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Emerging investigator series: toward the ultimate limit of seawater desalination with mesopelagic open reverse osmosis†

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Seawater desalination has become an important tool to attain global water security and sustainability. Among the available technologies, reverse osmosis (RO) has become the golden standard for seawater desalination due to its unparalleled energy efficiency. While RO is already efficient after development for half a century, there remains room for over 50% further reduction in energy consumption that can translate into tens of terawatt hours of potential annual energy saving. However, this significant energy saving cannot be achieved under the conventional paradigm of on-ground RO. In this analysis, we assess the idea of operating RO with open modules several hundred meters below the ocean surface (*i.e.*, the mesopelagic zone). This new process, namely mesopelagic open reverse osmosis (MORO), can potentially push the energy consumption of seawater desalination to its theoretical limit. We first describe the concept of MORO, and then examine both the theoretical potential of energy saving and the practical challenges facing the implementation of MORO. Our analysis provides a theoretical framework for the future development of MORO for more sustainable desalination.

Water impact

Seawater desalination is important for addressing water scarcity and sustainability challenges in populated coastal regions, whereas reverse osmosis (RO) is the golden standard for seawater desalination due to its high energy efficiency. Herein, we demonstrate the theoretical potential to save an additional 50% of energy consumed in RO by operating it in the mesopelagic zone.

Introduction

Due to population growth, industrialization, and climate change, freshwater scarcity continues to be a global challenge that impacts the livelihood of billions of people.[1] At the same time, nearly 50% of the global population live within 200 km of the coast and many of the communities impacted by water scarcity are located in coastal regions.[2] Therefore, desalination is in principle a viable avenue to achieve water security for a very large coastal population. Among the existing technological options, reverse osmosis (RO) has evolved to be the most energy-efficient and cost-effective technology for seawater desalination.[3] The superior energy efficiency of RO for seawater desalination is well grounded with scientific rationales and is unlikely to be challenged by any other technology in the near future.[3–7] The global capacity of seawater RO (SWRO) has increased rapidly (Fig. 1A, left axis), approaching ~70 million m^3 per day (*i.e.*, ~18.5 billion gallons per day) and comprising close to 70% of the current global desalination capacity.[8]

Thanks to several breakthrough innovations in SWRO, such as the development of high-performance thin-film composite polyamide (TFC-PA) membranes and energy recovery devices (ERDs), the specific energy consumption (SEC), *i.e.*, the energy required to produce a unit volume of product water, has been reduced by nearly an order of magnitude over the last half century (Fig. 1A, right axis). The current SEC of the state-of-the-art SWRO systems is ~2 kW h m^{-3} for the RO separation process alone and can be considerably higher than 3 kW h m^{-3} for the entire treatment train.[6,7] The practical minimum SEC for a water recovery of 50% (which is optimal) is ~1.5 kW h m^{-3}, which is being approached by the state-of-the-art SWRO systems (Fig. 1B). Using an ideal thermodynamically reversible RO process can further reduce the SEC to ~1.1 kW h m^3 at the same water recovery (WR) of 50%. The ultimate limit of SEC (note that SEC has the same dimension as pressure) for SWRO is

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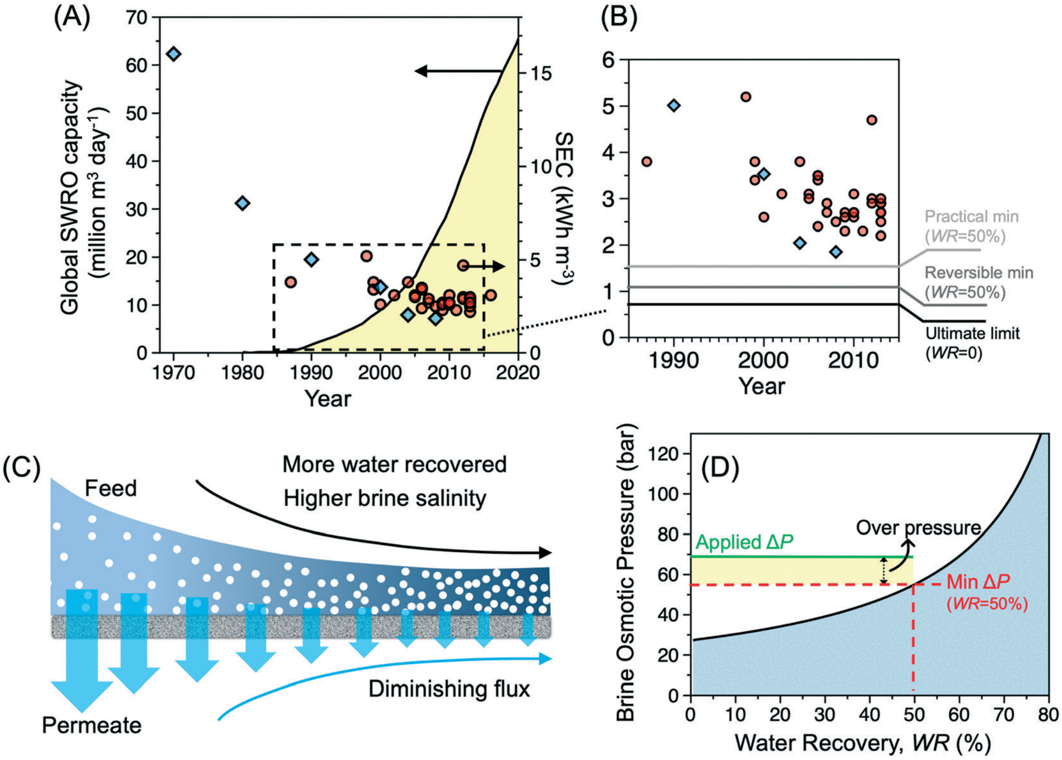

Fig. 1 (A) The global capacity (left axis) and SEC (right axis) of SWRO over the past five decades. The data for global capacity is adopted from ref. 8, whereas the data for SEC is adopted from ref. 3 (blue diamonds) and ref. 7 (red circles). (B) A subset of the SEC data in (A) with several theoretical SECs for benchmarking: practical minimum (WR = 50%), which is the minimum SEC to achieve a WR of 50% with a constant pressure, one-stage operation; reversible minimum (WR = 50%), which is the minimum SEC to achieve a WR of 50% with a thermodynamically reversible batch RO process; and ultimate limit, which is the SEC for applying a pressure infinitesimally higher than the osmotic pressure of seawater. (C) Variation of water salinity and permeate flux along an RO module as more water is recovered and the feedwater becomes concentrated. (D) Brine osmotic pressure as a function of water recovery (black curve), which determines the minimum applied pressure at a certain water recovery (red dashed line). The applied pressure is the minimum applied pressure plus the over pressure.

essentially the osmotic pressure of seawater if water recovery approaches zero (~0.75 kW h m^{-3}), which suggests that there is, in theory, room for a further cut of SEC by 50–75% from the state-of-the-art SWRO systems. Although not practically feasible, if all existing current SWRO systems approach the ultimate limit of SEC, the annual energy saving would be in the order of tens of terawatt hours.

Approaching this ultimate limit of SEC is practically impossible within the current technological framework of SWRO due to two major limitations. The first limitation concerns the accumulation of salt and the consequent build-up of osmotic pressure along an RO module (Fig. 1C). An optimized on-ground SWRO system recovers ~50% of the feed water[6] (also see the ESI†), meaning that the osmotic pressure of the brine exiting the module is twice as high as the seawater osmotic pressure (~27 bar). Therefore, an applied pressure higher than 54 bar (equivalent to ~1.5 kW h m^{-3}) is typically used (Fig. 1D). In addition to this minimum pressure, an "over pressure" (*i.e.*, the extra hydrostatic pressure) is required to overcome concentration polarization and the pressure drop along the module, and to provide additional driving force for water permeation. Together, the practical SEC for the RO separation process alone with a water recovery of 50% is ~2 kW h m^{-3} with the state-of-the-art systems.[3–7] While progress has been made to further lower the SEC by applying a lower average driving force *via* using either multi-stage,[9,10] closed circuit,[11–13] or batch RO,[14,15] limited energy saving can only be achieved with a lower flux and more complex system design and operation.

The second limitation concerns the "other energy consumptions" including that for pretreatment and for compensating the energy loss in high-pressure pumps and in ERDs. Pretreatment is generally required to prevent fouling of the membrane and the spacer, whereas an ERD is used to recover energy embedded in the pressurized brine stream.[16] While more detailed calculations are to be given in the following analysis, these energy consumptions can account for another ~2 kW h m^{-3}, as much as half of the total SEC in a practical on-ground SWRO system.[6,7,17,18]

Herein, we present a radically different technological framework to operate RO with the potential to reduce the practical SEC by 50–75% from its current state-of-the-art value. This approach, namely mesopelagic open reverse osmosis (MORO), overcomes the inherent limitation of osmotic pressure build-up in existing RO systems. In the following discussion, we will first introduce the concept and rationale of

MORO. We will then present a simplified analysis on the SEC of MORO as compared to conventional RO for seawater desalination. Lastly, practical considerations and technical challenges toward implementing MORO will also be examined.

The concept of mesopelagic open reverse osmosis (MORO)

In MORO, open RO module with either hollow fiber (HF) or tubular membranes are placed several hundred meters below the sea level, *i.e.*, in the mesopelagic zone. The active separation layer of the RO membrane is exposed to seawater with a hydrostatic pressure proportional to the water depth at which the MORO system is placed. When the hydrostatic pressure of the seawater exceeds its osmotic pressure (~27 bar, equivalent to ~275 m of water), water can permeate through the RO membrane that rejects the salt (Fig. 2A). The piezometric surface of the permeate will rise to ~275 m below sea level regardless of how deep the permeate tank is placed under the ocean. If we actively pump the desalinated water up to the ground (*i.e.*, sea level), seawater will continuously permeate through the RO membrane to replenish the permeate tank.

In practice, the system should be placed at least 300 m below sea level so that the additional hydrostatic pressure from the extra depth can provide the driving force for water permeation at a finite rate. To implement MORO for large-scale seawater desalination, we can construct structures with many open HF RO modules installed on water collection pipes that connect to an underwater pumping station (see Fig. 2B for an example of a branched structure MORO system). Water permeates through the RO membrane and flows through the collection pipes toward the pumping station where it is pumped to the ground for post-treatment and storage.

To a certain extent, the concept of MORO is not completely new, as ideas with different degrees of similarity have appeared in multiple non-academic articles where they are often referred to as deep ocean RO. However, it would be misleading to claim that deep ocean RO alone can save energy because it utilizes the natural hydrostatic pressure of the deep ocean instead of electrically driven high-pressure pumps. After all, the hydrostatic pressure corresponding to a

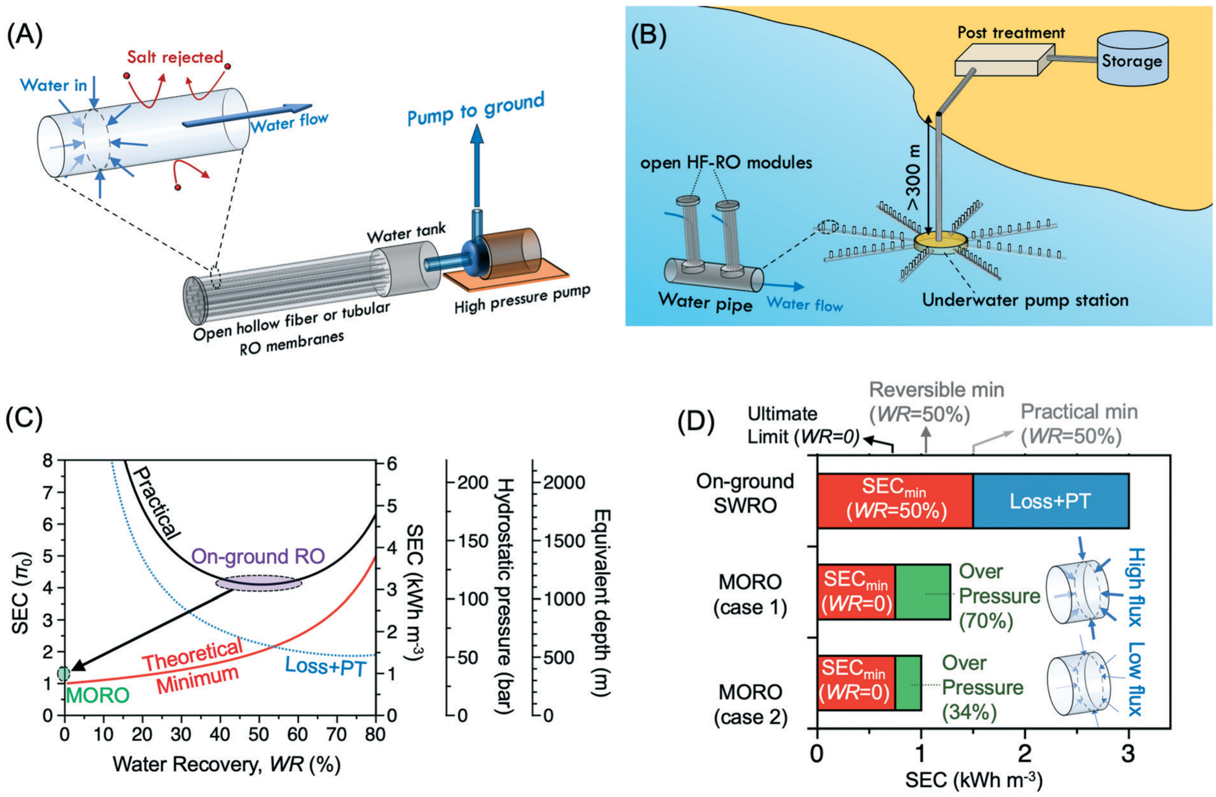

Fig. 2 (A) Illustration of the MORO concept with a single module system. The open RO module is composed of a bundle of HF RO membranes. Water permeates through the salt-rejecting RO membrane and the permeate is pumped to the ground. (B) An example for designing a MORO plant with a large number of open RO modules. (C) SEC in the units of seawater osmotic pressure, π_0, energy density, hydrostatic pressure, and equivalent depth, as a function of WR for the different contributions, including the minimum SEC for a constant pressure (CP) RO process alone (red curve), SEC for compensating loss in the energy recovery device, providing over-pressure in the RO module, and powering pretreatment (blue curve). The purple circle represents the optimized WR and the corresponding minimum practical SEC. The expected SEC for MORO, which operates at zero recovery, is denoted in green. (D) Comparison of the SEC for on-ground SWRO and two scenarios of MORO. In both cases, the simulations assume a membrane permeability of A = 2 L m^{-2} h^{-1} bar^{-1}, a mass transfer coefficient of k = 70 L m^{-2} h^{-1}, and an osmotic pressure of 27 bar for seawater. The permeate fluxes for cases 1 and 2 are 10 and 20 L m^{-2} h^{-1}, respectively.

certain ocean depth is theoretically the same as the SEC required to pump the water up to the sea level. In other words, deep ocean RO alone cannot result in energy saving. Therefore, performing deep ocean RO using closed RO modules as those used on the ground (*e.g.*, the conventional spiral-wound modules) cannot save substantial energy because of the inherent limitation of osmotic pressure build-up in any type of closed module. It is therefore the use of submerged open modules, not the use of the natural hydrostatic pressure of deep ocean, that leads to energy saving in MORO.

The submerged open RO modules are configurationally similar to the HF membrane modules used in some membrane bioreactors.[19] Using submerged open modules overcomes the limitation of salt accumulation intrinsic to closed modules and thus substantially reduces the osmotic pressure to be overcome for driving water permeation through RO membranes. However, submerged open modules for seawater desalination cannot be used on the ground or in shallow water using vacuum as the driving force as in MBR, because the maximum vacuum (1 atm) is still far below the osmotic pressure of seawater. Therefore, while deep ocean operation is not the direct cause of energy saving in MORO, MORO must be operated under deep ocean to provide sufficiently high hydrostatic pressure to overcome the osmotic pressure.

Energy consumption of MORO

For MORO, the SEC is mainly the energy required to pump the permeate against gravity to the ground and to overcome the pressure drop along the water pipes. In this section, we will mainly focus on the first part, *i.e.*, the energy for pumping water against gravity. Placing the MORO system deeper in the mesopelagic zone creates a larger driving force for water transport and leads to a higher water flux. However, more energy is required to pump the permeate to the ground when the permeate is generated deeper in the ocean. Therefore, the SEC of MORO is simply the osmotic pressure of seawater (π_0, ~27 bar or 0.75 kW h m^{-3}) plus an additional over-pressure required to drive water permeation at a finite flux. Specifically, SEC as a function of flux, J, can be estimated as (see the ESI†):

$$\mathrm{SEC}(=\Delta P)=\frac{J}{A}+\pi_0\exp\left(\frac{J}{k}\right) \tag{1}$$

where A is the water permeability of the RO membrane and k is the mass transfer coefficient. The second term in eqn (1) accounts for concentration polarization that leads to a slightly higher osmotic pressure at the membrane surface as compared to that in the bulk. While we use a fixed seawater osmotic pressure (π_0 ~27 bar) to demonstrate the concept, we note that π_0 is dependent on both location and depth. The top layer of the ocean (down to ~200 m) is a mixed layer and typically exhibits a limited temperature change.[20] Below the mixed layer is the thermocline where temperature drops rapidly (the rate of temperature decline is spatiotemporally dependent). Meanwhile, the salinity also changes with depth along the halocline, with the direction of change dependent on location. As the van't Hoff equation suggests that π_0 is proportional to both temperature and salinity, π_0 is both depth and location dependent. However, π_0 in the depth range of MORO operation (300–600 m) should not deviate from π_0 of the ocean surface by more than 10%.

We estimate the SEC for MORO and find it to be substantially lower than that for on-ground SWRO (Fig. 2C and D). For conventional on-ground SWRO, the optimal WR for the minimum practical SEC is well known to be around 50% (Fig. 2C). Reducing the WR is theoretically beneficial to energy efficiency because the lower brine osmotic pressure reduces the applied pressure and thus the SEC of the RO separation process alone (red curve in Fig. 2C). However, as all feedwater is subject to pretreatment and goes through a high-pressure pump that is not perfectly efficient, and the unrecovered brine also goes through an imperfect energy recovery device, a very low WR results in a large practical SEC with major contributions from pretreatment and energy loss in the high-pressure pump and energy recovery device (blue curve in Fig. 2C). Balancing the contributions from the intrinsic energy requirement and from other energy consumptions to minimize the overall SEC results in an optimal WR of ~50% and a practical SEC of ~3 kW h m^{-3}, which is about four times the seawater osmotic pressure.[9]

For MORO, the WR is practically zero as the feedwater is the entire ocean and thus the minimum required pressure in this case is simply π_0. In addition, no extra energy is used in MORO for pretreatment or supplementing the energy loss in the energy recovery device, because neither pretreatment nor an energy recovery device is or can be employed. Therefore, the overall SEC for MORO is expected to be less than half of that for an optimized conventional SWRO process. We estimate the SEC for MORO for two scenarios (*i.e.*, different fluxes) using eqn (1) with a water permeability of A = 2 L m^{-2} h^{-1} bar^{-1}, which is typical of polyamide-based RO membranes, and k = 70 L m^{-2} h^{-1}. The choice of mass transfer coefficient, k, which is around half of that in a typical spiral-wound RO module, is deliberately conservative considering the lack of crossflow in MORO. With these assumptions, we estimate the over-pressure required for achieving a permeate flux of 10 and 20 L m^{-2} h^{-1} to be ~9 and ~19 bar, respectively, which corresponds to an extra SEC of 0.25 and 0.53 kW h m^{-3}, respectively (Fig. 2D). Even with a flux of 20 L m^{-2} h^{-1}, the overall SEC of MORO is still lower than the minimum SEC at a WR of 50% for the RO separation process alone and is less than half of the practical SEC for on-ground SWRO.

Pressure drop along the water transport pipe

One major technical challenge for implementing MORO is attributable to the unfavorable coastal topography for connecting to the ground an engineered system placed >300 m deep in the ocean (Fig. 3A). Specifically, the very wide (~75 km on average) continental shelf is shallow and declines very slowly, at an average slope of only ~1.7 m km^{-1}, as it moves away from the coast.[20] Consequently, the working depth of MORO, which is around ~300 m or deeper, cannot be reached within the continental shelf. Beyond the continental shelf, the continental slope declines rapidly at a slope of ~70 m km^{-1}. Therefore, MORO should be placed just a few kilometers beyond the continental shelf. The problem, however, is that the desalinated water needs to be pumped through a very long pipe before it arrives at the on-ground post-treatment and distribution facility. Pumping a large volume of water would potentially require a large amount of energy and eradicate all the energy saving from using MORO.

The pressure drop (also quantified as the head loss) is strongly dependent on the flow rate, the pipe diameter, and the pipe length, and can be quantified by the Darcy–Weisbach equation:[21]

$$\mathrm{SEC_D} = \Delta P_\mathrm{D} = L\rho f_\mathrm{D}\frac{8}{\pi^2}\frac{Q^2}{D^5} \tag{2}$$

where $\mathrm{SEC_D}$ is the specific energy consumption to compensate pressure drop ΔP_D (again, $\mathrm{SEC_D}$ and ΔP_D have the same dimension), L is the pipe length, ρ is the water density, Q is the volumetric flow rate, D is diameter of the pipe, and f_D is the Darcy friction factor that is dependent on the characteristics of the pipe, the fluid, and the flow. The water flow in this application context is always in the turbulent regime. For baselines, we use a "smooth pipe" assumption to obtain the lower-bound of $\mathrm{SEC_D}$, with which f_D can be quantified using the following phenomenological equation:

$$\frac{1}{\sqrt{f_\mathrm{D}}} = 1.930\log_{10}\left(\mathrm{Re}\sqrt{f_\mathrm{D}}\right) - 0.537 \tag{3}$$

where Re is the Reynold number. We also estimate the $\mathrm{SEC_D}$ with medium and high pipe roughness (0.2 and 1 mm, respectively) using the Moody friction factor.[22]

Applying eqn (2) with the three pipe roughness assumptions to a series of scenarios with a pipe length of 80 km yields the pressure drop for different flow rates and pipe diameters (Fig. 3B). Plotting the pressure drop against flow rate in a $\log_{10}$–$\log_{10}$ graph reveals that ΔP_D scales with Q by a power of ~1.8. The results presented in Fig. 3B suggest that the pressure drop along this very long (80 km) pipe is negligibly small if the pipe diameter is sufficiently large and/or the flow rate is sufficiently low. For example, with 10 MGD (million gallons per day), the pressure drop is only ~2.3, 0.3, and less than 0.1 bar with a pipe diameter of 1.0, 1.5, and 2.0 m, respectively (for reference, seawater osmotic pressure is ~27 bar). Therefore, the extra energy to deliver the desalinated water to the ground, $\mathrm{SEC_D}$, is theoretically not an impediment for implementing MORO, as long as constructing the water transport pipes is economically viable. To minimize $\mathrm{SEC_D}$, we can either use a very large pipe or use multiple small pipes, whichever is more economically favorable. For example, if we need to build a MORO system of 100 MGD, which is comparable to the largest SWRO plant in the world (Sorek at Israel, 120 MGD), we can employ 10 water transport pipes with a diameter of 1.0 m and spend only an extra ~0.064 kW h to deliver 1 m^3 of desalinated water to the ground.

Other considerations for practical implementation

In addition to the relatively large water transport distance, there remain several major issues to be addressed toward the practical implementation of MORO which differs from the conventional on-ground SWRO process in its operation. The use of open modules in MORO, which is the key to energy

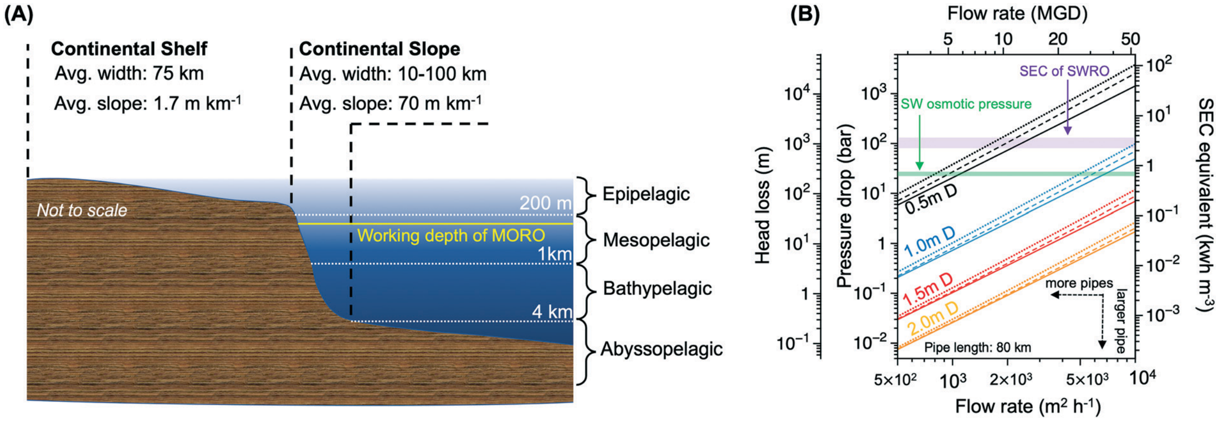

Fig. 3 (A) Illustration of the coastal topography featuring the continental shelf and continental slope. The continental shelf is on average 75 km wide but has a small average slope of ~1.7 m km^{-1}. The water on the continental shelf is in the epipelagic zone. The mesopelagic zone is usually reached in the continental slope which has an average slope of 70 m km^{-1}. The schematic is not to scale. (B) Pressure drop (in bar), head loss (in meters), and SEC equivalent (kW h m^{-3}) at different flow rates with cylindrical pipes of different diameters. The solid lines are obtained based on the smooth-pipe approximation according to eqn (3), whereas the dashed and dotted lines are constructed using a Moody friction factor with a pipe roughness of 0.2 and 1.0 m, respectively (performed using a pressure drop calculator provided in ref. 22). The osmotic pressure of seawater and the SEC of the state-of-the-art SWRO (RO process alone) are also given as benchmarks.

saving, has two major practical implications. On the positive side, MORO does not require any ERD because only the desalinated water is pumped to the ground. Therefore, the capital cost for installing ERDs and the energy loss due to the inefficiency of such devices are both eliminated. On the flip side, no active pretreatment can be performed in MORO as in on-ground SWRO processes due to the open module configuration. For on-ground SWRO, pretreatment is of paramount importance for protecting the RO unit process and ensuring its stable performance.[17,18] The lack of pretreatment will result in organic and biological fouling inside the spiral-wound RO modules, which can lead to irreversible performance deterioration over time.

There are two distinct characteristics of MORO that may considerably reduce its fouling potential. First, MORO is operated in the mesopelagic zone that has less than 1% of the solar irradiance at sea level, a lower temperature, and thus substantially lower microbiological activity and biomass than the epipelagic zone from which on-ground SWRO systems draw water.[23] Second, because feed water is not concentrated in MORO, concentration of foulants in on-ground SWRO, which would aggravate fouling near the exit of the feed stream in a spiral-wound module, would not occur in MORO. Despite these two advantages of MORO in reducing fouling propensity, whether organic and biological fouling is an important or even unsurmountable technical challenge remains uncertain until pilot experiments are performed in a real environment of the mesopelagic zone.

In typical SWRO plants, the operating pressure is progressively increased to overcome the additional water transport resistance induced by fouling, so that a constant flux can be maintained. Membrane cleaning will be performed once the operating pressure exceeds a certain limit. If fouling indeed occurs in MORO, the system can in theory be gradually lowered to a greater depth to gain the extra driving force required to maintain a constant flux. For membrane cleaning, an innovative approach based on the principle of osmotic backwash may be used.

In this approach, as illustrated in Fig. 4, we will reduce the pump pressure (of the same pump for delivering water to the ground) and reverse its direction to push water through the HF membranes from inside out. In the water production stage, water permeates from the exterior into the interior of the HF membranes (*i.e.*, forward flux) because the hydrostatic pressure of the mesopelagic zone, P_{HS}, exceeds the osmotic pressure difference, $\Delta\pi$. A pump pressure that is equal to P_{HS} plus the pressure drop along the pipe is applied to deliver the desalinated water to the ground. In the cleaning stage, the pumping direction is reversed, and the pressure is reduced, so that the net pressure, P_{Clean}, (*i.e.*, P_{HS} minus the applied pressure) is lower than $\Delta\pi$. Under these conditions, the desalinated water will permeate through the HF membranes from inside out and wash the foulants away. Such a cleaning scheme is in principle similar to, but different from, the osmotic backwash as we know it.[24,25]

The same cleaning method does not work for on-ground SWRO with TFC-PA membranes, because the large backpressure would potentially destroy the membrane by delaminating the polyamide layer from the polyethersulfone support. Thus, the applied pressure is only reduced, not reversed (in direction), in the osmotic backwash process for on-ground SWRO. In MORO, however, osmotic backwash is modified with a tweak to take advantage of the particular operating conditions of MORO in which the backpressure is countered by the hydrostatic pressure of the ocean. Because the total hydraulic pressure always exerts force on the polyamide layer against the support layer, pointing into the HF, the HF membrane is not at risk of delamination.

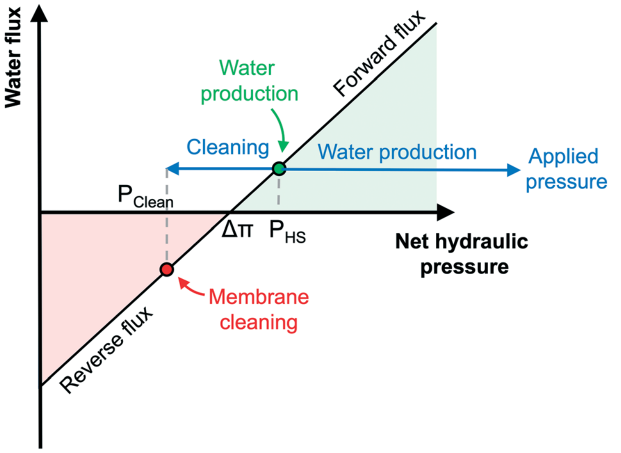

Fig. 4 Water flux as a function of net hydraulic pressure. The net hydraulic pressure is the natural hydrostatic pressure, P_{HS}, in the water production stage, and the difference between P_{HS} and the pressure applied in the membrane cleaning stage. In the water production stage, P_{HS} exceeds the osmotic pressure difference across the membrane, $\Delta\pi$. The forward water flux is proportional to the difference between P_{HS} and $\Delta\pi$. A pressure is applied to pump the desalinated water to the ground. In the cleaning stage, a pressure higher than $P_{\mathrm{HS}} - \Delta\pi$ is applied in the opposite direction so that the net hydraulic pressure, P_{Clean}, becomes lower than $\Delta\pi$ but remains positive. The reverse flux is proportional to the driving force which is the difference between $\Delta\pi$ and P_{Clean}.

Finally, the impacts of MORO on the local ecosystem also differs from that of on-ground SWRO. While MORO occupies a much larger volume of undersea space, no brine will be generated and discharged from MORO. MORO would only create a very small salinity gradient near the modules instead of generating a salinity shock as in conventional SWRO brine discharge. Moreover, the mesopelagic zone where MORO is installed has a vastly different ecology as compared to that of the epipelagic zone where water intake and brine discharge of on-ground SWRO occur.

Prospect and research needs

While RO has transformed the industry of seawater desalination over the last half century, MORO has the potential to again transform SWRO in the coming decades by enabling a substantial energy saving or even reaching the ultimate limit of energy consumption for seawater desalination. With a 60% reduction of the current SEC for SWRO, which appears to be practically feasible with MORO, an enormous annual electricity saving close to 90 TW h may be achieved based on the projected global SWRO capacity of ~101 million m^3 per day in 2030.[26] Being a radically new approach, MORO requires drastically different infrastructure that does not exist as of today and will face various practical challenges that need to be addressed before it can be widely adopted.

As the first step, we need to develop open RO modules suitable for the operating conditions of MORO. This would require redesigning RO membrane modules using hollow fibers without enclosures, similar to those used in membrane bioreactors. We will also need to investigate the potential of organic and biological fouling in MORO when operated in the mesopelagic zone or an experimental setting with similar environmental and operating conditions and test the strategies for fouling mitigation and membrane cleaning. Once MORO is proven technically feasible, in-depth technoeconomic analysis is needed to evaluate whether the substantial theoretical potential for energy saving can indeed be harnessed after various practical considerations, and whether MORO can become economically more favorable as compared with conventional SWRO on-ground. Lastly, the potential impact of installing large MORO systems on the ecosystem of the mesopelagic zone also needs to be studied to ensure the ecological compatibility of MORO. Despite all these practical challenges and uncertainties, MORO is worthy of future research and development because the reward from its success can potentially be very substantial.

Conflicts of interest

There are no conflicts to declare.

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