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Practical global salinity gradient energy potential

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ABSTRACT

Salinity gradient energy (SGE) is a clean and renewable energy source that can be harnessed from the controlled mixing of two water masses of different salt concentration. Various natural and artificial systems offer conditions under which SGE can be harnessed amongst which river mouths play the prominent role in a global assessment. The theoretical SGE potential at river mouths has been previously estimated to be 15,102 TWh/a, equivalent to 74% of the worldwide electricity consumption; however, practical extractable SGE from these systems depends on several physical and environmental constraints that are discussed here. The suitability, sustainability and reliability of the exploitation of this renewable energy are considered based on quantified descriptors. It is shown that practically 625 TWh/a of SGE are globally extractable from river mouths, equivalent to 3% of global electricity consumption. Although this is much smaller than the theoretical potential, is still a significant amount of clean energy.

Contents

Abbreviations: CapMix, Capacitive mixing; CRED, Capacitive reverse electrodialysis; PRO, Pressure retarded osmosis; RED, Reverse electrodialysis; REP, Reduced extraction periods; SGE, Salinity gradient energy; SSS, Sea surface salinity; SST, Sea surface temperature; ZEP, Zero extraction periods

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List of symbols and abbreviations

Symbols

A	time period of one year
CF	Capacity factor
EE	Extractable energy, Wh/y
EF	Extraction factor
EP	Environmental potential, W
G	Gibbs free energy of mixing, J/m^3
m	Number of moles, mol/m^3
Q	Discharge (flow), m^3/s
$\bar{Q}$	Mean river flow, m^3/s
Q_D	Design flow of the power plant, m^3/s
Q_E	Environmental flow, m^3/s
Q_N	River flow in natural conditions, m^3/s
Q_{OP}	Operation flow of the power plant, m^3/s
Q_R	Residual river flow, m^3/s
R	Universal gas constant, J/(mol K)
T	Absolute temperature, K
TP	Theoretical potential, W
V	Water volume, m^3
x_i	Molar fraction of Na^+ and Cl^-
y_i	Molar fraction of water
ΔS	Entropy change, J/K

1. Introduction

Society needs renewable and locally available energy, which may be found at river mouths, where settlements are dense and renewable energy potential is present in the form of salt concentration gradients. When two waters of different salt concentration mix, a release of free energy occurs driven by the difference in chemical potential between them [1]. If the mixing is controlled, the chemical potential can be used to generate electricity [2]. This power source is called salinity gradient energy (SGE); it is in principle completely clean and produces no CO_2 or any other harmful threat to the environment [3]. Several techniques have been developed to exploit available salinity gradient energy; in higher stages of development are the pressure-retarded osmosis (PRO) [4,5] and reverse electrodialysis (RED) [6]. Also technologies like capacitive mixing (CapMix) [7,8] and capacitive reverse electrodialysis (CRED) [9] are gaining momentum recently.

River mouths, where fresh water from terrestrial drainage mixes with saline seawater, are the most manifest locations for harnessing SGE, since here the sought salinity gradients are available and many of them are located near to cities and industrial communities [10,11]. First studies on the quantification of global SGE resources at river mouths in the 1970s estimated the global theoretical SGE potential to 1.4 and 2.6 TW [11–13]. More recent studies have quantified the theoretical potential to 0.23 TW [14], 3.13 TW [15] or 1.724 TW [16] (15,102 TWh/a, equivalent to 74% of the global electricity consumption in 2011 [17]); where only the last assessment considered ocean salinity near to the river mouths (from the World Ocean Database 2005) instead of global average values. Regional and Local scale estimations of SGE resources have been carried out at country level for Norway (Reported in [3]), United States [4,18], China [19], Colombia [20], Australia [21] and the region of Quebec in Canada [22]. Local scale estimations have been done for the Great Salt Lake [23], Mississippi River [4,24] and Columbia Rivers [4] (United States), Rhine and Meuse Rivers (The Netherlands) [2], León River (Colombia) [25], Amazon River (Brazil), La Plata – Paraná River (Argentina - Uruguay), Congo River (Congo – Angola) [4] and the Dead Sea [26].

Previous studies have based the calculation of theoretical SGE potential on major assumptions and simplifications, like using time averaged salinities and temperatures of fresh- and sea-water and taking into account all existent river mouths and the entire fresh water discharge of rivers (except [4]). These assumptions must be questioned for more realistic assessments considering the suitability, sustainability and reliability of SGE exploitation at river mouths: First, not all river mouths offer suitable conditions for harnessing SGE; in particular, locations with weak salinity gradient, poor water quality, or where resources are not permanently accessible are unsuitable locations for SGE generation [15,20,27], and must not be considered in a balance of the extractable potential. Second, it is not sustainable to exploit the entire discharge of rivers for energy generation; evidently, such intervention would generate a strong imbalance of the ecological, hydrodynamic and sedimentological processes at river mouths. Therefore, only a fraction of the mean discharge of rivers i.e. extraction factor (*EF*) may be used for SGE purposes to ensure environmental stability of the systems [15,25]. Third, the seasonal variability of fresh water discharge and the variability of salinity and temperature gradients between seawater and fresh water must be taken into account. The latter affects the reliability of harnessing SGE, which may be quantified by a capacity factor (*CF*) [25].

In this study, a new estimation of the practical extractable global salinity gradient energy resources at river mouths is obtained, considering the previously mentioned constraints. We start with an assessment of the global theoretical potential for those suitable river mouths where the variability of rivers' discharge is known; it is followed by a description of the limitations to the theoretical potential in terms of sustainability and reliability and how they are quantified. Finally the extractable global SGE potential and its worldwide distribution are presented and discussed.

2. Materials and methods

The practical extractable global SGE potential from river mouths (*EE*) may be expressed in terms of a reduction of the theoretical potential by an extraction factor (*EF*), and a capacity factor (*CF*), as:

$$EE = \sum_{k=1}^{sm} (TP_k * EF_k * CF_k) \quad (1)$$

In which only suitable river mouths (*sm*) are considered in the extractable potential estimation. The next sections describe the terms in Eq. (1) and the criteria to determine the suitability of river mouths.

2.1. Theoretical potential

When two waters with different salt concentration get in contact, they mix spontaneously to form a homogenous mixture in a process driven by the difference in chemical potential between both solutions where Gibbs' free energy is released. Ideally all the Gibbs' free energy may be converted into electrical power, representing the maximum available energy or theoretical SGE potential [16,28]. The theoretical potential from mixing seawater and fresh water at a river mouth k, can be determined from the chemical potential difference before mixing subtracted by the chemical potential after mixing [2]:

$$TP_k = (G_{s_k} + G_{r_k}) - G_{b_k} \quad (2)$$