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# Predicting Potential of Pressure Retarded Osmosis Power for Different Estuaries in Turkey

**Seda Saki,[a] Nigmet Uzal, [b] Murat Gökçek,[c] and Nuray Ates[d]**

[a]Department of Material Science and Mechanical Engineering, Abdullah Gul University, 38380, Kayseri, Turkey
[b]Department of Civil Engineering, Abdullah Gul University, 38380, Kayseri, Turkey; nigmet.uzal@agu.edu.tr (for correspondence)
[c]Department of Mechanical Engineering, Nigde University, 51100, Nigde, Turkey; mgokcek@ohu.edu.tr (for correspondence)
[d]Department of Environmental Engineering, Erciyes University, Kayseri, 38039, Turkey

*Pressure retarded osmosis (PRO) is an alternative renewable energy source recovered from the salinity gradient between the fresh water (feed solution) and salty water (draw solution). In order to implement osmotic power, the site-specific characteristics including the river and sea salinity, annual flow rates, ecological restrictions were taken into account. This study revealed a comprehensive analysis for a theoretical potential of PRO process for different estuaries in Turkey. In this study, the power potential prediction of PRO process for the Ceyhan, Sakarya, and Meric Rivers were analyzed via Gibbs free energy calculations. The net annual energy production is projected to be 167, 164, and 208 GWh/y for Ceyhan, Sakarya, and Meric Rivers, respectively. Meric River has the highest energy production of 208 GWh/yr with 186 $m^3$/s mean flow rate and 245 mg/L salinity. These results clearly show that Turkey's rivers having high salinity and flow rate are feasible and applicable for making the osmotic power plant economically. Thereby, it is providing essential direction to the improvement of its design, installation, and operation. The developed methodology for the evaluation of the osmotic power potential of other rivers can be considered as a basis to assess the whole potential on a worldwide level.* © 2018 American Institute of Chemical Engineers Environ Prog, 38:e13085, 2019

*Keywords: Gibbs free energy, pressure retarded osmosis, renewable energy, rivers of Turkey*

## INTRODUCTION

The largest and important source of greenhouse gas emissions is the combustion of fossil fuels with 25%, of which 21% is of industrial origin. The contribution of fossil fuel combustion and industrial processes to $CO_2$ emissions has increased by about 90% by 2011 [1]. To reduce the dependence of fossil fules, new alternative and sustainable energy sources should be explored [2,3]. The chemical potential conversion for power generation has been widely recognized as effective, environmental friendly, and alternative resources of renewable energy [4]. An alternative way for energy storage system is to convert electricity into Gibbs energy using concentration differences of the salty solutions. Sea water including NaCl could be obtained easy, environmental friendly and low cost to use this technology [5]. The most common approaches getting energy from salinity gradient differences are the pressure-retarded osmosis (PRO) [6,7], reverse electrodialysis [8,9], capacitive mixing [10,11], and hydrogel swelling [12]. PRO process known as a "Blue Energy," "Salinity Gradient Power" or salinity gradient osmotic energy is a clean and sustainable energy source that can be harnessed from the mixing of two different salt concentrations. A draw solution (DS) in higher concentration is fed at one side whereas a feed solution (FS) in lower concentration is pumped into the other side of the semi-permeable membrane to create an osmotic pressure gradient, which induces fresh water transport through the DS. This approach utilizes the natural process of osmosis, which allows preferential transport of species due to different salinities on either side of a semi-permeable membrane [13]. The pressurized fresh water could run through a hydroturbine converting chemical potential to electric power [6,14,15] (Figure 1). Since the global potential of osmotic power is projected to be huge with negligible chemical demand or $CO_2$ emissions, PRO becomes an important strategic thrust in solving universe renewable and sustainable energy problem [16].

Osmotic pressure is one of the important factors in power potential of PRO performance and is defined as the pressure that should be applied to the draw solution [17,18]. Experimental studies of benchscale PRO systems with higher osmotic pressure yielded higher power densities compared with similar experiments with lower osmotic pressures. PRO is focused on the salinity gradient difference between seawater and freshwater [19,20]. All around the world, rivers that flows into the sea is mixed naturally with seawater. Therefore, the osmotic power potential can be utilizable source without negative environmental impacts of power plants in nature [21,22]. A number of researchers have come across major real time effects of the installed devices such as seawater corrosion of the metal parts of the devices and on the environment and ecosystem and they have studied major developments in the feasibility of these system for its real case to generate energy from the PRO process in seas and rivers [23–25]. In Turkey, PRO is considered to be a source of renewable energy due to two reasons that: (i) the access to seawater is virtually unlimited, and (ii) fresh water is available throughout the year as rivers discharge water to seas, thus can be performed continuously all year long. As a result, local sites providing higher osmotic pressure difference between the two different salt concentration solutions can potentially generate more electric power [26,27]. Turkey surrounded by the Mediterranean, Aegean, Marmara, and Black Seas, with a total length of 10,765 km. The rivers selected in this study; Ceyhan, Sakarya, and Meric are draining into the eastern Mediterranean, Black, and Aegean

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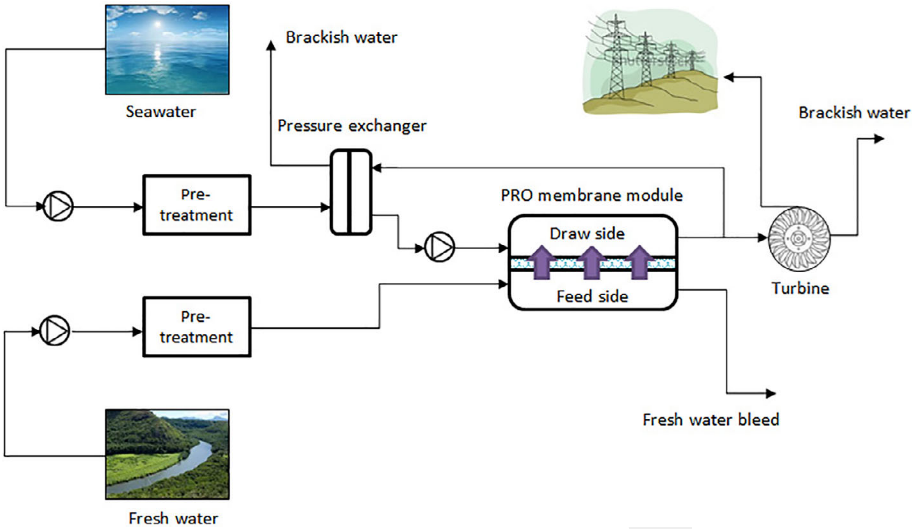

**Figure 1.** Schematics of PRO power generation. [Color figure can be viewed at **wileyonlinelibrary.com**]

Seas, respectively. Besides this, the Ceyhan, Sakarya, and Meric Rivers have been identified for their low salinity, ranging from 0.1% to 0.5%. To put this in perspective, the average salinities of Black [28], Mediterranean [29], and Aagean [30] seawaters are between 18% and 40%. The salinity differences of these rivers and seas indicate that Turkey is a possible location for future implementation of PRO in power generation, given the availability of high saline draw solution and fresh water supplies.

In this study, site-specific osmotic power potential with the PRO is investigated by considering three different estuaries in Turkey as a potential location. This study is a preliminary study related to PRO power potential of Turkey and the results from this study can increase understanding of large-scale PRO systems and inform decision making for those interested in future PRO implementations.

## METHODOLOGY

### Selected Sites and River Data

The Ceyhan, Sakarya, and Meric Rivers have desirable characteristics in terms of salinity and flow rate for potential PRO power plants. The Sakarya River is in the northwest Anatolian region of Turkey and its length is nearly 810 km. The drainage area of the Sakarya River, which is approximately 1/13 of the total area of Turkey, is about 56,000 km$^2$ [31]. The Ceyhan is one of the largest rivers flowing to the Mediterranean of Turkey, with an approximately 300 km length [32]. In energy potential evaluations, salinity and flowrate values of Aslantas, the main tributary of Ceyhan River, were used. The Meric is with a length of 480 km, the longest river that flows solely in the interior of the Balkan Peninsula [33]. Selected estuaries to determine salinity gradient energy potential is shown in Figure 2 [34].

In Turkey, flowrate is generally getting higher in the spring season due to snow melt and heavy rainfall. The average monthly flowrates per years for Ceyhan (2003 to 2007), Sakarya (1996 to 2000), and Meric (2003 to 2007) by years are given in Table 1. While the maximum flowrates for Ceyhan, Sakarya, and Meric Rivers are 242 m$^3$/s in March, 254 m$^3$/s April, 362 m$^3$/s in February, on the other hand, the minimum flowrates of rivers are 64 m$^3$/s in December, 62 m$^3$/s in October, and 91 m$^3$/s in July, respectively (Table 1).

Salinity is affected by seawater inputs, groundwater estuarine interflows, atmospheric deposition, diluting effects of stream inputs, surface water inflows from streams of the sea and precipitation [35]. The monthly salinity values measured in the rivers of Turkey vary greatly. Based on long-term records, the average annual salinity rates are changeable depend on month and climate changes. The monthly salinity values per years for Ceyhan (2003 to 2007), Sakarya (1996 to 2000), and Meric (2003 to 2007) by years were given in Table 1. Although salinity values for Ceyhan, Sakarya, and Meric Rivers decrease in June, May, and March; they increase in January, August, and July, respectively. The annual average salinity for Ceyhan, Sakarya, and Meric Rivers changes between 200–250 mg/L, 300–400 mg/L, and 200–300 mg/L, respectively (Table 1).

### Gibbs Free Energy of Mixing

Calculating the available specific energy from the mixing between river and seawater began with the Gibbs free energy of two mixtures with different chemical potential. The energy, which was released in the process, depends on both the specific composition of the solutions and the relative ratio in which the solutions are mixed. Under the conditions of reversible PRO process, the ideal work per unit volume of freshwater is the Gibbs free energy of mixing and a number of assumptions can be made to simplify in Equation 1 [36,37].

$$-\frac{\Delta G_{\text{mix}}}{iRT}=\frac{C_m}{\phi}\ln c_m-c_f\ln c_f-\frac{(1-\phi)}{\phi}c_d\ln c_d \qquad (1)$$

where, $\Delta G_{\text{mix}}$ (kWh/m$^3$) is the mixing energy per unit volume of fresh water. $C_m$ (mol/L or M), $C_f$ (mol/L or M), and $C_d$ (mol/L or M) symbolize the concentrations of the mixture, initial feed and initial draw solutions, respectively. The Van't Hoff factor is given by $i$ is the dissociation constant for the salt, which for NaCl is 2, $R$ (L·kPa/mol·K) is the universal gas constant, and $T$ (K) is the temperature. The ratio of the volume of the initial feed solution to the initial volume for the feed and draw solutions is represented by $\phi$. The obtained specific energy of the permeate flow is often be less than the theoretical specific energy due to irreversibility and system inefficiencies [37,38].

Since 1970s, water quality measurements of the rivers in Turkey have been carried out by Turkish General Directorate of State Hydraulic Works (SHW). These measurements include some parameters such as temperature, conductivity, pH, major ions (Ca, Mg, Cl, SO$_4$, and alkalinity) and other components (boron, sodium absorption ratio, selected heavy metals). Long-term measurements recorded at the downstream of the water

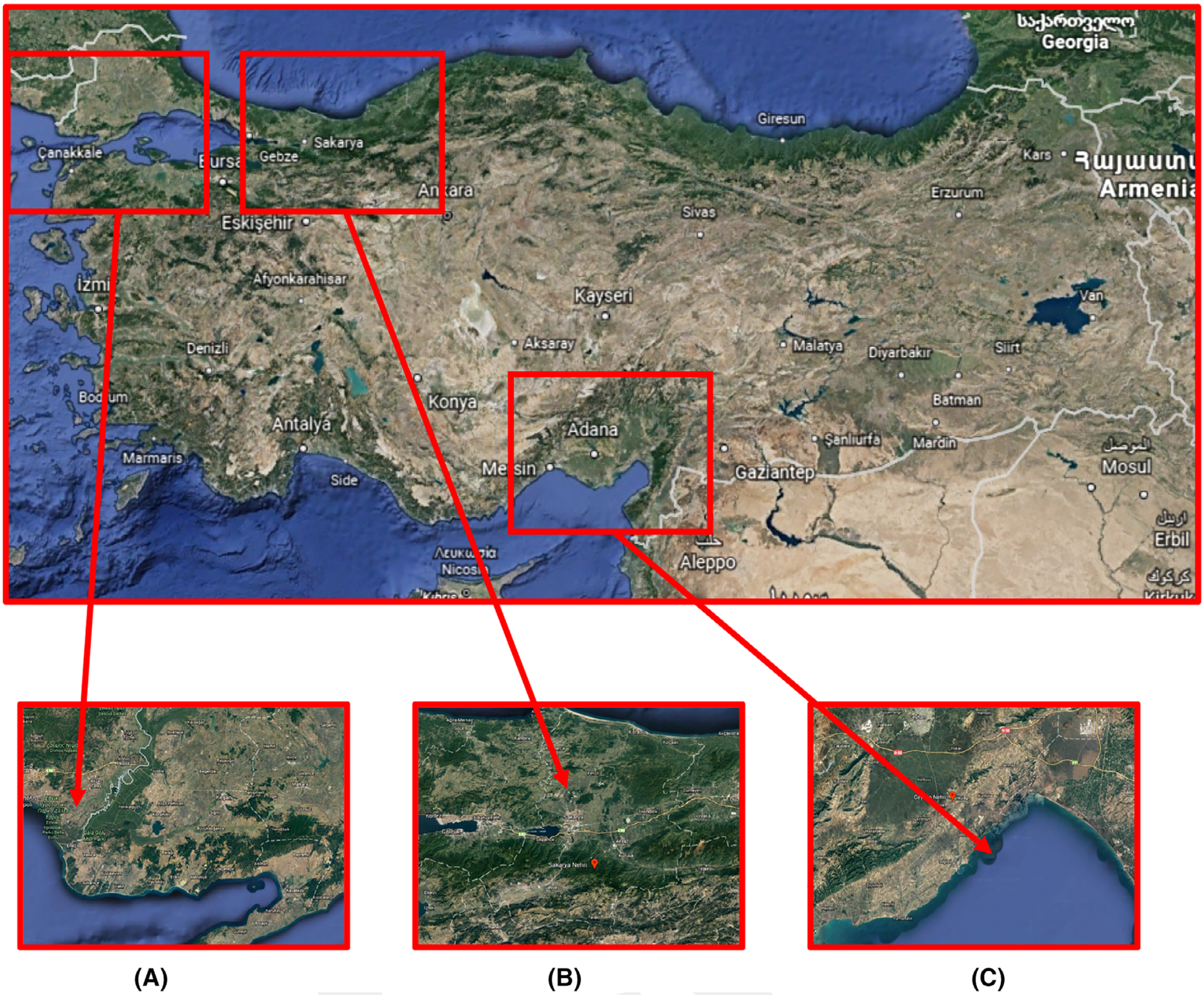

**Figure 2.** Aerial view of selected estuaries in Turkey: (a) Meric River, (b) Ceyhan River, and (c) Sakarya River [Color figure can be viewed at **wileyonlinelibrary.com**]

**Table 1.** Average flowrates and salinities of Ceyhan, Sakarya, and Meric Rivers.

| | **Ceyhan*** | | **Sakarya**** | | **Meric*** | |
|---|---|---|---|---|---|---|
| **Months** | **Flowrate ($m^3$/s)** | **Salinity (mg/L)** | **Flowrate ($m^3$/s)** | **Salinity (mg/L)** | **Flowrate ($m^3$/s)** | **Salinity (mg/L)** |
| January | 230 | 246 | 159 | 341 | 227 | 216 |
| February | 157 | 242 | 210 | 361 | 362 | 217 |
| March | 242 | 227 | 242 | 316 | 347 | 213 |
| April | 171 | 245 | 254 | 311 | 176 | 244 |
| May | 116 | 228 | 153 | 300 | 134 | 252 |
| June | 170 | 206 | 94 | 336 | 174 | 218 |
| July | 155 | 210 | 110 | 334 | 91 | 325 |
| August | 173 | 229 | 69 | 416 | 195 | 261 |
| September | 136 | 239 | 95 | 369 | 111 | 278 |
| October | 109 | 238 | 62 | 383 | 113 | 292 |
| November | 78 | 225 | 143 | 342 | 126 | 244 |
| December | 64 | 231 | 158 | 322 | 204 | 185 |

*2003–2007 mean flowrate and salinity value.
**1996–2000 mean flowrate and salinity value.

quality stations in major river basins show that flow rate and water quality values are highly variable. Regarding osmotic energy and power generation, the required flow rate and salinity of the fresh water through the power plant data were provided by SHW for the Ceyhan (2003–2007), Sakarya (1996–2000), and Meric (2003–2007) rivers (Table 1).

## Annual Energy Production

Net producible energy (NPE) for a PRO power plant can be calculated by Equation 2.

$$\mathrm{NPE} = \Delta G_{\mathrm{mix}} \times \text{membrane, hydraulic, and turbine inefficiencies } \left[\mathrm{kWh/m^3}\right] \quad (2)$$

In this study, membrane and hydraulic loss was considered as 40% and turbine-generator loss as 15%. Installed power (IP) for a PRO power plant is given by Equation 3.

$$\mathrm{IP} = NPE \times Q_P \times 3.6 \quad (3)$$

where, $Q_P$ is the flowrate ($m^3/s$). Annual energy production from a PRO power plant can be calculated from the estimated level of power generation and operation period (in hours) of power plant. Thus, the annual produced energy equation is:

$$E_{\mathrm{production}} = \mathrm{IP} \times \mathrm{CF} \times t \quad (4)$$

where, $E_{\mathrm{production}}$ (MWh) is the annual energy production, $W_{\mathrm{net}}$ (MW) is the power capacity of the power plant, CF is the capacity factor, and $t$ is the number of hours in a year.

## $CO_2$ Mitigation from Electricity Generated in the Site

PRO power plants emit no emissions and displace $CO_2$ and other greenhouse gases that would otherwise be released by conventional fossil-fuelled power plants [39]. A small quantity of $CO_2$ emissions can be emitted during building and maintained period of PRO power plants. It is possible to calculate the avoidance of $CO_2$ through fossil fuel displacement as following equation (Equation 5) [40]

$$\mathrm{CO}_{2\mathrm{avoidance}} = E_{\mathrm{production}} \times \mathrm{EF}_{\mathrm{elec}} \times 1000\ [\mathrm{kgCO_2}] \quad (5)$$

where, AEP is the annual electricity generation (kWh), $\mathrm{EF}_{\mathrm{elec}}$ is the emission factor, and in the present study, it was expected to be 0.86 kg $CO_2$/kWh [41].

## RESULTS

In PRO, the highest power density is obtained where the salinity is high for the feed and draw solutions. At high dilutions of the draw, the free energy of mixing per cubic meter draw increases sharply. For the site specific and technical potentials average river discharge flowrates can be actually used for calculations of energy generation. Yip and Elimelech (2012) reported the maximum extractable work in PRO process was less than the free energy of mixing [37]. In practical operations, when the process is operated in constant pressure mode, it is not allowed to run to equilibrium and as a result there was a loss of energy [38].

There is no entropy generation in a reversible thermodynamics process [42]. Figure 3 shows Gibbs free energy of mixing and salinity of Ceyhan, Sakarya, and Meric Rivers with respect to months. The highest mixing energies of Ceyhan, Sakarya, and Meric Rivers were: 0.596 kWh/$m^3$ in June, 0.361 kWh/$m^3$ in May, and 0.548 kWh/$m^3$ in March, respectively, when $\phi$ is 0.5 and temperature $T$ is 298 K. For the same conditions, the lowest mixing energies of Ceyhan, Sakarya, and Meric Rivers were: 0.591 kWh/$m^3$ in January, 0.351 kWh/$m^3$ in August, and 0.537 kWh/$m^3$ in July, respectively. PRO with seawater with 0.6 M concentration as draw solution and river water 0.015 M as feed solution, the theoretical maximum specific energy is 0.192 kWh/$m^3$ [38]. Another potential combination of Dead Sea water (5.7 M NaCl) as draw solution and brine as feed solution yielded a maximum ideal specific energy of about 1.0 kWh/$m^3$ using counter-current PRO [43]. For a PRO power plant operated at an actual efficiency of 60% with a river water feed solution and a seawater draw solution and the specific extractable work was 0.46 kWh/$m^3$. Assuming a further 20% lost from inefficiencies in PRO system components, 0.37 kWh of useful work can be derived per cubic meter of the river water feed solution [37]. In PRO process, the draw solution salinity affects both the osmotic pressure and the applied pressure. Therefore, the important point is to decide whether the salinity of the selected site is suitable for feasible PRO power generation systems [44]. The

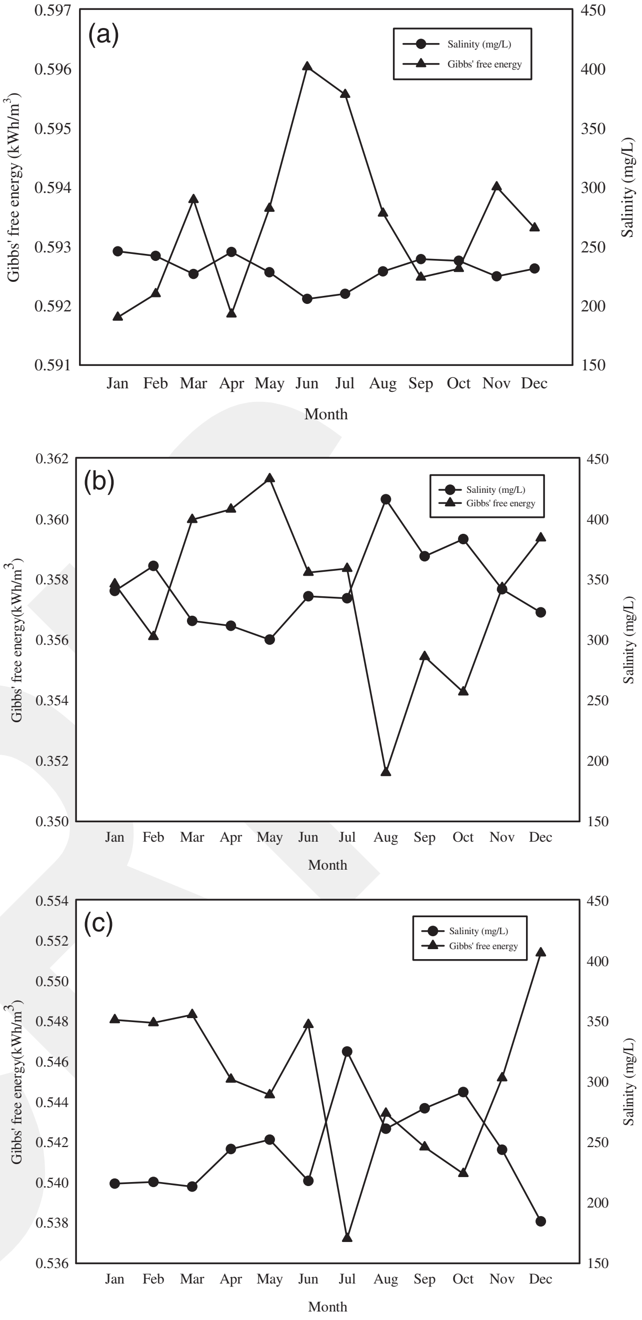

**Figure 3.** Gibbs free energy of mixing and average salinity of: (a) Ceyhan River, (b) Sakarya River, and (c) Meric River

salinity of Mediterranean, Black, and Aegean Seas used in this study are 653, 413, and 603 mM, respectively. Compared with the feed and draw solution salinity, the effect of the draw salinity on the total free energy is larger which led to increasing extractable energy. Although river salinity values are similar for all rivers, Black Sea salinity is the lowest among them. As a result, Gibbs free energy value is affected because of this high salinity ratio.

Because of membrane, turbine inefficiencies, pre-treatment requirements for both feed and draw solutions, the net power per $m^3$ mixing solution was less than its theoretical value [27,44,45]. Figure 4 shows the installed power potential of Ceyhan, Sakarya, and Meric Rivers calculated based on monthly average flowrates when membrane and hydraulic efficiencies are 40% and the energy consumption in ultrafiltration process as pre-treatment was 0.15 kWh/$m^3$. The solution pre-treatment is an important subsystem in this PRO power plant due to impurities from the incoming solutions. The primary metric to determine the quality of the solutions is water turbidity, which is designed to measure the relative clarity of water [46,47]. Membrane fouling happened when impurities from the feed and draw solutions are accumulated on the membrane and; as a result, the overall efficiency of the PRO power plant was reduced [48]. The water quality of Turkish Rivers shows a wide variability, being influenced by both natural and anthropogenic factors. Rivers that are mostly disposed to natural pollution is caused mainly by domestic (sewage) and industrial waste waters, and from irrigation return waters in Turkey. The effects of untreated domestic wastewaters on rivers decrease through downstream because of the natural biodegradation of chemicals and also dilution from tributaries. Pre-treatment of solutions is essential to ensure high quality of solutions going through the membrane module and ultimately minimizes membrane fouling [49]. The installed power potentials of Ceyhan, Sakarya, and Meric Rivers for PRO power generation depending on river flowrates are between 37 and 179 MW, 52 and 187 MW, 106 and 518 MW, respectively.

The PRO power potential considers the efficiencies in the energy conversion process and that the average river flow can be used for energy generation. However, technical and environmental constraints have to be considered in order to scale-up from the site specific potential to the exploitable potential. Most rivers exhibit temporal variability of the natural flow that is an important constraint for PRO power plants design [50]. On the other hand, for a PRO power plant project, it is important that a minimum flow in the riverbed should remain after the intake of a power plant in order to endure the protection of fauna and the ecosystem [51]. Turkey connects two continents and, consequently, acts as a major migration and mixing corridor with a gorgeous biodiversity, including a high number of endemic species. In particular, southern and southeastern Anatolia contains several local biodiversity hotspots within the large Mediterranean global hotspot area. In this study, for the calculation of the ecological potential of the prospective PRO power plant in Ceyhan, Sakarya, and Meric Rivers, 25% of the lowest values of the multiannual monthly flow series was used as ecological flow. Ortega *et al.* (2014) used an extraction factor of 20% and an ecological flow of 12% of the mean discharge that for the Leon River [14]. Installed power potential of Ceyhan, Sakarya, and Meric Rivers for ecological flow conditions are shown in Figure 5. The installed power potentials of Ceyhan, Sakarya, and Meric Rivers for PRO power generation with respect to river flowrates considering ecological criteria are between 28–170 MW, 32–174 MW, and 172–669 MW, respectively.

For the design of PRO power plants, average annual flow rate value of a river was taken and a flow equal to 20% of the average flow is proposed as a reference value for the design flow. These values were: 149, 146, and 186 $m^3$/s for Ceyhan, Sakarya, and Meric Rivers, respectively. A power factor for PRO power plants was varied between 0.6 and 0.85 MW/($m^3$/s). A power factor of 0.8 MW/($m^3$/s) was used for the calculation in this study. Prospective osmotic power plant parameters for Ceyhan, Sakarya, and Meric Rivers are shown in Table 2. While the average salinity of the Great Salt Lake was taken as 24% (or 240 g/L) and fresh solution salt concentration was considered to be 0.05% (or 0.5 g/L). Although the theoretical maximum osmotic energy from the Gibbs free energy of mixing of the two solutions is 5.54 kWh/$m^3$, the net annual energy production is 154 MWh with all the energy losses and consumption taken into account because of lower flowrates of the freshwater (1.54 $m^3$/s) and the saltwater (3.08 $m^3$/s) [52]. The proposed configuration for Lake Torrens in Australia could generate up to 2.6 GW for a 225 $m^3$/s seawater flow rate [19]. The theoretical power of the Great Salt Lake was around 162 GWh (5.7% of total net electricity generation) [52]. The

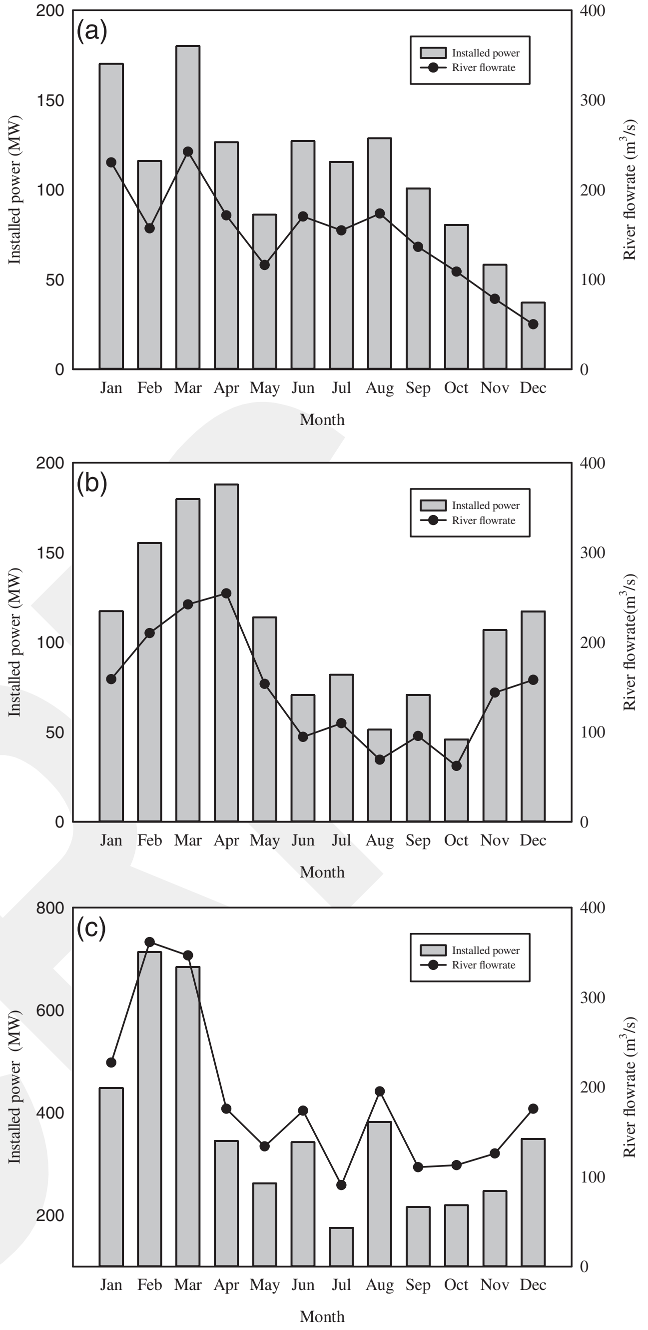

**Figure 4.** Installed power potential of: (a) Ceyhan River, (b) Sakarya River, and (c) Meric River

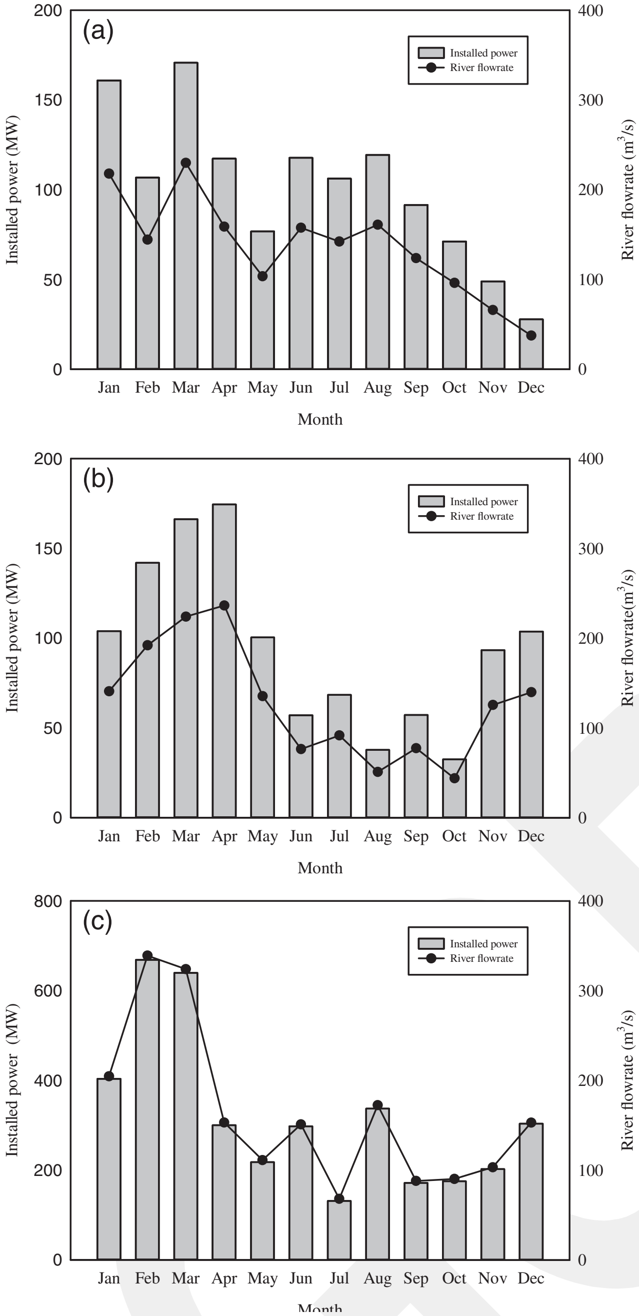

**Figure 5.** Installed power potential of (a) Ceyhan, (b) Sakarya, and (c) Meric for ecological flow conditions

Meric River has a high osmotic energy potential (208 GWh/yr), making it one of the most important rivers in Northeastern of Turkey. For Meric River osmotic plant, annual avoidance of $CO_2$ emission was calculated as 1.79E + 08.

## CONCLUSIONS

In this study, the potential of the salinity gradient of Ceyhan, Sakarya, and Meric Rivers (Turkey) were evaluated. The theoretical maximum osmotic energy from the Gibbs free energy of mixing of the two solutions were: 0.591, 0.361, and 0.537 kWh/m$^3$, respectively if the volume ratio approaches zero when $\phi$ is 0.5 and temperature $T = 298$ K. Depending on design flow, power factor, and installed capacity and annual electricity energy generation was calculated as 167, 164, and 208 GWh/yr for Ceyhan, Sakarya, and Meric Rivers, respectively. As the Government of Turkey has been funding research on new sources of renewable energy as a result of targets to reduce greenhouse gas emissions and to increase the supply of energy by renewable sources, the results of this study supporting that PRO power plant is technically reasonable for these regions. System design integration and cost analysis for a potential PRO power plant at the Turkey's Rivers can identify key aspects for building a successful PRO system. Also PRO is advantageous in terms of its ability to generate a constant and reliable supply of power as compared with other renewable sources, osmotic power with PRO can become an attractive alternative in the power generation mix. Another issue will probably be the attraction of investors to this new technology, given that PRO systems involve serious technical uncertainties such as, the lifetime of the membranes and the ongoing maintenance costs. Therefore, more research is required, for the progressive improvement of PRO systems to full scale commercial units.

**Table 2.** Osmotic power plant parameters at Ceyhan, Sakarya, and Meric River

| Category | Ceyhan | Sakarya | Meric |
|---|---|---|---|
| Mean flow [m$^3$/s] | 149 | 146 | 186 |
| Design flow [m$^3$/s] | 30 | 29 | 37 |
| Ecological flow [m$^3$/s] | 12 | 18 | 23 |
| Power factor [MW/(m$^3$/s)] | 0.8 | 0.8 | 0.8 |
| Capacity factor [−] | 0.8 | 0.8 | 0.8 |
| Installed capacity [MW] | 24 | 23 | 30 |
| Electricity generation [GWh/yr] | 167 | 164 | 208 |
| $CO_{2avoidance}$ [kg $CO_2$/yr] | 1.44E + 08 | 1.41E + 08 | 1.79E + 08 |

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