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Design aspects of small-scale photovoltaic brackish water reverse osmosis (PV-BWRO) system

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ABSTRACT

Clean drinking water is essential for survival and good health. Reverse osmosis is a very effective way to produce clean drinking water. Designing small scale photovoltaic powered brackish water reverse osmosis system (PV-BWRO) requires feed water characterization, proper pre-treatment setup, module design configuration, energy consumption evaluation and reject water management. Feed water characterization is done for optimum RO module arrangements and pre-treatment design to prevent fouling and scaling. Success of small scale PV-BWRO system designation depends on ability to minimize cost of water produced. Among all the parameters effecting cost, energy is the most influential. Energy consumption is reduced by including energy recovery device (ERD) in the system. It can be further reduced by including battery for stable supply of energy enabling the pumps to operate at optimum level. Problem with battery is energy loss during charging/discharging and high cost of maintenance and replacing. Instead of storing energy, another option is to store produced fresh water in storage tank. The capacity of the tank is determined based on average consumption of water by the population at the location of the system build. Reject water from RO system need to be managed properly. Improper disposal will cause contamination and disturb ecosystem. Powering RO systems with PV panels have a lot of advantages which includes maintenance free, easy installation and last up to 25 y.

Keywords: Desalination; Reverse osmosis; Brackish water; Small scale; Photovoltaic

1. Introduction

Water desalination is a process where clean water is obtained from high salinity water. Clean water is essential for survival and good health. Healthy population would able to contribute for development of their country. The objective of this paper is to have an overview on designation of small scale photovoltaics powered brackish water reverse osmosis system (PV-BWRO). Lessons and experience from brackish water and other type of RO systems is reviewed.

Small scale desalination systems are systems with capacity up to 60 m^3/d. Most of small scale systems are implemented in remote areas or home use. Large scale desalination systems have been successful commercially but not much success for small scale desalination systems [1].

Reverse osmosis (RO) is membrane desalination system. Advantages of RO are low energy requirements, modularity, compactness, easy installation, and simplicity in operation [2–4]. This enables RO system to produce cheap fresh water with high volume. RO systems are made of membrane, high pressure pump and power system (Fig. 1).

Photovoltaics (PV) are arrays of cells containing solar photovoltaic material known as solar cells which converts solar radiation into electricity. First generation of solar cells is made of silicon. Second generation of solar

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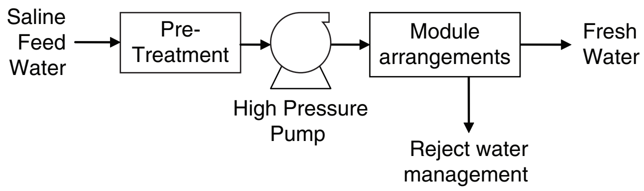

Fig. 1. Simple reverse osmosis system.

cells are called thin film which are made from different type of material such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), dye-sensitized solar cell, thin film silicon (TF-Si) and organic solar cell. The efficiency of second generation of solar cells is lower compared to first but they are much cheaper.

2. Water characterization

Countries around the world have different water quality acceptance. World Health Organization (WHO) standardized water quality acceptance by recommending drinking water with total dissolved solids (TDS) below 500 mg/l. Producing required drinking water standard with RO system depends strongly on membrane arrangements which are determined according to feed water quality.

Feed water quality varies on location and characterized according to its salinity level. Four main category of salinity are seawater with TDS concentration of 15,000 mg/l or more, brackish water or medium salinity water with TDS concentration between 1000 and 15,000 mg/l, low-salinity water with concentration between 500 and 1000 mg/l and fresh water with concentration below 500 mg/l.

Brackish water can be sub-divided into medium-salinity water with TDS up to 15,000 mg/l, medium-salinity water with high natural organic matter (NOM) and TDS up to 15,000 mg/l, medium-salinity tertiary effluent with high total organic carbon (TOC), biological oxygen demand (BOD) and TDS up to 15,000 mg/l.

Composition of brackish water from different location might have different ion content even though they share same TDS value. A complete water characterization is an important part of RO system designation to determine scaling potential of feed water. El-Manharawy and Hafez [5] proposed water molar classification based on the molar concentration of the chloride content (in mm) and the molar ratio of the dissolved sulfate/alkalinity (in mm) of the natural waters. It is based on the molar concentration of chloride due to control solubility of bicarbonate and sulfate ions to a great extent. Detailed water classification consists of four major water classes and 10 water types (Table 1):

Table 1
Guideline of RO scale potential as based on water molar classification [5]

Class	Type	Chloride range	(SO_4/Alk.) mm	Carbonate scale potential	Sulfate scale potential
Class D: Very high chloride	10	600–1000 mm (>26,000 mg/l)	>20 (sulfate end)	Rare	Extremely high
	09	400–600 mm (~21,000 to ~26,000 mg/l)	15–20	Very low	Very high
Class C: High chloride	08	200–400 mm (~14,000 to ~21,000 mg/l)	10–15	Low	Very high
	07	150–200 mm (~7000 to ~14,000 mg/l)	5–10	Medium	High
Class B: Medium chloride	06	60–150 mm (~1800 to ~7000 mg/l)	2–5	High	Medium
	05	10–60 mm (~700 to ~1800 mg/l)	1–2	Extremely high	Medium
Class A: Low chloride	04	5–10 mm (~180 to ~700 mg/l)	0.5–1.0	High	Low
	03	2.5–5.0 mm (~90 to ~180 mg/l)	0.2–0.5	Medium	Low
	02	1.5–2.5 mm (~50 to ~90 mg/l)	0.1–0.2	Low	Rare
	01	<1.5 mm (<50 mg/l)	<0.1 (carbonate end)	Rare	Rare

1. Class A: Low chloride water (type 01, 02, 03, 04).
2. Class B: Medium chloride water (type 05, 06).
3. Class C: High chloride water (type 07, 08).
4. Class D: Very high chloride water (type 09, 10).

In some countries like Bangladesh, India, China and Vietnam, feed water would have high level of arsenic which is poisonous [6]. A complete water characterization would able to detect this and suitable pre-treatment or module arrangement can be incorporated to produce safer drinking water [7]. Table 2 shows maximum limit of substances in drinking water while Table 3 shows maximum allowable limit of toxic substances in drinking water [8]. An example of brackish water composition from groundwater at Australian National Park is shown in Table 4 [9].

Table 2
Maximum limit of toxic substances in drinking water [8]

Substances	Maximum limit, mg/l
Lead	0.05
Selenium	0.01
Arsenic	0.05
Chrome	0.05
Cyanide	0.1
Cadmium	0.005
Mercury	0.001
Antimony	0.01
Silver	0.01

3. Fouling and scaling

Fouling and scaling is difficult to be characterized due to the complexity of feed water composition [10]. A complete water composition would allow incorporating a suitable pre-treatment to prevent fouling and scaling. Fouling is accumulation of particles and colloidal material in water on the surface of membrane. Scaling of the other hand is due to deposition of soluble salts. Fouling and scaling increases pressure drop

Table 4
Example of brackish water composition [9]

Parameter	Unit	Sample value
Arsenic (As^{3+})	mg/l	<0.005
Boron (B^{3+})	mg/l	0.21
Calcium (Ca^{2+})	mg/l	142.1
Chloride (Cl^{-})	mg/l	1843
Fluoride (F^{-})	mg/l	<0.10
Iron ($Fe^{2+/3+}$)	mg/l	28.87
Magnesium (Mg^{2+})	mg/l	192
Manganese (Mn^{2+})	mg/l	0.5
Nitrate (NO_3^{-})	mg/l	<1.0
Nitrite (NO_2^{-})	mg/l	<0.1
Potassium (K^{+})	mg/l	19.2
Sodium (Na^{+})	mg/l	1125
Sulphate (SO_4^{2-})	mg/l	340
Total hardness ($CaCO_3$)	mg/l	1146
pH	–	6.7
Conductivity	mS/cm	6.35
Turbidity	NTU	370

Table 3
Maximum allowable of substances in drinking water [8]

Substance	Allowable limit, mg/l	Maximum allowable in case no better resource is available, mg/l	Type of effect within the maximum limit shown in this Table
Total dissolved salts, TDS	500	1500	Acceptability
Total hardness, ($CaCO_3$)	100	500	Acceptability
Detergents, ABS	0.5	1	Pollution indicator
Aluminum	0.2	0.3	Acceptability
Iron	0.3	1	Acceptability
Manganese	0.1	0.2	Acceptability
Copper	1	1.5	Acceptability
Zinc	5	15	Acceptability
Sodium	200	400	Acceptability
Nickel	0.05	0.1	Health
Chloride	200	500	Acceptability
Fluoride	1	1.5	Health
Sulfite	200	500	Acceptability
Nitrate	45	70	Health

causing increase in energy expenditure, loss in flow and decrease efficiency in reverse osmosis system [11].

Fouling is caused by organic matter, inorganic salt precipitation, colloidal or particulate deposits and growth of microorganism in long duration of [9]. According to Flemming [12], there are four major types of fouling; crystalline fouling, organic fouling, particle and colloid fouling and microbiological fouling.

Crystalline fouling is deposition of excess mineral in solution. It is enhanced by availability of additional nucleation sites during fouling process and presence of calcium sulfate particles [13]. Usage of aluminum sulfate coagulant and phosphonate based antiscalant is high contributor of Al and P which is the main element of fouling [10].

Organic fouling is due to plants, oil and grease in feed water. Humic acid produced by plants with concentration between 0.5 and 20 mg/l would form chelates with metal ion like iron forming fouling on membrane surface [14]. Another substance that could cause fouling is SiO_3^{2-} with concentration between 10 and 20 mg/l [15,16].

Particle and colloid fouling is deposition of clay, silt, particulate humic substances, debris or silica. Size and amount of particle in feed water need to be analyzed and removed at pre-treatment stage to avoid membrane fouling. Fouling tendency of water is evaluated with silt density index (SDI). SDI is obtained by measuring the rate at which a 0.45 µm filter is plugged when subjected to a constant water pressure of 30 psi. According to Bonnelye et al. [17], SDI of 3 or less would have less fouling on membrane. Typical deep well water has a SDI of 3 [15].

Growth of microorganisms like bacteria, fungi, algae, viruses and higher organism could form bio-film causing fouling. Bio-fouling is more difficult to control than other type of fouling. SDI has no influence on bio-fouling potential. Flemming [12] highlighted that even though the number of microorganisms can be reduced by using pre-treatment, microorganisms could multiply very quickly when nutrients are available. Feed water microorganisms count higher than 106 CFU/ml could cause problem if no suitable pre-treatment is done.

Fritzmann et al. [15] summarized potential scaling elements such as dissolved inorganic substances like silica and iron, cations like Ca^{2+} and Mg^{2+} and anions like SiO_3^{2-} and CO_3^{2-}. The content of Ca^{2+} and Mg^{2+} in water gives information about the hardness of the water. Feed water with about 1500–3000 mg/l of these substances is considered hard water. Scaling tendency for brackish water is evaluated using Langelier saturation index (LSI). LSI is done by predicting the pH at which water is saturated in calcium carbonate and expressed as the difference between the actual system pH and the saturation pH. Negative value of LSI indicates water has a very limited scaling potential while positive LSI when water is being supersaturated with $CaCO_3$ and has tendency to form scale. In practice, LSI between –0.5 and +0.5 will not display enhanced mineral dissolving or scale forming properties. Scaling can be minimized by reducing the concentration of mineral forming ions below the critical threshold which can be done by two-stage RO with chemical demineralization [18]. It is done by using intermediate chemical demineralization (ICD) followed by secondary RO of the treated primary RO concentrate.

4. Pre-treatment

A complete feed water characterization would enable to design a proper pre-treatment by taking into account the cost, maintenance, complexity and the quality of the product water. Combination of few types of pre-treatment is normally used for better conditioning of feed water before it goes to RO membranes. Pre-treatment able to reduce fouling and scaling on RO membranes increasing the life span of membrane and decreasing the maintenance cost.

Pre-treatment is categorized into chemical and physical. Chemical pre-treatment is done by adding chemicals such as acid and coagulant and flocculants into feed water. Mechanical filtration such as sand filters, cartridge filters, membrane filtration and mechanical filtration through screening are examples of physical pre-treatment. Conventional pre-treatment uses combination of chemical and physical. Starting with chemical treatment of water using flocculation, settling, then followed with physical treatment of sand filtration and cartridge filtration [20].

Acid is added into feed water as part of chemical pre-treatment to regulate pH in the range of 5–7. This is the ideal range for the membrane and also increases solubility for $CaCO_3$, which reduces scaling. Most common acid used for this purpose is sulfuric acid (H_2SO_4). Results from Lopez-Ramirez's [21] study shows that feed water with high pH value (11–12) able to remove suspended solids more effectively but increases calcium concentration in the system.

Coagulant and flocculation process eliminates suspended solids. The process starts by adding coagulant agent to feed water and mixed quickly and violently. Coagulant chemicals are such as metallic salts like alum or polymers. Coagulant chemicals neutralize electrical charges of the particles allowing it to cluster forming large clumps. Flocculation process follows when coagulants formed cluster together forming large floc. Tran et al. [22] analyzed RO membrane after 1 y operational in a brackish water treatment plant concluded that one of major contributor of fouling is aluminum due to aluminum sulfate coagulant usage which is also supported by studies done by Gabelich et al. [23].

Antiscalant is used to reduce the hardness of feed water. It prevents scalling by delaying reaction between calcium magnesium and bicarbonate working opposite of coagulants. Antiscalant prevents substances from clustering; however precipitation would still occur if the ion concentrations are high. Condition such as water composition, pH and temperature of the feed water would influence the effectiveness of antiscalant and the amount of antiscalant needed. Experiments need to be conducted in order to establish the optimal dosage requirement of the particular feed water. According to study done by Tran et al. [22], phosphonate based antiscaling could contribute high level of phosphorous causing fouling on membrane. Al-Rammah [24] experimented with different antiscalant and concluded that phosphino-carboxylate antiscalant is the most effective, cheap, safe, easily available and easy to use compared to other commercial antiscalant but it always depends on feed water composition as pointed out by Alawadhi [25].

Chlorination prevents biological growth and disinfects feed water. Chlorine is added to feed water as sodium hypochlorite or chlorine gas, which hydrolyzes to hypochlorous acid (HOCl) and hydrochloric acid (HCl). Introducing chlorine in feed water reduce biological fouling. For continuous chlorination at the intake point, free residual chlorine concentration of 0.5–1.0 mg/l should be maintained along the pre-treatment line to prevent bio-fouling [26]. Chlorine would shred organics which cultivates biological growth, reduce fouling but the shred organics become nutrients and enhance biological growth on membrane surface where no chlorine is present. This is overcomed by shock injecting chlorine periodically.

Currently the usage of membrane as pre-treatment is gaining popularity as the price of membrane reduces. Lorain et al. [27] experimented using ultra-filtration (UF) membrane for pre-treatment and concluded that it is very convenient and effective in filtering out foulants. Thekkedath et al. [28] supports this based from studies conducted by the author. Membrane usage also reduces chemical requirement. UF modules are used for removing particulates, bacteria and viruses and RO membrane for removing salts [29]. The downside of using membrane is fouling and scaling on the pre-treatment membrane itself [30,31]. Fouling on UF can be removed easily with pressurized dead end ultra filtration while bio-fouling can be removed with pressurized dead end ultra filtration coupled with chlorine backwashes.

5. RO design configurations

Module arrangement is an important part of designing a RO system. Arrangement of module is determined by feed water composition and product water quality needed. There are varieties of arrangement used by brackish water researchers to optimize the performance of RO system. On average, brackish water RO system could achieve about 90% water recovery with initial pressurization reach up to 27 bar [32].

5.1. Single-stage

Simple single-stage module arrangement is shown in Fig. 2 [33]. The feed water is pumped into the RO module with a designated pressure by high pressure pump. It then splits into product water and reject water. Product water is filtered while the reject water is with higher saline than feed water. With efficiency independent of the water recovery and generated feed pressure, optimal water recovery is not influenced by efficiency of high pressure pump but specific energy consumption increases with decreasing pump efficiency (Fig. 3) [34].

Module arrangement shown in Fig. 4 is a single-stage RO system with ERD. ERD could reduce energy consumption of RO system [35]. It reduces optimal minimum energy location to lower recoveries and SEC increases as efficiency of the pump reduces (Fig. 5) [34]. ERD could reduce the energy consumption and operating cost of the system but initial cost of installation would be high.

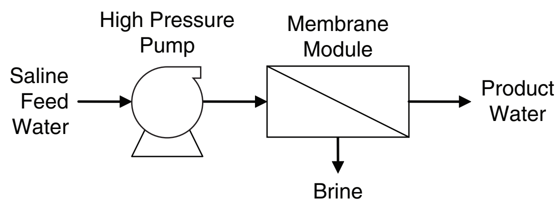

Fig. 2. Single-stage module arrangement [33].

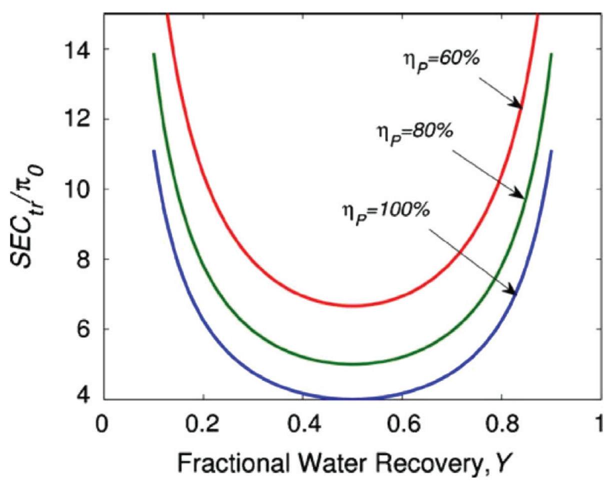

Fig. 3. Normalized SEC for single-stage RO system with pump efficiency, η_p at salt rejection of 99% [34].

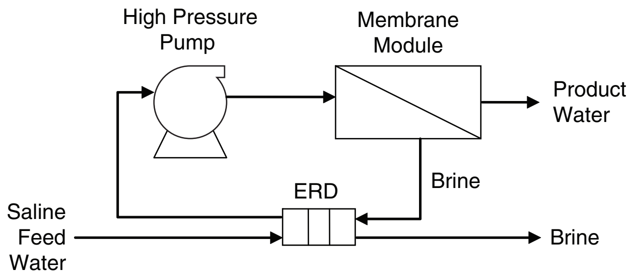

Fig. 4. Single-stage module arrangement ERD.

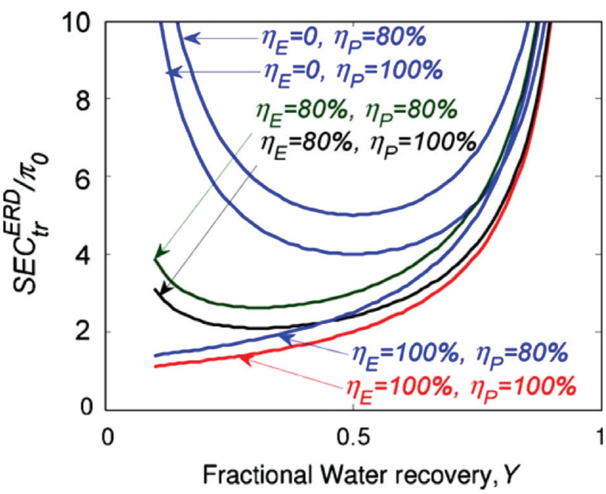

Fig. 5. Normalized SEC with ERD for single-stage RO system with pump efficiency, η_p and ERD efficiency, η_E at salt rejection of 99% [34].

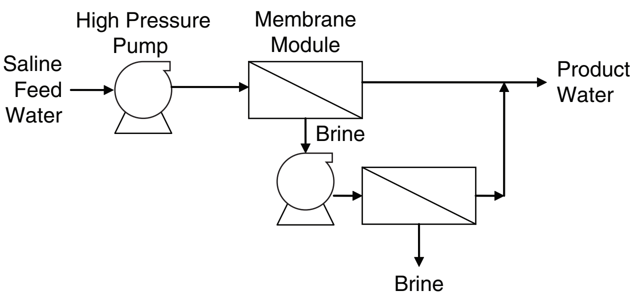

Fig. 6. Single-stage module arrangement with module connected to reject water with booster pump [33].

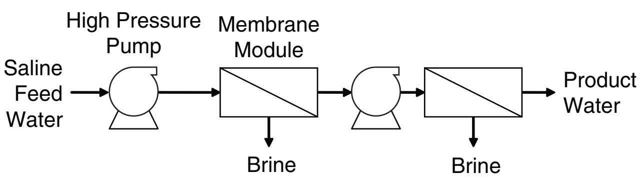

Fig. 7. Two-pass RO system without an ERD.

5.2. Two-stage

Two-stage system with booster pump is shown in Fig. 6. Booster pump increases the feed pressure from first module before entering the second module. System build with the booster pump depends on pressure of reject water from the first module [33]. If the booster pump is not included, then the RO system must be operated above minimum brine or reject flow rate to prevent concentration polarization from occurring. With a booster pump, the feed water pressure and water flux can be increased to an optimum value and second stage can be operated in nominal hydraulic conditions. Advantage of adding a booster pump is smaller membrane area which leads to higher total recovery rate and therefore reducing the electricity consumption and the investment costs [35].

Almulla et al. [36] used BWRO membrane as the first module and SWRO membrane as second module in the arrangement shown in Fig. 6. This arrangement would able to increase recovery rate up to 83%. It able to reduce boron concentration in brackish water more economically and consumes lesser energy compare to ion exchanging by boron selective resins or use of special RO membranes developed for boron removal in low or natural pH [37]. Boron concentration in the desalination product should be below 0.3 mg/l according to EU. This arrangement is also a very successful method for eliminating fluoride from brackish water [38]. There are no operation changes in using SWRO membrane as part of BWRO system.

Another innovative way for an optimum performance is provided by Nemeth et al. [19] by using hybrid combination of ultra-low and conventional RO membranes. Hybrid system able to improve permeates quality. It is possible to create a hybrid array by mixing membrane element types within a pressure vessel itself [39].

5.3. Two-pass

Two-pass RO system would able to provide product water with very low salinity. It is suitable for feed water with very high salinity. First pass would reduce water salinity and further reduction of salinity is done by second pass. Pressure of product water after first pass will be lower than the osmotic pressure of the second stage therefore pressure pump is needed to increase pressure from atmospheric to pressure between 20 and 40 bar which enables water pass the second membrane (Fig. 7). The second pass generally able to operate at high average permeates flux with recovery rate between 85% and 90% due to very low concentration of suspended particles and dissolved salts [40].

Two other variety of two-pass RO system is with inclusion of ERD as shown in Fig. 8 and with ERD and

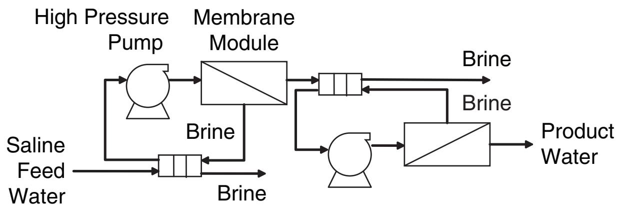

Fig. 8. Two-pass with ERD.

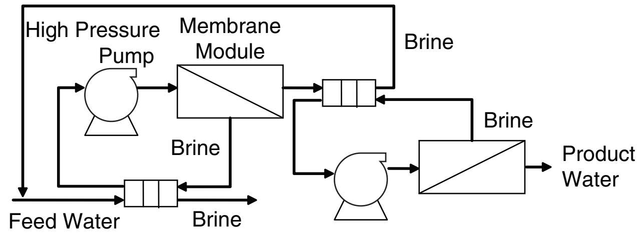

Fig. 9. Two-pass with ERD and recycling the concentrate of the second-pass to the feed water of the first-pass.

recycling the concentrate of the second pass to the feed of the first-pass (Fig. 9). The former have constant feed water salinity while recycling the concentrate of the second pass to the feed stream of the first-pass reduces the salinity of feed water in the latter [34].

The choice between single stage configuration and two-pass configuration for same level of total water recovery and salt rejection depends on lowest energy consumption which can be compared when the applied pressure is equal or more than thermodynamic cross flow limit without energy recovery devices [41,42]. Generally most authors agree two-stage system is more energy efficient compared to single stage system, however, Zhu et al. [42] pointed out that for brackish water, single stage system is the most cost-effective compared to two-pass system. Two-pass system would be energy efficient than single-stage if water recovery of single stage is below 50%.

5.4. Three-stage

Lu et al. [43] proposed three different optimum module arrangements based on simulation study which is three-stage system. The authors favored three-stage system oppose to single stage system. The proposed module arrangement is shown in Fig. 10 for feed water concentration of 3000 mg/l, Fig. 11 (6000 mg/l) and Fig. 12 (12,000 mg/l). In Fig. 10, brine from third module is partly recycled back for higher recovery while other flows to ERD. Fig. 11 shows much simpler module arrangement compared to the arrangement for feed water concentration of 3000 mg/l (Fig. 10). The arrangement is the same but with lesser number of pumps. In module arrangement as shown in Fig. 12, concentrate from first module splits into two, one flowing to second module after pressure is increased with a pump while the other flows to the third module through a pump.

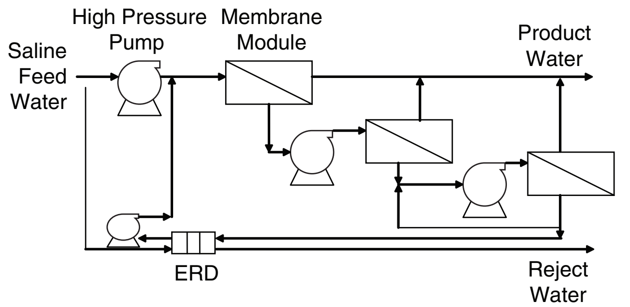

Fig. 10. Optimum module arrangement for feed concentration of 3000 mg/l [43].

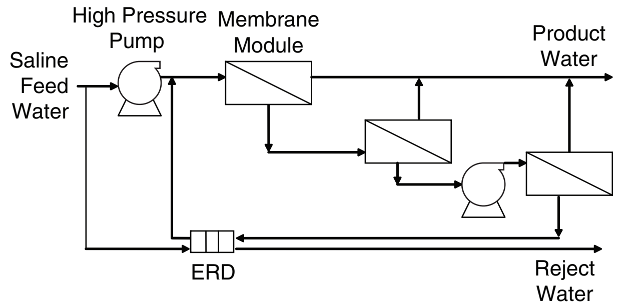

Fig. 11. Optimum module arrangement for feed concentration of 6000 mg/l [43].

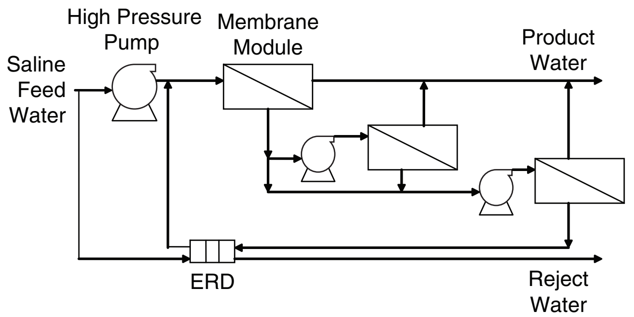

Fig. 12. Optimum module arrangement for feed concentration of 12,000 mg/l [43].

6. Energy consumption

One of the biggest advantages of RO system is low energy consumption compared to all the other desalination systems available which is only around half of the energy needed compared to other thermal processes [44]. Yet, energy consumption contributes up to 45% of total cost of a RO system [41,42]. Investment cost for energy supply for RO systems in rural areas is almost 60% [45]. This makes renewable energy source like PV able to bring down the cost of water produced in rural areas.

According to Al Suleimani and Nair [46], high pressure pump and pre-feed pump consumes the most amount of energy. Pumps are essential component for a RO system. It is used to extract water by overcoming the pressure difference which makes the reverse osmosis possible. Pressure requirement for brackish water can reach up to 42 bar [42]. Schafer et al. [9] points out that the capability of the pump to maintain continuous flow with high pressure would able to reduce the operating pressure. Energy consumption increases as pressure increases [48]. Higher pressure means more product water. Another way to reduce energy consumption is by varying feed pressure with time according with TDS of feed water [41].

Membrane configuration and salinity of the feed water are other factors that influence the energy requirement of RO system [51,52]. The choice of configuration includes single stage, two-stage, two-pass and three-stage. Zhu et al. [41] established that if desired salt rejection can be achieved with single stage, it would be more energy favorable compared to other configuration for the same level of total water recovery and salt rejection. The comparison would be valid when the applied pressure is close or near to the limit imposed by the thermodynamic cross-flow restriction.

According to Herold and Neskakis [3], energy consumption of the overall system increases as the feed pressure increases while feed pressure is influenced by the salinity of the feed water which plays a major role for energy consumption. Fig. 13 by Eyad [53] shows the relationship between energy consumption and water salinity.

Feed water salinity depends on location and may fluctuate due to seasonal rainfalls [41]. Colangelo et al. [54] pointed out that it is difficult to compare the specific energy consumption of the RO systems due to the wide range of feed water salinity which influences the module arrangements. Richards and Schäfer [55] estimated from his experiments that the power needed to produce 0.001 m^3 of fresh water from feed water of 3500 mg/l is between 2 and 8 kW h/m^3.

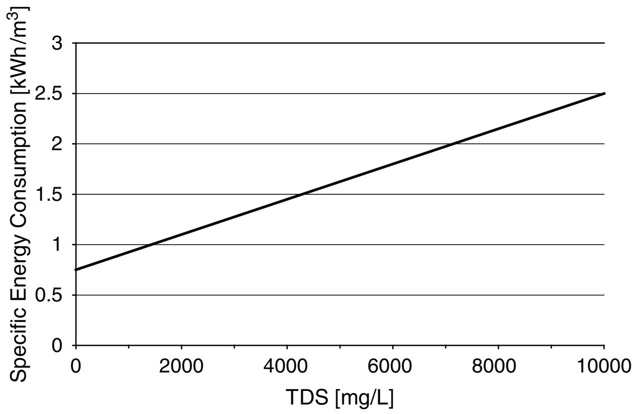

Fig. 13. Energy consumption of the RO desalination sub-unit as a function of TDS [53].

Energy consumption can be further reduced using energy recovery devices (ERD) [56,57]. ERD utilizes the energy of pressurized concentrate from brine and reject to reduce the power consumed [58]. In a study done by Harris [59], the author stated that including ERD as part of a RO system able to lower energy consumption of RO plant up to 40%.

In large RO desalination plants, commonly used ERD is pressure-exchange system (PES) and pelton wheel turbines [2]. Another type of ERD which is getting attention is ERI's pressure exchanger [58]. Studies have shown that pressure exchanger is the most efficient ERD [42]. Thomson et al. [58] pointed out that in most small scale RO system, ERD component is not included. A RO system without ERD would able to be build with lower investment but loses in the long run as the running cost increases. Small scale system without ERD consumes up to three times more energy [60]. In recent years, there have been a lot of advancement and research in this field. Some researchers have adapted the large scale ERD and scale it down for the use of small scale system. This reduces energy requirement of RO systems. Mohamed and Papadakis [49] did simulation study and concluded that the power consumption can be reduced about 50% by using pressure exchanger to recover the hydraulic energy at the same time reducing the size of the high pressure pump by about 48%.

Dulas Limited demonstrated use of a Danfoss axial piston hydraulic motor for energy recovery in seawater RO [60]. Pump integrated energy recovery mechanism within a seawater RO system was developed in 1985 but its high manufacturing costs inhibited further development initially. The concept was further developed for brackish RO system later on. In 1996, Thomson et al. [58,61] incorporated Clark pump as ERD component in small scale seawater RO system. This system showed very good energy efficiency. Spectra Clark pump recovers mechanical energy from brine stream and returns it to feed flow. It reuses the energy and not wasting it. Spectra Clark pump is able to work efficiently with a broad range of operation [62], which makes it possible for a RO to be integrated with PV. Clark pump can be easily incorporated as part of a BWRO system.

7. Battery

Using battery as part of PVRO makes it more efficient and reduces energy consumption of the pumps [63]. This is due to the fact that batteries are able to provide stable energy flow to RO system [64]. Stable energy feed produces stable flow of fresh water maximizing the output of RO system. Battery based system reduces the size and cost of PVRO system as the size of the photovoltaic system used to power RO system could be dramatically reduced [63].

Calangelo et al. [54] developed mathematical model and simulated PVRO system with and without batteries. The author concluded that system with minimum battery capacity is the most efficient in terms of cost and productivity. System with battery able to operate continuously even during the period without Sun which increases the productivity. A battery based PVRO system would able to operate 24 h a day where the energy stored in the battery would run the system during night time. In order for this to happen, batteries are needed in a large quantity. With battery, even cloudy period will not be a problem.

Including batteries as part of PVRO system have its advantages; however there are downsides of using batteries too. Thomson et al. [61] experimented seawater PVRO without battery and found that a battery-less system could have a reasonable performance with a much lower cost. Batteries have short life expectance, especially in hot climates. Energy loss in battery can be more than 25% in hot places [58]. Sunny climate is good for photovoltaic system but it is an enemy for lead acid batteries which commonly used with most of the PVRO systems. Another problem with battery is energy loss during charging and discharging. This is inheriting weakness of battery. Batteries are also hazardous and could cause pollution if it is mishandled [9]. Initial cost and maintenance of including batteries is high [50].

Designer of PVRO system need to understand the need of their system as well as the cost of installation before including battery. Operating battery only when the capacity is more than its minimum capacity could prevent damages on the batteries and prolong the lifetime of the battery reducing the cost of fresh water [65]. Duration of operation is the key that determines the need of using battery. An alternative to using battery is to store produced fresh water in storage tank [66]. The tank size is determined by the output of the system and average consumption of water by the population at the location.

Gocht et al. [38] distinguishes PV powered RO system operating mode into continuous operation, which operates 24 h per day and discontinuous operation. Continuous operating system need to include large bank of batteries to provide power during night or cloudy times. Discontinuous operation system is set to operate during day for 5–7 h depending on location for its optimum operating hours.

8. PV-BWRO system

Radiation from Sun varies depending on location. It is essential to know the amount of solar radiation received at a particular location at a given time [67]. Local meteorological need be evaluated to maximize energy output from installed solar module. Tilt angle of solar module is very crucial. Data of solar radiation at different tilt angle everyday for whole year need to be collected in order to determine the optimum tilt angle for solar module. Total number of solar module and arrangement is determined on the need of voltage and current of RO system.

Electricity which is produced by PV is direct current (DC). It can be used by any electrical appliances that uses DC or to charge a battery. However, most of electrical appliances use active current (AC) to operate. In this case, an inverter is needed to convert DC to AC. Electricity generated by PV is direct, simple, maintenance-free, quiet, clean, renewable and economic in rural areas [64]. Solar modules are connected together to generate more power depending on the needs. Summary of small scale PV-BWRO plant extracted from Garcia-Rodriguez [68] is shown in Table 5.

PVRO is a promising desalination technology in remote areas [39,61]. According to Garcia-Rodriguez [68], photovoltaic energy is used to power brackish water desalination system with production between 0.1 and 60 m^3/d. Herold et al. [69] demonstrated small PVRO system which produces 1 m^3/d at remote area where no grid electricity is available have higher specific energy consumption compared to medium and large but initial cost is lower compared to other desalination system [39]. PVRO system is more needed in remote areas than any other. In these locations, skilled personals are hard to find. A simple system with minimum maintenance like PVRO system is desired. A PVRO system is very reliable and easy to manage and operate [70]. It is also environment friendly. Comparison of conventional diesel generator and solar power source is summarized in Table 6 [46].

Table 5
Small scale BWRO plants powered by photovoltaic system [68]

Plant location	Plant capacity	PV system
Cituis West, Jawa, Indonesia	1.5 m^3/h	25 kWp
Concepción del Oro, Mexico	1.5 m^3/d	2.5 kWp
Eritrea	3 m^3/d	2.4 kWp
Hassi-Khebi, Argelie	0.95 m^3/h	2.59 kWp
Heelat ar Rakah camp of Ministry of Water Resources, Oman	5 m^3/d	3250 kWp
INETI, Lisboa, Portugal	0.1–0.5 m^3/d	–
North of Jawa, Indonesia	12 m^3/d	25.5 kWp
Perth, Australia	0.1–0.5 m^3/h	1.2 kWp
Red Sea, Egypt	50 m^3/d	19.84 kWp (pump) 0.64 kWp (control)
Thar desert, India	1 m^3/d	0.45 kWp
University of Almería, Almería, Spain	2.5 m^3/h	23.5 kWp
Wanoo Roadhouse, Australia	–	6 kWp

Table 6
Comparison of conventional diesel generator and solar power source [46]

Aspect	Conventional diesel generator	Solar photo-voltaic system
Environmental	Noisy, flue-gas emissions, etc.	Environmentally friendly (no noise or pollution)
System life	5–10 years with regular maintenance	Over 20 years (no moving parts)
Maintenance	Regular maintenance is required. When the equipment goes for overhauling, spare/standby generator is required	The PV system needs practically no maintenance
Spare parts	Spares and routine checks are required	Only the boost charge battery requires attention, every 3–6 months
Consumables	Fuel, lubricants, filters, etc., (expensive to mobilize to remote locations)	No consumables are required
Efficiency	Efficiency of the diesel plant deteriorates in course of time	The efficiency of the solar photo-voltaic plant is maintained more or less constant throughout its life

9. Reject water management

Reject water is by-product of RO desalination process. Concentration of reject water is much higher than concentration of feed water as water molecules are pressured through membrane leaving behind all the bigger molecules. Water with high concentration need to be disposed properly or it will cause contamination and disturb the ecosystem. According to Squire et al. [71], disposal of concentrate is one of important factor influencing feasibility of membrane application and also contribute significant portion of overall cost of water treatment. At recent years, environmental awareness has increased pushing governments to implement more stringent regulations for disposal of concentrate.

Mohamed et al. [72] pointed out that reject water could cause contamination due inorganic salt and slurries from feed water, rejected backwash, washing solutions and compounds from pre- and post-chemical treatment such as antiscalent, antifoaming agents, polyphosphates, coagulant aids, chlorine residue and acid. Heavy metals such as nickel, copper, molybdenum and other lesser toxic metals such as iron and zinc could cause corrosion. Reject water from RO system does not produce more pollutant material or mass in the water stream unlike conventional water treatment but redistributes what is present in the feed water [73].

Example of concentrate of feed, permeate and reject water is shown in Table 7 which was extracted from Squire et al.'s [71] paper while Table 8 shows the

Table 7
Analyses of Bunwell RO prototype plant feed, permeate and reject water (mg/l) [71]

Parameter	Feed	Permeate	Concentrate
pH	6.94	5.63	6.96
Conductivity, μS/cm	784	41	2380
Nitrate	<0.22	<0.22	<0.22
Total hardness	430	32	1740
Alkalinity	356	24	1290
Chloride	49	5	196
Silica	25.2	1.05	125
Sulfate	80	1	369
Sodium	22.7	3.7	94.3
Potassium	2.26	0.34	10.4
Copper	<0.005	<0.005	<0.005
Magnesium	8.27	0.2	37
Calcium	149	3.9	846
Zinc	<0.006	<0.006	<0.006
Aluminum	<0.01	<0.01	0.024
Manganese	0.031	<0.002	0.086
Iron	2.17	0.047	9.79
Phosphorous	0.044	<0.03	0.246
TDS	535	49	2010

Table 8
Proposed EA discharge consent limits (mg/l) [71]

Parameter	EA limit
pH	6.0–9.0
Conductivity, μS/cm	2310
Alkalinity	770
Chloride	170
Sulfate	340
Copper	0.01
Zinc	0.01
Aluminum	0.02
Manganese	0.08
Iron	10
Suspended solids	50
Total volume, m^3/d	250
Maximum discharge rate, l/s	6

concentration which is safe to be disposed without any effect to environment.

Mohamed et al. [72] discussed six method of reject water disposal from inline plants which includes discharge into well engineered solar evaporation pond, disposal to wastewater system, land application which includes irrigation and percolation ponds, injection into deep saline aquifers, disposal into land surface and disposal into sea through a pipeline. Ahmed et al. [74] summarized factors that influence the choice of disposal methods including volume or quantity of concentrate, quality or constituents of concentrate, physical or geographical location of the discharge point of the concentrate, availability of receiving site, permissibility of the option, public acceptance, capital and operating costs, and ability for the facility to be expanded. A lot of small RO plants dispose their reject water in municipal sewerage systems [74]. Table 9 shows summary of reject water disposal method in USA out of 137 plants with capacity of 98 m^3/d or more [72].

Table 9
Methods of reject water disposal in USA [72]

Method of disposal	(%)
Surface water	48
Discharged to wastewater treatment plants	23
Land application	13
Deep well injection	10
Evaporation ponds	6

10. Cost

Cost of water production generally consists of the cost of energy consumption, equipment, membranes, labor, maintenance and financial charges [34,41,42]. Other parameters which influences the cost are feed water characteristics such as TDS, turbidity, temperature, heavy metals, product water quality, applied pressure, recovery ratio, plant location, cost of land, disposal system, membrane performance, etc. [8]. Investment on equipment includes membranes, PV panels, inverter, solar charger, battery, pumps, concentrate disposal, storage tanks [75]. Cost of fresh water would be high for small scale due to high cost of PV [76] and cost of labor [77]. Including PV for grid connected RO system would cost additional of 39% [47]. Concentrate disposal influences overall cost of fresh water which can alter optimal energy cost [42].

Energy consumption contributes the highest proportion of the total cost of RO system [78]. Incorporating ERD would able to reduce the energy consumption up to 40% operating of operating cost at efficiency as high as 94% [59]. Reduction of energy consumption would reduce cost drastically and should be given high priority.

Feed pressure should be operated close to exit brine osmotic pressure to enable operation at minimum level of energy consumption [79]. This should be possible as current brackish water membranes have high permeability. Main issue about membrane is fouling. Based on study done by Thomson et al. [61], fouling of membrane is dependent on the water quality. This is an important criterion as one of the costs of maintenance is membrane cleaning or membrane replacement when fouled could not be cleaned to the required specification. Using high efficiency pre-treatment able to reduce membrane replacement cost between 6% and 10% [80]. Fig. 14 shows that by increasing the membrane life time the cost of water decreases significantly [81].

Al Suleimani et al. [46] came to conclusion from their study that by taking into count of maintenance and running cost, a PVRO system are more cost-effective than other systems however have higher initial investment. Using PV to power RO system would able to provide clean water to people who are not connected to the grid power source which is isolated and does not have skilled person for maintenance.

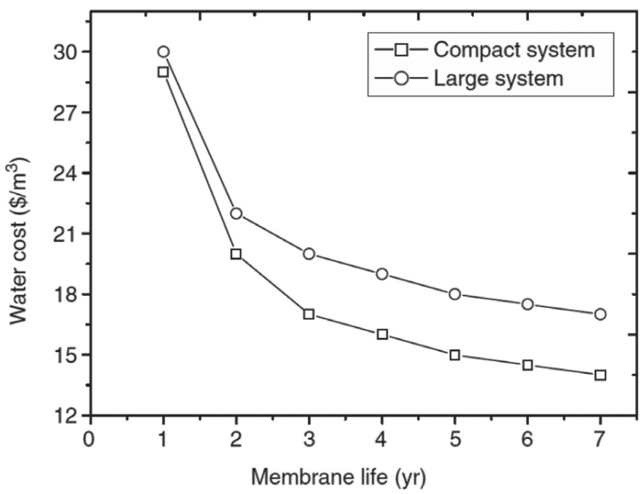

Fig. 14. The effect of increasing the plant lifetime on the distilled water cost [81].

Gocht et al. [38] did a comparison study in Jordon for three combination of operation which is 24 h per day operating system, 8 h per day operating system and 10 h per day operating system and concluded that 8 h per day operating system are the most cost-effective. Operating full 8 h during day time without battery but storing unused water in storage tank which will be used at night or cloudy days. A system with or without battery do make a different in term of its cost. Replacement of battery after every 5–8 years increases cost. Using battery also increases the cost of maintenance and operation. Based on quality and cost, RO produced water provides clean drinking water within the allowable limits with a relatively reasonable price [82]. Small scale system in remote areas with simple design, reliable operation and energy recovery devices would able to reduce desalination cost by more than 25% [81].

11. Conclusion

Success of small scale PV-BWRO system designation depends on ability to minimize cost of water produced. Cost is the major constrain in building an effective PV-BWRO system. Cost of water production is mainly influenced by initial investment on equipments, labor building the system, financial charges, cost of land, cost of operational and cost of maintenance. Among all the parameters effecting cost, energy is the most influential. Energy is used to power high pressure pump and pre-feed pump which is chosen based on feed water salinity. Knowing salinity of feed water would enable a good choice of pump and RO design configuration. RO design configuration should be kept as simple as possible based on feed water salinity. Single stage would be the best choice for brackish water consuming the lowest amount of energy. Different configuration should only be applied if desired product water salinity is not achievable with single stage. Location and seasonal rainfalls fluctuates salinity of feed water. Continuous monitoring of TDS would enable optimum operation of pumps by varying pressure accordingly. Feed pressure could be maintained close to exit brine osmotic pressure to reduce energy consumption of pumps to minimum. Implementation of ERD could further reduce energy consumption by recovering hydraulic energy in the brine stream. Including battery for stable supply of energy enables the pumps to operate at optimum level reducing energy consumption. Number of battery should be kept as minimum as possible only to provide stable supply of energy and batteries are not advisable to be used to store energy. Problem with battery is energy loss during charging/discharging and high cost of maintenance and replacing. Instead of storing energy in batteries, it is better to store produced fresh water in storage tank. The capacity of the tank is determined by the output of RO system which is designed based on average consumption of water by the population at the location of the system build. Initial investment on PV panels is high but it is one time investment and maintenance-free. PV panels can last up to 25 y without additional cost. It is a very effective way of producing energy in areas where other source of energy is expensive. A well designed system, taking consideration of all the parameters influencing cost by researches presented in this review would able to bring down cost of water produced by PV-BWRO system.

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