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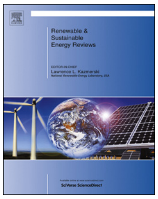

Practical global salinity gradient energy potential

O.A. Alvarez-Silva [a,b,*,1], A.F. Osorio [a], C. Winter [c]

[a] OCEANICOS – Research Group in Oceanography and Coastal Engineering, Universidad Nacional de Colombia, Carrera 80 # 65-223, 050041 Medellín, Colombia
[b] Departament of Physics, Universidad del Norte, 081007 Puerto Colombia, Colombia
[c] MARUM – Center for Marine Environmental Sciences, University of Bremen, Leobener Strasse, 28359 Bremen, Germany

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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

[*] Corresponding author at: OCEANICOS – Research Group in Oceanography and Coastal Engineering, Universidad Nacional de Colombia, Carrera 80 # 65-223, 050041 Medellín, Colombia.

E-mail address: oaalvare@unal.edu.co (O.A. Alvarez-Silva).

[1] Current permanent address: Universidad del Norte, 081007 Km.5 Vía Puerto Colombia – Barranquilla, Colombia. Tel: +57 5 3509509x8831.

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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:

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

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]:

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

in which G_s, G_r and G_b are the Gibbs free energy of mixing of seawater (s), fresh water (r) and brackish water after mixing (b), in Watts, respectively. The free energy of each electrolyte $i = s,\ r,\ b$ depends on the volume, salinity and temperature of the solutions in the mixing and is given by:

$$G_i = T_i Q_i m_i R \left[x_i \ln(x_i) + y_i \ln(y_i)\right] \tag{3}$$

in which T (in K) is the absolute temperature, Q (in m^3/s) is the water flow rate ($Q_b = Q_s + Q_r$), m (in mol/m^3) is the total moles per unit volume, R is the universal gas constant ($8.314\ J\ mol^{-1}\ K^{-1}$), and x and y are the molar fractions of ions (Na^+ and Cl^-) and water respectively [28].

A global theoretical potential based on the individual potential of all river mouths in data K sums up to:

$$TP = \sum_{k=1}^{K} TP_k \tag{4}$$

For the global assessment, the fresh water runoff dataset by Dai and Trenberth [29] was used; it includes monthly stream flow at most downstream station for the world's 921 largest ocean-reaching rivers (Fig. 1), accounting for 73% of the global total runoff. The average records length is 35.5 a, and 49.1 a for the world's top 200 rivers [30]. A volume ratio between fresh- and sea-water in mixing of 1:1 was assumed ($Q_r = Q_s$). Monthly sea surface salinity (SSS) for the year 2012 in the vicinity of river mouths from Aquarius [31] and SMOS [32] satellite missions were used to define the salinity of seawater. These databases differ in the spatial domain at the edge to the continents, where river mouths are located (Fig. 1A); we used SSS from the closest point to each river mouth where data is available independently of the database, and SMOS where data from both sources is available at the same distance (Fig. 1B). The salinity of rivers' fresh water was assumed constant and equal to the global mean (0.0022 mol/l = 0.13 PSU) [33]. The temperature of both waters was assumed to be equal to the sea surface temperature (SST) near to the mouths ($T_r = T_s = T_b$). Monthly climatology of SST for years 1971–2000 from NOAA_OI_SST_V2 was used [34,35].

2.2. Suitability of river mouths

The most important physical condition limiting the suitability of river mouths for SGE generation is the steepness and stability of the salinity gradient [10,15]. Only in river mouths where strong stratification induces high and steady salinity differences over a short distance the theoretical SGE potential is higher than the energy required to deliver the fresh- and sea-water towards the power plants [27].

The stratification of river mouths depends on the buoyancy forcing by fresh water discharge and the mixing by tides; strongly stratified river mouths result from high to medium river discharges and low to medium tidal ranges [36]. It has been shown that the tidal range sufficiently characterize mixing as the most limiting factor for harnessing SGE at river mouths and that only river mouths located in regions where the mean tidal range is smaller than 1.2 m (Fig. 1C) are considered to be suitable locations [27]. Hence, only those river mouths were considered for the estimation of the global extractable SGE potential.

River mouths in polar regions are neither considered as suitable locations since ice coverage, mainly during winter time [37], constrains accessibility and water extraction for SGE generation [15].

2.3. Sustainability, environmental flow and extraction factor

Most rivers feature temporal variability of the natural flow Q_N, which is a major constraint for SGE power plants design. This variability determines the assessment of the so-called "extraction factor" EF, which is the ratio between the design flow Q_D of the power plant (amount of fresh water that can be extracted from the river for energy generation), and the mean river flow $\overline{Q}$:

$$EF = Q_D / \overline{Q} \tag{5}$$

The assessment of the extraction factor must consider the environmental impact of water extraction and also technical and economic issues [25]. Environmental considerations limit the design flow in order to reduce harmful impact on the flora, fauna, nutrients, circulation, sediment transport and other uses of fresh water resources. As a general concept, the residual river flow after extraction $Q_R = Q_N - Q_D$, must not fall below a critical value known as the "environmental flow" Q_E [25], which refers to the fraction of the river discharge that must remain to satisfy the environmental demands of the river [38].

Different methods have been developed for assessing the environmental flow. The most common being the Tennant method due to the considerable collection of data involved in its development and the simplicity of its application [39]. According to this method fair ecological conditions are preserved at an environmental flow of 30% of the mean rivers' discharge and the minimum recommended is 10%. More robust habitat simulation and holistic methods may be applied in local scales when the attributes of the riverine ecosystems are known in detail [38], however, at global scales, the application of a non-resource intensive method is more feasible. Here following the Tennant method, the environmental flow was defined as 30% of the mean rivers' flow:

$$Q_E = 0.3\overline{Q} \tag{6}$$

The threshold condition $Q_R \geq Q_E$ may lead to periods when fresh water extraction must be lower than the design flow (reduced extraction period), or stopped completely (zero extraction period, Fig. 2). A high design flow thus may lead to longer reduced extraction periods. Certainly reduced extraction periods shall be minimized for environmental reasons, but also for technical and economic reasons, in order to avoid a high variability of the energy generation rate, which affects the plant efficiency. Here the design flow and the extraction factor were determined for each river mouth so that the reduced extraction periods have the same length than the zero extraction periods. Under this design condition, the environmental stress induced by water extraction is not greater than what the river mouths handle under natural conditions. The zero extraction periods were first estimated for each river mouth as the time per year that the river flow Q_N is lower than the environmental flow Q_E; meanwhile the reduced extraction periods were calculated as those when $Q_E < Q_N < (Q_E + Q_D)$.

2.4. Reliability and capacity factor

From the considerations above it follows that SGE plants may not operate at full load throughout the whole year, instead, three power plant operation flows (Q_{OP}) may occur [25]:

i. if $Q_N > (Q_D + Q_E)$: full capacity operation, $Q_{OP} = Q_D$ (standard mode).
ii. if $Q_E < Q_N < (Q_D + Q_E)$: partial capacity operation, $Q_{OP} = Q_N - Q_E$.
iii. if $Q_N < Q_E$: no operation $Q_{OP} = 0$.

The ratio between the actual annual energy yield of a power plant, and the theoretical annual generation calculated assuming that the power plant operates permanently at full capacity, is known as "capacity factor" [28]. It may be calculated for each river mouth as the equivalent ratio of the operation flow Q_{OP} over a year (T) to the design flow over the same time interval (ideal operation

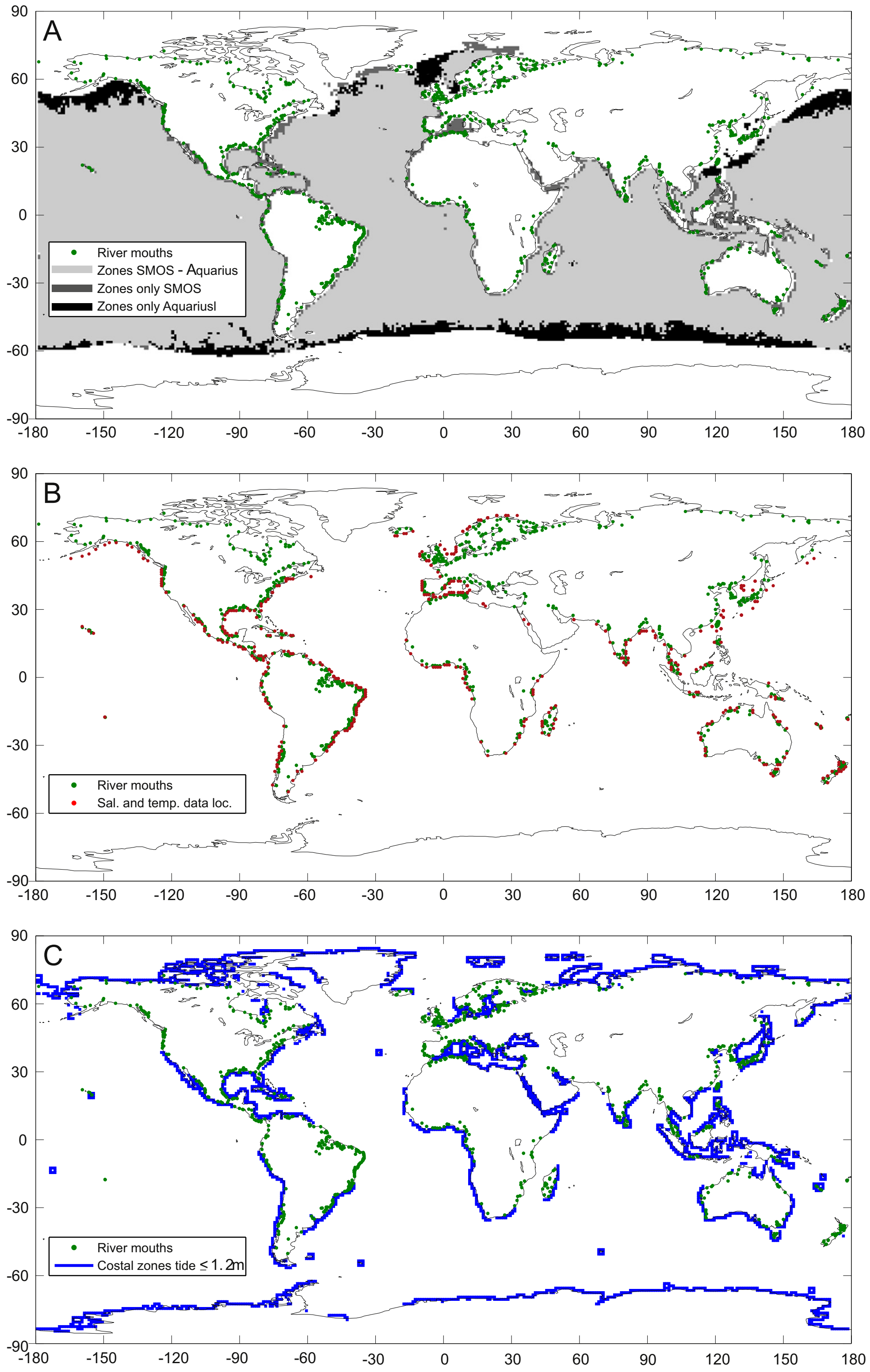

Fig. 1. Data and its spatial distribution in relation to the location of river mouths. (A) coverage areas of Aquarius and SMOS sea surface salinity data; (B) location of sea surface salinity and sea surface temperature data for each river mouth; (C) coastal regions with mean tidal range ≤ 1.2 m (FES2012 model. http://www.aviso.altimetry.fr/).

condition considering permanent standard mode):

$$CF = \frac{\int_0^T Q_{OP} dt}{Q_D T} \tag{7}$$

The capacity factor depends on the extraction factor, as it defines the design flow, and on the environmental flow, as it defines the operation flow.

To assess the extractable energy, the capacity factor is expressed as full load hours per year by multiplying this factor by the total hour per year (8760 h/a). In this way, the capacity factor refers to the hours per year that a SGE plant may operate at full load to produce the actual annual energy yield [25].

3. Results

3.1. Theoretical potential and suitable river mouths

Here the global theoretical SGE potential has been calculated to be 1183 GW on average ranging between 1063 GW in March and 1328 GW in October due to the monthly variability of SSS and SST. As mentioned before, these results are based on the 921 largest rivers accounting for 73% of the global fresh water runoff into the ocean. A linear extrapolation to 100% runoff would lead to 1621 GW of theoretical potential, which is in the same order of magnitude as a most recent estimation by Kuleszo et al. of 1724 GW [16]. However, only 448 river mouths of the 921 can be considered as suitable locations for SGE generation; the theoretical potential for these suitable river mouths is 412 GW, with monthly variability between 404 GW and 427 GW.

3.2. Extraction factor and environmental potential

For an environmental flow of 30% the average zero extraction periods of analyzed systems were found to be 11% of the year; and the extraction factor producing reduced extraction periods (REP) the same length of time per year is ~0.20 (Fig. 3), leading to a design flow equivalent to 20% of mean rivers' discharge.

For an extraction factor of ~0.40, the 95th percentile of the REP curve in Fig. 3 reaches a time of 50% of the year (6 months); it means that for a design flow of around 40% of the river flow, 5% of all river mouths locations would be under REPs for six months per year, which implies strong environmental stress conditions and also a major technical limitations for energy generation, since the power plants located in those river mouths would operate at partial load half part of the time. The percentage of river mouths subject to this environmental and technical unfeasible conditions increase fast with further increases of the extraction factor; e.g. for extraction factor of 0.75, 50% of the systems would be down at environmental flow conditions six months per year or more.

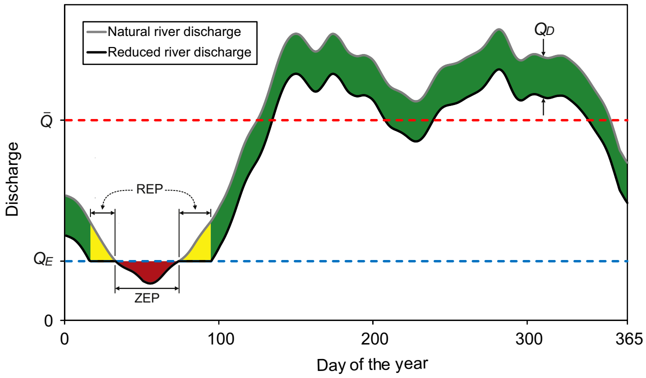

Fig. 2. Effects of fresh water extraction for SGE generation on the annual hydrologic regime of an exemplary river. Gray line: natural river discharge before fresh water extraction Q_N; Black line: reduced river discharge after fresh water extraction Q_R. Mean river discharge $(\bar{Q})$ and Environmental flow (Q_E), are shown. Green belts show the periods when the power plant operates at full load ($Q_{OP}=Q_D$), here the difference between natural discharge and reduced discharge represents the design flow. Yellow belts show the periods when power plant operates at partial load ($Q_{OP}=Q_N-Q_E$), here the reduced flow after extraction is the environmental flow, those are reduced extraction periods (REP). Red belts show the periods when power plant is in shut down, natural discharge is lower than environmental flow, exploitation is not performed ($Q_{OP}=0$), those are zero extraction periods (ZEP). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The relation between the extraction factor and the theoretical potential is known as the environmental potential (*EP*), for a river mouth *k*:

$$EP_k = EF_k * TP_k \tag{5}$$

It may be interpreted as the maximum extractable SGE potential from river mouths considering only environmental constraints, and assuming ideal reliability and energy conversion efficiency, therefore, it is equivalent to the potential capacity of the SGE plants.

For an extraction factor of 0.2, the global environmental potential of SGE at suitable river mouths is 82.5 GW, with monthly variability between 80.9 GW and 85.4 GW.

3.3. Capacity factor

As mentioned in Section 2.4, the capacity of the SGE plants depends on the extraction factor and on the environmental flow;

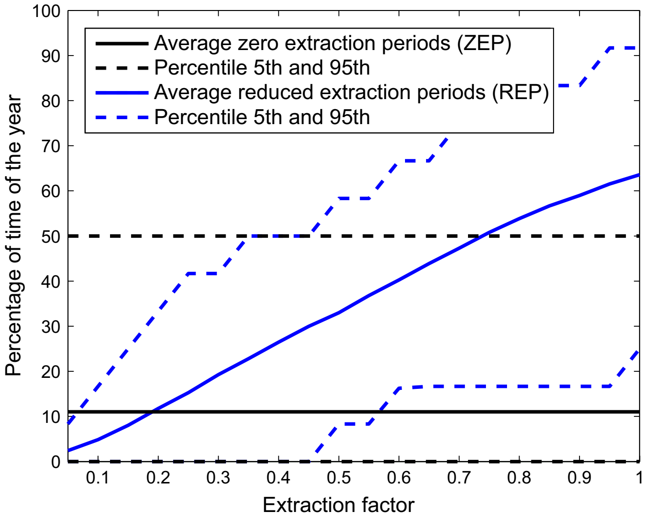

Fig. 3. Percentage of time of the year with ZEP and REP, statistics for all suitable river mouths assuming environmental flow of 30% of the mean flow.

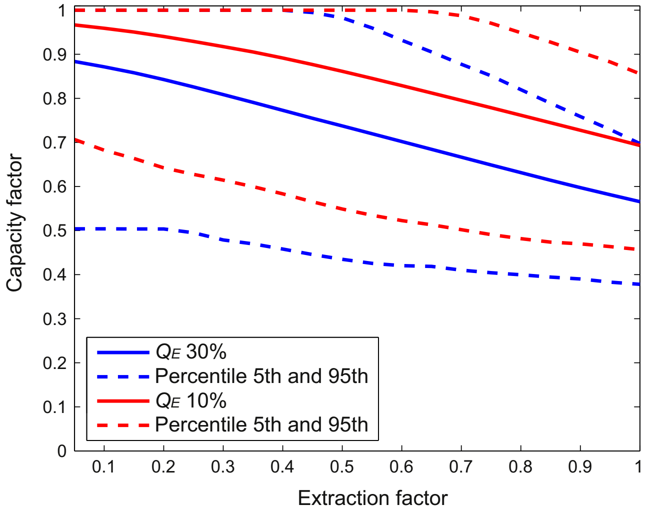

Fig. 4. Capacity factor of SGE at river mouths. Statistics calculated for worldwide suitable river mouths as a function of the extraction factor and the environmental flow (Q_E).

the effect of these two variables on the global capacity factor is shown in Fig. 4.

For an extraction factor of 0.2 and an environmental flow of 30%, the capacity factor of SGE generation at river mouths is 0.84 on average, equivalent in full load hours to: 7358 h/a. It shall be noted that this capacity factor is very high compared to other renewables; it is more than double of the 40% estimated as maximum for waves and tidal energy power plants [40], and also higher than the 45% and 23% calculated for wind energy and solar photovoltaic energy respectively [41,42].

4. Discussion

According to the previous analysis and Eq. (1), the global extractable SGE potential was calculated to 625 TWh/a; equivalent to 17% of the theoretical potential for suitable river mouths.

The worldwide distribution of the global extractable potential is shown in Fig. 5. Here can be seen that SGE is a decentralized energy source; suitable river mouths can be found all over the world, making SGE appropriate for cities and industries located close to river mouths, but also for remote communities settled near these systems and lacking centralized energy access. The top 30 river mouths with greatest extractable energy account for 77% of the total resources (Table 1). However, 286 systems in 64 countries have a potential capacity of 10 MW or greater, being Brazil, United States, Mexico, Japan and Malaysia the countries with highest number of river mouth systems.

About 34% of river mouths with an energy density greater than 2.0 MW/m^3 (i.e. energy potential per cubic meter of fresh water) are located in the Mediterranean Sea and 29% in the Caribbean Sea and Gulf of Mexico (Table 2), being the regions with better oceanographic conditions for harnessing SGE. The Mediterranean Sea particularly is a semi-enclosed basin where the excess of evaporation over precipitation and runoff make the basin progressively more saline from the open boundary to the interior [43], which is reflected in the increase of energy density eastward of the basin. River mouths with highest energy density are not necessarily the systems with highest extractable energy (Table 2), due to the low fresh water discharge of the rivers; however, the implementation of several small and medium size power plants in high energy density regions could compensate the low individual potentials.

Two variables defining the extractable SGE resources are subject to design: the extraction factor and the environmental flow. Previous results are based on extraction factor of 0.2 and environmental flow of 30%. The behavior of the global extractable energy as a function of these two variables is shown in Fig. 6. Higher values of the extractable energy would be derived considering higher extraction factors or lower environmental flows, e.g. assuming extraction factor of 0.4 and environmental flow of 10%, the extractable energy would rise to 1321 TWh/a. However, cautious considerations in environmental terms are desirable for

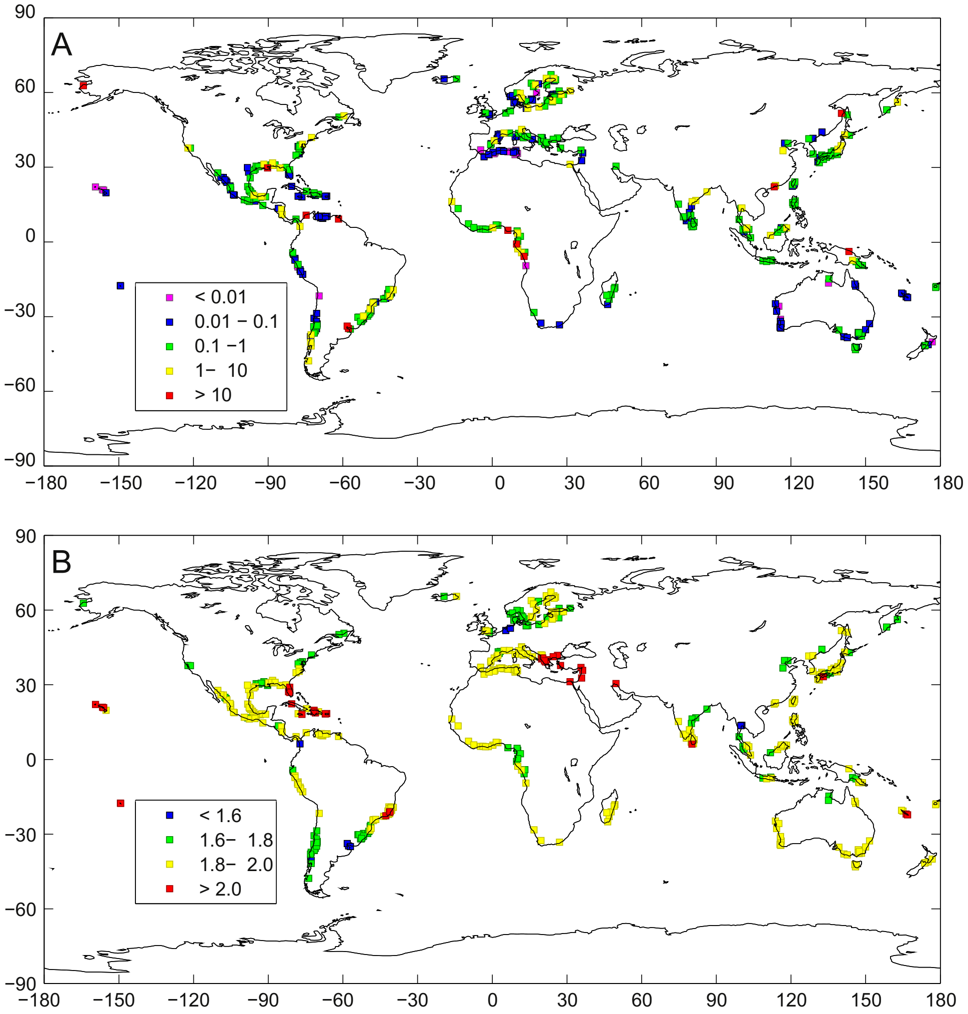

Fig. 5. Global map of extractable salinity gradient energy resources. (A) Extractable energy (TWh/a). (B) Energy density (MJ/(m^3/s)).

Table 1
World's top 30 river mouths with highest extractable energy.

River	Country	Basin	Energy density (MW m^{-3} s^{-1})	Mean discharge (m^3/s)	Theoretical potential (GW)	Potential capacity (MW)	Extractable energy (TWh/a)
Congo	CD	SEA	1.64	39,858	65.2	13,046	114.3
Orinoco	VE	NWA	1.85	31,163	57.8	11,554	73.2
Mississippi	US	NWA	1.68	17,039	28.6	5722	49.9
Parana	AR	SWA	1.57	15,544	24.4	4876	42.7
Amur	RU	OKH	1.82	9720	17.7	3530	19.7
Magdalena	CO	CBN	1.89	7130	13.5	2690	23.6
Xijiang	CN	SCS	1.87	6961	13.0	2601	15.6
Yukon	AK	BRN	1.74	6372	11.1	2221	11.7
Niger	Ni	NEA	1.76	5700	10.0	2003	13.2
Uruguay	AR	SWA	1.57	5646	8.9	1771	15.5
Ogooué	GA	SEA	1.77	4689	8.3	1657	13.5
Sepik	PG	SWP	1.93	3758	7.3	1452	12.7
Godavari	IN	IND	1.71	3038	5.2	1041	3.3
Purari	PG	CRL	1.77	2338	4.1	826	7.2
Rajang	MY	SCS	1.75	2227	3.9	779	6.8
Usumacinta	MX	NWA	1.92	1899	3.6	729	5.3
Sanaga	CM	NEA	1.68	1985	3.3	666	4.1
Mahanadi	IN	IND	1.72	1883	3.2	647	4.2
Rhone	FR	MED	1.88	1707	3.2	641	5.6
Jacui	BR	SWA	1.76	1735	3.1	611	5.4
Krishna	IN	IND	1.74	1642	2.9	571	2.1
Atrato	CO	CBN	1.58	1768	2.8	559	4.9
Po	IT	MED	1.81	1513	2.7	549	4.8
Nile	EG	MED	2.08	1254	2.6	523	4.6
Beijiang	CN	SCS	1.87	1335	2.5	499	3.4
Doce	BR	SWA	1.98	1244	2.5	492	4.3
Volta	GH	NEA	1.94	1075	2.1	416	2.1
Huanghe	CN	YLW	1.65	1183	2.0	391	3.2
Alabama	US	NWA	1.86	919	1.7	342	2.8
Bío Bío	CL	SEP	1.66	1010	1.7	335	2.1

Table 2
World's top 20 river mouths with highest energy density.

River	Country	Basin	Energy density (MW/(m^3/s))	Mean discharge (m^3/s)	Theoretical potential (GW)	Potential. capacity (MW)	Extractable energy (GWh/a)
Bueyuek Mendere	TR	MED	2.10	99	207	41	290
Nile	EG	MED	2.08	1254	2613	523	4579
Ceyhan	TR	MED	2.08	223	464	93	565
Assi	SY	MED	2.08	30	63	13	86
Yarmuk	JO	MED	2.08	9	18	4	32
Papenoo	PF	PAC	2.07	13	27	5	45
Papeiha	PF	PAC	2.07	6	13	3	23
Vjosa	AL	MED	2.05	146	299	60	394
Maritza	BG	MED	2.05	110	225	45	352
Acheloos	GR	MED	2.05	52	106	8	56
Aliakmon	GR	MED	2.05	50	103	21	119
Nestos	GR	MED	2.05	40	81	16	114
Osumi	AL	MED	2.05	32	65	13	81
Devolli	AL	MED	2.05	30	61	12	80
Aracthos	GR	MED	2.05	20	42	21	127
Macacu	BR	SWA	2.04	11	22	4	39
Grande de Anasc	PR	CBN	2.04	9	18	4	27
Culebrinas	PR	CBN	2.04	8	17	3	21
Damuji	CU	CBN	2.03	9	17	3	18
Itabapoana	BR	SWA	2.03	57	116	41	290

global scale estimation, letting less conservative scenarios for detailed local scales analysis.

There are still several steps between the extractable SGE resources discussed here and the finally net generated energy, which are related mainly to the technical potential (or efficiencies of the energy conversion techniques) and with the required water pre-treatment before energy generation. Estimations of the technical potential at global scale have been carried out for pressure retarded osmosis and reverse electrodialysis [15,16], however recent findings on the implementation of these techniques at river mouths should be taken into account in later assessments. Meanwhile, low energy cleaning techniques of the generation devices rather than water pre-treatment have shown significant reductions of fouling on experimental scales [44], however, more

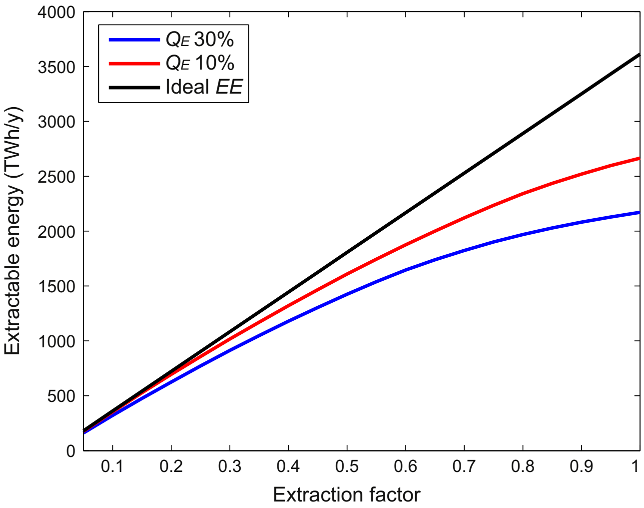

Fig. 6. Global extractable SGE from river mouths as function of the extraction factor and the environmental flow (Q_E) for worldwide suitable river mouths, comparing with the ideal extractable energy (ideal EE) calculated for $CF = 8760$ h/a.

research in this line is necessary for defining the viability of SGE generation at river mouths. On the other hand, additional SGE resources may be available from deep river mouth systems as fjords, where the tidal mixing has a lower impact [45] and stratification may be strong even for mean tidal range higher than 1.2 m.

5. Conclusions

A global assessment of the extractable SGE resources from river mouths was carried out here considering the main constraints affecting the theoretical potential related to the suitability, sustainability and reliability of SGE harnessing at these natural systems.

Constraints are quantified in the extraction factor, the capacity factor (both depending in turn on the environmental flow), and the selection of suitable systems, and used to define the extractable potential according to Eq. (1), which behind its simple form involves several physical and environmental considerations.

With an overall of 49% of river mouths considered to be suitable location, an environmental flow of 30% of the mean rivers discharge, an extraction factor of 0.2, and an average capacity factor of 0.84, the global extractable potential has been found to be 625 TWh/a, equivalent to 3% of the global electricity consumption [17]. Even though it is much smaller than previous theoretical estimations of the resources, is still more clean energy than the electricity consumption of most of the countries [17], keeping the SGE as an interesting alternative for future green economic growth. The high capacity factor indicates that SGE is reliable and continuous, basic requirement for competiveness of renewable energies that are major drawbacks for other sources [46,47].

Not only the global extractable SGE potential, but also its worldwide distribution has been presented here. The global maps show that SGE is a decentralized and broadly available energy source. Suitable river mouth with potential installed capacity of more than 10MW can be found all over the world.

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