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Salinity gradient energy potential at the hyper saline Urmia Lake – ZarrinehRud River system in Iran

Arash Emdadi [a, *], Petros Gikas [b], Maria Farazaki [b], Yunus Emami [c]

[a] Energy Institute, Istanbul Technical University, 34469, Maslak, Istanbul, Turkey
[b] School of Environmental Engineering, Technical University of Crete, 73100, Chania, Greece
[c] Mechanical Engineering Department, Urmia University of Technology, Urmia, P O 57155- 419, Iran

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A B S T R A C T

Salinity gradient has globally high potential for electric energy production, especially where low salinity rivers discharge into hyper-saline lakes. Lake Urmia is world's second hyper-saline lake, with a number of low salinity rivers discharging into the lake, the most significant of which is ZarrinehRud River. Based on thermodynamic calculations and on field data, the theoretical potential of energy production at the above system has been calculated between 400 and 1000 MW, while the technical potential is expected between 40 and 50% of that.

Two processes for the production of electricity from salinity gradients were investigated: PRO and RED. The revenue of such attempt is a function of membrane cost, power density, lifetime expectation and sale price of electric power. Based on the available technology, the project is expected to be viable if membranes with power density above 5 W/m^2 and 10 years lifetime expectancy or 10 W/m^2 and 5 years lifetime expectancy will be used. The cost of membranes for a 25 MW plant has been estimated between 75 and 150 million USD, while the cost of electric energy from a full-scale PRO plant is expected to be between 65 and 130 USD/MWh (comparable with the cost of electric energy generated from other renewable energy sources).

1. Introduction

The increased global demand for energy has resulted in the recent decade to overconsumption of fossil fuels. However, fossil fuel energy is not a sustainable option, as fossil fuel reserves are finite, while the emission of carbon dioxide during the use of fossil fuels exacerbates the green house effect in the atmosphere. Alternatively, the use of renewable energy sources, such as anaerobic digestion, geothermal power, wind power, small-scale hydropower, solar power, biomass power, tidal power and wave power can provide green energy in a far more sustainable way [1]. One of the least exploited renewable energy sources is salinity gradient power [2,3], hereto the energy that is released whenever two aqueous solutions with different salinity concentrations mix together [2], known as “blue energy”. From the thermodynamics point of view, the driving force for energy production during the mixture of solutions with salinity gradients is the Gibbs free energy gradient, as Gibbs free energy indicates the spontaneous available energy which is available in a closed system [4]. Gibbs free energy of a system is a positive function of chemical potential, which (for a solution) is a positive function of the concentration of a diluted component. Thus, the higher the salt concentration, in an aqueous solution, the greater the potential for energy release, when the above solution is mixed with fresh water (or water with low salt concentration). The potential of salinity gradient power as a commercial renewable energy source, has been considered since1950s [5], such potential may be utilized for electric energy production in cases which a low salinity river flows in to salty lake. The production of energy from salinity gradients has low environmental impact, as the mixture of the river water with the saline water of the lake occurs naturally, at the mouth of the river, and the generated energy is released as heating energy to the local environment.

As mentioned above, energy extraction through the reverse electrodialysis process was first reported by Pattle [5], while Murphy [6] utilized the latter process for the desalination of brackish water. Lacey [7] proposed the basic mathematical equations for the

* Corresponding author.
E-mail addresses: emdadia@itu.edu.tr (A. Emdadi), petros.gikas@enveng.tuc.gr (P. Gikas), emamiyunus@yahoo.com (Y. Emami).

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reverse electrodialysis process, while Weinstein and Leitz [8] used Lacey's equations to predict the electrical energy yield. Further equations for the estimation of the performance of reverse electrodialysis unit for salinity gradient power (SGP) extraction was conducted by Forgacs [9]; while an alternative approach for the calculation of energy potential for the reverse electrodialysis process has been proposed by Emren and Bergstrom, who proposed the use of the activities of solutions instead of concentrations [10].

A few pilot facilities have been established to exploit the salinity gradient energy potential [11]. In November 2009, the Norwegian utility company “Statkraft” launched a 10 kW prototype plant in Tofte, south of Oslo, Norway. Statkraft's prototype plant funnels freshwater from Tofte River and salty water from a neighboring fjord into two adjoining chambers separated with a thin permeable membrane. The freshwater forces its way through, driving up the level and pressure on the saltwater side, which in turn drives a turbine to produce electricity. On the other hand, REDstack (a spin-off Dutch R&D company) Wetsus (centre of excellence for sustainable water technology, The Netherlands) (www.wetsus.nl), is now scaling up its 5 kW pilot plant, at the salt refinery in, Harlingen, The Netherlands, to a 50 kW demonstration plant, located in Breezanddijk.

The global potential for salinity gradient is enormous. By accounting for the discharge of all rivers into the ocean, the total power, due to SGP, may be calculated between 1.4 and 2.6 TW [12–15], which is between 40 and 80% [11] of the global demands for electricity. It is thus obvious the significance of the salinity power and the potential role that it may play in the future in the global energy balance.

The present manuscript, examines the potential for electrical energy production from salinity gradients, at the mouth of ZarrinehRud River, in Lake Urmia – a high salinity lake in Northwestern Iran. Despite the fact that the renewable energy potential of Iran has been assessed by a large number of studies, there are not published works on energy production potential from SGP. The present work attends to provide a spherical view of the above mentioned issue, by the calculation of the theoretical and technical SGP potentials, the proposal of the best available technology and the estimation of the cost of such plant for the production of electrical energy, at the mouth of ZarrinehRud River in Lake Urmia.

2. Geographical and regional concepts

2.1. Lake Urmia

Urmia Lake is the 20th largest lake by area and the 2nd hyper saline lake on earth [16]. It is located at Northwestern Iran, at the borders of East and West Azerbaijan provinces, at latitude between 37 and 38 and longitude between 45 and 46 [17] (Fig. 1). The surface area of the lake has been severely reduced the last decade; in 2009, it was about 3100 m^2, with length at north–south direction between 140 and 144 km and width between 16 and 63 km [18,19].

The maximum depth of the lake is 16 m, and contains more than 50 islands [20]. Lake Urmia is divided into north and south part, separated by a causeway with a water corridor; however water flow between the two parts is minimal [21]. The average annual precipitation on the lake is about 341 mm, while the average temperature is about 11.2 °C, with average maximum and minimum 2.5 °C (January) and 23.9 °C (July), respectively. A number of endemic species live in the lake, with *Artemia urmiana* being the most significant, with numerous applications in aquaculture [21]. Lake Urmia has been proclaimed as an “international wetland” according to Ramsar convention, and as a “conserved region of biosphere” under the umbrella of UNESCO. In general, morphology, chemistry and sediments of Urmia Lake resemble those of the Great Salt Lake in Utah, U.S.A [20]. Significant variations of the level of water surface have been historically monitored. Water level had reached a maximum at 1995, then it was decreased sharply and stabilized to a lower level [22]. Fig. 2 depicts the level of the surface of the water in Lake Urmia between 1931 and 2006.

Lake Urmia is supplied with water by about 30 large and small rivers, which discharge about 4.6 million cubic meters of water on annual basis [23]. All rivers carry fresh water into the lake, except Aji Chay and some seasonal creeks which convey saline water, as they flow through salt domes near the city of Khoy [24,25]. The points of discharge and the percentage annual contribution of water of the most significant rivers to Lake Urmia are shown in Fig. 3. Based on Fig. 3, ZarrinehRud River is by far the major water source for Lake Urmia.

A number of studies have been conducted to determine the concentration of anions and cations in the lake. Na^+,K^+,Ca^{2+} and Mg^{2+} are the main cations, while Cl^-, HCO_3^-, SO_4^{2-} are the main anions, however, significant variations in ions concentration has been reported. Lake Urmia has been characterized as oceanic type because of the predominant existence of sodium, chloride and sulfate ions [26]. Table 1 summarizes the findings of various studies on ions concentrations for Lake Urmia. For some of those, like Ca^{2+}, significant variations have been reported between the north and south parts of the lake. NaCl is the major salt constituent of Lake Urmia and thus, more extended data on NaCl concentration are available. “Urmia Regional Water Resources Organization” has carried out a monitoring program for the determination of salts concentration in Lake Urmia. The average values of the relative data for the salts ions concentrations for year 2008 are firstly presented, in Table, while the procedures and methods for the determination of concentrations of the various ions are provided in Table 2.

2.2. ZarrinehRud River

ZarrinehRud River is the biggest river that debouches into Urmia Lake (Fig. 3), with average annual flow of approximately 1583 million cubic meters of water. ZarrinehRud River is about 302 km long; it emanates from Chehelcheshme Mountains, and crosses a number of cities in Iran, such as ShahinDezh, Keshavarz and Miandoabbefore, before reaching the south part of Lake Urmia. As stated above (see Fig. 3), ZarrinehRud River contributes about 42% of the total river water discharged into Lake Urmia [24]. The average discharge of Zarrineh Rud River into Urmia Lake for the period 1988 to 2008, at the Sarighamish station has been monitored by “Urmia Lake Regional Water Organization”, and is firstly presented in Fig. 4. According to Fig. 4, the flowrate of ZarrinehRud River varies significantly from year to year. For the studied period, the maximum annual average flowrate (approximately 120 m^3/s) has been monitored on 1992, while the minimum annual average flowrate was below 10 m^3/s. The observed significant variations may be attributed to climate conditions variability as well as to anthropogenic activities.

The concentrations of various dissolved components in ZarrinehRud River for the period 2005–2009, measured by the “Urmia Environment Organization” and “Urmia Regional Water Organization”, which are firstly presented in the present manuscript, are shown in Fig. 5. Based on the available data for 2005–2009, the concentrations of various ions in the water of ZarrinehRud River were relatively stable, with the exemption of the last year (2009), where a significant increase is observed (Fig. 5).

The salinity of the water at the mouth of ZarrinehRud River in Urmia Lake has been measured by a number of studies. Karbassi et al. have measured the salinity in various locations of Urmia Lake, to lie between 228 and 340 g/L [23]. The geographical locations of some of the measurements, the geographical position of the