



Elevation-distributed multistage reverse osmosis desalination with seawater pumped storage

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Abstract

A seawater reverse osmosis (RO) plant layout based on multistage RO with stages located at different elevations above sea level is described. The plant uses the weight of a seawater column from pumped storage as head pressure for RO (gravity-driven multistage RO) or to supplement high-pressure pumps used in RO (gravity-assisted multistage RO). The use of gravitational force reduces the specific energy for RO compared to using high-pressure pumps. By locating the RO stages at different elevations based on demand sites, the total specific energy consumption for RO and permeate transport to different elevations above sea level is reduced from that for locating the RO process entirely at sea level followed by lifting the desalinated water. A final RO stage at sea level uses seawater pressurized by energy recovery from the residual energy of the brine generated from the preceding RO stage. Examples of the plant layout that do not include pump inefficiency and head losses in pipes are described for South Sinai, Egypt, which is a mountainous region that suffers from water scarcity. A gravity-driven multistage RO with a storage tank at 660 m above sea level is considered. For five RO stages located 316–57 m above sea level with 10% recovery at each stage, the specific energy is ~32% lower than that for a plant located at sea level operating at the minimum specific energy followed by lifting the same quantity of desalinated water to the elevations of the distributed RO stages. For two stages located at 222 and 57 m above sea level with 30 and 20% recovery, respectively, the reduction in specific energy is ~27%. For gravity-assisted five-stage RO with the first stage at 260 m above sea level, while the last stage is at sea level with 10% recovery at each stage the reduction in specific energy is ~32%. The proposed RO plant layouts can be adapted to other regions with comparable topography.

Keywords Reverse osmosis · Seawater desalination · Distributed multistage layout · Gravity-driven reverse osmosis · Pumped storage

Abbreviations

HPP	High-pressure pumps
SE _{min}	Minimum specific energy
PV	Photovoltaic
PHES	Pumped hydroelectric energy storage
RO	Reverse osmosis
SWRO	Seawater reverse osmosis
SE	Specific energy
TDS	Total dissolved solids

Introduction

Most of the Middle East is in a state of water poverty (Maftouh et al. 2022; Bozorg-Haddad et al. 2020). To meet the increasingly rising demand for freshwater, seawater desalination is used and new plants are being built or are planned. The reverse osmosis (RO) technology has advanced to the point of making it the most efficient among seawater desalination methods, with most recently built and planned seawater plants based on RO (Elimelech and Phillip 2011). However, seawater desalination is an energy-intensive process with specific energy (SE, energy required to generate a unit volume of permeate water) that increases with the osmotic pressure of the water available for desalination (Liu et al. 2011). The osmotic pressure of seawater is proportional to the total dissolved solids (TDS) concentration. The TDS of seawater varies from 30,000 ppm to slightly above 40,000 ppm, depending on the region (Anis et al. 2019). For

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a TDS of 35,000 ppm, the minimum SE is approximately 1.07 kWh/m^3 for 50% recovery (Lin and Elimelech 2015). In reality, the SE of large-scale desalination plants is much higher than that, with the SE of seawater reverse osmosis (SWRO) typically $2.5\text{--}4.0 \text{ kWh/m}^3$ (Voutchkov 2018). The SE of most currently operating SWRO plants is $3.5\text{--}4.5 \text{ kWh/m}^3$, which includes seawater pre-treatment and post-treatment processes (Kim et al. 2019).

Reduction of the SE of SWRO was achieved by increasing the efficiency of the various components needed in the RO process and by improved system design. Significant advances have already been made in developing high permeability membranes with high salt rejection (Hailemariam et al. 2020), and energy recovery devices based on pressure exchange with the efficiency of about 95% used for recouping residual energy stored in the brine (Kim et al. 2019). Also, for a plant size of $100,000 \text{ m}^3/\text{day}$, the efficiencies of high-pressure pumps (HPP) and low-pressure booster pumps reach 88.5–90 and 88%, respectively (Torre 2008). Therefore, further development at the component level will not significantly reduce the SE of SWRO, although it can improve operational aspects of RO, such as reduced fouling of the membranes, improved durability of HPP, and reduced costs of components.

At a system level, several approaches have been studied. These approaches aim at limiting waste energy in the RO process by keeping the energy used to pressurize the membranes close to the thermodynamic minimum energy needed for separation. Two promising approaches that have been studied are batch RO processing (Park et al. 2020; Wei et al. 2020; Cordoba et al. 2021) and multistage RO (Lin and Elimelech 2015; Jeong et al. 2019). In batch processing, the applied pressure on a batch is increased to slightly above the thermodynamic minimum energy needed for separation till a certain permeate recovery is reached. In multistage RO, the RO process is divided into several stages with increased pressure corresponding to that needed to exceed the minimum required energy for the water salinity to generate an acceptable flow of permeate. In the first stage, a pressure slightly above the osmotic pressure of the feed is applied. The higher salinity of the retentate (brine) is fed into the second stage with a higher pressure to recover more permeate. Pumps are used between the RO stages. This process continues for several stages, keeping the applied pressure above, but close to, the required minimum for RO. The more stages included, the closer the SE will be to the thermodynamic limit. However, adding RO stages requires more pumps, RO modules, and pressure vessels making the plant more complicated (Wang et al. 2020a). Both batch and multistage RO are promising for bringing the SE of RO closer to the thermodynamic minimum energy requirements.

Another area of SWRO system efficiency improvement is the use of renewable energy to drive the RO process.

Among the energy sources that are gaining utility in RO are solar photovoltaic (PV) and wind energy or hybrids of both (Esmailion 2020; Maleki 2018; Mito et al. 2019; Khan et al. 2018; Karimanzira 2020). Alternative energy for RO applications includes wave and tidal energy and geothermal energy or hybrids, such as a hybrid of PV and tidal energy (Delgado-Torres et al. 2020; Leijon et al. 2020), and various hybrids of PV, solar thermal, wind, and geothermal (Esmailion 2020). Solar and wind energy use for SWRO can be connected to the grid or operated off-grid. Solar-wind energy-powered multigeneration systems for electric power generation, freshwater production, hydrogen generation, and providing cooling and heating loads were studied. The results showed a reduction in the total unit cost of the products (Esmailion et al. 2022). SWRO powered by renewable energy sources is a sustainable method for providing desalinated water near coastal locations without or with a sufficient electrical grid. The intermittent nature of solar and wind energy requires storage, as commercial RO plants are designed to work at constant feedwater flow and controlled water pressure to the RO unit. This requires a steady power level for pumps supplying the pressure on the RO membranes. Also, the steady operation of SWRO plants maximizes desalinated water production, is easier to maintain, and maximizes the use of capital investment. To achieve steady operation of SWRO with off-grid PV or wind energy, it is necessary to have reliable and efficient energy storage.

Many countries in the Middle East have significant potential for renewable energy, in particular solar and wind. Middle East countries with significant reserves of oil and gas recognize the need to develop an economy based on renewables. The use of renewables in desalination can help in meeting the needs of the populations in the Middle East (Esmailion et al. 2021). A case study of the large-scale use of solar and wind energy combined with efficient pumped hydroelectric energy storage (PHES) for combined energy generation and gravity-driven SWRO was conducted for Iran, a country rich in fossil fuels (Slocum et al. 2022). The analysis showed that renewables with PHES can significantly contribute to meeting the future needs for energy storage and freshwater of the population of Iran while shifting the country's use from fossil fuels to renewables.

SWRO plants are built at locations near seashores to facilitate access to feedwater and disposal of brine. When mountains are near seashores, PHES becomes attractive and is competitive with other electrical energy storage methods, such as batteries. It was proposed to combine renewable energy with PHES, where the stored seawater is used for both hydropower generation and as head pressure for RO (Slocum et al. 2016). The study noted that the ideal heights of PHES for electrical generation and that required to generate enough pressure for RO coincide and are in the range

of 500–700 m. The hydropower requirement for one person uses 10–20 times more water than the individual freshwater requirement (Slocum et al. 2016). Therefore, the combined hydropower and RO based on PHES reduces the total energy/water system cost and allows efficient disposal of the brine by dilution with water from the hydropower. The electrical round-trip energy efficiency of PHES varies between 70 and 85% with about half the loss in the pump cycle and the other half in the electrical generation cycle (Barbour et al. 2016). Therefore, pump inefficiency and head losses in pipes in raising the water to the upper reservoir amount to approximately 7.5–15%.

Other studies discussed RO operation based on gravitational potential energy in which seawater head pressure in a vertical shaft (Lin and Chen 2019), or of a weight that is lifted (Fadigas and Dias 2009), is used to apply pressure to the RO membranes. A review of hydrostatic pressure use in RO desalination indicated possible energy savings (Charcosset et al. 2009). In the water column head pressure approach, seawater is pumped to a height sufficient for the pressure needed for RO. Then, the weight of the seawater column is used to apply pressure to the RO membrane. Lifting the seawater can be achieved using pumps operated by PV energy without battery storage, saving the capital and operating costs of storage (Chandel et al. 2015). In a recent National Renewable Energy Lab report, the cost of storage was indicated to be higher than that of the PV panels for utility-scale PV-plus storage (Ramasamy et al. 2021). The cost of storage for residential PV systems was indicated to be several times more than the PV panels, depending mainly on the resiliency of the system (Ramasamy et al. 2021). The pumped seawater can act as an efficient way to store water when the electricity demand is low, therefore, reducing the cost of electricity for operating the SWRO plant.

At locations where mountains are close to the seashore, the energy used for lifting the water adds to the total energy required for supplying the desalinated water to demand sites. Neglecting losses in the pumps and pipes, raising freshwater to a height $h = 500$ m requires 1.363 kWh/m^3 compared to a minimum SE of $\sim 1.07 \text{ kWh/m}^3$ required for desalinating seawater with a TDS of 35,000 ppm at 50% recovery (Lin and Elimelech 2015). The energy required to lift water 1000 m is 2.725 kWh/m^3 , which is comparable to the SE of an efficient SWRO plant (Voutchkov 2018). Pumping water to high altitudes is significantly more costly than pumping water at the same altitude. For example, pumping water 100 m vertically costs as much as transporting water about 100 km horizontally (Zhou and Tol 2005). The energy consumption for delivering desalinated water to high altitudes near SWRO plants must be considered along with the energy used to operate the plant.

This article describes an SWRO plant layout for supplying water to demand sites at high elevations using less

energy than an SWRO plant entirely at sea level. In this elevation-distributed multistage RO desalination plant layout, the feed seawater is pretreated near the shore at sea level. Then, the treated seawater is pumped to a high elevation and stored in a reservoir or a tank. The elevated seawater storage supplies water to the RO stages, which are located at demand elevations. Seawater gravitational pressure alone or in combination with HPP is used to feed RO stages, each located at a certain elevation above sea level based on desalinated water demand. The retentate from one stage is fed into the next stage which is located at a lower elevation to keep the pressure on the RO membranes high enough to generate a certain desalinate recovery required at that stage. Post-treatment is conducted as required after each stage. The brine output of the last stage is at the highest pressure in the SWRO plant. The energy stored in the pressurized brine is used to drive another RO stage near the shore at sea level. Then, the brine can be mixed and disposed of in seawater.

The proposed approach reduces the total energy use for the combined RO desalination and desalinated water lifting to demand elevations higher than the sea level. Moreover, pumped water storage with efficient alternative energy sources, such as PV with or without grid connection, can be used to operate water pumps to store the water at a reservoir or a tank for RO. Gravity-driven RO can operate more efficiently than the conventional RO using HPP because the potential energy of the water column is reduced only when the water flows through the RO module. The RO stages can be operated continuously throughout the day maximizing their output and providing stable operation of the SWRO plant.

Methodology

Background on multistage pass-through RO

For SWRO, the lowest pressure required for desalination is thermodynamically limited by the osmotic pressure of the feed. The lower the salinity of seawater, the lower its osmotic pressure; therefore, less energy is needed to separate the desalinated water from it. For a Red Sea location, the TDS was measured to be 42,070 (Abdel-Aal et al. 2015), corresponding to an osmotic pressure $\pi_0 = 30.343$ bar (Osmotic pressure calculator, Lenntech, URL xxxx). This seawater condition is used in the analysis presented here.

In a single-stage cross-flow RO module with constant pressure, the increase in the saline solution osmotic pressure downstream of the RO membrane channel requires that the pressure applied to the feed to equal or exceed the maximum osmotic pressure in the membrane channel (Song et al. 2003). The need to apply pressure significantly more than the osmotic pressure of the feed increases the minimum SE

required to generate a unit volume of permeate. Multistage RO aims at operating the stages at applied pressures that increase from one stage to the next based on the increase of the osmotic pressure of the brine from the preceding stage and, therefore, reduces the overall energy consumption of the RO process. In single-stage single-pass RO, the minimum applied pressure for recovery R is equal to the brine osmotic pressure. The resultant minimum specific energy $SE(R)$ dependence on the osmotic pressure π_0 is (Lin and Elimelech 2015; Liu et al. 2011; Wang et al. 2020a):

$$SE(R) = \frac{\pi_0}{1 - R} \tag{1}$$

Figure 1(a) shows the dependence of SE, normalized to the feed osmotic pressure π_0 , on recovery. The striped area under the curve represents the minimum energy for a thermodynamically reversible process to generate a unit volume of permeate SE_{min} when the applied pressure is continuously maintained equal to the equilibrium brine pressure, which is (Lin and Elimelech 2015; Shrivastava and Stevens 2018):

$$SE_{min} = -\frac{\pi_0}{R} \ln(1 - R) \tag{2}$$

where SE_{min} is the minimum energy to generate a unit volume of permeate. For 50% recovery and $\pi_0 = 30.343\text{bar}$, $SE_{min} = 1.168 \text{ kWh/m}^3$. The blue area on top of the minimum pressure curve represents the additional energy required in the cross-flow RO. The rectangular area (the sum of the minimum required energy and the additional required energy) in Fig. 1(a) represents the minimum practical energy consumed in a single stage with a constant applied pressure required for 50% recovery, which is 1.686 kWh/m^3 . The larger R , the larger the difference between the

thermodynamic and the practical SE. The energy remaining in the pressurized retentate is represented by the area of the light-yellow rectangle, which for 50% recovery is 1.686 kWh/m^3 , similar to the minimum practical energy consumed.

In multistage cross-flow RO, the excess energy above the thermodynamic required energy is reduced as the number of stages is increased and the SE approaches the value in Eq. (2). However, having a large number of stages is not practical as each stage requires pumps, pressure vessels, connections, and control instrumentations. Figure 1(b) shows SE for a five-stage RO with 10% recovery at each stage. In this case, SE is represented by the shaded area and is 1.257 kWh/m^3 . The energy remaining in the pressurized retentate is the same as for the single stage.

Gravity-driven RO

SWRO requires proximity to the shore for seawater intake and for efficiently disposing of the brine. Most SWRO plants operate with around 50% recovery as lower recovery wastes energy and chemicals used in pretreatment, while higher recovery reduces the efficiency of the RO process. In areas where there are high elevations close to seawater, PHES is suitable for energy storage in the form of the potential energy of water that is pumped from sea level to a higher reservoir. PHES is used to store excess energy from the grid during off-peak hours by pumping water from a lower source to a higher reservoir, then using the stored water to operate turbines generating electricity (Hunt et al. 2020; Javed et al. 2020a). The advantages of using renewables in PHES and RO are the ability to use an intermittent energy source without having to adjust for demand, the high efficiency

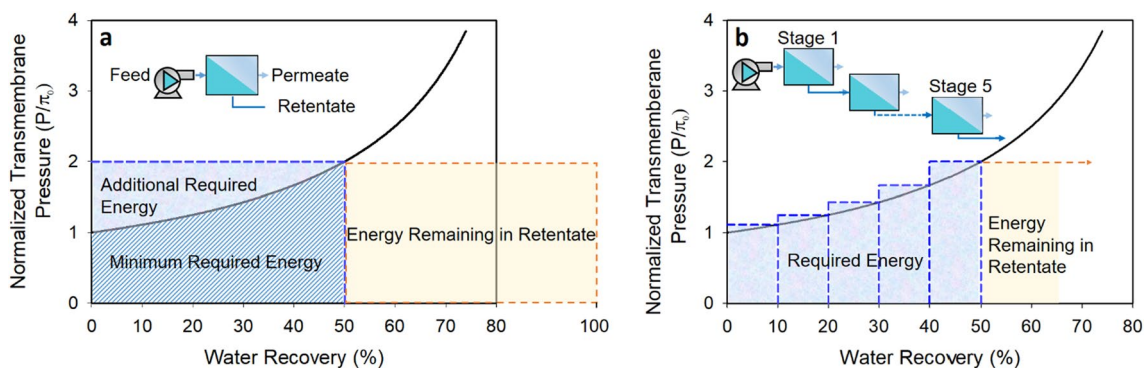


Fig. 1 (a) Theoretical transmembrane pressure normalized to the osmotic pressure of the feed seawater ($\pi_0 = 30.343\text{bar}$) for single-stage constant pressure RO with 50% recovery. The shaded area is the thermodynamic minimum required energy SE_{min} . The blue area on top of the minimum pressure curve represents the additional required energy in the cross-flow RO process. The energy remaining in the pressurized retentate is equal to the sum of the minimum required

energy and additional required energy for 50% recovery. (b) The normalized transmembrane pressure for a five-stage RO with 10% recovery at each stage. The retentate pressure is increased from one stage to the next. The area of the rectangles is the required energy, which is the sum of the minimum required energy and the additional required energy

of PHES, and the direct conversion of gravitational force into head pressure for RO (Slocum et al. 2016; Slocum et al. 2022). Seawater can be pumped to high locations using an intermittent source of energy such as PV or wind. The SWRO plant would then continuously operate with limited seawater storage. For example, an SWRO plant delivering 50,000 m³/day with 50% recovery requires pumping 100,000 m³/day to the storage location. A seawater storage capacity of 50,000–100,000 m³ would assure continuous operation. The stored seawater volume could be in the lower end of that range when assuming constant desalinated water demand and that seawater is pumped to the storage location for more than 12 h/day. Storing this volume of seawater requires one storage tank, preferably with cathodic protection and leak detection to prevent seawater from seeping into the ground.

When HPP are used to drive a single-stage cross-flow RO, the applied transmembrane pressure must be higher than the highest osmotic pressure of the feed into the RO unit, which increases with recovery, as shown in Fig. 1(a). Maintaining this pressure requires energy added to SE_{min}. This energy is supplied by the HPP and increases the SE of the RO. In gravity-driven RO desalination, pumps are used to lift water and store it at a certain height *h*, then the pressure of a water column is applied to the RO membrane, as shown in the inset of Fig. 2. Because of this decoupling of the energy used for lifting water from the pressure applied to the membrane, the RO process does not consume the additional required energy shown in Fig. 1(a). Instead, that potential energy remains in the water column and is only consumed when seawater flows through the RO module

generating desalinated water. Therefore, gravity-driven RO can be more efficient than RO using HPP.

Energy losses in pumps and head losses are not considered for the proposed elevation-distributed multistage SWRO. This is also the case for the SWRO plant at sea level which is assumed to operate at SE_{min} in Eq. (2) and used for comparison with the proposed SWRO configuration. Pumping seawater over long distances involves added head losses that depend on the volume flow rate, pipe diameter, pipe material, and density and viscosity of seawater. The present SWRO plant distributed layout has head losses similar to the previously proposed integrated PHES with RO when considering the water flow that is only used for desalination (Slocum et al. 2016). On the other hand, desalinating seawater at a location near the water source and then pumping the desalinated water to demand sites also involves head losses which, due to the reduced volume, will be less than in the proposed elevation-distributed multistage SWRO. The cost of head losses when pumping water a few km horizontally is small (Zhou and Tol 2005), and would not significantly affect the SE of the elevation-distributed SWRO when compared to a plant at sea level followed by pumping the desalinated water to elevated demand sites.

When using HPP, friction losses in the retentate and permeate channels require higher pressures leading directly to more energy consumption. When gravitational pressure is used in RO, accounting for these head losses requires increasing the height of the water column that is applying pressure on the membrane. However, part of that potential energy is recovered in the retentate. In the gravity-driven RO, a low permeability membrane mainly affects the permeate generation rate as the potential energy of the seawater column remains stored until the seawater flows downward. To the contrary, when HPP are used, they continuously consume energy to maintain the pressure on the RO membrane.

For the ideal conditions assumed in the analysis, the transmembrane pressure needed for RO can be calculated from Eq. (1). For a seawater density of 1029 kg/m³ (corresponding to TDS = 42,070) (Sharqawy et al. 2010; Nayar et al. 2016, to achieve 50% recovery, the water column pressure needed is $p = 2.00\pi_0$, with $\pi_0 = 30.343\text{bar}$. The column height needed to reach that pressure is $h_0 = \frac{p}{\rho_0 g} = 601\text{m}$, where ρ_0 is the seawater density in kg/m³ and *g* is the acceleration of gravity. When considering head losses in pipes and friction losses in RO membranes, the water column height needs to be increased to achieve the desired permeate flux.

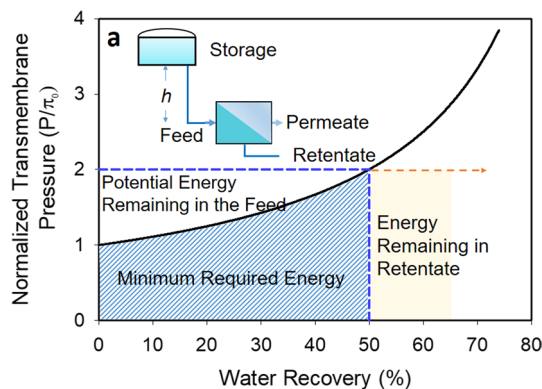


Fig. 2 Theoretical transmembrane pressure normalized to the difference in the osmotic pressure of seawater and permeate for a gravity-driven, single-stage, constant pressure RO with 50% recovery. The inset is a representation of a seawater storage tank or reservoir at a height *h*₀ above the RO module. The shaded area is the thermodynamic minimum energy requirement. For gravity-driven RO, the additional required energy shown in Fig. 1 remains as potential energy in the seawater column. The energy remaining in the pressurized retentate is the same as in Fig. 1(a)

Topography of South Sinai for case studies of gravity RO

The South Sinai Governorate is an arid land with an area of 31,272 km² that resembles a triangular shape surrounded on the East by the Gulf of Aqaba and the West by the Gulf of Suez (www.sis.gov.eg, Story, 68582, South Sinai Governorate?lang=en-us, accessed 11, 24, 2022. xxxx). According to the 2021 statistic issued by the Egyptian Central Agency for Mobilization and Statistics, the South Sinai population was 170,987 (www.sis.gov.eg, Story, 68582, South Sinai Governorate?lang=en-us, accessed 11, 24, 2002. xxxx). The very low population-to-area in South Sinai is mainly due to the lack of freshwater resources. The average rainwater in El Tor measured over 22 years from 1961 to 2015 is 16 mm and in Ras Seder measured over the 18 years from 2000 to 2017 is 10 mm (Gado and El-Agha 2020). Over the past two decades, water desalination has become the major source of freshwater in South Sinai due to freshwater scarcity and distance from the public water network (El-Sadek 2010). Continuous expansion of RO desalination of water from the Red Sea and Gulf of Aqaba is expected (Chenoweth and Al-Masri 2022).

The area of South Sinai is mostly covered with mountains, the highest is Mount Catherine, at 2,629 m above sea level, and is located next to Mount Sinai at 2,285 m above sea level (Noaman 2017). The mountainous areas reach near seawater, especially in the East where mountains edge the Gulf of Aqaba and near the Southern tip of the Sinai. On the Western side, where the Sinai borders the Gulf of Suez, the shore slopes reach mountains at distances from the shore that varies from a few km to about 20 km. Supplying fresh water to the mountainous parts of South Sinai requires lifting water vertically from desalination plants at the seashore which uses energy that is added to that for SWRO. The freshwater scarcity and cost of delivering desalinated water to the mountainous regions in South Sinai have been a major factor in keeping the vast majority of that region scarcely inhabited. Gravity-driven distributed multistage RO with RO stages placed at high elevations aims at reducing the combined cost of desalination and lifting the desalinated water.

Seawater desalination can also take advantage of the abundant renewable energy at and near South Sinai. South Sinai has an average Global Horizontal Irradiance (GHI) ranging from 5500 to 6500 Wh/m² as measured over years 2005–2014 (El-Metwally 2017). The GHI near the Gulf of Aqaba and Gulf of Suez is ~6000 Wh/m², making the area attractive for solar energy to operate water pumps for pumped storage. The use of wind power in South Sinai is also attractive. The mean power density of wind measured over 8 years at a height of 50 m from the ground at Nabq near the Southern end of the Gulf of Aqaba was 367 W/m², and at Ras Sedr at the North of the Gulf of Suez was 368 W/m²

(Mortensen et al. 2006). On the West side of the Gulf of Suez at the Gulf of El-Zayat, the mean wind power density is 900–950 W/m² (Mortensen et al. 2006).

Figure 3(a) shows a Google Earth map of part of South Sinai with two locations suggested as examples for the proposed gravity-driven distributed multistage SWRO with pumped storage. These two locations are proposed to demonstrate the reduced energy consumption for the combined RO desalination and desalinated water delivery at different elevations compared to an SWRO plant at sea level followed by lifting the desalinated water. The first location considered is South of Taba on the Gulf of Aqaba shown in Fig. 3(b). At this location, the mountain touches the shore and rises to 650 m above sea level at a distance of about 1 km from the shore. The topography in this example is ideal for a gravity-driven distributed multistage RO. The location is also near seashore resorts and the town of Taba. The second example is the South of El Tor, the administrative capital of South Sinai, on the Gulf of Suez, shown in Fig. 3(c). In this location, and along a large stretch of the Gulf of Suez, the land rises slowly eastward towards the mountains. The elevation above sea level reaches 400 m at a distance of about 20 km from the seashore followed by mountains. This location provides a wide shore suitable for population centers and economic activities provided that freshwater is available. Therefore, this location is used here as an example of gravity-assisted SWRO with RO stages distributed over the 20 km stretch from the mountains to the shore.

South Sinai's mountainous regions are mainly composed of igneous and metamorphic rocks with the Eastern coast mostly narrow with high sloping mountains, while the Western coast has a relatively wide plain covered by sedimentary rocks (El-Rayes et al. 2015). Site selection for PHES combining energy generation and gravity-driven RO must be suitable for the tunnels needed for power generation and the area topography must allow relatively large water reserves to be stored at high elevations (Slocum et al. 2016). For seawater PHES, there is the additional requirement that the upper water reservoir is well-sealed to avoid seeping of the seawater into the ground. In an area such as the Eastern side of South Sinai, tunneling could be challenging because of the nature of the rocks and the many faults and fractures trending parallel to the Gulf of Aqaba (Elkafrawy et al. 2021). Maps of deep and shallow faults along the Gulf of Aqaba and at Taba are shown in Fig. 2 by Elkafrawy et al. (Elkafrawy et al. 2021), and in Fig. 1 of Khalil, respectively (Khalil 2016). For the proposed distributed multistage RO, the requirements on geological features are more relaxed because there is no need for tunneling and the water storage requirements are much less than in PHES. Using one commercial storage tank can provide enough storage to continuously operate a 50,000 m³/day RO plant.

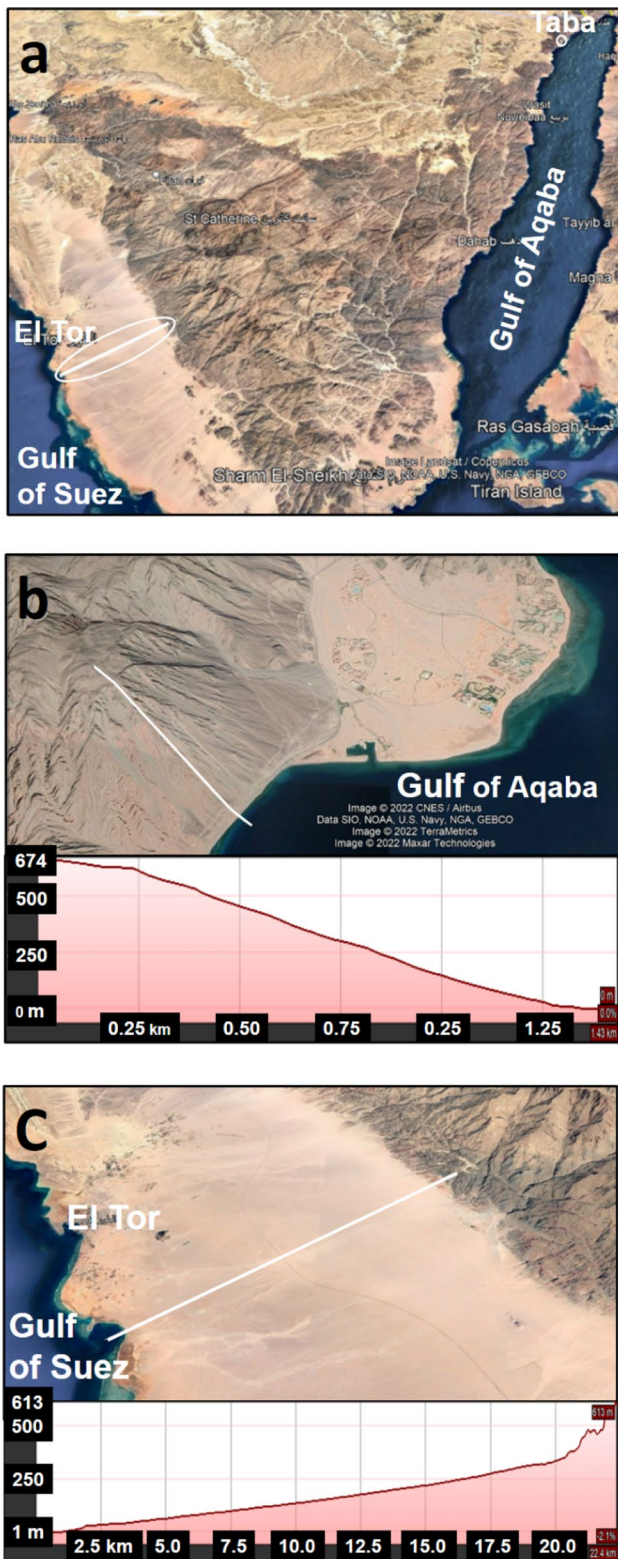


Fig. 3 (a) Google Earth map of part of the South Sinai with two locations considered for gravity-driven distributed RO shown in (b), and gravity-assisted distributed RO shown in (c). The elevation plots of the two locations are shown

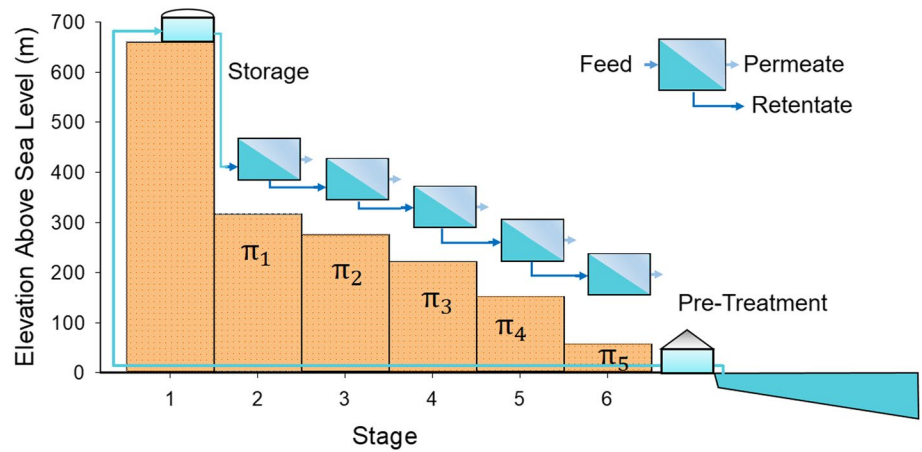
The proposed SWRO plant requires long pipes carrying seawater and the generated permeate. The length of these pipes depends on the local topography. The two examples in Fig. 3 require pipes to run a distance of a few km in Fig. 3(b) and a few tens of km in Fig. 3(c). Corrosion protection and leak detection are issues that must be considered, but these issues are also present in seawater PHES. A review of water pipe inspection technologies was provided by Liu and Kleiner (Liu and Kleiner 2013). Water supply and drainage pipes are typically buried at a shallow depth of about one to a few meters under the surface, depending on the soil characteristics and regional temperature (Stampolidis et al. 2003; Jeong and Abraham 2004). In South Sinai where a temperature drop below water freezing is not reported at sea level (Gamal 2017), insulated above-ground piping is suitable, and the pipes can potentially be used to collect solar energy as heat (Wang et al. 2020b).

Gravity-driven and gravity-assisted distributed multistage RO

Gravity-driven multistage RO

A gravity-driven elevation-distributed multistage SWRO plant is proposed for the topography in Fig. 3(b). The number and location of RO stages depend on the desalinated water demand site elevations and practical plant design aspects, such as limiting the number of stages to reduce capital and maintenance costs. A final stage is located at sea level to recover the brine energy and use it for seawater desalination. A schematic of the proposed plant layout is shown in Fig. 4. For this example, desalinated water is supplied at different heights up to 316 m above sea level. The mountain rises to 674 m above sea level at a distance of 1.25 km from the shore. Seawater pretreatment is done near the shore at sea level, then the treated water is pumped to an elevation of 660 m, where it is stored in a tank or a reservoir. The energy source for the pumps can be optimized based on the solar and wind conditions in the area or excess power in the grid. Also, lifting the water can be done by using HPP or multiple pumps supplying lower pressure along with small water storage tanks placed in series at different elevations. The storage elevation of 660 m is selected to provide a pressure of $1.11\pi_0$ at the first stage of the RO modules, which is located 316 m above sea level. This pressure results in a 10% recovery from the first RO stage. Then, stages 2 through 5 are located successively at elevations lower than the first stage to achieve 10% recovery at each stage with 50% total recovery. The different elevations of the RO stages are selected so that the water column applies pressures of $\pi_2, \pi_3, \pi_4,$ and π_5 with values of 1.25, 1.43, 1.67, and 2.00 π_0 , respectively. Based on the gravitational force, the pressure at the input of stage n is:

Fig. 4 Arrangement of the five-stage distributed gravity-driven RO stages located on different elevations that correspond to demand sites. This distributed RO can be implemented at a location such as in Fig. 3(b). The pressure of the feed at each stage is $\pi_1, \pi_2, \pi_3, \pi_4,$ and $\pi_5 = 1.11, 1.25, 1.43, 1.67,$ and $2.00 \pi_0$, respectively. The feed for the 6th stage at sea level with pressure π_6 comes from the PX device used to recover the energy in the brine and transfer that energy to treated seawater



$$P_n = \sum_{n=1}^5 (\rho_{n-1}g(h_{n-1} - h_n)) \tag{3}$$

where ρ_{n-1} is the water density entering stage n , h_0 is the height of the reservoir above sea level, and h_1 through h_5 are the heights of the RO stages $n = 1$ through 5 . The heights to achieve 10% recovery at each stage correspond to 316, 275, 222, 152, and 57 m above sea level. The final 6th stage with pressure π_6 is located at sea level. The energy in the brine after stage 5 is recovered by the pressure exchanger (PX) energy recovery device and used to pressurize seawater fed into stage 6.

The energy needed to pump seawater to the storage reservoir is:

$$E = \rho_0gh_0V \tag{4}$$

where ρ_0 the seawater density, h_0 is the storage reservoir height, and V is the pumped volume of seawater. If we neglect head loss in pipes and assume 100% efficiency for the operation of the pumps raising the seawater to the reservoir, then the gravitational energy stored in the reservoir is consumed in the downward flow only when water is allowed to flow generating permeate at each stage. When only the gravitational force of the water column causes the downward flow through the RO stages and if we also neglect head losses in the downward flow, the energy consumed in stages 1 through 5 is the sum of the energy consumed at each stage. From Eq. (2) this sum is:

$$E_c = \sum_{n=1}^5 \left(-V_n \frac{\pi_{n-1}}{R_n} \ln(1 - R_n) \right) \tag{5}$$

where V_n is the volume of water entering stage n , π_{n-1} is the osmotic pressure of feed water entering stage n , and R_n is the recovery at stage n . The value of E_c adds up to the minimum energy for a thermodynamically reversible process yielding

10% recovery at each stage. This analysis assumes that water transport between stages is controlled to allow the required permeate to be generated in each RO stage.

The energy remaining in the brine E_b after the 5th stage in the pass-through gravity-driven multistage RO in Fig. 4 is:

$$E_b = E - E_c \tag{6}$$

where E and E_c are defined in Eqs. (4) and (5), respectively. When HPP are used, energy is consumed to pressurize the feed flow to the osmotic pressure of the brine and that energy continues to be consumed all the time the pump is operating regardless of how much permeate is generated, which depends on the membrane permeability. For gravity-driven RO, potential energy is stored in the water column and is consumed only when water flows downward.

In gravitational RO, transport energy losses can be reduced compared to PHES since there are no losses in electrical generation using turbines as in PHES. Friction losses in the RO modules in gravity-driven RO are expected to be similar to that in multistage RO at sea level. There will be extra losses due to friction in the long tubes used to transport seawater to the reservoir and downward to the RO stages. These losses due to friction h_f (m) can be estimated from the Darcy-Weisbach formula (Brown 2003):

$$h_f = \frac{fL\langle v \rangle^2}{2Dg} \tag{7}$$

where f is the Darcy friction factor, L is the length of the pipe, D is the inner diameter of the pipe, and $\langle v \rangle$ is the mean flow velocity of the fluid. As indicated previously, the hydro-power requirement for one person uses 10–20 times more water than the individual freshwater requirement for PHES, while the height requirement for PHES and that for RO is similar (Slocum 2016). Therefore, if the pipes used for the gravity RO have similar L, D, f , the h_f as for the proposed

distributed gravity-driven RO, head losses would be much less than in PHES since the flow rate, and consequently $\langle v \rangle$, is significantly lower.

This example is suitable for supplying fresh water to small communities and resorts to be located in the mountains overlooking the Gulf of Aqaba at elevations corresponding to or near where the RO modules are located. The proximity of the mountains to already established seashore resorts in the town of Taba, which is located within viewing distance of the borders of three countries neighboring Egypt, adds to the attractiveness of this site for expanding tourism and associated service activities.

Gravity-driven RO operates near the SE_{min} when inefficiencies of water pumps, head losses in water transport, and friction losses in the RO modules are not considered. With these assumptions, the SE for the RO layout in Fig. 4 follows Eq. (2) for 50% recovery giving $SE = 1.168 \text{ Wh/m}^3$. The specific energy consumed to lift seawater to the reservoir at an elevation 660 m above sea level is given by Eq. (4). After setting the water volume at 2 m^3 to generate 1 m^3 of desalinate for a total of 50% recovery at stages 1 through 5, the specific energy to lift seawater to the reservoir is 3.701 kWh/m^3 . The difference between the energy used to pump seawater to the reservoir and that used to desalinate water in stages 1 through 5 remains in the brine exiting stage 5 when not accounting for head losses in pipes and other friction losses in the RO modules. Recovering the potential energy stored in the brine after stage 5 and using it for desalination can be accomplished by placing another RO module at sea level to recover more water from the brine. Because of the high salinity of the brine after stage 5, this approach is not the most energy-efficient and will not be justified unless there is a need for large R , such as for subsequent extraction of minerals from the brine. A more efficient approach is to transfer the brine energy to pre-treated seawater through a PX energy recovery device, as shown in Fig. 5. The pressurized seawater osmotic pressure π_0 can then be desalinated in RO stage 6, which is at sea level.

A similar SE is obtained if seawater is pumped to a height that gives enough head pressure for 50% recovery then the water column pressure is used to drive RO at sea level. However, by placing RO stages at the desalinated water demand elevations, the energy for pumping the desalinated water to the five heights is saved. In the example of Fig. 4 with 50% recovery in stages 1 through 5 distributed equally at each of the five heights, this amounts to $\sum_{i=1}^5 mgh_{ROi} = 0.557 \text{ kWh/m}^3$, where $h_{RO} = 316, 275, 222, 152, 57 \text{ m}$ above sea level. In this example, locating the multistage RO modules at different elevations results in $\sim 32\%$ lower SE compared to SWRO at sea level operating at SE_{min} followed by lifting the same quantity of desalinated water to the elevations of the distributed RO modules. For the elevation-distributed multistage SWRO, the potential energy of the permeate generated at

different elevations is not considered because the comparison assumes that the demand sites are at the elevations of the distributed modules. For RO with five stages using HPP to reach 50% recovery, as in Fig. 1(b), $SE = 1.257 \text{ kWh/m}^3$ for desalination in addition to the energy required to lift the desalinated water to demand sites. A comparison of the SE of the distributed RO in Fig. 4 to the five-stage RO in Fig. 1(b) shows a reduction of $\sim 36\%$ for the gravity-driven distributed RO when desalinated water production and transport are considered. These comparisons assume that there is an additional stage (6th stage) at sea level used to recover the brine energy E_b , as shown in Fig. 5. E_b is transferred to pre-treated seawater through PX. The pressurized seawater is fed into the 6th RO stage at sea level. When head losses are not included, the height of the storage tank does not affect the efficiency of the elevation-distributed RO as a higher tank will result in more energy recovered in the 6th stage. Practically, the storage tank height should be kept just above that required to reduce head losses and other inefficiencies in pumping the seawater volume and in energy recovery.

The number of RO stages, their heights, and recovery at each stage can be varied depending on water demand, energy efficiency, capital cost, and serviceability. When comparing gravity-driven elevation-distributed multistage RO to that of gravity-driven RO operating at sea level followed by lifting the desalinated water, the saving in overall energy consumption is the energy needed to lift the water from sea level to the higher stages. This energy saving is because the desalinate is generated at the water demand elevations while

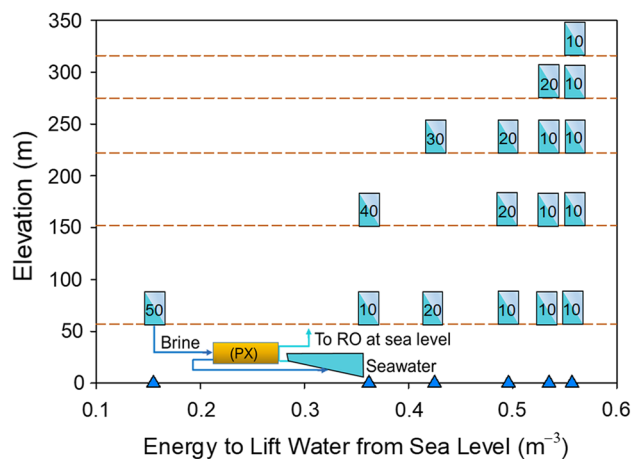


Fig. 5 Different arrangements of the RO stages, ranging from five stages to one at heights of 316, 275, 222, 152, and 57 m above sea level. The recovery at each RO stage is indicated. The total recovery in every shown arrangement adds to 50%. The energy-saving for the multistage elevation-distributed RO compared to RO at sea level followed by lifting the desalinated water is indicated on the x-axis for each arrangement and is 0.557, 0.535, 0.496, 0.425, 0.362, and 0.155 kWh/m^3 from right to left. The energy stored in the brine from the last stage can be transferred to seawater using a PX energy recovery device for an additional RO stage at sea level

recovering the potential energy of the retentate after each stage during the downward flow. Figure 5 shows six different arrangements of the RO stages at the same heights as in Fig. 4. The x-axis shows the energy to lift 1 m³ of desalinated water from an SWRO plant at sea level. The number indicated on each RO stage is the recovery at that stage in %. The energy to lift water from sea level to the RO stages is indicated by the blue triangles on the x-axis. This energy-saving is reduced from 0.557 kWh/m³ for the five stages in Fig. 4 to 0.425 kWh/m³ for two stages at 222 and 57 m with a recovery of 30 and 20%, respectively. This example shows that the reduction of the number of stages to two results in ~27% energy savings. Ignoring energy consumption due to head losses and assuming that the pumps operate at 100% efficiency, the stored energy in the pumped seawater can be fully recovered in the downward flow. To utilize this energy, the brine from the last stage is used with a PX energy recovery device to transfer almost all of its energy to seawater at sea level near the shore for an additional desalination stage, as shown in the lower part of Fig. 5.

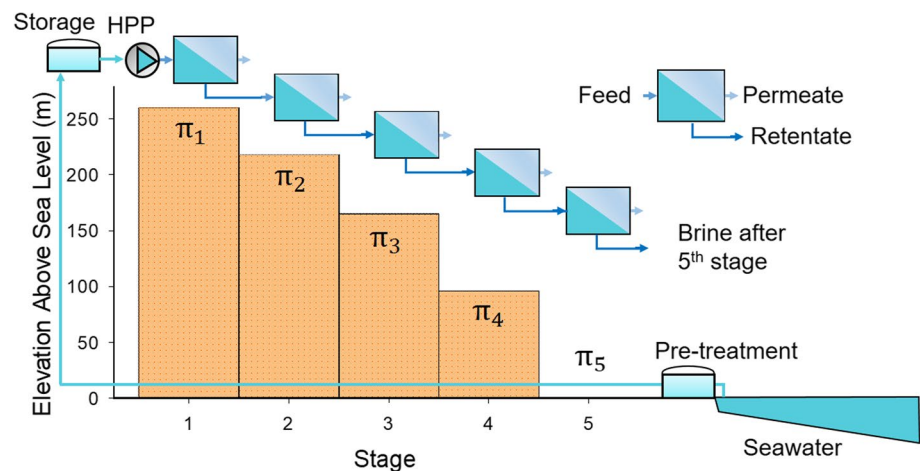
For the elevation-distributed multistage SWRO, pre-treatment of seawater is conducted near the seawater supply source following the same procedure used to control bio-fouling in SWRO plants. The increased piping length in the proposed SWRO plant is not expected to affect the rate of membrane biofouling. Also, any potential biofilm buildup in the pipes transporting the treated seawater is not expected to limit the efficiency of pumping the seawater because of the large inner diameter of the pipes. Post-treatment of the desalinate can be conducted after each stage. For a layout with a limited number of RO stages, e.g., two stages at 222 and 57 m with a recovery of 30 and 20%, respectively, post-treatment after each stage should not significantly increase the capital or operating costs. Post-treatment for drinking water is used to remove boron and remaining sodium chloride by a second pass RO, remineralize the water to match the requirement for drinking water and reduce corrosion,

and for disinfecting the water (Liang et al. 2013; Cohen et al. 2017). For irrigation, boron is usually removed by ion exchange and then the water is remineralized to achieve suitable sodium, calcium, and magnesium concentrations (Öztürk et al. 2008). For process water used in heating and cooling or manufacturing, the TDS is usually sufficiently low after the first RO pass but can be lowered further with a second pass operated by a booster pump. For the large-scale adaptation of the distributed multistage RO, one possibility is to separate residential, agricultural, and industrial activities by elevation.

Gravity-assisted multistage RO

The gravity force of the seawater column can also be used to supplement HPP when elevations near the seashore are not high enough for gravity SWRO or when there are other practical reasons to use HPP in SWRO, such as the distance of mountains from the shore, the topography of the region, and maintenance considerations. An example of gravity-assisted elevation-distributed multistage SWRO is shown in Fig. 6, which can be implemented at a location such as that shown in Fig. 3(c). Similar to Fig. 4, the seawater pretreatment is conducted at sea level near the shore. Then, the treated seawater is lifted 260 m above sea level, which is about 16 km from the shore. A storage tank, HPP, and the first RO stage are located at that elevation. The HPP supply seawater to the RO stage at a pressure of $1.11\pi_0$ to generate a 10% recovery at that stage. Gravity force from the sloping land towards the shore is then used to increase the feed pressure for the other stages. In addition to the 1st stage at an elevation of 260 m with 10% recovery, the heights of the following 4 stages with 10% recovery at each are 218, 165, 96, and 0 m above sea level. Similar to the configuration shown in Fig. 4, a 6th stage is also located at sea level near the seashore and is used to recover energy in the brine using a PX device to pressurize seawater with osmotic pressure π_0 followed by

Fig. 6 Arrangement of the five-stage distributed gravity-assisted RO stages located on different elevations that correspond to demand sites. This distributed RO can be implemented at a location such as in Fig. 3(c)



the RO stage. This final pressure recovery stage (not shown in Fig. 6) is similar to that shown in Fig. 5. The number of RO stages, their heights, and the recovery at each stage can be varied. Also, stage 5 can be eliminated as it is already at sea level. This example is suitable for supplying desalinated water to communities located on the sloping shores near the city of Al Tor, which has the highest population in South Sinai. In this example, the RO modules are located at various distances from the Gulf of Suez starting from the shore to 16 km away from the shore, along the line shown in Fig. 3(c).

Figure 7 shows the theoretical transmembrane pressure normalized to the osmotic pressure of seawater for a gravity-assisted five-stage RO with 10% water recovery at each stage. The SE for the RO layout in Fig. 6 is illustrated in Fig. 7 by the sum of the areas colored in green, blue, and yellow, which adds up to $SE = 1.178 \text{ kWh/m}^3$. This value is close to $SE_{\min} = 1.168 \text{ kWh/m}^3$ from Eq. (2) due to the small additional energy required by the HPP, which is represented by the area in yellow color. The energy consumed by the HPP providing the pressure of $1.11\pi_0$ to the first stage is represented by the sum of the green and yellow areas. The blue area represents pressure provided by the gravitational force which, when added to the pressure of the retentate from stage 1, is used to apply pressure to the RO membranes of stages 2 through 5. If this gravity-assisted SWRO plant is completely located at the seashore, then the SE required for transporting the desalinated water to heights $h_{ROi} = 260, 218, 165, 96 \text{ m}$ with 10% recovery for each stage is $\sum_{i=1}^4 mgh_{ROi} = 0.503 \text{ kWh/m}^3$, which is

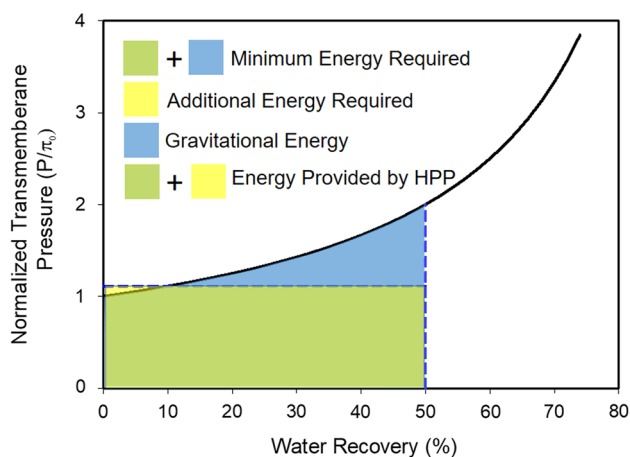


Fig. 7 Theoretical transmembrane pressure normalized to the difference in the osmotic pressure of seawater and the permeate for a gravity-assisted five-stage RO with 10% water recovery at each stage. The HPP provide a pressure of $1.11\pi_0$ to the first state. The added pressure to stages 2 through 5 is due to the gravitational force with each stage located at a height to generate 10% recovery. The specific energy $SE = 1.178 \text{ kWh/m}^3$ is represented by the sum of the areas shaded green, blue, and yellow

saved in the elevation-distributed configuration of Fig. 6. In the example of Fig. 6, the energy needed to pump seawater 260 m above sea level for 50% recovery in the 5 stages is 1.458 kWh/m^3 of which 1.178 kWh/m^3 is used for desalination with 10% recovery in each of the 5 stages and the remaining energy is left in the brine after stage 5, which can be recovered.

The above two examples of distributed multistage RO with gravity force used alone or to supplement HPP to operate five RO stages with 10% recovery in each were selected without considering configuration optimization. Lesser stages, as included in Fig. 5, are more maintainable. The elevation of each stage is based on the water requirement at its elevation. Because lifting water to a certain height requires far more energy than pumping water horizontally, it is energetically favorable to pump the desalinated water generated at each elevation to demand sites at the same elevation following a fixed elevation contour corresponding to each stage.

Summary and concluding remarks

The proposed elevation-distributed multistage SWRO with seawater pumped storage reduces the energy consumption for supplying desalinated water at high elevations near seashores compared to conducting RO at sea level and then lifting the desalinated water to demand sites. The studied SWRO plant layout is based on using renewable energy for pumping seawater to high-elevation storage to provide head pressure for RO. Pumped water storage efficiency for RO is limited only by the efficiency of the pumps and head loss in pipes. PHES for electric energy generation has an efficiency comparable to lithium-ion batteries (87% and 85%, respectively) (Javed et al. 2020b). The direct use of seawater head pressure is expected to have an efficiency comparable to, or slightly better than, lithium-ion batteries storing PV energy. PHES is a mature technology with little room for efficiency or cost improvement, while the specific cost of storage using lithium-ion batteries is expected to reduce with their further expanded use. For large-scale utility demand, the availability and cost of elements used in the batteries, and their recycling, can become important (Zubi et al. 2018).

With the significant advancement in RO desalination at the components level that has been adopted in RO plants for about two decades, further component development is not expected to significantly reduce SE (Hailemariam et al. 2020; Torre 2008). The more recent development of RO at a system level offers approaches to reducing energy waste in RO. These approaches aim at keeping the energy used to pressurize the membranes close to the thermodynamic minimum energy needed for separation (Lin and Elimelech 2015; Wei et al. 2020; Cordoba et al. 2021; Jeong et al.

2019; Park et al. 2020). The proposed SWRO layout aims at reducing the sum of energy consumption for the SWRO and desalinated water transport to high elevations, further extending the energy savings at the system level and efficiently utilizing renewable intermitted energy sources for desalination. The main limitation of the present study is neglecting energy losses in the pumps and pipes. However, these losses are also present in PHES and the previously-proposed integrated PHES with RO (Slocum et al. 2016). Another limitation is the geographic location suitability of the proposed SWRO plant where the proximity of mountains to seawater is needed combined with the presence of freshwater demand sites at high elevations.

A recent survey of desalination plant capacity in the South Sinai Governorate indicates that the Governorate has 14 plants with a total design capacity of 161,000 m³/day in addition to a plant under construction with a capacity of 6000 m³/day (Elsaie et al 2022). These modest seawater desalination capacities are mainly dedicated for use in inhabited areas at or near the seashores. Expanding residential areas and commercial activities in South Sinai require a source of sustainable and affordable fresh water delivered to elevations above sea level. The proposed elevation-distributed multistage RO reduces the energy required in this case and uses renewable energy that is abundantly available in the region. The speed and extent of the implementation of the proposed SWRO plant layout will depend on the planned population growth in South Sinai at the high elevations away from the seashore. This approach can be applied to other regions in the Middle East and elsewhere where the topography is suitable. In the Middle East, some of the mountainous regions on both sides of the Red Sea are suitable locations. The proposed SWRO plant layout can also be adapted to the PHES for combined electrical energy generation and gravity-driven RO seawater desalination proposed for several locations in different countries including the Northern tip of the Gulf of Aqaba (Slocum et al. 2016).

Implementation of the proposed elevation-distributed multistage SWRO can start with designing and constructing a small-scale experimental plant for testing the concept, gaining experience with pumped seawater storage and gravity-driven RO, and improving plant efficiency and reliability. The SWRO plant can be located at a site that requires a modest desalinated water capacity of 5,000 to 10,000 m³/day at two high elevations (e.g., 222, and 57 m, similar to the example in Fig. 5) in addition to at sea level. The storage tank can be located at a height of about 660 m above sea level, similar to the example in Fig. 5. Electricity needed to operate the pumps for pumped seawater storage can come from the grid or off-grid PV. This experimental SWRO plant can be used to gain experience in seawater pre-treatment at the site location and conducting RO using the head pressure of a water column. Moreover, the experimental plant can

be used for identifying the most suitable RO membranes, configuring the best layout of the piping, selecting suitable seawater storage, maximizing energy saving from the distributed RO stages, operating the PX device at sea level for recovering energy stored in the brine water column after the second stage, and disposing of the brine while minimizing environmental impact. The data gathered from such an experimental SWRO plant can then be used to optimize the design and select suitable components for the expanded use of the proposed SWRO plant layout.

The following is a summary of the main points of the present study:

- Pumped water storage is ideal for storing excess energy from intermittent sources, such as PV and wind, reducing energy costs for desalination. The SE for gravity-driven RO from the head pressure of a seawater column can be lower than that for RO using HPP as the potential energy of the seawater column is reduced only when downward flow occurs, which also results in permeate generation. On the other hand, HPP continuously consume energy during their operation, with their energy consumption increasing when more pressure is required in the cross-flow RO.
- For a multistage gravity-driven SWRO plant with the RO stages located at demand sites above sea level, the energy needed to lift the desalinated water from an SWRO plant that is entirely located at sea level is saved. When energy losses in pumps and pipes are neglected, placing five RO stages at different elevations results in 0.557 kWh/m³ lower SE compared to an SWRO plant at sea level operating with $SE_{min} = 1.168$ kWh/m³ followed by lifting the desalinated water to demand sites. For two RO stages, the SE reduction is by 0.425 kWh/m³. The reduction in SE depends on the demand and storage tank elevations. Irreversible losses that are not considered in the present study are losses in pumps, water pipes, and RO modules.
- At locations where the upper reservoir elevation is not sufficient to provide head pressure for RO, adding HPP near the reservoir to provide sufficient pressure for the first RO stage, then using the gravitational head pressure for subsequent RO stages lowers the SE. This configuration takes advantage of the low recovery at the first stage (e.g., for a recovery of 10%), in which the SE can approach the thermodynamic limit.
- The stated saving in the SE for the proposed elevation-distributed multistage gravity-driven SWRO is not accounting for possible additional savings due to storing excess energy generated by renewables during off-peak hours by pumping seawater to the elevated reservoir. Although excess energy from renewables can be stored in lithium-ion batteries with comparable efficiency as PHES for electric energy generation, using PHES for head pres-

sure in SWRO bypasses the inefficiencies of RO driven with continuously-operated HPP.

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Declarations

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Consent for publication Not applicable.

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