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The potential of salinity gradient energy based on natural and anthropogenic resources in Sweden

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ABSTRACT

This paper presents assessment of natural and anthropogenic sources of blue energy within Swedish territory to identify suitable spots for implementing new projects. The natural energy potential of salinity gradients was found to be higher in southwest Sweden, and a national energy resource potential of 2610.6 MW from seawater/river water mixing will be reduced to a technical potential ranging from 1044.3 MW to 1825.4 MW considering technical and environmental constraints. It has been found that the theoretical extractable energy potential in Sweden is equivalent to 13% of the total electricity consumption and 6.2% of the total final energy consumption by energy commodities.

Anthropogenic water sources were also highlighted as promising low and high-concentration solutions for SGE extraction. Gotland was identified as an attractive location for generating salinity gradient power. The total salinity gradient power obtainable by mixing municipal wastewater with seawater in Sweden was estimated to be 11.8 MW. The most promising site for this process was determined to be Gryaab AB Ryaverket in Gothenburg, which accounted for 45.8% of the total national potential from anthropogenic sources.

1. Introduction

The salinity gradient energy (SGE), which is also known as blue energy [1], is the energy released upon mixing two aqueous solutions with different salinities (and thus different chemical potentials) and can be harvested by converting the difference between the chemical potentials of the two solutions into electrical energy.

In 1973, J. D. Isaacs [2] claimed that the maximum global theoretical potential of SGE technology is between 1.4 TWh and 2.6 TWh, and in 1978 Gerald Wick [3] estimated that the global salinity gradient potential (SGP) is about 2.6 TW, which is 20% of the current global energy demand [4]. Other studies have estimated the SGE to be 1.724 TW [5], 3.13 TW [6], 0.23 TW [7], or 1.72 TW [8].

Several studies have since been conducted to estimate the potential of SGE at local and regional scales. SGE potential was generally overestimated since environmental and technical restrictions were not considered carefully. In a global assessment of the extractable SGE for river and seawater mixing, Alvarez-Silva et al. (2016) concluded that the available energy reduced to 625 TWh/a from 15102 TWh/a because of limited suitable locations, extraction factor (0.2) and capacity factor (0.84) [9]. Moreover, on the technical side, incomplete mixing, pumping requirements [10], divalent ions [11] and fouling [12] cause reduction in generation of net power. One recent example concluded that the global potential for SGE amounts to 1650 TWh/year, with the potential in Europe being 170 TWh/year and that in Norway alone being up to 12 TWh/year, which is equivalent to 10% of the country's current energy consumption [13]. Other studies have evaluated the potential of SGE in the Congo River (Congo - Angola); the Amazon river (Brazil); the La Plata - Parana river (Argentina - Uruguay) [14]; the Mississippi river, the Great Salt Lake, and the Columbia river (USA) [15]; the Leon river (Colombia) [16]; the Dead Sea [17]; the Rhine and Meuse rivers (Netherlands) [8]; China [18]; Australia [19]; Colombia [20]; the United States [21]; Quebec [22]; and Norway [23].

Several techniques for SGE conversion have been proposed, of which the two most prominent are reverse electrodialysis (RED) and pressure-retarded osmosis (PRO). RED was described by Pattle 70 years ago [24] as a novel way of extracting renewable energy using ion-exchange membranes, while Norman and Loeb proposed PRO, a membrane

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process based on semi-permeable osmotic membranes resembling those used for reverse osmosis (RO) [17]. The state-of-the-art technologies for harvesting blue energy is presented in section 4.

The most abundant feed sources for SGE harvesting are seawater and river water. Additionally, anthropogenic sources of water can also be used as SGE feed solutions. Municipal and industrial wastewater could be suitable low salinity feeds, while desalination brine could be used for high salinity feeds.

Another way of harnessing SGE is by mixing SWRO brine with seawater. This approach has the advantage that vast quantities of seawater are available near SWRO plants. However, it also has the drawback of a shallow salinity gradient, which would probably make the attainable net power too low to be practically useful.

Sweden is richly endowed with marine-river systems that include many estuaries potentially suitable for SGE extraction. However, to the authors' knowledge, there has been no theoretical evaluation of the potential of this marine energy resource in Sweden. This paper, therefore, presents the first analysis of the potential of SGE as a source of blue energy for Sweden, evaluating the technical potential of blue energy extraction using both natural and anthropogenic resources. The natural resources considered in the analysis were rivers (as a freshwater source) and the Baltic and North seas as saltwater sources. By considering each source's variability in terms of volume, salinity, and temperature, Sweden's most favorable spots for SGE harvesting from natural sources were identified. Even though the SGE estimation is carried out for sources in Sweden, the applicability of the methods paves the way for different countries. In addition, the potential for energy recovery using artificial low- and high-salinity sources was evaluated and the relative merits of different SGE technologies were compared.

2. Methodology

2.1. Theoretical analysis

The Gibbs free energy of mixing for an ideal dilute solution ($\Delta_{mix}H = 0$) can be expressed as:

$$\Delta_{mix}G = \Delta_b G - (\Delta_c G + \Delta_d G) \quad \text{Eq. 1}$$

Here, the subscripts c, d, and b represent the concentrated, the dilute; and the brackish solution obtained by mixing, respectively.

The free energy of mixing can also be related to the entropy of mixing $\Delta_{mix}S$ using Eq. (1):

$$\Delta_{mix}G = -(n_c + n_d)T_b\Delta_{mix}S_b - (-n_cT_c\Delta_{mix}S_c - n_dT_d\Delta_{mix}S_d) \quad \text{Eq. 2}$$

Here, n represents the number of particles (mol), T is the temperature (K), and $\Delta_{mix}S$ is the molar entropy of mixing (J•(mol•K)$^{-1}$), which can be expressed as follows:

$$\Delta_{mix}S = R\sum_i x_i \ln x_i \quad \text{Eq. 3}$$

Here, R is the universal gas constant (8.314 J/(mol•K)) and x_i is the mole fraction of component i. In the case of seawater and freshwater, the main components i are Na^+, Cl^-, and H_2O.

In general, the amount of electrical energy generated by mixing a low salinity fluid (e.g., a river) with one of higher salinity (e.g., seawater) depends on several factors, including the volumes of water involved, the temperature differences between them, the chemical characteristics of the salt, environmental constraints, and the available infrastructure. Although a full assessment of the power of a given salinity gradient would require consideration of all these factors, a theoretical estimate for a river-sea system can be obtained using just four variables [25]: the discharge volume to the sea at the river mouth, the water temperature, the river salinity, and the sea salinity. In this work, the theoretical potential energy produced by a salinity gradient (P_{SG}, in kW) in a river-sea system is estimated using the practical approach proposed by Forgacs [26,27] which can be expressed as:

$$P_{SG} = 2RT \times Q \times \left[C_R \ln\frac{2C_R}{C_R + C_S} + C_S \ln\frac{2C_S}{C_R + C_S}\right] \quad \text{Eq. 4}$$

Here, T is the absolute temperature (K), R is the universal gas constant (8.314 J/(mol·K)), C_S is the sea water salt concentration (mol/m^3), C_R is the river salt concentration (mol/m^3), and Q is the river discharge (m^3/s).

Seawater salinities in units of g/kg were obtained from databases (see section 3.1). For practical reasons, the river salinity (C_R) was taken to be a constant (0.005 mol/L) in all calculations, following a previous report [16]. It is important to note that all parameters used to estimate the theoretical P_{SG} vary over time. This can be accounted for by calculating the P_{SG} using average values. To this end, annual average river discharges (Q), salinities, and sea temperatures at river mouths, were obtained from the data sources described in section 3.1.

This theoretical framework assumes ideal conditions and is applied to all sites with a potential salinity gradient in this work. A more realistic assessment for blue energy exploitation would require careful consideration of technical and environmental constraints, including sustainability, environmental flows and extraction, reliability, and capacity factors [9]. Various research groups have therefore proposed estimators for quantifying SGE resources that account for different variables and constraints [28,29]. These estimators include the theoretical potential, environmental potential, extractable potential, technical potential, and site-specific potential.

Constraints applying to natural sources were not taken into account when performing calculations for anthropogenic sources because effluents are not subject to the same environmental constraints as rivers and would be discharged into receiving water bodies in any event. Therefore, SGE values were calculated based on the total wastewater volumes available at the different sites under consideration. The volumetric mixing ratio of wastewater with seawater/brine was assumed to be 1 unless otherwise stated. When considering the mixing of wastewater with seawater, average regional concentration and temperature values were used, as described in section 3.1. Other assumptions made when performing calculations for wastewater are explained in the sections discussing the properties of the different wastewater streams considered in this work.

2.2. Identifying suitable spots

2.2.1. Energy generation using natural sources

Sweden's unique river system forms an estuarine system along the country's coastline. Estuaries are interesting locations for SGE exploration because they are locations in which river water mixes naturally and continuously with seawater.

A major reason for Swedish interest in SGE is that Sweden has a large freshwater discharge to the sea of about 6000 m^3/s [30]. The country's largest river is the Göta Älv (Göta River), which is 731 km long from source to sea; its average and maximum discharges are 575 m^3/s and 1000 m^3/s, respectively.

The Swedish coastline has a length of around 3218 km and is mainly bordered by the Baltic Sea, which is semi-enclosed. However, the Swedish west coast is connected to the Kattegat and Skagerrak systems, acting as a transition zone between the North Sea and the Baltic Sea. Because water exchange between the Baltic Sea and the North Sea is limited, the average salinity of the southern parts of the Baltic Sea is considerably higher than that of the northern parts.

2.2.2. Energy generation from anthropogenic discharges

To evaluate the SGE potential of wastewater streams from the anthropogenic resources, it is essential to understand their characteristics and the processes by which they are formed. Because the composition and availability of these effluents vary from site to site, their compatibility with SGE technologies must be evaluated individually.

Swedish municipal wastewater undergoes both chemical and biological treatment, and around 97% of the country's urban wastewater passes through a modern treatment plant. Although only 28% of these WWTPs are located in the coastal areas that have the highest densities of residents and industrial sites, 59% of the country's total wastewater (652M m3/year) was processed in the coastal zone (See Fig. 1b). Consequently, the country's total number of treatment plants fell from 478 to 426 between 2000 and 2018 even though the population grew from 8.9 million to 10.2 million in that time.

Stockholm, Gothenburg, and Malmö are Sweden's three largest cities, housing around 25% of the country's population. Although Gothenburg has only around one-third of Stockholm's population, the Gryaab WWTP in Gothenburg has the highest wastewater discharge of any Swedish WWTP (13986 m^3/h) because it is the only plant serving a very large catchment area. Coastal WWTPs generally discharge their wastewater effluent to the sea or a river estuary (as in the case of the Gryaab plant). As such, they could be excellent locations for harvesting SGE released by mixing wastewater with seawater.

In general the salt concentration of the wastewater effluent is expected to be comparable to that of fresh/river water. Because conductivity is not generally used as a primary parameter for evaluating wastewater quality, it is only rarely specified in reports on WWTP performance. However, in 2008, Svenskt Vatten Utveckling (the research division of the Swedish water organization) conducted a comprehensive investigation at the Käppalaverket, Himmerfjärdsverket, Duvbacken and Lotsbroverket WWTPs in Sweden. Among other things, this investigation included measurements of the conductivity of the influents and effluents of WWTP processes, which can be used to estimate the salinity of the effluent wastewater. It was found that the conductivity of the effluent from biological nitrogen separation processes was 21–28% lower than the inflow conductivity at all plants other than Duvbacken. Across all of the studied plants, the conductivity of the discharged wastewater varied between 0.62 and 0.86 mS/cm [32] and was thus below that of a 0.01 M NaCl solution (1.185 mS/cm) [33]. Similar results were obtained in other studies. For example, Kingsbury et al. (2017) determined the conductivity of wastewater treatment plant effluent samples to be 0.44 mS/cm [34].

The temperature of household wastewater is raised by various human activities, which increases its Gibbs free energy of mixing (see eq. (4)). The relative warmth of wastewater was demonstrated by Hao et al., who found that the wastewater temperature was stable at around 17 °C all year round and was thus well above the atmospheric temperature in winter but was 4–5 °C below the atmospheric temperature between June and September [35].

Sweden is rich in natural freshwater sources. However, the islands of Gotland and Öland suffer from seasonal water stress, particularly during summertime because many people have summer houses on these islands and the influx of holidaymakers increases the demand for fresh water. In the last decade, four brackish water reverse osmosis desalination plants have been constructed to address this problem. The Herrvik and Kvarnåkershamn RO plants in Gotland were designed to process 20 and 312 m^3/h seawater, respectively, while the Sandvik and Mörbylånga RO plants in Öland can treat 125 and 17 m^3/h of water. The brine rejected from these RO plants could be utilized for SGP extraction by mixing it with seawater, potentially offsetting the energy consumption of the RO plants. Better still, the brine could be mixed with WWTP effluent, which would release more energy because the salinity gradient would be steeper.

3. Results and discussion

3.1. SGE from natural sources

3.1.1. Salinity, the temperature of the Baltic and the North Sea, and the distribution of river flow rates

To assess the national potential for SGE generation, Sweden's coast was divided into 11 zones that collectively have a coastline of 1600 km - the Gulf of Bothnia, Norra Kvarken, Bothnia Sea, Åland Sea, Gulf of Finland, North Gotland Sea, Västra Gotlandshavet, Östra Gotlandshavet, Bornholm Sea, Hanö Bay, Arkona Sea, Sother Sound, Öresund, Kattegatt, and Skagerrak (see Fig. 4). Data on the surface salinity of the seawater in each zone was obtained from the database of the Swedish Meteorological and Hydrological Institute (SMHI) via the Svenskt HavsARKiv website (SHARKweb: https://sharkweb.smhi.se/hamta-data/). The colored regions in Fig. 2 indicate the sampling zones where the seawater temperature and concentration were measured along the Swedish coast.

The SGE potential in each zone is affected by the salinity and temperature of the seawater as well as the discharge from rivers. Baltic Sea is a closed basin having a poor mixing with ocean, high river influx and low evaporation resulting in low salinity. Moreover, total dissolved solids (TDS) transported by rivers into the Baltic Sea is lower than North Sea. For example, TDS of Lule and Göta rivers were 20.1 and 55.7 ppm, respectively, in 2022 (https://miljodata.slu.se/MVM/Search).

Because the salinity of the Gulf of Bothnia is comparatively low and it experiences freezing temperatures in winter, parts of the sea in this zone freeze, forming a 0.5 m thick ice sheet. Conversely, the southern and southwestern coastal zones (Öresund, Kattegatt, and Skagerrak) have a high salinity of 20–34 g/kg, which is similar to that of the Atlantic Ocean (See Fig. 2). The surface temperature of the sea around Sweden varies widely throughout the year, as shown by the standard deviations presented in Fig. 2 and the temperature variation data presented in Fig. 3. Table 1 shows that the sea water temperature in the studied Swedish coastal areas varies between −0.4 °C and 24 °C, with an annual average

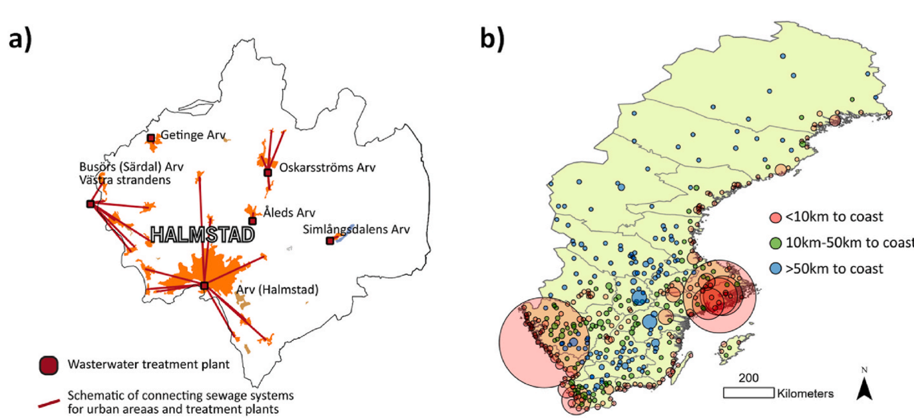

Fig. 1. a) Centralization of wastewater treatment in Halmstad [31] and **b)** Wastewater treatment plants in Sweden. The size of the symbols is proportional to the volume of wastewater discharged from the plant.

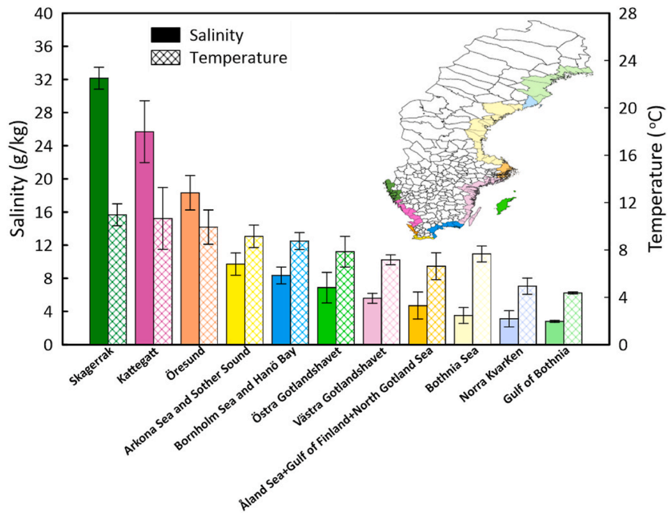

Fig. 2. Geographical variation in seawater salinity and temperature along the Swedish Baltic and North Sea coastlines within a distance of 1.85 km from the coast (Source: SHARKweb).

of about 10 °C.

Fig. 4a shows the rivers whose outflows were measured during the 2014 Swedish national monitoring program. Together, these rivers collect 82% of Sweden's surface runoff; the boundaries of their watersheds are shown in the below figure.

To assess the SGE resources that these rivers provide, their discharges into the sea were expressed in terms of their average flow values (m^3/s) and sorted (see Fig. 4b). This figure contains data for a total of 87 rivers. To maximize the amount of river flow data available for analysis, data were obtained from the Swedish Water Archive (SVAR) and processed using the S-HYPE hydrological model made available by SMHI Vattenwebb. This model is integrated with a dynamic map that enables the visualization and downloading of data from models of watercourses and coastal areas in Sweden (https://vattenweb.smhi.se/station/).

3.1.2. SGE mapping of natural sources

Fig. 5a–b shows the theoretical power available from the salinity gradients at river mouths in different locations around the country. The locations with the highest theoretical power are generally found in the southern part of the country, where the Baltic Sea meets the North Sea. This is presumably due to the higher salinity of the sea in this region compared to the coastal zones in the northeastern part of the country.

The theoretical SGP potential shown in these figures represents the maximum useable power (P_{SG}) that could be extracted from the salinity gradient of a given river mouth which is 2610.6 MW (2.6 GW). However, the need to respect technical and environmental constraints in Sweden means that only a portion of this theoretical potential can be extracted. The technical SGP potential (TP_{SG}) is the maximum power that can be extracted without violating these constraints. Table S1 presents the locations and estimated TP_{SG} values for the 87 Swedish river mouths with the highest estimated TP_{SG} values.

3.2. SGE from anthropogenic resources

3.2.1. Industrial wastewater/seawater

Table 2 shows the amount of water extracted, used, and discharged by Sweden's five most water-intensive industrial sectors, which collectively account for 95% and 91% of the country's industrial seawater and river water extraction, respectively. The geographical distribution of sites associated with these sectors is shown in Fig. 6a, which demonstrates that industrial activity is concentrated in southern Sweden. The water consumption of these sectors decreases in the following order:

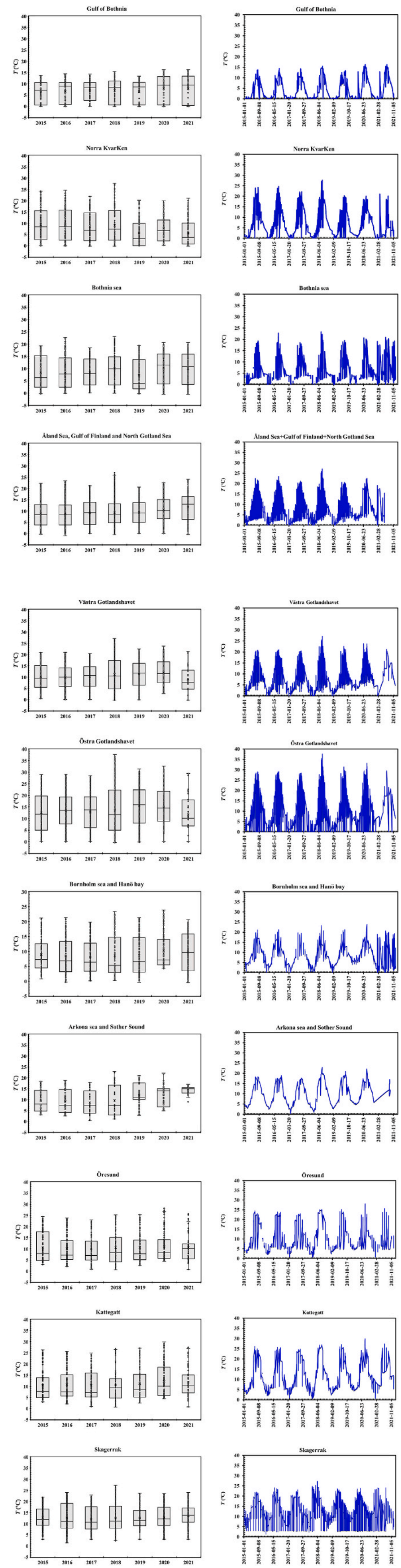

Fig. 3. Monthly temperature variations along the Swedish coastline.

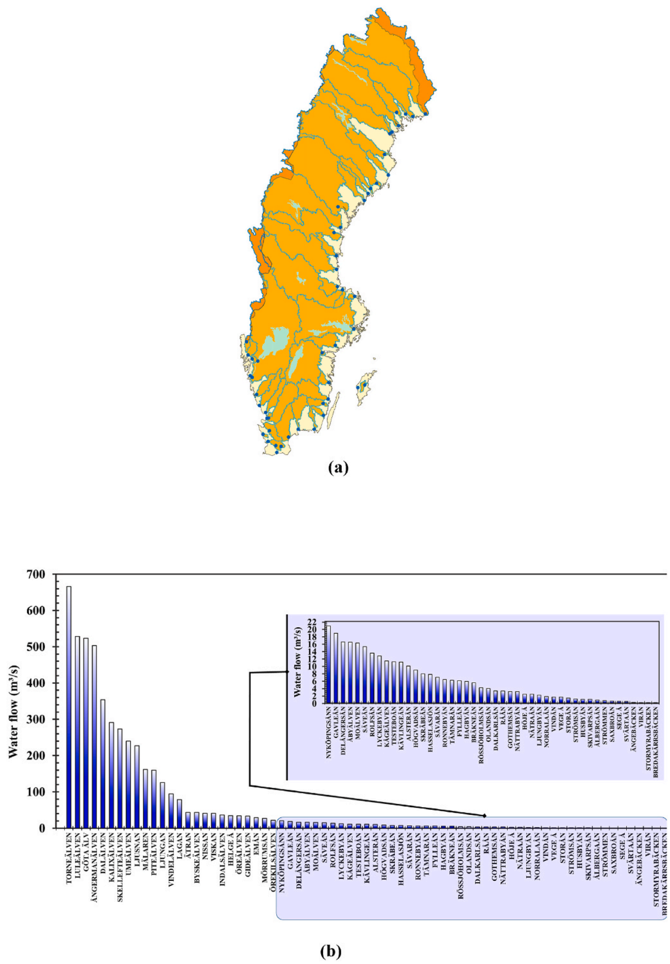

Fig. 4. a) Swedish river outlets (blue dots) and the catchment areas of the corresponding river basins (orange), some of which extend beyond Sweden's borders into Norway and Finland (shown in dark orange) [30]; **b)** Average flow rates of Swedish rivers discharging into the sea (source: https://vattenweb.smhi.se/station/).

Table 1
Seawater temperatures in Swedish coastal areas.

	Minimum (monthly average)	Maximum (monthly average)	Yearly average
Gulf of Bothnia	0.21 (March)	21.4 (August)	6.23
Norra Kvarken	0.14 (March)	17.0 (August)	7.05
Bothnia Sea	1.02 (March)	20.7 (August)	10.94
Åland, Gulf of Finland, and North Gotland	1.08 (March)	19.76 (August)	9.45
Västra Gotlandshavet	0.00 (March)	20.88 (August)	10.23
Östra Gotlandshavet	3.67 (March)	18.30 (August)	11.21
Bornholm Sea and Hanö Bay	−0.4 (March)	23.9 (August)	12.50
Arkona Sea and Sother Sound	0.27 (March)	22.9 (August)	13.06
Öresund	0.63 (March)	23.17 (August)	14.19
Kattegatt	0.63 (March)	23.17 (August)	15.22
Skagerrak	0.53 (March)	20.41 (August)	15.67

pulp and paper > chemical and pharmaceutical > steel and metal > electricity, gas, and heating > mineral extraction. The pulp and paper industry stands out because its entire water demand must be met using fresh water sources, whereas other industries can use seawater to at least some extent.

Irrespective of whether the extracted water is used for cooling or as process water, the European Union's directives on industrial emissions stipulate that it must be treated before being discharged to a receiving body [37]. Although a small quantity of discharge may be sent to the municipal sewage system, the majority is treated at wastewater treatment plants owned by the industry. In 2020, 913 and 684 M m^3 of water were discharged to the sea and freshwater sources by the five industries listed in Table 2. Some of these effluents, if treated as wastewater, could potentially be used as SGP sources, providing a sufficient difference in salinity between the receiving water body and the wastewater at the discharge point. However, careful assessments are needed to accurately estimate the SGP potential of industrial effluent because its water quality is process-dependent and site-specific.

Unlike process water, the concentration and composition of cooling water are unchanged by industrial use. The pulp and paper industry extracts 843 M m^3 of fresh water, of which 32% is used as cooling water, and 390 M m^3 is ultimately discharged to seawater. Assuming that 272 M m^3 of fresh wastewater with a NaCl concentration of 0.01 M and a temperature of 20 °C is mixed with an equal volume of seawater whose salinity and temperature are equal to the average values for Sweden (11.4 g/kg and 10 °C), 5.28 MW of power could be harvested. The potential SGE from combining these two solutions could be increased (converging to a maximum of around 8.35 MW) by increasing the volumetric proportion of seawater in the mixing solution (See Fig. 6b), which should be feasible since seawater is available in effectively unlimited quantities.

However, if this approach is applied to other kinds of cooling water, the potential for SGP extraction from industrial wastewater could be seriously overestimated. For example, seawater is preferred as cooling water in the steel industry as long as it does not come into direct contact with the steel products, and this cooling seawater is returned to its original source (i.e., the sea) at a slightly elevated temperature after use [38]. Because the composition and salinity of the cooling water is unchanged, the Gibbs free energy of its mixing with seawater results exclusively from the temperature difference between the two water sources; the concentration difference can be assumed to be negligible. Based on the volumes of extracted and discharged seawater listed in Table 2, one can reasonably conclude that seawater used for cooling is returned to its original source in all industries other than pulp and paper. Consequently, the available mixing energy is insignificant for these industries, meaning that their cooling wastewater is unsuitable for use in SGP harvesting.

3.2.2. Municipal wastewater/seawater

Sweden has an immense potential for SGE generation from mixing wastewater effluents and seawater at WWTPs near the coast, of which there are around 180. The volume of effluent discharged from WWTPs depends strongly on the nearby human activity and varies between 164 and 335,674 m^3/day. The total volume released to seawater from coastal plants is approximately 1.9 M m^3/day [40,40].

Accurate estimation of the theoretical SGP that can be extracted from the mixing of wastewater and seawater requires considering the geographical variation in the temperature and salinity of the seawater. Therefore, the theoretical SGP for WWTP effluents was evaluated by applying the approach previously used to calculate the theoretical SGP for natural resources (see section 3.1 for details). The theoretical SGP for each WWTP was then obtained by assuming that the temperature and concentration of the WWTP effluents were 15 °C and 0.01 M NaCl.

The theoretical SGP for every WWTP in Sweden within 10 km of the coast is shown in Fig. 7. Due to the low salinity and temperature of the Baltic Sea, the salinity gradients of WWTPs discharging into the Baltic are much lower than those of WWTPs discharging into the North Sea. Therefore, for a given plant discharge volume, the extractable energy is higher on Sweden's western coast than on the eastern coast. The total mixing energy extractable from all WWTP effluents was estimated to be 11.8 MW, of which Gryaab AB Ryaverket (Gothenburg) contributed 45.8%, Sjölunda Avloppsreningsverk (Malmö) contributed 9.3%,

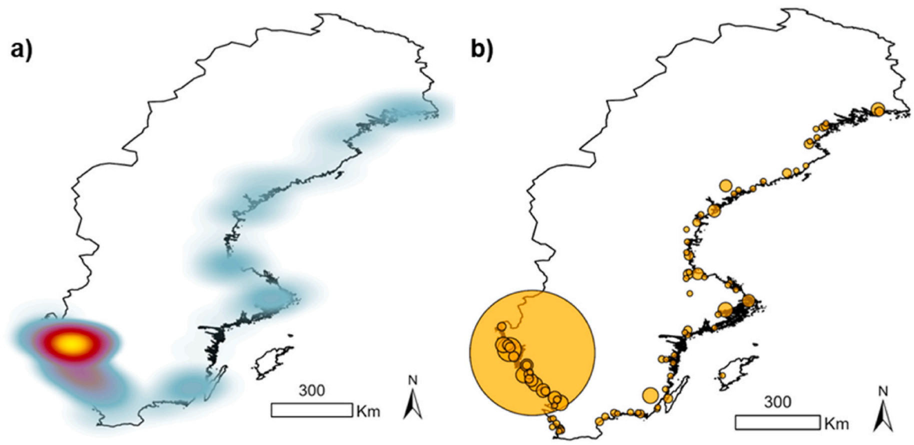

Fig. 5. Theoretical estimates of the power of salinity gradients in Sweden based on natural resources at 87 river mouths. **a)** Heat map; **b)** Proportional symbol map (the largest and smallest circles indicate SGPs of 896 MW and 8.62 kW, respectively (See Table S1 for more information).

Table 2
Water abstraction, use, and discharge volumes of the five industrial sectors with the highest water consumption in Sweden [36].

Industry	Water abstraction (M m^3)		Water use (M m^3)		Water discharge (M m^3)		
	Sea	Fresh	Cooling	Process	Sea	Fresh	Sewer
Pulp and paper	0	842.9	272.1	510.4	389.9	321.8	6.8
Chemical pharmaceutical	313.3	158.0	440.0	30.1	332.9	65.0	9.6
Steel and metal	158.4	202.1	248.4	51.6	142.2	181.2	22.9
Electricity, gas, and heating	40.6	145.7	16.8	73.5	42.4	77.3	8.9
Mineral extraction	5.1	69.7	3.4	60.5	5.4	38.7	7.5

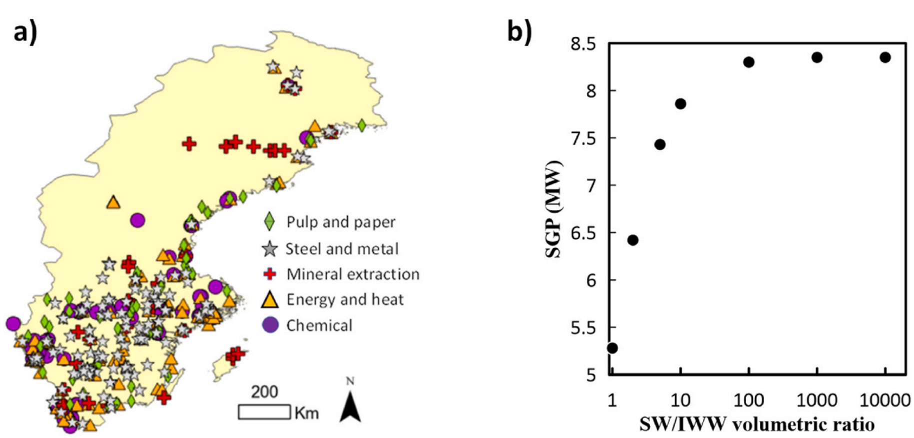

Fig. 6. a) Locations of industrial facilities within the five sectors with the highest water consumption in Sweden [39] and **b)** Salinity gradient power extractable by mixing cooling water effluent from the pulp and paper industry with varying proportions of seawater.

Henriksdals Reningsverk (Stockholm) contributed 5.4%, Öresundsverket AVR (Malmö) contributed 4.9%, and Västra Strandens arv (Halmstad) contributed 3.9%.

3.2.3. SGE from mixing SWRO brine with seawater or municipal wastewater

The RO unit operated with 0.50 recovery factor produces a waste that is roughly two times concentrated compared to seawater assuming 99% rejection. In Sweden, SWRO units are in islands. Water chemistry analysis of seawater samples resulted in conductivity of 934 and 900 mS/cm in Gotland and Öland, respectively (SHARKweb: https://sharkweb.smhi.se/hamta-data/). Using eq. S1 (from supporting info), the seawater TDS values are estimated as 5980 and 5760 ppm whereas SWRO brine TDS is expected to be double, roughly.

Brine solutions from RO plants are valuable feed solutions for SGP despite generally being seen as environmentally harmful waste due to their high salinity. Their adverse environmental impact can be alleviated by mixing them with more dilute solutions such as seawater or WWTP effluent. The latter option is preferable in terms of energy harvesting because it generates a steeper salinity gradient and increases the dilution factor of the brine. The wastewater discharge volumes from the WWTPs on both islands (323 m^3/h for Gotland and 153 m^3/h for Öland) are comparable to the brine effluent volumes from their RO plants. Based on these discharge volumes as well as the local temperature and seawater salinity, the available theoretical mixing power was estimated to be 63 and 18 kW in Gotland and Öland, respectively. These values are roughly twice those that would be achieved if the wastewater was mixed with seawater instead of RO brine (Fig. 8).

Although the extractable power was significantly lower than the values achievable on the Swedish mainland, recovering the Gibbs free

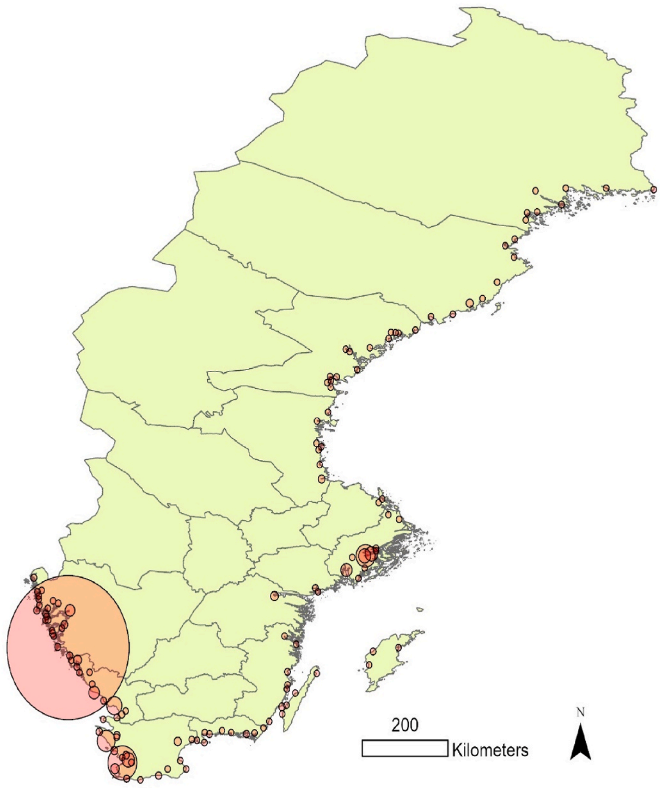

Fig. 7. SGP for WWTPs within 10 km of the coast in Sweden. The sizes of the circles are proportional to the SGP extractable from the mixing of effluent and seawater at each WWTP; the largest and smallest circles indicate SGPs of 5401 kW and 0.2 kW, respectively (See Table S2 for more information).

energy of mixing could help to reduce the islands' energy requirements. The recovered energy could then be used at wastewater treatment plants or seawater RO plants to reduce the need for imported energy.

3.3. Hot spots for SGE in Sweden

3.3.1. Natural sources

The potential availability of SGE was highest along Sweden's southern and southwestern sea coasts, where the salinity of the seawater is highest (Öresund, Kattegatt, and Skagerrak). Particularly high potentials were identified in around Gothenburg (~896 MW). It should be noted that the analysis has an important limitation arising from the reliance on estimates that can only be considered rough approximations due to differences in sampling time periods between the datasets that were used, the neglect of temporal fluctuations in discharge, and the simplified theoretical approach. Nevertheless, it provides useful preliminary guidance for identifying regions with potentially exploitable SGE.

3.3.2. Anthropogenic sources

When considering anthropogenic water sources as potential feed solutions for SGP generation, it is important to note that the amount of energy extracted depends heavily on the volumes of the solutions being mixed, their concentration differences, and their temperatures. Considering these criteria, one of the most promising hot spots for SGE is Gryaab AB Ryaverket WWTP in Gothenburg. This WWTP has the advantage of being located on Sweden's southwest coast, where the salinity of the seawater (34 g/kg) that would be used in the high concentration compartment of a hypothetical SGE facility is roughly equal to the standard ocean salinity of 35 g/kg and is substantially higher than the salinity on Sweden's east coast (2–10 g/kg). Moreover, the sea is warmer on the southwestern coast, which further increases the SGE potential. A final advantage of the Gryaab plant is that it is currently Sweden's largest WWTP, with a treated water volume of 13986 m^3/h. It processes influent water from a 240 km^2 catchment area using advanced treatment technologies, and its discharge can be regarded as fresh water [41]. Moreover, the Gryaab WWTP operates a biological treatment process that raises the temperature of the effluent due to bacterial activity. Its wastewater effluent is an excellent candidate for use in the low concentration compartment of an SGE plant.

In 2021, the annual energy consumption of the Gryaab WWTP was reported to be ~40240 MWh, excluding energy supplied via the local district heating system [42]. Mixing its 3.9 m^3/s treated wastewater output with an equivalent or greater volume of seawater would release at least 19443 MWh of energy, corresponding to 49.5% of the WWTP's total energy consumption.

The second most promising SGP location identified in the analysis was the island of Gotland. While there are other WWTPs with high discharge volumes that could recover significant quantities of energy through mixing, Gotland has the advantage of easy access to RO brine, which allows for a steeper salinity gradient than is possible with seawater. This increases the amount of energy extracted per unit volume of mixed solution. Moreover, because SGP technologies involve diluting the brine, they have the potential to reduce the adverse environmental impact of highly concentrated RO waste. Integrating RO and SGP technologies thus enable waste re-utilization that increases the efficiency and sustainability of desalination plants and could help overcome the concerns of stakeholders and locals [43].

Although the use of RO brine as a feed solution for SGP units is attractive, Li et al. showed that a transposed process in which the

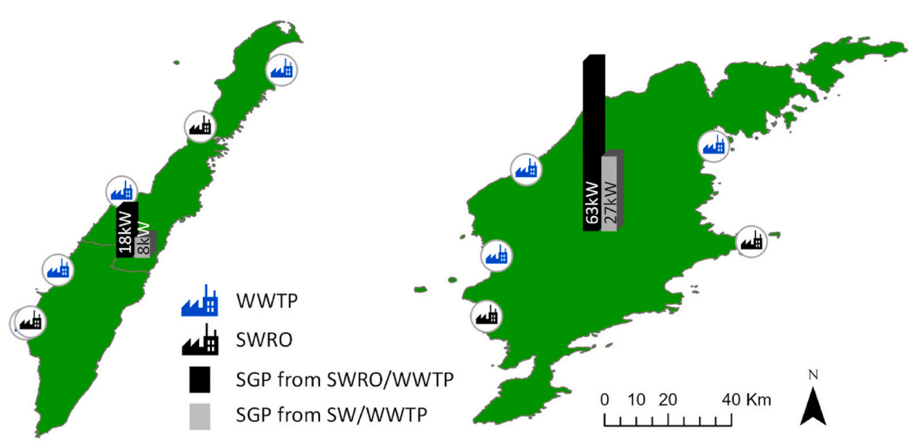

Fig. 8. Salinity gradient potential of RO plants and WWTPs in Öland (left) and Gotland (right).

effluent from an SGP unit serves as a feed solution for an RO plant can increase the overall efficiency of an integrated system combining RO and SGP facilities because it reduces the transmembrane pressure required to overcome the osmotic pressure and eliminates the need for pre-treatment to remove sparingly soluble salts that cause severe fouling [44]. Applying such an SGP-RO approach in Gotland could significantly offset the energy consumption of the island's RO plants and WWTPs, although it would not transform them into net energy generators.

3.4. Implementation of SGE in Sweden

Despite the early implementation of the SGE concept in the 1950s and the development of the first laboratory prototypes in the 1970s, no SGE pilot plants were constructed until 2009 [45], when Statkraft built a 10 kW capacity SGE pilot plant in Tofte, Norway. This plant was operated until 2012 [46], and its levelized cost of energy (LCOE) was reported to be 120 EUR/MWh, corresponding to roughly 0.144 USD/kWh (1 EUR = 1.2 USD) for a 25 MW power plant. However, Statkraft terminated the project and suspended PRO development in 2013 due to a lack of cost-effective membranes for commercial assemblies [47]. Kyowakiden Industry Co., Ltd. conducted the world's first demonstration test of PRO using brine from a seawater desalination plant [48].

The first RED pilot plant was operated at the Afsluitdijk closure dam in the Netherlands between 2012 and 2016. This plant's capacity was 50 kW, and it was developed as a partnership project by REDstack (the developer), FUJIFILM (a membrane manufacturer), and the Wetsus research institute [17]. Another RED pilot project was launched in 2014 in Tripani, Italy, to investigate energy recovery without relying on freshwater; the feed solutions were concentrated brine from a salt extraction facility and brackish seawater. The 1 kW capacity pilot plant generated 330 W of electricity [47] and is still being operated for testing purposes by the University of Palermo and Wetsus. The most notable of these newer projects are the RED plants built by REAPower and the Blue Energy project. REAPower is a Dutch consortium that has constructed a RED plant at the Afsluitdijk dam in the Netherlands, [49]. The Blue Energy project is a European FP7 research project examining a RED pilot plant with an installed capacity of 1 kW located in the Ettore and Infersa salt pans in Marsala, Italy. The feed solutions for this plant are saturated brine and brackish water [50]. Table 3 provides an overview of previous pilot-scale for SGE.

Most of the river mouths with promising theoretical energy values identified in this work are located on Sweden's southern and southwestern sea coasts (Öresund, Kattegatt, and Skagerrak), where the salinity of the seawater is comparable to that of the Atlantic ocean (i.e., between 20 and 34 g/kg; See Fig. 2). These locations may however not achieve high SGE values in practice because the freshwater discharge volumes of most southern rivers are substantially lower than those of rivers in the north of the country. It is possible that this issue could be overcome by constructing several small and medium-sized SGE plants in regions with high energy densities.

Two locations where SGP plants using artificial sources could be constructed were identified as Gryaab AB Ryaverket WWTP in Gothenburg and the island of Gotland. Construction of plants at these sites should be comparatively straightforward because of the nearby infrastructure for WWTPs and RO plants. Another advantage is that their feed solutions are the treated effluents of other plants, eliminating the need for pretreatment steps and the related costs. For example, the SWRO plants in Öland and Gotland have pre-filtration and ultrafiltration units, and the effluents from WWTPs can also be considered to be treated:. It should be noted that the given values are likely to be improved since Henriksdals plant is being upgraded and modernized with an MBR, which is expected to be the biggest when it is completed. However, wastewater treatment alone is not always sufficient for fouling-free operation; previous studies had shown that ultrafiltration and low-pressure RO pretreatments implemented to avoid severe fouling resulted in negative net power when PRO was used to extract energy from the mixing of brine and wastewater [55]. Moreover, technically, RED can produce greater energy from solutions whose concentrations are similar to or lower than those of ocean water [4]. RED may therefore be more suitable than PRO for generating SGP by mixing RO brine and WWTP effluent in Öland and Gotland.

The proposed SGP plant in Gothenburg, which would mix seawater with wastewater, presents similar infrastructural concerns to an RO plant because it would require the construction of a seawater intake. The visual impact of such a plant should be low due to the modularity and compactness of the membrane units. Moreover, its only noise output should be some emission from high-pressure PRO pumps, which can be easily suppressed with appropriate insulation [56]. When selecting an SGP process for this site, the feed solutions' salinity gradient and the foulant content both favor RED. In particular, using a natural solution (i.e., seawater) in the high-concentration compartment increases the likelihood of fouling, which greatly reduces the efficiency of PRO membranes. Given the high technical power potential of seawater/freshwater mixing, electrochemical conversion of the Gibbs free energy of mixing by RED appears to be the most attractive option at this site.

In addition, according to market reports and data from the energy regulatory authorities, the average price of electricity in Sweden is about 0,323 €/kWh (Source: https://www.scb.se/). On the other hand, the levelized cost of electricity for RED and PRO, taking into account pumping and hydraulic equipment and filtration cost costs, operating and maintenance costs, and expected energy production of 200 kW for RED, is around 0.079 €/kWh [57] and generally range from 0.056 to 6.33 €/kWh [1,57–60]. In contrast, the range of estimates for PRO was 0.056–1.95 €/kWh [1,15,61–63]. The lack of availability of high performance, stable and low cost membrane materials are the main barriers to commercialization.

However, considering future developments in membrane performance and price, the LCOE of producing electricity from river and seawater using RED or PRO is competitive with other renewable energy sources.

4. Technologies for harvesting blue energy

To date, RED and PRO are the two most prevalent SGE technologies and present a series of trade-offs, such as the energy efficiency of RED when operating with seawater and river sources, in contrast to PRO, which is more energetically efficient with concentrated brines [64]. Some of the previous pilot-scale projects faced issues on excessive energy consumption by pretreatment and feed pumping that overcame the energy production [1]. Alvarez-Silva et al. (2019) calculated that using

Table 3
Pilot-scale projects for harvesting salinity gradient power.

Project/City (Country)	LC	HC	Process	Target	Ref.
Statkraft/Tofte (Norway)	River water	Seawater	PRO	10 kW	[46]
REDstack/Afsluitdijk (The Netherlands)	River water	Seawater	RED	50 kW	[17]
Saltpower/Sønderborg (Denmark)	Groundwater	Geothermal water	PRO	20 kW	[51]
Reapower/Trapani (Italy)	Brackish water	Saltwork brine	RED	1 kW	[47]
Mega-ton/Fukuoka (Japan)	WWTP effluent	SWRO brine	PRO	100 kW	[52]
Global-MVP/Busan (South Korea)	WWTP effluent	SWRO-MD brine	PRO	25% reduction at SWRO energy consumption	[53]
PUB/(Singapore)	–	NEWater brine	PRO	Energy reduction of SW desalination	[54]

membrane-based water pretreatment can reach 10% of theoretical SGP [65]. Also, power consumption by pump reduces net power density significantly; Vermaas et al. (2011) measured gross power density and net power density as 2.2 and 1.2 W/m2 at their maximum for changing intermembrane distance and flow rate [10,65].

It is noteworthy that while both RED and PRO are membrane-based processes, the former is based on ion transport through charge-selective IEMs, while the latter is driven by water permeation through salt-rejecting membranes. Various authors studied the effect of impurities and possible pretreatment strategies. Ju et al. (2022) concluded that among cartridge filter (CF), microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), activated filter media (AFM), and granular activated carbon (GAC), NF pretreatment was the most effective process increasing RED power density by filtering out total organic carbon and mainly divalent ions [66]. Applying the same pretreatment methods on bench scale and pilot scale PRO resulted similarly [67]. However, it should be noted the spent energy on pretreatment was not considered on the produced power density.

The successful application of PRO and RED requires addressing the existing challenges regarding fouling, ions crossover, and membrane trade-off of permeability and selectivity. Considering performance determining properties, PRO membranes require higher water flux while RED membranes must be more conductive and counter-ion selective to increase generated power.

Researchers have developed different PRO membrane mitigation strategies to overcome these limits to reduce the fouling problem [68]. Another critical factor that detrimentally reduces the driving force for water flux in PRO is the internal concentration polarization phenomenon [69]. According to numerous studies, an improved morphology design of the membrane support layer contributes to overcoming part of this mass transport limitation [70].

At the heart of RED's process is the RED stack, which contains the ion exchange membranes. Because of the low ionic conductivity and concentration polarization which significantly affect the power generation performance of the process during operation, several measures to overcome these detrimental effects have been taken to reduce them to some extent by minimizing the spacing between the membranes [10].

The main challenge for the commercialization of RED is the high cost of ion exchange membranes; however, the global increase in energy demand and scientific advances could reduce these costs. With the introduction of new materials, improvement of fabrication methods, and increased production of RED membranes over the last decade, significant cost reductions have been achieved, leading to the increased use and implementation of RED. Therefore, several key research topics have been addressed to overcome the existing RED technology constraints by conducting much work, such as modeling and simulation [71], stack design [72], membrane development [73], performance optimization and hybrid applications [74], the adaptation of mixed matrix nanofibrous membranes [75], the use of profiled IEMs prepared by micromolding [76] and most recently by employing charged nanochannels IEMs aiming to increase the energy extracted from RED [77]. All these efforts indicate the great potential for harvesting SGE by RED installations.

Finally, it is worth noting that, as stated in the European Commission's report, the costs of SGE technology remain high, the reliability and capacity of the majority of existing technologies in marine environments are not yet fully recognized, and the electricity generated is expensive, limiting the use and industrialization of this technology. However, the European Commission states that these costs and limitations could be reduced by improving and developing SGE technologies [78].

5. Conclusions and perspectives

Salinity gradient power could facilitate the transition away from fossil fuels in Sweden. The present assessment indicated that the potential for natural energy extraction was greatest at river mouths on Sweden's west coast, particularly around Malmö, Lund, and Gothenburg. Sites with a potential power resource of 896 MW were identified in these regions. Across the country, the total theoretical SGP potential was estimated to be approximately 2610.64 MW from 87 estuaries. It has been found that the theoretical extractable energy potential in Sweden is equivalent to 13% of the total electricity consumption, 6.2% of the total final energy consumption by energy commodity, 32.7 times the supply of primary solar power, 1.1 times the supply of primary wind power, 35.2% of the primary supply hydropower, 2.5% of the supply primary nuclear power, and 2.5 times the imported electricity. These percentages were calculated based on the report published by the Swedish Energy Agency regarding energy in Sweden 2021. Additionally, the total theoretical SGP potential would be sufficient to supply electricity to the 10229946 people in Sweden, providing an average electricity consumption of 255.2 W per person. Furthermore, Sweden's total theoretical SGP potential is twice higher compared to other countries, such as Norway, and over 51% of that is calculated for Canada.

SGP generation by mixing industrial, municipal, and SWRO wastewater could provide a further 17 MW of power. While this value is 2 orders of magnitude lower than the SGP potential of natural sources, anthropogenic sources have the advantage of enabling waste utilization and process intensification, leading to sustainable strengthening of the water-energy nexus.

In practice, environmental, economic, and social constraints mean that only a portion of the theoretical energy estimated in this work could be extracted. Nevertheless, the analysis presented herein shows that Sweden has an opportunity to exploit solution mixing energy to facilitate sustainable development. It is hoped that the present study will serve as a starting point for more detailed energy assessments using more sophisticated estimation methods and higher-resolution input data.

Moreover, considering imperfect efficiencies of RED ($\eta = 18.1\%$) and PRO ($\eta = 56.1\%$) [1], the extracted SGP is expected to be lower [64].

CRediT authorship contribution statement

Mohamed Essalhi: Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing, review & editing. **Ahmet Halil Avci:** Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, review & editing. **Frank Lipnizki:** Conceptualization, Funding acquisition, Investigation, Supervision, Methodology, Resources, Validation, Writing – review & editing, review & editing. **Naser Tavajohi:** Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Validation, Project administration, Supervision, Writing – review & editing, review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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