Salinity Gradient Energy is Not a Competitive Technology for Renewable Energy

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Introduction

Salinity gradient energy (SGE) refers to the energy released when two solutions of different salinities mix.[1-3] For example, the SGE released when freshwater in a river enters the ocean is estimated to be equivalent to installing, at the river mouth, a hydraulic dam of ~280 m in height.[4] Such an equivalence makes SGE appear to be attractive as a new type of sustainable energy, especially considering that even the tallest dams in the world have similar heights as these virtual "SGE dams". The theoretical global potential of SGE was evaluated to be more than 15,000 TWh/year, whereas the practical potential was estimated to 625 TWh/year.[5]

The idea of using engineered system to extract SGE was proposed more than half a century ago,[6,7] and has gained significant momentum in the past 15 years. Academic research in SGE has focused mostly on material development and to a lesser extent on process development, optimization, and analysis. A small SGE-based power plant prototype (2-4 kW) was operated by Startkraft, a Norwegian power company, from 2009 to 2014, proving SGE's technical feasibility at the pilot scale.[8] The Startkraft experiment was terminated due to the challenge of developing the technology to be economically competitive "within the foreseeable future".[9]

Some argue that SGE was not sufficiently competitive because it was in its early stage of development, and that with better material and system design it could eventually become a viable source of sustainable energy. We believe that SGE has intrinsic limitations that make it very challenging, if not impossible, to become economically competitive against alternative forms of sustainable energy.[3] Such limitations are fundamental and cannot be addressed by engineering better materials or systems. In this Commentary, we will present the rationales to show why SGE is not a viable technology for sustainable energy generation. We mainly focus on the science and engineering aspects of SGE limitations but will also briefly discuss economics which eventually dictates the technology adoption or its lack thereof.

Technologies

Three major categories of engineered systems have been developed for extracting SGE (**Fig. 1**): pressure retarded osmosis (PRO), reverse electrodialysis (RED) or its variants, and capacitive mixing (CapMix). These three processes strongly relate to their counterparts in desalination, with PRO corresponding to reverse osmosis (RO), RED to electrodialysis (ED), and CapMix to capacitive deionization (CDI). After all, SGE is a controlled mixing process whereas desalination is essentially a separation (i.e., de-mixing) process. The three categories of engineered systems are described briefly below. More detailed description of these processes can be found elsewhere.

Energy is extracted in PRO by the expansion (or increase in flow rate) of a pressurized, high salinity draw solution to drive a turbine (**Fig. 1A**).[10,11] This expansion is caused by spontaneous water transport, through a salt-rejecting membrane, as driven by trans-membrane osmotic pressure difference. In RED, the concentration gradient-driven diffusion of ions through ion exchange membranes (IEM) generates an electric current, thereby producing electric power. In conventional RED, both cation and anion exchange membranes are used (**Fig. 1B**), and the system operates in a way opposite to electrodialysis (hence "reverse electrodialysis).[12-14] The more recently developed RED variant, named nanopore power generation (NPG), can generate current with only one type of IEM (**Fig. 1C**).[15,16]

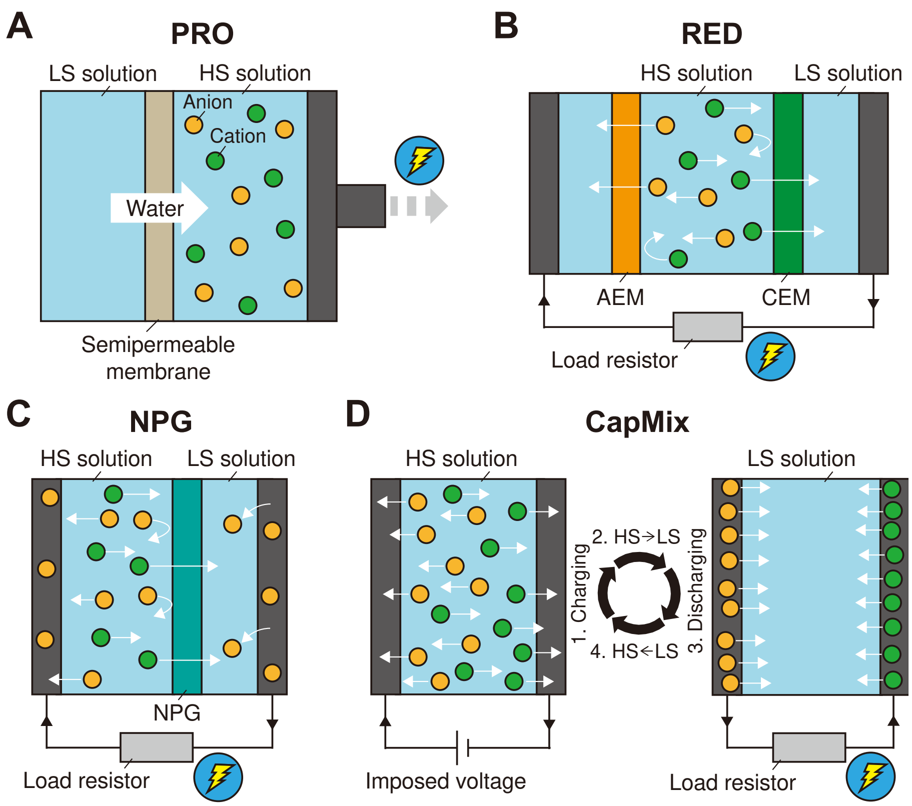
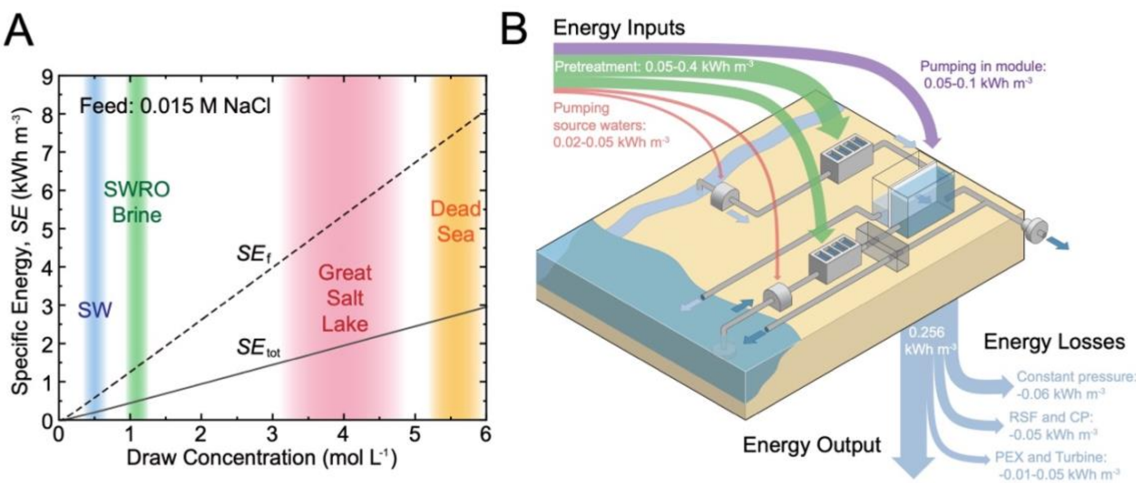


Figure 1. Illustration of four processes for SGE extraction. (A) pressure retarded osmosis (PRO), which relies on transmembrane water transport; (B) reverse electrodialysis (RED); (C) nanopore power generation (NPG); and (D) Capacitive mixing (CapMix). The three electrochemical SGE technologies (RED, NPG, CapMix) rely on ion transport through cation exchange membranes (CEM), anion exchange membranes (AEM), nanopore membranes (typically cation exchange) and/or ion transport into ion-storage electrodes. High salinity and low salinity solutions are denoted as HS and LS solutions, respectively.

CapMix leverages the principle that the equilibrium potential of an electrode (e.g., activated carbon, ion intercalation materials) depends on the ion concentration of the solution the electrode is in contact with (**Fig. 1D**).[17,18] By alternately exposing the electrodes to a high salinity solution (charging stage) and then a low salinity solution (discharge stage), net energy can be extracted in CapMix because the energy generated in the discharge step exceeds the energy consumed in the charging step. CapMix is less extensively investigated as compared to PRO and RED.

Key Technical Performance Metrics

Although each SGE technology may have its process-specific performance metrics, three general metrics are universally important due to their impacts on the process economics: (volumetric) energy density, energy conversion efficiency (or thermodynamic efficiency), and power density. The energy density is defined as the energy extracted per volume of solution, which has also been called specific energy (*SE*). When we say the SGE from seawater/river water mixing is equivalent to a 280 m dam, the energy density (0.75 kWh/m^3, equivalent to the seawater osmotic pressure, see sidenote[1]) is defined based on the volume of the river water.[4] Early SGE studies focused on *SE* defined based on the volume of the feed solution, which is convenient for estimating the overall availability of SGE. Later studies found that defining the *SE* based on the combined volume of feed solution (e.g., river water) and draw solution (e.g., seawater) could be convenient to simplify system optimization.[19,20] Herein, we denote the *SE* defined based on feed solution volume as SE_f and that defined based on combined feed and draw solution volume as SE_{tot}. Previous analysis has revealed that the thermodynamic limit of SE_{tot} for seawater/river water SGE is ~0.25 kWh/m^3 — roughly one third of the thermodynamic limit of SE_f (**Fig. 2A**).[18] The *SE* of real SGE systems is lower than these thermodynamic limits.



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[1] In the water dam equivalence, a 280 m water column generates hydraulic pressure of ~27 bar which corresponds to the osmotic pressure difference between seawater and river water. If we simplify river water as salt-free with zero osmotic pressure, then 27 bar is the osmotic pressure of seawater. Having the same dimension, an osmotic pressure of 27 bar can also be converted to an energy density of 0.75 kWh m^{-3}. Therefore, the theoretical maximum of energy density for seawater/river water SGE is 0.75 kWh per volume of the river water.

Figure 2. Theoretical and practical specific energy (SE). (A) theoretical SE normalized by feed volume (*SE_f*, dash line) vs that normalized by total volume (*SE_{tot}*, solid line) for a given feed solution (salinity equivalent to 0.015M NaCl) and draw solutions of different salinity. *SE_{tot}* is maximized by choosing an optimal ratio between the feed and draw volumes according to Ref. 18. (B) Estimated ranges of specific energy outputs and inputs for a practical seawater/river water PRO plant. The specific energy is normalized by the total volume. In panel (A), SW and SWRO represent seawater and seawater reverse osmosis brine, respectively. Figure 2B is adapted from Ref. 26 with permission.

For a given pair of feed and draw solutions with known volume (or flow rate) ratio and osmotic pressures, the theoretical thermodynamic limit of *SE* can be calculated using the Gibbs free energy of mixing.[4,19] *SE* of real systems depends on both the theoretical limit of *SE* and the energy conversion efficiency, with the latter defined as the ratio between extracted energy and the Gibbs free energy of mixing. Energy conversion efficiency quantifies the extent to which an SGE system can extract the theoretically available energy. An SGE system has a higher energy conversion efficiency if parasitic energy losses (due to inefficiency of ancillary equipment, energy need for pretreatment, and pressure drop in flow channels) and the unextracted SGE at the end of the process are minimized. In addition, energy conversion efficiency is also inversely correlated to the process kinetics which is quantified by power density.

Power density is the metric that quantifies SGE process kinetics, and its definition can be process dependent. In general, power density can be defined as the power generated per area of the functional materials which are semi-permeable membrane in PRO, IEM in RED (or NPG), and ion storage electrodes in CapMix. Direct comparison of power density between different SGE technologies is unmeaningful because the costs of the functional materials vary significantly between technologies. In early SGE literature, there was a mythical argument, not substantiated by rigorous theoretical analysis, that PRO will become economically competitive when its membrane power density exceeds 5 W/m^2.[21,22]

Focusing on power density as the performance metric is erroneous as it ignores energy conversion efficiency as an important metric. There is an intrinsic tradeoff between power density and energy conversion efficiency, regardless of the technological choice. Operationally, if only a small portion of the available energy is extracted, the system can maintain a large driving force and yield a high power density.[23-25] Many bench-scale studies, especially those performed to characterize novel materials, used the maximum driving force in their experiments. In scaled-up SGE systems, however, the average driving force will be substantially lower, yielding an average “module power density” much lower than what most bench-scale studies reported.

Using PRO for example, in cases where a relatively high power density is achieved at the cost of energy conversion efficiency, the input energy for operating the SGE system can exceed the extracted energy(**Fig.2B**).[26] Therefore, the system size (i.e., membrane area) is a critical parameter for optimizing a PRO process to find the right balance between energy conversion efficiency and power density.[27] A more advanced metric called *net power density* has been recently proposed for PRO to account for the energy losses associated with pumping, pretreatment, and other components.[27] Regardless of the definition, a process-relevant power density must be evaluated at the system level instead measured using a small membrane coupon as a reported in studies developing materials for SGE.

PRO is the Most Promising SGE Technology

By analyzing how driving force breaks down into useful work and other losses and how it diminishes as SGE is extracted, Yip and Elimelech presented a convincing comparison between PRO and RED.[28] The major conclusion from the comparative analysis was that PRO has the theoretical characteristics to outperform RED in both energy conversion efficiency and membrane power density, let alone the fact that IEMs used in RED are substantially more costly than semi-permeable membrane used in PRO. By analyzing multiple scenarios with different combinations of feed and draw solution concentrations, the authors also showed that the comparative advantages of PRO over RED are even greater when the salinity difference between the feed and draw solutions is larger.

As an RED variant, NPG has been reported to be able to extract SGE with an extraordinarily high power density (at the order of 10^3 kW/m^2).[29,30] However, more careful analysis revealed that such a power density is attainable only at a single pore level. More practical (areal) power density of NPG using membranes with many nanopores should approach that of RED using commercial IEMs.[31] Additionally, because current NPG systems use only cation exchange membranes, its theoretically extractable energy is only half of that for the conventional RED.[31,32] Therefore, NPG cannot bring any paradigm shift that will change the systematic advantages of PRO over RED.

In the absence of comprehensive comparison between CapMix and RED or PRO, we believe that CapMix is unlikely a competitive SGE extraction technology. Based on theoretical analyses and evaluation of literature data of the desalination counterparts of SGE technologies, RO outcompetes ED which outcompetes CDI in the salinity range relevant to SGE.[33-35] The same technical reasons that make RO superior to ED and CDI also explain the competitive edges of PRO over RED and CapMix. Moreover, the finite electrode capacity and the consequent operational intermittence increase the operational complexity of CapMix, rendering it even more unattractive vs. PRO and ED. The limitations of CapMix are supported by its performance data reported in literature.[18,36,37]

The comparison between different SGE technologies leads to the conclusion that PRO is the superior process for extracting SGE. If PRO, the most competitive SGE extraction process, is proven practically non-viable, then SGE is practically non-viable. The viability of PRO is thus the focus of the discussion in the next two sections.

PRO has Major Technical Limitations in Most Scenarios

We previously showed that the maximum energy density of PRO using seawater and river water is ~0.25 kWh/m^3 (i.e., the limit of SE_{tot}). Such a theoretical limit can only be obtained using an unrealistic, thermodynamically reversible PRO process. In an optimized, counter-current, constant pressure PRO process, SE_{tot} is reduced to ~0.19 kWh m^{-3} even without considering important practical factors such as concentration polarization, parasitic losses, and pretreatment cost.[19] More detailed modeling studies considering those practical factors reported SE_f in the range of 0.1 to 0.15 kWh/m^3 with a membrane power density < 2 W/m^2, depending on the choices of system and operational parameters.[38,39] Such an SE_f correspond to an SE_{tot} of ~0.03 to ~0.05 kWh/m^3 (as the optimal ratio between draw and feed solution flowrates was found to be ~2). A more conservative analysis that assumed a higher cost of pretreatment (in *SE* equivalent) even suggested that no net energy can be generated in a realistic seawater/river water PRO plant.[26]

Comparing the optimistic estimates of realistic SE_f (~0.03 to ~0.05 kWh/m^3) to its theoretical limit as equivalent to a 280 m water dam (0.75 kWh/m^3) clearly shows that seawater/river water PRO is not as promising as it appeared. Applying PRO with a draw solution with much higher salinity, such as hypersaline brine from Dead Sea or Great Salt Lake, will increase the power density by roughly an order of magnitude.[19,26] Working with such high salinities requires new PRO membranes and modules capable of operation at ultrahigh pressure.[40] Additionally, the available pairings of such hypersaline draw solution and low salinity feed solution are very limited globally and they exclusively exist in areas where solar energy is abundant, which leads to the discussion of next section regarding the economics of PRO as compared to other mainstream renewable.

The Economics of PRO is Unfavorable

The above discussion focusing on the technical performance metrics aims to provide technical rationales regarding why PRO is unlikely economically competitive. However, achieving a definitive conclusion still requires technoeconomic analysis that informs us the cost of PRO for energy generation. To this end, the levelized cost of energy (LCOE), which accounts for capital and operating costs, has been evaluated by different research groups.[26,41] Even with the most optimistic estimates, the LCOE of PRO with seawater and river water was assessed to be consistently >$1/kWh (as high as $3/kWh with more realistic estimates), which is at least an order of magnitude higher than other forms of renewable energy such as solar, wind, geothermal, and hydroelectric.[3] We note that these estimates were based on optimized PRO system considering both energy conversion efficiency and membrane power density. Only when using a highly saline brine (>18%) as the draw solution and with an optimistic estimate would PRO possibly become cost-competitive vs. the other forms of renewable energy.[42] However, natural sources of such high salinity brine are rare, and they exist in areas where freshwater resource is extremely scarce (e.g., Dead Sea and Great Salt Lake). For industries that generate such high salinity brines, dilution of such brines is unlikely an option regardless of whether SGE is performed. Such industrial brines typically require proper management approaches such as deep well injection or zero liquid discharge.[43]

Other Applications of SGE also Face Practical Challenges

Although PRO (and thus SGE in general) is economically not viable in the face of other forms of renewable energy that are cheaper and more abundant, it has been explored for sustainable energy storage and enhancing the efficiency of desalination. For example, it has been proposed that RO can be applied to generate a feed solution (fresh water) and a draw solution (RO brine) as a means of energy storage when renewable energy is in excess. When energy is needed in peak hours, PRO or other types of SGE processes could be used to extract the energy stored in salinity difference (**Fig. 3A**).[44-46]

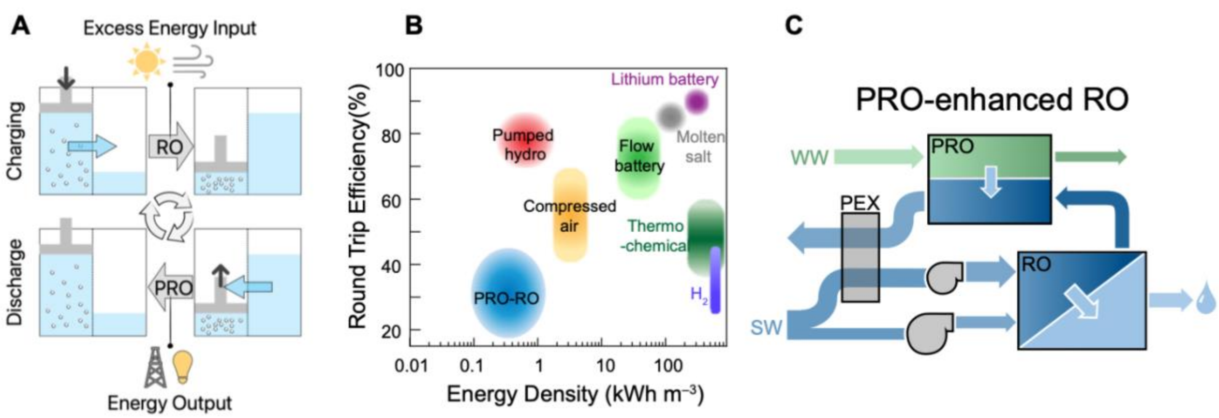

Figure 3. **PRO for renewable energy storage and enhancing RO** (A) Illustration of an integrated PRO-RO system for storing renewable energy. When there is an excess of renewable energy, the system will operate in the “charging mode” in which RO is used to produce freshwater and create a concentrated draw solution. When energy needs to be extracted from the system, the system will operate in the “discharge mode” in which PRO is used to generate useful work. (B) Round trip efficiency and energy density of PRO-RO energy storage as compared to other existing means of the energy storage. Each cloud represents an estimate of the ranges for both performance metrics (from Ref.46). (C) Integration of PRO into a seawater RO system to recoup the energy embedded in the high salinity of the concentrated brine. SW, WW, and PEX represent seawater, wastewater, and pressure exchanger, respectively. Figure 3B is adapted from Ref. 26 with permission.

The main challenge for SGE-based energy storage is the low energy density. As mentioned, the SE_{tot} with a draw solution of seawater salinity is capped at ~0.25 kWh/m^3.

Even if we increase SE_{tot} by a factor of 10 via increasing the draw solution salinity, the energy density (2.5 kWh/m^3) is still minuscule compared to most other means of energy storage. An energy density of 2.5 kWh/m^3 is only comparable to that of pumped hydro and compressed air,[47] which have lower capital cost, simpler system, more reliable operation, and much longer lifetime. We note that the SE_{tot} here is the theoretical limit (based on Gibbs free energy of mixing) and real PRO systems can only extract a fraction of SE_{tot}, making the comparison even more unfavorable for RO-PRO as a means of energy storage.

Additionally, SGE-based energy storage may also suffer from a low-to-moderate round-trip efficiency. In RO-PRO energy storage, the round-trip efficiency is the product of energy utilization efficiency of RO and the energy conversion efficiency of PRO. Both efficiencies depend on multiple factors such as system configuration, salinity of the draw and feed solutions, water flux, and water recovery in RO (or volume fraction in PRO). Even if we optimistically assume both utilization efficiency and conversion efficiency to be 60%, the round-trip efficiency is below 40% which is substantially lower than that of existing utility-scale energy storage technologies (~80%).[48] Considering both the energy density and roundtrip efficiency, RO-PRO based SGE is intrinsically unattractive as a utility-scale energy storage technology (**Fig. 3B**).

In another proposed application, PRO is combined with seawater RO to use the RO brine as the draw solution and a low salinity, impaired wastewater stream as the feed solution (**Fig 3C**).[49-53] The use of PRO in this context is to recoup the osmotic energy embedded in the RO brine to reduce the overall energy consumption of RO, which is theoretically sensible. However, the advantage of this proposed use of PRO is questionable in two ways even without considering practical factors such as fouling. First, if we treat the additional PRO component as a source of energy, doubling the draw solution salinity from seawater to RO brine is still insufficient to make PRO economically competitive vs. other forms of renewable or conventional energy. Second, if impaired wastewater is indeed available where seawater RO is needed, the more energetically and economically sensible approach is to perform wastewater reclamation for non-portable or even portable reuse to reduce the demand for seawater RO, instead of using the wastewater to improve the energy efficiency of seawater RO via generating SGE with RO brine.[54,55] Alternatively, we can use treated wastewater to indirectly dilute seawater using either forward osmosis[56] or salinity exchange electrodialysis[57], which reduces the energy consumption of SWRO but also overcomes the psychological barrier of direct portable reuse of wastewater. These approaches of "indirect dilution" are likely more effective use of salinity gradient than using PRO to augment RO.

Concluding Remarks

We hope that the analysis and discussion presented in this Commentary can convince the readers that SGE will not become a mainstream, cost-competitive form of renewable energy, even with substantial system and material improvements. Such a conclusion is arrived with the logic that, if the most promising SGE technology, PRO, cannot economically compete with other forms of renewable energy, then SGE as a category of renewable energy is not economically viable. While the final verdict must rely on LCOE from technoeconomic analysis, this Commentary focuses mainly on the technical performance metrics to help the readers understand the technical rationales behind the high LCOE of PRO. The main limitations are the intrinsically low energy density of seawater/river water SGE and the low energy conversion efficiency of PRO (and other SGE technologies), which cannot be overcome with better membrane materials or system designs.

While SGE has been proven technically feasible, the analyses presented in this Commentary show that SGE is not economically competitive vs. other forms of renewable energy. We further emphasize that developing better membranes, electrodes, or systems will not improve SGE to become sufficiently competitive. While fundamental research inspired by, or related to, the concept of SGE remains scientifically interesting, it is misleading to claim that SGE is highly promising and that developing novel materials is critical to bringing SGE to large-scale applications.

In fact, we should even feel fortunate that SGE is not practically viable. As SGE is a reverse process of desalination, if the energy density of seawater were high enough for SGE to be competitive, then seawater desalination would become much less viable (for instance, we will never desalinate brines from Dead Sea or Great Salt Lake to obtain freshwater). Seawater desalination is critical to water security in many regions of the world where alternative ways of obtaining freshwater are very limited or virtually non-existent.[58] In contrast, SGE is just one candidate in the diverse portfolio of clean energy with alternatives (e.g., solar and wind) that are more abundant, universally accessible, and economically competitive.

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References

1. Yip, N.Y., Brogioli, D., Hamelers, H.V.M., and Nijmeijer, K. (2016). Salinity Gradients for Sustainable Energy: Primer, Progress, and Prospects. Environ Sci Technol *50*, 12072-12094. 10.1021/acs.est.6b03448.
2. Logan, B.E., and Elimelech, M. (2012). Membrane-based processes for sustainable power generation using water. Nature *488*, 313-319. 10.1038/nature11477.
3. Lee, B., Wang, L., Wang, Z., Cooper, N.J., and Elimelech, M. (2023). Directing the research agenda on water and energy technologies with process and economic analysis. Energ Environ Sci. 10.1039/D2EE03271F.
4. Yip, N.Y., and Elimelech, M. (2012). Thermodynamic and Energy Efficiency Analysis of Power Generation from Natural Salinity Gradients by Pressure Retarded Osmosis. Environ Sci Technol *46*, 5230-5239. 10.1021/es300060m.
5. Alvarez-Silva, O.A., Osorio, A.F., and Winter, C. (2016). Practical global salinity gradient energy potential. Renewable and Sustainable Energy Reviews *60*, 1387-1395. https://doi.org/10.1016/j.rser.2016.03.021.

6. Pattle, R.E. (1954). Production of Electric Power by mixing Fresh and Salt Water in the Hydroelectric Pile. Nature *174*, 660-660. 10.1038/174660a0.
7. Norman, R.S. (1974). Water Salination: A Source of Energy. Science *186*, 350-352. doi:10.1126/science.186.4161.350.
8. Helfer, F., Lemckert, C., and Anissimov, Y.G. (2014). Osmotic power with Pressure Retarded Osmosis: Theory, performance and trends – A review. J Membrane Sci *453*, 337-358. https://doi.org/10.1016/j.memsci.2013.10.053.
9. Statkraft Shelves Osmotic Power Project. (2014). https://www.powermag.com/statkraft-shelves-osmotic-power-project/.
10. Achilli, A., and Childress, A.E. (2010). Pressure retarded osmosis: From the vision of Sidney Loeb to the first prototype installation — Review. Desalination *261*, 205-211. https://doi.org/10.1016/j.desal.2010.06.017.
11. Sarp, S., Li, Z., and Saththasivam, J. (2016). Pressure Retarded Osmosis (PRO): Past experiences, current developments, and future prospects. Desalination *389*, 2-14. https://doi.org/10.1016/j.desal.2015.12.008.
12. Lacey, R.E. (1980). Energy by reverse electrodialysis. Ocean Engineering *7*, 1-47. https://doi.org/10.1016/0029-8018(80)90030-X.
13. Turek, M., and Bandura, B. (2007). Renewable energy by reverse electrodialysis. Desalination *205*, 67-74. https://doi.org/10.1016/j.desal.2006.04.041.
14. Mei, Y., and Tang, C.Y. (2018). Recent developments and future perspectives of reverse electrodialysis technology: A review. Desalination *425*, 156-174. https://doi.org/10.1016/j.desal.2017.10.021.
15. Macha, M., Marion, S., Nandigana, V.V.R., and Radenovic, A. (2019). 2D materials as an emerging platform for nanopore-based power generation. Nat Rev Mater *4*, 588-605. 10.1038/s41578-019-0126-z.
16. Siria, A., Bocquet, M.L., and Bocquet, L. (2017). New avenues for the large-scale harvesting of blue energy. Nat Rev Chem *1*. UNSP 0091, 10.1038/s41570-017-0091.
17. Rica, R.A., Ziano, R., Salerno, D., Mantegazza, F., Van Roij, R., and Brogioli, D. (2013). Capacitive Mixing for Harvesting the Free Energy of Solutions at Different Concentrations. Entropy-Switz *15*, 1388-1407.
18. Hatzell, M.C., Cusick, R.D., and Logan, B.E. (2014). Capacitive mixing power production from salinity gradient energy enhanced through exoelectrogen-generated ionic currents. Energ Environ Sci *7*, 1159-1165. 10.1039/C3EE43823F.
19. Lin, S.H., Straub, A.P., and Elimelech, M. (2014). Thermodynamic limits of extractable energy by pressure retarded osmosis. Energ Environ Sci *7*, 2706-2714. 10.1039/c4ee01020e.
20. Straub, A.P., Lin, S.H., and Elimelech, M. (2014). Module-Scale Analysis of Pressure Retarded Osmosis: Performance Limitations and Implications for Full-Scale Operation. Environ Sci Technol *48*, 12435-12444. 10.1021/es503790k.
21. Skilhagen, S.E., Dugstad, J.E., and Aaberg, R.J. (2008). Osmotic power — power production based on the osmotic pressure difference between waters with varying salt gradients. Desalination *220*, 476-482. https://doi.org/10.1016/j.desal.2007.02.045.
22. Skilhagen, S.E. (2010). Osmotic power — a new, renewable energy source. Desalin Water Treat *15*, 271-278. 10.5004/dwt.2010.1759.

23. Straub, A.P., Lin, S., and Elimelech, M. (2014). Module-Scale Analysis of Pressure Retarded Osmosis: Performance Limitations and Implications for Full-Scale Operation. Environ Sci Technol *48*, 12435-12444. 10.1021/es503790k.

24. Banchik, L.D., Sharqawy, M.H., and Lienhard, J.H. (2014). Limits of power production due to finite membrane area in pressure retarded osmosis. J Membrane Sci *468*, 81-89. https://doi.org/10.1016/j.memsci.2014.05.021.

25. Wang, Z., Wang, L., and Elimelech, M. (2022). Viability of Harvesting Salinity Gradient (Blue) Energy by Nanopore-Based Osmotic Power Generation. Engineering-Prc *9*, 51-60. https://doi.org/10.1016/j.eng.2021.02.016.

26. Straub, A.P., Deshmukh, A., and Elimelech, M. (2016). Pressure-retarded osmosis for power generation from salinity gradients: is it viable? Energ Environ Sci *9*, 31-48. 10.1039/c5ee02985f.

27. Chung, H.W., Swaminathan, J., Banchik, L.D., and Lienhard, J.H. (2018). Economic framework for net power density and levelized cost of electricity in pressure-retarded osmosis. Desalination *448*, 13-20. https://doi.org/10.1016/j.desal.2018.09.007.

28. Yip, N.Y., and Elimelech, M. (2014). Comparison of Energy Efficiency and Power Density in Pressure Retarded Osmosis and Reverse Electrodialysis. Environ Sci Technol *48*, 11002-11012. 10.1021/es5029316.

29. Feng, J.D., Graf, M., Liu, K., Ovchinnikov, D., Dumcenco, D., Heiranian, M., Nandigana, V., Aluru, N.R., Kis, A., and Radenovic, A. (2016). Single-layer MoS2 nanopores as nanopower generators. Nature *536*, 197-+. 10.1038/nature18593.

30. Zhang, Z., Wen, L., and Jiang, L. (2021). Nanofluidics for osmotic energy conversion. Nat Rev Mater *6*, 622-639. 10.1038/s41578-021-00300-4.

31. Wang, L., Wang, Z., Patel, S.K., Lin, S., and Elimelech, M. (2021). Nanopore-Based Power Generation from Salinity Gradient: Why It Is Not Viable. Acs Nano. 10.1021/acsnano.0c08628.

32. Kim, D.K., Duan, C.H., Chen, Y.F., and Majumdar, A. (2010). Power generation from concentration gradient by reverse electrodialysis in ion-selective nanochannels. Microfluid Nanofluid *9*, 1215-1224. 10.1007/s10404-010-0641-0.

33. Lin, S.H. (2020). Energy Efficiency of Desalination: Fundamental Insights from Intuitive Interpretation. Environ Sci Technol *54*, 76-84. 10.1021/acs.est.9b04788.

34. Qin, M., Deshmukh, A., Epsztein, R., Patel, S.K., Owoseni, O.M., Walker, W.S., and Elimelech, M. (2019). Comparison of energy consumption in desalination by capacitive deionization and reverse osmosis. Desalination *455*, 100-114. https://doi.org/10.1016/j.desal.2019.01.003.

35. Patel, S.K., Biesheuvel, P.M., and Elimelech, M. (2021). Energy Consumption of Brackish Water Desalination: Identifying the Sweet Spots for Electrodialysis and Reverse Osmosis. ACS ES&T Engineering. 10.1021/acsestengg.0c00192.

36. Brogioli, D. (2009). Extracting Renewable Energy from a Salinity Difference Using a Capacitor. Phys Rev Lett *103*. Artn 058501
10.1103/Physrevlett.103.058501.

37. Sales, B.B., Saakes, M., Post, J.W., Buisman, C.J.N., Biesheuvel, P.M., and Hamelers, H.V.M. (2010). Direct Power Production from a Water Salinity Difference in a Membrane-

Modified Supercapacitor Flow Cell. Environ Sci Technol *44*, 5661-5665. 10.1021/es100852a.

38. Wang, Z., Hou, D., and Lin, S. (2016). Gross vs. net energy: Towards a rational framework for assessing the practical viability of pressure retarded osmosis. J Membrane Sci *503*, 132-147. https://doi.org/10.1016/j.memsci.2015.11.035.

39. O'Toole, G., Jones, L., Coutinho, C., Hayes, C., Napoles, M., and Achilli, A. (2016). River-to-sea pressure retarded osmosis: Resource utilization in a full-scale facility. Desalination *389*, 39-51. https://doi.org/10.1016/j.desal.2016.01.012.

40. Straub, A.P., Yip, N.Y., and Elimelech, M. (2014). Raising the Bar: Increased Hydraulic Pressure Allows Unprecedented High Power Densities in Pressure-Retarded Osmosis. Environ Sci Tech Let *1*, 55-59. 10.1021/ez400117d.

41. Newby, A.N., Bartholomew, T.V., and Mauter, M.S. (2021). The Economic Infeasibility of Salinity Gradient Energy via Pressure Retarded Osmosis. Acs Es&T Engineering *1*, 1113-1121. 10.1021/acsestengg.1c00078.

42. Chung, H.W., Banchik, L.D., Swaminathan, J., and Lienhard V, J.H. (2017). On the present and future economic viability of stand-alone pressure-retarded osmosis. Desalination *408*, 133-144. https://doi.org/10.1016/j.desal.2017.01.001.

43. Tong, T.Z., and Elimelech, M. (2016). The Global Rise of Zero Liquid Discharge for Wastewater Management: Drivers, Technologies, and Future Directions. Environ Sci Technol *50*, 6846-6855. 10.1021/acs.est.6b01000.

44. Bharadwaj, D., and Struchtrup, H. (2017). Large scale energy storage using multistage osmotic processes: approaching high efficiency and energy density. Sustain Energ Fuels *1*, 599-614. 10.1039/C6SE00013D.

45. He, W., and Wang, J. (2017). Feasibility study of energy storage by concentrating/desalinating water: Concentrated Water Energy Storage. Appl Energ *185*, 872-884. https://doi.org/10.1016/j.apenergy.2016.10.077.

46. Rao, A.K., Li, O.R., Wrede, L., Coan, S.M., Elias, G., Cordoba, S., Roggenberg, M., Castillo, L., and Warsinger, D.M. (2021). A framework for blue energy enabled energy storage in reverse osmosis processes. Desalination *511*, 115088. https://doi.org/10.1016/j.desal.2021.115088.

47. Fact Sheet | Energy Storage. (2019). https://www.eesi.org/papers/view/energy-storage-2019.

48. Utility-scale batteries and pumped storage return about 80% of the electricity they store. (2021). https://www.eia.gov/todayinenergy/detail.php?id=46756.

49. Sharqawy, M.H., Zubair, S.M., and Lienhard, J.H. (2011). Second law analysis of reverse osmosis desalination plants: An alternative design using pressure retarded osmosis. Energy *36*, 6617-6626. https://doi.org/10.1016/j.energy.2011.08.056.

50. Wan, C.F., and Chung, T.-S. (2016). Energy recovery by pressure retarded osmosis (PRO) in SWRO–PRO integrated processes. Appl Energ *162*, 687-698. https://doi.org/10.1016/j.apenergy.2015.10.067.

51. Li, M. (2017). Reducing specific energy consumption of seawater desalination: Staged RO or RO-PRO? Desalination *422*, 124-133. https://doi.org/10.1016/j.desal.2017.08.023.

52. Altaee, A., Millar, G.J., and Zaragoza, G. (2016). Integration and optimization of pressure retarded osmosis with reverse osmosis for power generation and high efficiency desalination. Energy *103*, 110-118. https://doi.org/10.1016/j.energy.2016.02.116.
53. Lee, S., Park, T.-s., Park, Y.-G., Lee, W.-i., and Kim, S.-H. (2020). Toward scale-up of seawater reverse osmosis (SWRO) – pressure retarded osmosis (PRO) hybrid system: A case study of a 240 m3/day pilot plant. Desalination *491*, 114429. https://doi.org/10.1016/j.desal.2020.114429.
54. Mo, W., Wang, R., and Zimmerman, J.B. (2014). Energy–Water Nexus Analysis of Enhanced Water Supply Scenarios: A Regional Comparison of Tampa Bay, Florida, and San Diego, California. Environ Sci Technol *48*, 5883-5891. 10.1021/es405648x.
55. Muñoz, I., Milà-i-Canals, L., and Fernández-Alba, A.R. (2010). Life Cycle Assessment of Water Supply Plans in Mediterranean Spain. Journal of Industrial Ecology *14*, 902-918. https://doi.org/10.1111/j.1530-9290.2010.00271.x.
56. Seo, J., Kim, Y.M., Chae, S.H., Lim, S.J., Park, H., and Kim, J.H. (2019). An optimization strategy for a forward osmosis-reverse osmosis hybrid process for wastewater reuse and seawater desalination: A modeling study. Desalination *463*, 40-49. https://doi.org/10.1016/j.desal.2019.03.012.
57. Jarin, M., Dou, Z., Gao, H., Chen, Y., and Xie, X. (2022). Salinity exchange between seawater/brackish water and domestic wastewater through electrodialysis for potable water. Frontiers of Environmental Science & Engineering *17*, 16. 10.1007/s11783-023-1616-1.
58. Elimelech, M., and Phillip, W.A. (2011). The Future of Seawater Desalination: Energy, Technology, and the Environment. Science *333*, 712-717. 10.1126/science.1200488.