Electronic Supplementary Material (ESI) for Environmental Science: Water Research & Technology.

Emerging investigator series: Toward the Ultimate Limit of Seawater Desalination with Mesopelagic Open Reverse Osmosis

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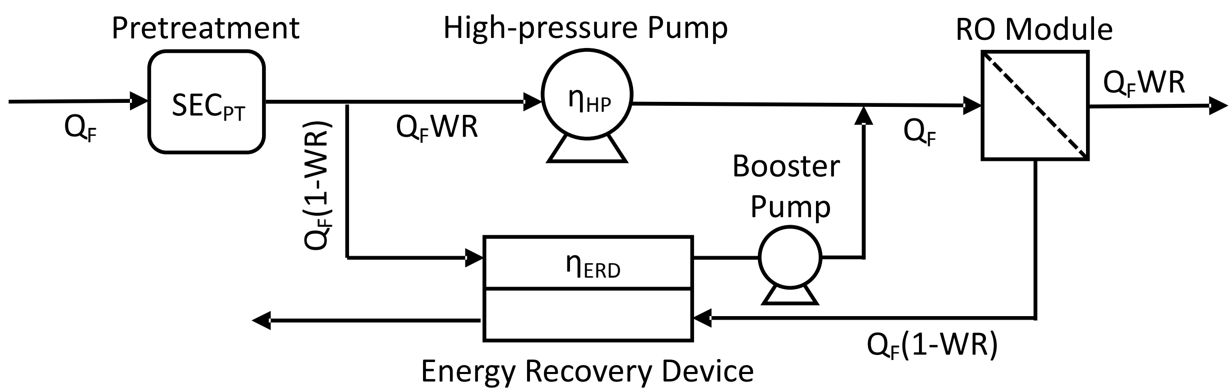
S1. Derivation of the Specific Energy Consumption (SEC) for on-ground SWRO



RO Operating Pressure. For a single-pass constant-pressure RO, the minimum applied pressure, Δp_{min}, is the osmotic pressure of the existing brine (as a function of WR), $\pi_b(WR)$.

$$\Delta p_{min} = \pi_b(WR) = \frac{\pi_0}{1 - WR} \quad (1)$$

where π_0 is the feed (i.e., seawater) osmotic pressure. In practice, an excess pressure (also called over-pressure), Δp_{ex}, is applied on top of Δp_{min} to (a) provide a finite driving force even at the end of the module, and (b) compensate the pressure drop due to the frictional loss along of the water flow along the feed channel. Therefore, the actual applied pressure, Δp, is the sum of Δp_{min} and Δp_{ex}:

$$\Delta p = \Delta p_{min} + \Delta p_{ex} = \frac{\pi_0}{1 - WR} + \Delta p_{ex} \quad (2)$$

Power for RO. Assuming the feed influent (volumetric) flowrate to be Q_F, the power for pressurizing the entire feed stream to acquire Δp is theoretically.

$$P_{RO} = \Delta p Q_F \quad (3)$$

Power Recovered from ERD. The flowrate of the exit brine is $Q_F(1-WR)$. Such a brine stream is still pressurized at $(1-\varepsilon)\Delta p$ with $\varepsilon\Delta p$ being the pressure drop in the module. Assuming the efficiency of the energy recovery device (ERD) as η_{ERD}, the power that is recovered by the ERD is

$$P_{ERD} = \eta_{ERD}(1-\varepsilon)\Delta p Q_F(1-WR) \qquad (4)$$

The exiting feed stream from the ERD has a pressure lower than the working pressure, Δp. Therefore, a booster pump is used to raise the pressure to Δp. Because the energy requirement for the booster pump is relatively small, we do not account for the inefficiency of the booster pump to simplify our analysis

Power Loss in HP. The ERD can only pressurize an incoming stream at the same flowrate of the brine stream. Therefore, we need to use high-pressure pumps (HP) to pressurize a stream with a flowrate of $Q_F WR$. Assuming that the efficiency of the HP to be η_{HP}, the power loss in the HP for raising the pressure to Δp is

$$P_{HPL} = \Delta p Q_F WR\left(\frac{1}{\eta_{HP}} - 1\right) \qquad (5)$$

where the subscript "HPL" stands for high-pressure pump loss.

Effective Power for Pretreatment. Because the entire feed stream undergoes pretreatment, the power consumption for pretreatment can be described as

$$P_{PT} = Q_F SEC_{PT} \qquad (6)$$

where SEC_{PT} is specific energy consumption (energy per volume of feed water) for pre-treatment (which can also include intake). We note that the chemical cost for pretreatment can also be included in SEC_{PT} by first converting it to monetary cost and then to energy equivalent based on the energy prize. With such a treatment, SEC_{PT} represents both the energy and chemical cost of pretreatment and P_{PT} is referred to as the effective power for pretreatment.

Total Power. The total power of the system (excluding post-treatment) is given by

$$P_{Tot} = P_{RO} + P_{HPL} - P_{ERD} + P_{PT} \qquad (7)$$

Total Specific Energy Consumption. The total specific energy consumption of the process, defined as energy consumed to generate a unit volume of permeate, is given by

$$SEC_{Tot} = \frac{P_{Tot}}{Q_F WR} \tag{8}$$

Combining equations 3 to 8 yields

$$SEC_{Tot} = \frac{\Delta p\big(1 - \eta_{ERD}(1-\varepsilon)(1-WR)\big) + SEC_{PT}}{WR} + \Delta p\left(\frac{1}{\eta_{HHP}} - 1\right) \tag{9}$$

Plugging equation 2 into equation 9:

$$SEC_{Tot} = \frac{1}{WR}\left[\left(\frac{\pi_0}{1-WR} + \Delta p_{ex}\right)\left(1 - \eta_{ERD}(1-\varepsilon)(1-WR) + WR\left(\frac{1}{\eta_{HP}} - 1\right)\right) + SEC_{PT}\right] \tag{10}$$

To simplify the equation, let us define $\eta_{ERD}(1-\varepsilon)$ as α and $\left(\frac{1}{\eta_{HHP}} - 1\right)$ as β, eqution 10 then becomes

$$SEC_{Tot} = \frac{1}{WR}\left[\left(\frac{\pi_0}{1-WR} + \Delta p_{ex}\right)(1 - \alpha(1-WR) + WR\,\beta) + SEC_{PT}\right] \tag{11}$$

which can be simplified as

$$SEC_{Tot} = \frac{\pi_0}{WR}\left[\left(\frac{1 + WR\,\beta}{1-WR} - \alpha\right) + \frac{\Delta p_{ex}}{\pi_0}(1 + WR\,\beta - \alpha(1-WR)) + \frac{SEC_{PT}}{\pi_0}\right] \tag{12}$$

The osmotic pressure of seawater, π_0, is roughly constant ~ 27 bar. To simplify our analysis, we can also express Δp_{ex} and SEC_{PT} using π_0 as the unit. Using equation 12 with the parameters specified in Table S1, we can generate the results presented in Figure 3.

Table S1. Parameters used in assessing SEC of on-ground SWRO

	Value for simulation		Value for simulation

Δp_{ex}	$0.2\pi_0$	ε	5%
SEC_{PT}	$0.8\pi_0$	$\alpha = \eta_{ERD}(1-\varepsilon)$	~90%
η_{HP}	90%	$\beta = \left(\frac{1}{\eta_{HP}} - 1\right)$	~11%
η_{ERD}	95%		

S2. Derivation of Specific Energy Consumption (SEC) for MORO

First of all, the SEC for MORO can be approximated by the hydrostatic pressure of the location where the system is placed. This is because the energy required to deliver a unit volume of desalinated water to sea level is simply the hydrostatic pressure of the MORO system plus the pressure drop along the water pipe. The head loss along the water pipe, Δh, can be estimated using the Darcy-Weisbach equation:

$$\frac{\Delta h}{L} = f_D \frac{\rho \langle v \rangle^2}{2\ D} \quad (13)$$

where L is the length of the pipe and is roughly equal to the depth of the MORO system, f_D is the Darcy friction factor, ρ is the water density, $\langle v \rangle$ is the mean flow velocity, and D is the hydraulic diameter. From equation 13, it can be calculated that the pressure drop is rather small as long as the diameter of the tube is not too small.

Table S2.

	Case 1	Case 2
Capacity (MGD)	20	100
Tube diameter (m)	1	2
Pressure drop (bar)	0.05	0.03

f_D=0.5 mm; ρ=998.206 kg m-3; L=300 m

Based on these calculations, the pressure drop along the water pipe is far less than 1% of the hydrostatic pressure and can thus be ignored in our analysis. Now let us consider the relationship between the flux of water permeation through the membrane, J, and hydraulic pressure difference across the RO membrane, ΔP. Because is no salt accumulation inside a module (as open modules are used in MORO), the osmotic pressure of the feed water (i.e., seawater) is always π_0. Considering concentration polarization, J as a function of Δp has been well established as

$$J = A\left(\Delta p - \pi_0 exp\left(\frac{J}{k}\right)\right) \tag{14}$$

Rearranging equation 14 yields

$$\Delta p = \frac{J}{A} + \pi_0 exp\left(\frac{J}{k}\right) \tag{15}$$

which is equation 1 in the manuscript.