electric current by means of suitable electrode reactions at the end compartments closing the membranes stack, and finally collected by an external load.

Recently, several experimental works at the laboratory scale have demonstrated that reverse electrodialysis can be suitable for different applications, e.g. for power production from natural salinity gradients [3–9], for waste heat recovery using artificial solutions in a closed loop [10,11], and for wastewater treatment when coupled with electrochemical and biological processes [12,13]. Such experimental investigations notably contributed to understand the fundamental aspects of the RED process. However, the great majority of such works were performed on laboratory-scale RED units, using a relatively small cell pair area (e.g. 10x10 cm^2) and small number of cell pairs (typically 5–10, up to 50 in some cases [8,9]). The only example of a scaled-up unit reported in the literature is a RED stack with 75 $\times$ 25 cm^2 membrane area and 50 cell pairs, which was tested in laboratory conditions with artificial river water and seawater reaching a power output of 16 W (i.e. 0.85 W/m^2 of membrane area) [14,15].

The use of real fresh water and seawater has been recently investigated by Vermaas et al. [16], analysing the effect of fouling within laboratory-scale RED units. In that case, a heavy impact of fouling was detected: in particular, a 40% reduction of the power output was observed during the first day of operation, when only a 20 μm filter was used for pre-treatment [16]. The main cause of this performance reduction was attributed to colloidal and organic

Acronyms and Abbreviations: ERS, Electrode Rinse Solution; RED, Reverse electrodialysis; SGP, Salinity gradient power; E-I, Stack potential vs external current curve (also called polarisation curve)

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fouling, which is especially crucial for AEMs, as the fouling layer was composed by large anions (e.g. clay minerals and silica shell of diatoms). The adoption of anti-fouling strategies is therefore necessary to ensure a suitable pre-treatment of natural streams. With this regard, periodic air sparging and switching of feed streams have been proposed as valuable methods to reduce colloidal fouling [17].

In order to further push the development of RED technology, a prototyping and scaling-up phase is now of paramount importance, aiming to shift the target of power production towards the industrial scale. With this regard, the official opening of the first pilot-scale installation in The Netherlands, within the Blue Energy project, was announced in 2014. Such plant is located on the Afsluitdijk, a 32 km-long dyke that separates the IJssel Lake from the Wadden Sea, and is fed with seawater (~28 g/l) and fresh water from the lake (0.2–0.5 g/l). Up to now, no data have been publicly reported since the official opening (November 2014): the only published information was provided by Post et al. [14] in 2010, i.e. when the pilot was still in its conceptual design stage. According to the available literature information, the Blue Energy pilot plant in its final configuration will be fed with 220 m^3/h of seawater and fresh water, aiming at the generation of 50 kW gross power output as maximum target.

An interesting alternative to the use of seawater and fresh water as feed streams is the use of concentrated brines in combination with low-concentration saline waters, which allows to further enhance the power outputs of the process [18–20]. As an example, a power density above 6 $W/m^2_{membrane}$ was recently achieved in laboratory investigations using concentrated brines and low-salinity waters as feed solutions [9,20]. In particular, regarding the dilute stream, fresh water can often represent the main contribution to the internal electric resistance of the stack, thus limiting the power output. Therefore, the use of a low-concentration saline stream instead of fresh water allows to lower the internal stack resistance, though reducing the inlet concentration difference. For this reason, a trade-off has to be identified regarding the optimal value of concentration that reduces the stack resistance without appreciable loss in terms of driving force. This concept was the basis of the REAPower project [21], whose main goal was to demonstrate the potential of reverse electrodialysis technology using saline streams and concentrated brines as feed solutions.

This idea was firstly addressed through modelling works [22] and experimental demonstration at laboratory scale [9,23]. In particular, a process simulator was developed by Tedesco et al. [24] to describe the operation of a RED plant fed with such high saline solutions. Investigating the effect of salt concentration on power density for a laboratory RED unit (10 x10 cm^2 cell pair area), optimal feed conditions were identified in the use of brackish water (0.08–0.1 M NaCl) as dilute and brine (4.5–5 M NaCl) as concentrate [24]. Assuming similar feed conditions on a pilot scale, a power output of more than 1 kW was predicted for a plant equipped with 3 RED modules of 44x44 cm^2 and 500 cell pairs [25].

Following these modelling predictions, a demonstration plant was designed and constructed as final accomplishment of the REAPower project. The plant is located within the saltworks of Ettore e Infersa in Marsala (Trapani, Italy): such location provides both feed streams for power production, i.e. brackish water (from a shoreline well) as dilute, and almost saturated brine from saltworks as concentrate (Fig. 1).

Focus of this work is to present the activities carried out during the design, installation and testing of the 1st phase of the REAPower demonstration plant. A RED unit with 44x44 cm^2 membrane area equipped with 125 cell pairs was installed in such environment and tested both with real solutions (brine and brackish water) and with artificial NaCl solutions. The performance of the plant was monitored over a period of five months of operation, providing for the first time experimental data on a full-scale RED pilot plant operating in a real environment.

2. Plant design and installation

2.1. The installation site

The Ettore-Infersa saltworks in Marsala (Trapani, Italy), situated on the west coast of Sicily (Fig. 1A), is one of the most important areas in the Mediterranean Sea for the production of sea-salt. With its availability of large amounts of concentrated brines, this site represents a perfect location for demonstrating the feasibility of RED technology with highly concentrated solutions.

A saltworks is a delicate natural environment where sodium chloride is extracted from seawater, exploiting the natural evaporation caused by solar energy and wind. Process waters (starting from seawater) flow along large basins driven by gravity or by low-prevalence pumps. Due to evaporation, salt concentration increases along the basins ending with a brine saturated in NaCl which is used for the final crystallisation process. A careful flow distribution (regulated through small canals and gates) allows to precipitate undesired salts such as calcium sulphates and carbonates in intermediate basins, while sodium chloride crystallises only in the last basins. The final product has a purity in NaCl normally higher than 97% (i.e. food-grade salt) [26].

Clearly, any saltworks area is a feasible location for salinity gradient power production, due to the large availability of

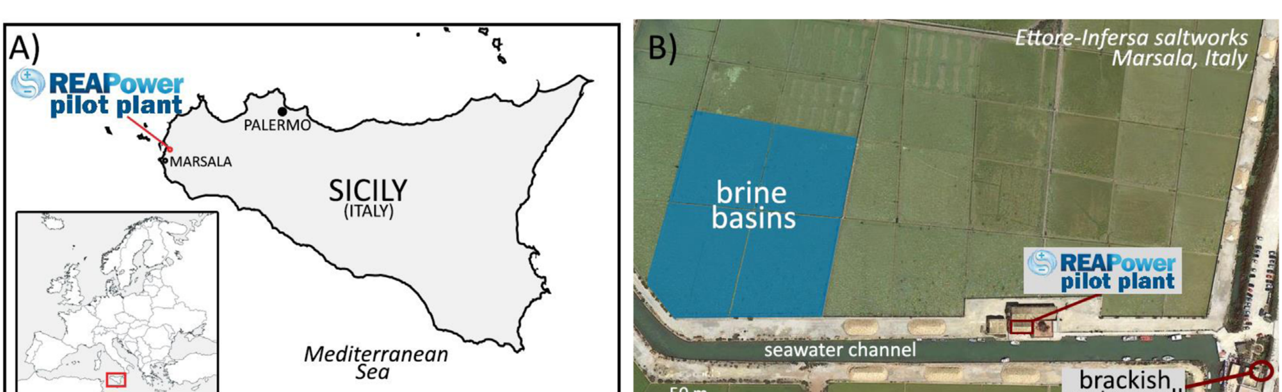

Fig. 1. (A) Location of the REAPower pilot plant in Marsala (Italy). (B) Satellite image of the REAPower plant installation site (*Ettore-Infersa* saltworks, Marsala, Italy). Saturated brine from basins and brackish water from a shoreline well are available in the same area as feed streams for the RED process.