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Analysis of energy usage at membrane water treatment plants

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ABSTRACT

The production and supply of potable water using seawater and brackish water desalination, and reclamation of wastewater for reuse by membrane processes has seen a rapid growth in the last decade to meet the growing demands of water in many regions of the world. Energy consumption plays a critical role in the selection of appropriate membrane treatment technologies for potable water production. For example, wastewater reclamation for reuse by membrane filtration is more attractive than reverse osmosis (RO) desalination due to much lower specific energy consumption and materials costs. Specific energy consumption reflects the energy efficiency of a membrane process but is not a realistic indictor for comparing the power requirements of different membrane processes. A parameter called, comparative-kW, is proposed for comparing the power requirements of various membrane based plants operating under a wide range of product water recoveries. Several cases are analysed to illustrate the usefulness of comparative energy parameter, c-kW.

Keywords: Membrane systems; Energy consumption; Desalination; Wastewater; Potable water; High purity water

1. Introduction

One billion people worldwide do not have access to potable water, and half of the world's population lacks adequate water purification. By the year 2050, between two and seven billion people will face water shortages [1]. Current shortages of potable water around the world and looming water scarcity especially in the developing countries is the driving force behind the implementation of membrane technologies for water treatment and potable water production. Until the late 1970s, reverse osmosis (RO) separation was mainly a demonstration technology aimed at proving itself a viable process for water desalination. Since the 1990s, membrane-based separation processes integrated with traditional separation systems have been successfully deployed in large desalination, wastewater and municipal water treatment plants [2–5]. More than a dozen large seawater RO plants with product water production capacities of up to 500,000 m^3/d (~130 million gal/d) have been commissioned in the last decade driven by a substantial reduction in desalinated seawater energy consumption (from 10 kWh/m^3 to 2.6 kWh/m^3) and cost (from \$1.75/m^3 to < \$0.90/m^3) in the last 30 years. Membrane processes also minimise waste and pollution unlike coagulation-clarification. The overall market for membranes and membrane systems is expected to reach \$1B in 2010.

2. Background

Synthetic membrane processes — MF, UF, NF, RO — perform versatile functions. In liquid separations they are used for desalinating and purifying different types of waters: seawater, brackish water, surface water and groundwater for potable use, high purity water production for industrial use, as well as domestic and industrial wastewater. The characteristics of major membrane processes are detailed in Table 1. Membrane engineering is a "Green Technology"; membrane processes are both energy efficient and environment friendly. Unlike traditional separation processes such as distillation and evaporation, membrane processes are independent of thermodynamically imposed efficiency limitations on heat utilisation. These energy limitations of traditional separation processes, along with water shortage predictions, provided the impetus for the development and commercialisation of RO desalination during the last 40 years.

Reverse osmosis is virtually the hub of all integrated membrane plants used in water reclamation for indirect and direct potable water reuse. For example, the well-known plant in Orange County, California treats 265,000 m^3/d of municipal secondary effluent water using membrane filtration, RO and ultraviolet radiation. The highly potable water is injected into coastal aquifers for replenishing groundwater and preventing contamination of aquifers by seawater intrusion.

Reverse osmosis is now the major unit operation in the production of high purity water in semiconductor, pharmaceutical, food, and beverage industries [4]. For example, RO has virtually replaced demineralisation by dual-bed (cation-anion) ion exchange (DBIX) prior to mixed-bed ion exchange (MBIX) polishing in the last 20 years. Higher operating costs of IX systems and generation of chemical wastewater combined with increased reliability and performance of RO systems to replace DBIX. RO treatment is more cost effective than IX especially when the feed water total dissolved solids (TDS) is greater than 350 mg/l since the cost of IX is directly proportional to the concentration of ions in feed water.

3. Membrane system performance

The transport properties of a semi-permeable membrane are determined by the permeability of the membrane and by a driving force both of which impact energy requirements. The flux of the solvent is directly proportional to the applied pressure and is given by the equation at constant temperature:

$$J_w = A(\Delta P - \Delta \Pi) \tag{1}$$

where J_w is membrane water flux, A is membrane permeability coefficient, ΔP is hydraulic differential pressure across the membrane, and $\Delta\Pi$ is osmotic pressure differential across the membrane. Flux is related to product recovery, one of the key performance parameters defined as: %recovery = (product flow/feed flow) × 100. For liquids other than pure water, however, the proportionality does not exist as shown in Fig. 1 due to fouling and/or concentration polarisation. Fouling causes a loss in water flux and quality, lower yield (recovery), reduced operating efficiency (higher energy consumption), lost service time due to more frequent cleaning, premature membrane replacement, and higher operating costs. Although most of the flux drop is recoverable following cleaning, raw water pretreatment is essential to prevent or mitigate fouling and scaling.

The viability of a membrane process for potable water production depends on the energy consumption. The power input reflects the pressure energy required to pump water molecules through a size/charge selective membrane and is expressed as specific energy consumption (SEC) in kWh/m^3 of product water. The following relationships are used to calculate energy consumption:

$$\text{Required pump power, kW} = \frac{\text{feed water flow rate, m}^3/\text{h} \times \text{feed pressure, bar g}}{\text{pump efficiency} \times 36} \tag{2}$$

$$\text{Required motor power, kW} = \frac{\text{pump power}}{\text{motor efficiency}} \tag{3}$$

$$\text{SEC} = \frac{\text{required motor power, kW}}{\text{product water flow rate, m}^3/\text{h}} \tag{4}$$

Estimates of SEC of various sample membrane systems are provided. The data are used to generate a novel power parameter for comparing power requirements of various membrane plants used for water purification.

Table 1
Characteristics of membrane processes

Membrane process	Nominal pore size (A°)	Average permeability (L/m².h.bar)	Driving force (bar g)
Microfiltration (MF)	1000–100,000	500	1–3
Ultrafiltration (UF)	20–1000	150	2–5
Nanofiltration (NF)	5–20	10–20	5–15
Reverse osmosis (RO)	2–5	5–10	15–75

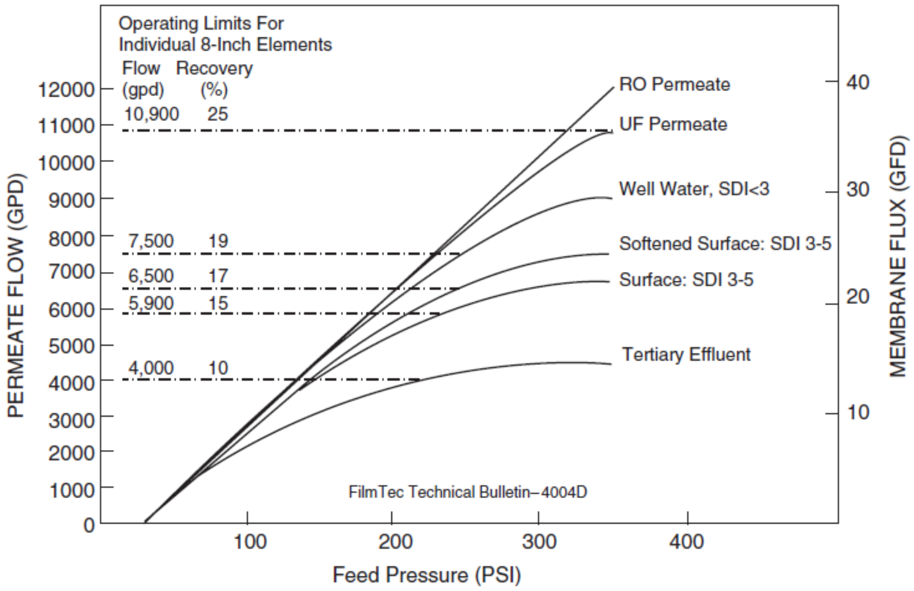

Fig. 1. Membrane flux characteristics of a thin-film composite polyamide membrane, spiral-wound RO module with various feed waters.

4. Case studies

Membrane processes discussed include seawater RO (SWRO), brackish water RO (BWRO), RO, brine recovery RO (BRO), pressurised MF/UF (pMF/UF), immersed membrane bioreactor (iMBR), cross-flow membrane filtration (XMF) and electrodeionisation (EDI). Process flow schematics depicting these membrane processes are shown in Fig. 2. RO and NF systems are typically two or three-stage depending on product water recovery and feed water quality as shown in Fig. 3, and single-pass or double-pass as shown in Fig. 4.

For our illustrative purposes we have assumed membrane-based water treatment plants sized for feed water flow rates of 22.5 and 45 m^3/h. Specific energy consumption data for various membrane processes based on published data are given in Table 2 [2,5,7–15].

Estimates of total energy consumption and the power

Table 2
Specific energy consumption of membrane processes

Membrane process	Specific energy consumption (kWh/m^3)	Typical applications
SWRO	2.6–3.5	Seawater* desalination w/energy recovery
SWRO + RO	3.0–4.0	Two-pass seawater* desalination w/energy recovery
BWRO	0.6–1.0	Brackish water desalination; TDS > 1500 ppm
BWRO+BRO	0.8–1.5	High recovery, i.e. primary RO + brine RO
RO	0.3–0.5	Feed water TDS < 1000 ppm
Pressurised MF/UF	0.1–0.2	Surface water, wastewater, RO pre-filtration
Submerged MF/UF	0.05–0.1	Surface water, wastewater, RO pre-filtration
External MBR	2.0–4.0	Landfill leachate, industrial wastewater, RO pre-filtration
Immersed MBR	0.3–0.9	Municipal/industrial wastewater, RO pre-filtration
Cross-flow MF	2.5–3.0	High hardness, high silica wastewater; metals wastewater
ED (A)**	1.0–4.0	Brackish water desalination
ED (B)**	10.0–15.0	Seawater desalination
EDI	0.2–0.3	RO permeate polishing, high purity water

* Total dissolved solids ~ 34,000 ppm; ** Electrodialysis
Temperature = 25°C

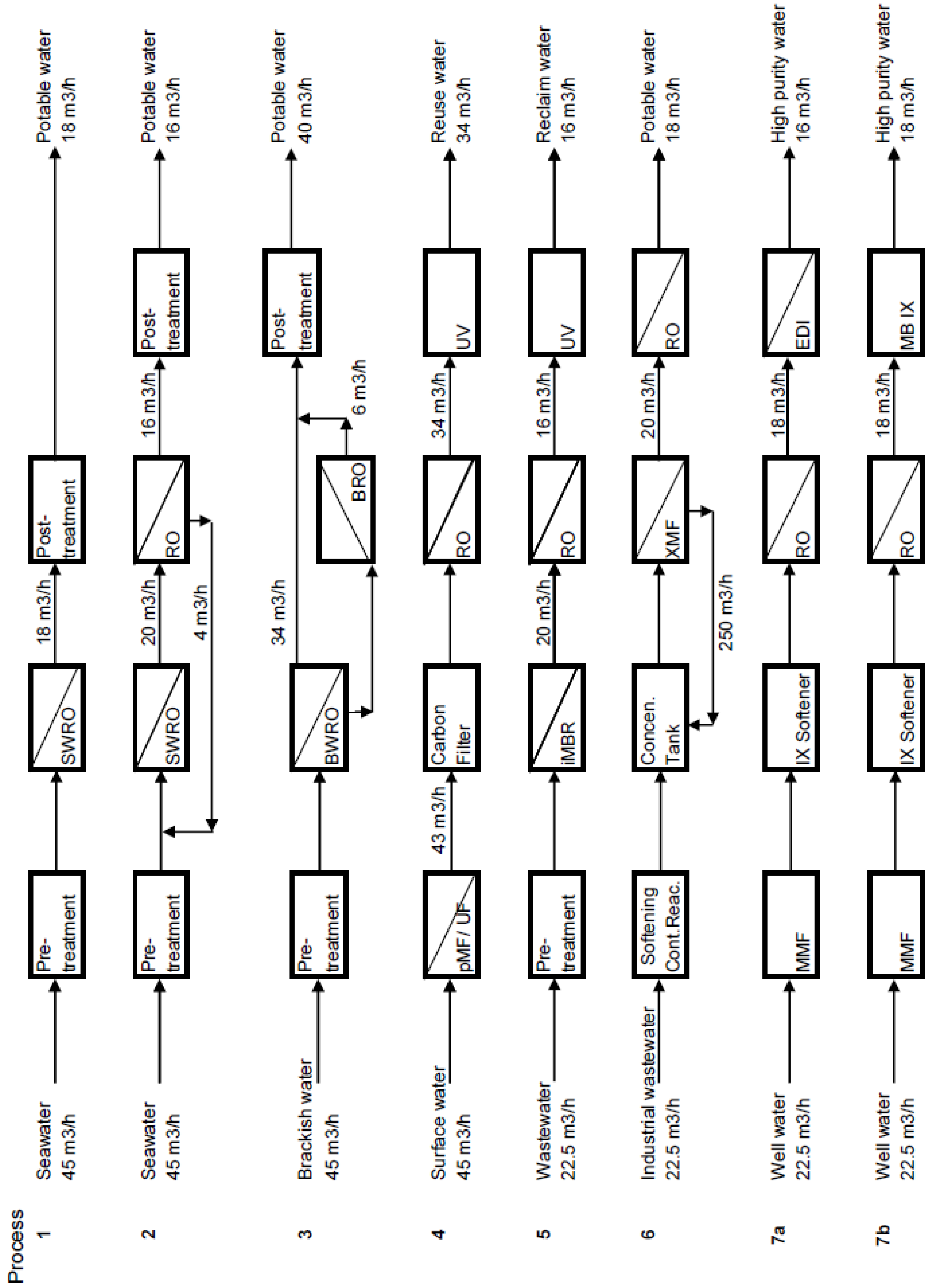

Fig. 2. Block flow diagrams of sample membrane process plants.

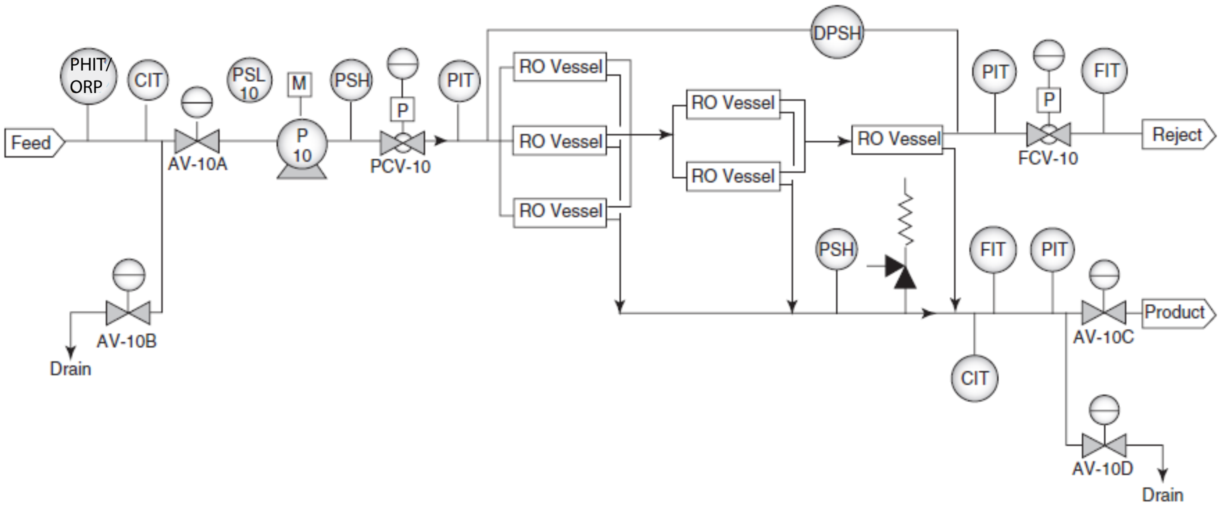

Fig. 3. A typical P&ID of a single-pass, three-stage RO/NF unit. PCV and FCV are automatic modulating pressure control and flow control valves, respectively. AV-x are automatic on/off valves.

required for each system are given in Table 3. System power requirement includes energy consumption for the membrane process, pre-treatment, post-treatment and distribution, and is based on typical figures, e.g. energy consumption for a SWRO system is typically 70–80% of the total plant energy, and energy consumption for a RO system is 40–50% of total plant energy [7,12–14]. A figure of 70% was assumed both for SWRO and XMF systems since their specific energy consumptions are similar, and 50% for all other systems.

4.1. Process 1 — Seawater desalination I

This is a single-pass SWRO system capable of producing 18 m^3/h potable water operating at 40% recovery (Fig.2) based on a feed water flow rate of 45 m^3/h. The product water quality for a single-pass SWRO unit is typically 300–500 mg/L total dissolved solids (TDS), which is well below the World Health Organisation (WHO) drinking water limit of 1000 mg/L. The process energy consumption is 54 kW based on a specific energy consumption of 3.0 kWh/m^3 with energy recovery (Table 3). The desalination plant power required is 77 kW when the energy consumption for a SWRO unit is 70% of the total plant energy as mentioned above.

The specific energy consumption of SWRO has dropped from 10 kWh/m^3 to 2.6 kWh/m^3 in the last 30 years [2,5,12–14] as a result of improvements in membranes, systems design and hardware. The process is, however, still considered energy intensive. Additional reductions of 10–20% are achievable when operating with modified staged designs of membrane arrays [2,14] and/or operating in a combined heat and power mode [13], e.g., energy consumption reduction of 7–11% was achieved when an alternate energy source such as fuel cell stack waste heat was used to pre-heat RO feed water from 20°C to 30°C [8,9].

The thermodynamic minimum is 0.8 kWh/m^3 [7,13,14]. The lowest energy consumption achieved in pilot studies in 2006 is 1.6 kWh/m^3 [2,17]. The likelihood of reducing the energy consumption of commercial SWRO systems to < 2.0 kWh/m^3 is, however, unlikely [13,14] because of a number of reasons; low product water recovery (< 50%), high osmotic pressure and membrane concentration polarisation.

4.2. Process 2 — Seawater desalination II

This is a double-pass RO system similar to the ones shown in Fig. 4. A two-pass SWRO system is required to produce potable water with TDS less than 200 mg/L and to meet the WHO's drinking water standard for boron of 0.5 mg/L. Boron standards, however, vary, e.g. European Community = 1 mg/L, and USA has no limit except in California = 1 mg/L [2]. Boron concentration in seawater is usually between 4.0 and 6.0 mg/L depending on the location (in contrast typical river water has boron concentration of 0.05–0.2 mg/L). Since, the boron concentration in the permeate from a single-pass SWRO is generally > 0.8 mg/L, a 2nd-pass RO is required with the feed water pH > 9.0. It is difficult to remove boron for the following reasons: boron exists as a weakly dissociated boric acid, H_3BO_3 at pH < 8.2, which is typically the pH of seawater, and the molecular size of boric acid is so small that is difficult to remove by size exclusion. At pH > 9.3 boron gets ionized to borate ion $H_2BO_3^-$ resulting in high rejection by RO membranes that are generally negatively charged [6,18].

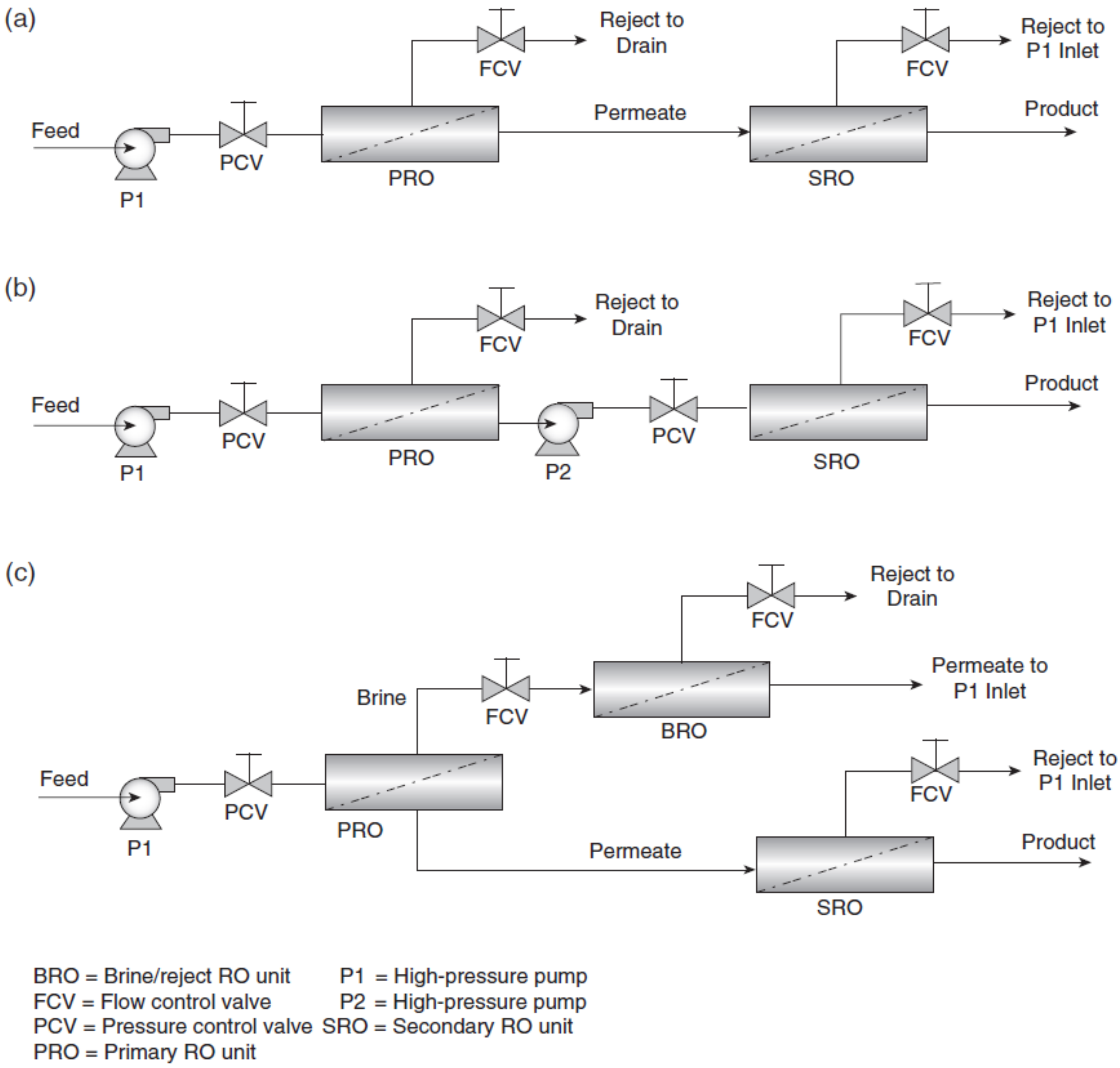

Fig. 4. RO system flow schematics: (a) two-pass RO without inter-pass pressure boosting; (b) two-pass RO with inter-pass pressure boosting; (c) two-pass RO with brine recovery.

As shown in Fig. 2, the 1st-pass SWRO unit permeate flows to the 2nd-pass RO unit @ 20 m^3/h operating at 45% recovery based on a feed water flow rate of 45 m^3/h. The pH of 2nd-pass RO feed is raised to > 9.0 with caustic soda. The 2nd-pass RO unit produces 16 m^3/h operating at 80% recovery (recoveries > 80% are typical for 2nd-pass RO units). The 2nd-pass RO reject flows to the SWRO inlet @ 4 m^3/h (with TDS substantially lower than the 1st-pass RO seawater feed). The process energy consumption is 65 kW based on the specific energy consumption of 3.0 kWh/m^3 for the SWRO unit with energy recovery, and 0.3 kWh/m^3 for the 2nd-pass RO unit (Table 3). The desalination plant power required is 93 kW when the energy consumption for a SWRO unit is 70% of the total plant energy as mentioned earlier.

4.3. *Process 3 — Brackish water desalination*

This is a high recovery brackish water RO system. Typically, BWRO plants operate at 70–80% recovery so that 20–30% of feed water is wasted as concentrated brine. Product water recoveries greater than 75–80% are generally constrained by the solubility limits of sparingly soluble scale forming compounds discussed earlier; as the feed/brine water gets concentrated in the channel above the membrane, e.g. by a factor of 4 at 75% recovery and 10 times at 90% recovery, the salt concentration also gets concentrated. The salt concentration is even higher at the membrane surface due to concentration polarisation, and must not be more than 20% higher than in the feed/brine channel. In the case of brackish waters, $CaCO_3$ and

Table 3
System power and comparative power of sample membrane system*

Process No.	Membrane process	Feed flow rate (m^3/h)	Product flow rate (m^3/h)	Overall product recovery (%)	Specific energy consumption (kWh/m^3)	Process energy consumption+ (kW)	System power requirement (kW)	System comparative power** (c-kW)
1	SWRO	45	18	40	3.0	54	77	193
2	SWRO →	45	20		3.0	65+	93	262
	RO		16	36	0.3			
3	BWRO + BRO	45	40	89	1.0	40	80	90
4	pMF/UF →	45	43		0.15	20	40	53
	RO		34	76	0.4			
5	iMBR →	22.5	20		0.5	17	33	46
	RO		16	71	0.4			
6	XMF →	22.5	20		3.0	65	93	116
	RO		18	80	0.3			
7a	RO →	22.5	18		0.4	11	22	31
	EDI		16	72	0.25			
7b	RO + MBIX	22.5	18	80	0.4	7	14	18

Pump and motor efficiencies are assumed to be 65% and 88%, respectively, 1 m^3/h = 4.4 gpm (US)
*Product water recovery, %R: SWRO = 40%, BWRO = 75%, BRO = 55%, RO = 80%, pMF/UF = 95%, iMBR = 90%, XMF = 90% where %R = (product flow rate / feed flow rate) × 100.
+e.g. (20 × 3) + (16 × 0.3) = 65
**c-kW = (feed flow rate / product flow rate) × system power requirement, kW

gypsum ($CaSO_4.2H_2O$) are the most common scalants. Gypsum (solubility product, K_{sp} = 1.9×10^{-4} at 25°C) is much more soluble than calcium carbonate (K_{sp} = 8.7×10^{-9} at 25°C). Limiting salts can be identified from their K_{sp} values. The deposition of the scale forming compounds can be limited to an extent by reducing the pH with acid and/or by the use of anti-scaling chemicals, which interrupt crystal growth at the nucleation stage.

Because of high costs of disposing brine, and the need to reclaim and conserve water, primary RO (PRO) reject water can be purified using a high recovery brine RO (BRO) and/or NF system to recover additional potable water and reduce the volume of the brine stream as shown in Fig. 4c. Such PRO+BRO hybrid systems can achieve overall product water recoveries of 87-96% for low to medium TDS(< 4,000 mg/L) brackish waters [9,19].

In the configuration shown in Fig. 2, low salinity brackish water (TDS ~1700 mg/L) flows to the BWRO system, which produces 34 m^3/h potable water when operating at about 75% recovery based on a feed water flow rate of 45 m^3/h. In order to increase the yield, the reject (TDS ~6700 mg/L) flows to the BRO unit @ 11 m^3/h. The product water flow rate from the two RO units is 40 m^3/h resulting in an overall recovery of 89%. The process energy consumption is 40 kW based on the specific energy consumption of 1.0 kWh/m^3 (Table 3). The desalination plant power required is 80 kW when the energy consumption for a BWRO unit is 50% of the total plant energy.

4.4. Process 4 — Surface water

UF and MF (effective pore size of the membrane is ≤ 0.1 μm) are being increasingly used for surface water and wastewater treatment for re-use, e.g. secondary or tertiary effluent is treated for industrial, non-potable and, in some cases, potable water reuse using UF/RO (or MF/RO) plus advanced oxidation techniques such as UV disinfection and hydrogen peroxide. Several prominent examples of advanced reclamation plants include Water Factory 21 in California, NEWater Factory in Singapore and the Goreangab Reclamation plant in Namibia [2–4]. Wastewater reclamation for reuse by membrane filtration is more attractive than SWRO desalination due to much lower energy consumption and materials costs. For example the cost for producing RO product water from secondary effluent and seawater is estimated to be \$0.30/m^3 and \$0.70/m^3, respectively [2].

Depending on the quality of feed water, e.g. surface water or low TDS groundwater, MF or UF is sufficient for producing reuse quality water without RO or UV disinfection [15]. The pMF+RO process shown in Fig. 2 is based on a feed water flow rate of 45 m^3/h. The product water flow rate is 34 m^3/h at an overall recovery of 76% when the MF and RO recoveries are 95% and 80%, respectively (MF/UF system recoveries of up to 99% are achievable when the reject is also recycled to the feed water inlet [15]). The process energy consumption is 20 kW based on the specific energy consumption of 0.15 kWh/m^3 for the pMF/UF unit, and 0.4 kWh/m^3 for the RO unit (Table 3). The integrated membrane plant power required is 40 kW when the energy consumption for the integrated system is 50% of the total plant energy.

4.5. Process 5 — Municipal wastewater

The hybrid MBR+RO wastewater system process shown in Fig. 2 is based on a feed water flow rate of 22.5 m^3/h. The system produces 16 m^3/h reuse water with MBR unit operating at 90% and RO unit operating at 80% recovery. The process energy consumption is 17 kW based on the specific energy consumption of 0.5 kWh/m^3 for the iMBR unit, and 0.4 kWh/m^3 for the RO unit (Table 3). The system plant power required is 33 kW when the energy consumption for the system is 50% of the total plant energy.

The configuration couples an MBR unit with an RO unit for wastewater treatment. Biological degradation of organic pollutants is carried out in the bioreactor by adapted microorganisms, and the microorganisms (biomass) are removed from the treated wastewater or mixed liquor (activated sludge) with MF/UF membranes. Since the effective pore size of the membrane is ≤0.1 μm, the MBR effluent is highly clarified and substantially disinfected [11]. For municipal wastewater treatment, MBRs are very attractive as compared to conventional treatment due to a small foot-print, and high effluent quality required for water re-use or as pre-treatment for RO or NF processes. Further, in recent pilot tests at NEWater Factory in Singapore, it has been shown that MBR + RO produces water with a slightly superior quality product water for industrial use, and at lower cost than the existing MF + RO system for treatment of secondary sewage mainly because MBRs eliminate the need for secondary and/or tertiary filtration [2,11].

4.6. Process 6 — Industrial wastewater

For wastewater streams high in metals, hardness (> 800 mg/L as $CaCO_3$) and/or silica (> 60 mg/L), softening is required prior to recovering water by RO for reuse. For such streams, softening pretreatment followed by clarification and filtration is used. The basis for softening is as follows: while temporary hardness (calcium and magnesium hardness due to carbonate) can be controlled by acidifying RO feed water, permanent hardness (due to sulphate) is relatively independent of the pH. When calcium sulphate and silica limit RO recovery, lime or caustic softening is necessary to achieve higher recovery. Softening (pH = 10.5–11 lowers hardness to 50 mg/L), removes calcium as $CaCO_3$ whereas SiO_2 is partially sorbed by $Mg(OH)_2$ ($K_{sp} = 1.2\times10^{-11}$ at 25°C) floc and removed by co-precipitation with magnesium.

One process sometimes used for low flow rates (< 50 m^3/h) is lime or caustic soda softening followed by cross-flow microfiltration (XMF) and RO polishing [19,20]. The MF membrane (pore size < 0.2 μm) is tubular with a diameter of 1.27 cm or 2.54 cm. Due to the large diameter of the tubes, the membranes can handle feeds with solid levels of up to 5% at a very high membrane flux (375–500 L/m^{2}h). The XMF filtrate is of high quality with turbidity < 0.1 NTU and SDI < 3.0.

In the process configuration shown in Fig. 2, wastewater flows to a contact reactor @ 22.5 m^3/h. The supernatant from the concentration tank flows to the XMF membrane array and is recirculated @ 250 m^3/h and 3–4 bar g with 10–15% recovery per recirculation/pass until 85–95% of the feed is recovered. In cross-flow MF/UF systems, operation at high velocity (shear rate) minimizes solute cake build-up on the membrane surface and controls fouling. The filtrate pH is lowered with acid to ~6.0 before it flows to the RO unit @ 20 m^3/h. Because of the high quality of filtrate – turbidity < 0.1 NTU, SDI < 3.0, hardness < 50 ppm, silica < 20 ppm — the RO unit can operate at 85–90% recovery without fouling/scaling. Thus, the XMF–RO hybrid system recovers 75–85% of wastewater for reuse. The specific energy consumption of XMF is, however, much higher than semi dead-end MF/UF processes (Table 2) because of very high cross flow recirculation rates.

The process energy consumption is 65 kW based on the specific energy consumption of 3.0 kWh/m^3 for the XMF unit, and 0.3 kWh/m^3 for the RO unit (Table 3). The system plant power required is 93 kW when the energy consumption for the integrated system is 70% of the total plant energy as mentioned earlier. The estimated total power required is about the same for a two-pass SWRO system with comparable product water flow rates but at nearly twice the recovery.

4.7. Process 7 — Mobile water treatment

RO mobile systems are commonly deployed to provide potable water or demineralised water during emergencies and as a backup source at industrial sites [4,6]. Two cases are presented in Fig. 2 based on a feed water flow rate of 22.5 m^3/h. In configuration 7a, RO product water is polished in an EDI unit to produce high purity water. The process energy consumption is 11 kW based on the specific energy consumption of 0.4 kWh/m^3 for the RO unit, and 0.25 kWh/m^3 for the EDI unit [21]. The system plant power required is 22 kW (Table 3) when the energy consumption for the system is 50% of the total plant energy.

In configuration 7b, RO product water is polished in a MBIX unit to produce high purity water. The process energy consumption is 7 kW based on the specific energy consumption of 0.4 kWh/m^3 for the RO unit (Table 3). The permeate pressure is adequate for desalinated water to flow through the MBIX resin bed to the point of use. The system plant power required is 14 kW when the energy consumption for the system is 50% of the total plant energy.

Because of a small foot-print, high product water recovery and low power requirements, these configurations are well-suited for mobile systems.

5. Comparative energy parameter

Estimated power requirements of membrane systems for typical cases are given in Table 3. The data indicate that the two-pass SWRO (process #2) and XMF (process #6) systems require about 93 kW power for producing nearly the same amount of treated water, 16–18 m^3/h whereas the high recovery RO system (process #3) requires 80 kW for producing 40 m^3/h treated water.

However, this data can be misleading since it is based on the amount of product water produced; for example, in the case of process #1 and #6 with feed water flows equal to 45 and 22.5 m^3/h, respectively, the product water recoveries are 40% and 80% to attain the same product throughput, 18 m^3/h. This is further evident from the fact that while the specific energy consumption of the single-pass SWRO process (#1) is three times higher than the high recovery RO process (#3), the system power requirement is about the same. Hence, for meaningful system performance comparisons, a new parameter, comparative-kW, is proposed:

$$\text{c-kW} = \left(\frac{\text{feed water flow rate}}{\text{product water flow rate}}\right) \times \text{system power requirement} \tag{5}$$

The data in the last column in Table 3 is calculated using the above equation. It highlights the following points:

- The c-kW of the SWRO-RO desalination system (#2) is more than twice that of the XMF-RO system (#6), i.e. 262 c-kW vs. 116 c-kW even though the energy consumption of the two processes is identical (65 kW). This is due to the fact that the overall product water recovery of the SWRO-RO system is less than half of the XMF–RO system (36% vs. 80%).
- Even though the system power requirement of the high recovery RO system (#3) is 86% of the SWRO-RO system (#2), i.e. 80 kW vs. 93 kW, c-kW is only 34% (90 c-kW vs. 262 c-kW).
- While the system power requirement of system #1 and #3 are the about the same, c-kW of system #1 is twice that of system #3. This is because the overall product recovery of system #3 is more than twice of #1.

6. Summary

Energy consumption plays a critical role in the selection of appropriate membrane treatment technologies for potable water production. The data show that SWRO, external MBR and XMF processes are the most energy intensive. Specific energy consumption is a well-established parameter that reflects the energy efficiency of a membrane process, e.g. the SEC of SWRO has dropped from 10 kWh/m^3 to 2.6 kWh/m^3 in the last 30 years [2,5,13,14].

Specific energy consumption also decreases with increase in recovery [8,9,22,23]. However, since SEC is a function of product water flow rate, it is not a realistic indicator for comparing different membrane processes operating under a wide range of product water recoveries. A parameter based on normalized power, c-kW, is proposed for comparing the energy consumption of commonly deployed membrane water treatment systems used for producing potable water from various impure water sources, and operating under different set of conditions.

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