Design and performance of small-scale reverse osmosis desalination for brackish water powered by photovoltaic units: a review

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Abstract. The reverse osmosis (RO) water desalination system powered by the photovoltaic (PV) unit is commonly used to produce drinking water due to their reasonable price. This review focused to display different designs of small-scale PV powered brackish water RO (PV-BWRO) systems that were installed to improve the water productivity at remote areas. The configuration of BWRO units, which determined the operating cost, permeate flow and amount of rejected water, is of great concerns in this work. The specific energy consumption (SEC), total capital cost and water production cost are also analysed to display the feasibility of application of PV unit for small-scale BWRO desalination system. The single-stage configuration was suitable for most of small-scale BWRO systems owning high recovery rates (i.e., higher than 50%). The PV solar system pairing with batteries was not recommended at production capacities below 5 m³ for their high cost and short lifetime. Independently operated PV-BWRO systems required the highest capital cost while produced the lowest operating and overall production costs compared to hybrid systems.

1. Introduction
Water covers a major portion of the Earth’s surface, in which only 3% of the water on Earth is fresh water. Given the freshwater scarcity, the population growth in many developing countries around the world has worsened the problem, leading to the shortage of portable water for human consumption and use [1]. According to WWAP (United Nations World Water Assessment Program), the water shortage is expected to affect up to 40% of world inhabitants by 2030. Climate change and sea level rise have additionally raised serious concern on the salinization of water source, both surface water and groundwater, and water supplies in coastal areas. Therefore, enormous efforts have been prioritized to make new water resources available and minimize the impact on economic growth and social well-being of billions of people [2]. Owning to the increasing amount of brackish water over the world, the desalination of brackish water is an essential practice to supply clean drinking water.

Desalination is the process aiming to remove dissolved salts and minerals from saline water. Water desalinating practice enables the potential of using readily available water resources such as seawater...
and brackish water to produce portable water. Water desalination processes are classified into two main groups according to the using technique and intended products. The processes that allow water to pass through a membrane without a phase change belong to the membrane desalination group; or those that involve a phase change belong to the thermal desalination group [3]. Membrane processes are more economical for brackish water desalination [4]. Representative membrane desalination techniques include electro-dialysis (ED), electro-dialysis reversal (EDR), ion exchange (IE), capacitive deionization (CDI), reverse osmosis (RO), and forward osmosis (FO).

Among membrane desalination processes, RO and ED are widely used for the freshwater production, respectively accounting for 65% and 3% of the global desalination capacity [5]. Processes for extracting salt such as ED, IE and CDI are not economically competitive for seawater applications because of the high cost of electrode, the expensive ion exchange membranes and relatively short life time of membranes [3, 6]. In recent years, CDI technology has been further developed for improving both salt removal and energy efficiency. Simulating researches, but not yet laboratory- and real-scale verifications, showed promising results for the application of RO-CDI hybrid systems in ultrapure water production as well as seawater desalination [7, 8].

Brackish water is water having total dissolved solid (TDS) between 1,000 and 10,000 milligrams per liter (mg/L) (USGS Water Availability and Use Science Program: National Brackish Groundwater Assessment). In many countries, where the water scarcity problem is either severe or less, reverse osmosis (RO) of brackish water has been applied to prepare drinking water. Brackish water RO (BWRO) system is a relatively straightforward process, comparing to reverse osmosis of seawater (SWRO). The main challenge associated with RO membrane is surface fouling on the polyamide layer due to the precipitation or deposition of salts and colloidal compounds, organic gel formation, and microbial attachments [9-11]. BWRO systems lowered the possibility of membrane malfunction, energy demands and costs.

BWRO systems require the initial pressure about 27 bars, whereas seawaters have high concentrations of inorganic mineral ions and need higher initial pressurization, by a factor of 4 – 10 and up to 70 bar, to pass through RO membranes, and thus increased the energy consumption [12, 13]. The specific energy consumption (SEC) estimated from small-scale BWRO systems (production capacity < 3 m³/day) ranges widely (0.2 – 25.6 kWh/m³) and higher SECs associated with small sizes of the system and a lack of configuration optimization [14].

Depending on the composition of feed waters, the design of a good desalination RO system needs to accomplish the following criteria: a) the feed pressure and number of membranes are minimized and b) the recovery and product quality are maximized. Accordingly, brackish groundwater is commonly exploited as feed water to BWRO systems producing drinking water. A major advantage of using groundwater over surface water presents in a less critical pre-treatment demand [15]. Groundwater sources are generally free-particles, lower in organic and pathogen pollution, and easy-access to consumers. However, groundwater usually contains more minerals followed a long-term contact with the deep crust, resulting in high levels of hardness, iron, and manganese. This increases the potential of membrane fouling by insoluble salts of sulfide, silicate, phosphate, and carbonate [15, 16]. Temperature variation of intake water of BWRO systems should be measured to avoid exceeding the limits that would further promote scale formation [17, 18]. Inorganic fouling or scaling can affect the system performance by reducing productivity and permeate quality, increasing energy and maintenance costs, and shorten membrane lifetime [12]. A significantly raised maintenance cost was usually associated to additional pretreatment of feed water and frequent membrane cleaning [12, 19, 20].

The main objective of this study is to overview critical and remarkable aspects on design and operation conditions of small-scale BWRO systems using photovoltaic (PV) solar energy for drinking water supply. Lessons and experience from recent investigation are reviewed to discuss on socio-economic feasibility of BWRO systems.

2. Brackish Water Reverse Osmosis (BWRO) systems
Given recent advances in dramatically reducing the energy consumption, RO technology is of great importance in the desalination application [21-24]. The most used RO membrane is the thin-film composite (TFC) polyamide membrane without predefined pores, comprising of an upper active polyamide layer, a micro-porous interlayer and a structural support layer [25]. Water in higher salinity solutions could pass through the semipermeable RO membrane to lower salinity solutions with a pumping pressure excessive to the osmotic pressure. As more freshwater is recovered, feed water becomes more and more saline due to the ability of RO membranes to reject most dissolved chemical species including monovalent ions such as sodium and chloride. Current developments on RO membranes have focused on surface improvement and the enhancement of salt rejection and fouling resistance [25-27].

Brackish water reverse osmosis (BWRO) systems hugely vary in size, up to 98,000 m$^3$/day, regarding to daily per capita water consumption, total population and daily operational time [17, 28]. Small-scale BWRO systems, which typically supply a community of about 2000 people, are usually installed in remote and coastal areas, thus commercially receive less attention compared to large-scale systems [29]. Assuming that about 2 liters of drinking water per person is the minimum daily need, the typical size of BWRO systems would adequately assign 4 m$^3$/day to 2000 people. For this reason, a small-scale BWRO system is defined as having a production capacity of less than 5 m$^3$/day in this review. The incompetent cost of water production is an additional reason for remaining low deployment of small-scale BWRO systems, even being integrated with renewable energy supplies such as solar photovoltaic (PV) and wind energy [30-32]. Table 1 presented lowest water production costs from BWRO systems with different production capacities. Despite mentioned disadvantages, there is a continued interest in developing small-scale BWRO systems with special needs. For instance, to small communities experienced catastrophes or those in rural areas where drinkable water is not available, small-scale BWRO system powered with PV unit could be rationally supportive, making daily average productions of less than 5 m$^3$ from brackish waters containing salt concentrations of less than 5000 ppm [36]. Critically, beside common major determinants involved in the optimization of large-scale system performance and energy cost, the selection and design of small-scale systems often rely on prominent local factors such as technical assistance for operation and maintenance and the availability of a supply chain for spare parts [29, 30].

**Table 1.** Production costs of BWRO systems with different production capacities

| Production (m$^3$/day) | Typical costs ($/m^3$) | Ref. |
|------------------------|-------------------------|------|
| <20                    | 5.6 – 12.9              | [33] |
| 20 - 1200              | 0.8 – 1.3               | [33] |
| 6,000 – 30,000         | 0.1 – 0.3               | [34] |
| Large scale            | 0.2 – 0.4               | [35] |

The most basic BWRO system includes the pre-treatment module, high-pressure pumps, the RO membrane module, and the post-treatment module, arranged as shown in Figure 1 [37]. Pre-treatment essentially reduces potential of fouling and prolongs the lifespan of RO membranes. For the last decade, low-pressure membrane processes such as microfiltration (MF) and ultrafiltration (UF) were adopted as pre-treatment for RO system [19]. In comparison to conventional processes with the chemical addition (coagulation, flocculation, and adsorption), low-pressure membrane processes offer a consistent and adequate quality of feed water. In case of BWRO systems integrating with renewable energy sources, MF/UF pre-treatment modules can help to save land areas and require simple installation and maintenance [38]. NF-based pre-treatments for BWRO systems could ensure better feed water quality but result in higher production costs compared to MF/UF modules [39]. Potential pre-treatment options for BWRO systems are presented in Table 2.
Table 2. Pre-treatment options for BWRO systems (adapted from Li et al. [14])

| Pre-treatment technique | Target removal |
|-------------------------|----------------|
| Screening               | - Remove suspended particles such as sand, silt and clay mineral particles, salt crystals (CaCO₃, CaSO₄, BaSO₄, etc) |
| Cartridge filter        | - Eliminate organic matter such as organic macromolecules (proteins, polysaccharides, etc), organic colloids and microorganisms |
| Media filtration        | - Eliminate organic matter such as organic macromolecules (proteins, polysaccharides, etc), organic colloids and microorganisms |
| Conventional processes  | - Avoid scale formation via bulk or surface crystallization |
| Scale inhibitors/acids  | - Dechlorination of feed-water disinfected with chlorine |
| Bisulftes               | - Destabilize suspended solids, maximize microfloc formation of small-suspended solids and colloidal particles, and promote the formation of macroflocs |
| Chemical addition       | - Destabilize suspended solids, maximize microfloc formation of small-suspended solids and colloidal particles, and promote the formation of macroflocs |
| Coagulants and flocculants | - Destabilize suspended solids, maximize microfloc formation of small-suspended solids and colloidal particles, and promote the formation of macroflocs |
| Disinfection            | - Deactivate waterborne microorganisms |
| Chlorination            | - Eliminate microorganism by oxidative effects |
| UV light                | - Eliminate microorganism by oxidative effects |
| Adsorption              | - Remove dissolved organic matter and biopolymers |
| Activated carbon        | - Remove free chlorine |
| Membrane processes      | - Remove particulates without using chemicals (removal efficiency of 100% with UF or MF) |
| UF                      | - Remove biofilm-forming bacteria (removal efficiency of 90% with UF or MF) |
| NF                      | - Remove organic matter economically instead of UF or MF combined with chemical pre-treatment |

High pressure pumps increase the pressure of pre-treated feed water and reverse the osmotic water flow passing through RO membranes. Studies showed that the pump efficiency has an influence on the energy consumption but not on the water recovery [40]. The advance of membrane technology and energy recovery devices (ERDs) over the last 50 years has brought down the energy intensity of SWRO desalination plants [41, 42]. The energy can be extracted from high-pressure reject streams (or brine) to reduce the required energy from pressure pumps (Figure 2). Unfortunately, most of installed small-scale BWRO systems are still prone to high energy demands due to the super small component’s inefficiency and the lack of optimized configuration including ERDs [14, 43].
In order to improve system performance, there are several ways to modify the configuration of membrane modules. The RO membrane module may contain one or several modules with many membrane elements arranged in series or parallel in a module. The ultimate objectives are to achieve a satisfied quality of produced water and long-term robustness of the plant with increasing energy efficiency, water recovery, and membrane lifetime [31]. For example, two-stage and two-pass designs, presented in Figure 3 and Figure 4, were adopted to increase the recovery rate up to 90% and improve salt rejection and permeate quality [44-48]. Innovatively, by mixing different membrane types within a pressure vessel or between modular stages, studies showed optimum operations of BWRO systems, by increasing the recovery rate up to 83% and reducing the permeate TDS by 20% [41, 45, 49]. Capital cost and energy consumption are important to consider for the installation of BWRO systems with same levels of total water recovery and salt rejection. Normally, multi-stage configurations required higher capital costs and less energy consumption than single-stage configurations, particularly if water recovery of the latter below 50% [31, 41, 50]. However, given that most of the small-scale BWRO systems have high recovery rates, single-stage designs would be more cost-effective [40].
Some feed waters may contain high concentrations of uncharged dissolved species such as boron (H₃BO₃). Boron is not easily removed in normal BWRO processes and would raise maintenance costs with multi-stage designs [51, 52]. For two-stage systems, the cost for boron removal was estimated about 0.06 Euro/m³ [53]. High levels of boron in feed waters may pass the RO membrane and exceed the criteria for drinking water established by WHO, 0.5 mg/l. Studies suggested that using SWRO membranes in single-stage BWRO systems could effectively increase boron retention efficiencies [46, 54].

The typical post-treatment of BWRO-permeate used for drinking includes conditioning and disinfection [55]. The BWRO-permeate is virtually free of dissolved compounds, thus it is necessarily mineralized to meet the desired quality for drinking water according to guidelines. Mineral-deficient drinking water could have an impact on human health, relating not only to the risk of cardiovascular disease but also to other serious diseases [56]. Table 3 showed a preliminary assessment of mineral contents in bottled mineral water commercializing in Vietnam and their suggested ranges for drinking. Main conditioning process of BWRO-permeate for drinking should involve mineral adding such as calcium, magnesium and bicarbonate, and pH adjustment [57].

| Brand  | pH | TDS | Ca⁺ | HCO₃⁻ | Mg²⁺ | K⁺ | Na⁺ | F⁻ | Cl⁻ | SO₄²⁻ | SiO₂ |
|--------|----|-----|-----|-------|------|----|-----|-----|-----|------|------|
| Fiji   | 7.9| 210 | 19  | 150   | 15   | 18 | ND  | 0.24| ND  | 1.7  | 0.24 |
| LaVie  | ND | 310 - 11, 360 | 17 | 280 - 330 | 3 - 6 | 2 - 3 | ND  | < 0.5 | < 0.1 | ND  | ND  |
| Vinh Hao | 7.2 | 375 | 1.6 | 439 | 1.0 | 3.7 | 153 | 1.3 | ND  | ND  | ND  |
| Vikoda | 8.5 | ≤ 500 | 1.6 | 145 | 0.02 | 2 | 55 | ≤ 1.15 | < 0.01 | ND  | ND  |
| Thach Bich | ND | 333 | 1.74 | 54.1 | 0 | 3.99 | 105 | 0.9 | 0 | ND  | ND  |
| Suggest Range | 7-8 | 100 - 200 | 20 - 300 | 100 - 500 | 10 - 15 | 5 - 10 | 20 - 100 | 0.8 - 1.2 | 0.005 - 0.075 | 50 - 250 | 20 - 10 |

*Rosborg, I. 2016. Drinking Water Minerals and Mineral Balance. Springer
Unit is ppm, except pH; ND = no data

The RO membranes could not remove bacterial cells completely from the tap water [58]. The reason how bacterial cells pass through the RO membrane remains unclear, but this could be a constant source of inoculation for the drinking water distribution system. A study showed that RO permeate water was not biologically stable. Previous studies observed remarkable biofilm accumulation and bulk cell growth in the RO permeate water [59]. Therefore, post-disinfection of the RO permeate water and in the distribution system is necessary to inhibit bacterial growth. UV disinfection are common post-treatment processes of RO-permeate with low contents of TOC, suspended particles and low microbial loads for drinking purpose [60].

3. Small-scale PV-BWRO systems
Main factors determining the choice of desalination technologies include the upfront capital cost, the energy consumption, and ecological consequence. Particularly, the energy consumption is a critical factor that affects the economic efficiency of desalination plant. Compared to other commonly used water desalination techniques, BWRO units consume lowest amounts of electrical energy, from 1.5 to 2.5 kWh/m³ [5]. The significant electricity consumption of BWRO units is to apply high pressures through RO membranes, which is up to 80 bars for technical and economic reasons. Conventionally, the high associated expense on energy sources, mostly fossil fuels, is required to operate BWRO systems.
Burning fossil fuels is known to accelerate global climate change. Consequently, this driving energy source for desalination units is expected to reach an annual rate of 400 million tons of carbon equivalents by 2050 [61]. Therefore, the use of renewable energy as alternative power sources for desalination units can meet the requirement for sustainable development. Among 1% of current global desalination plants powered from renewable energy sources, about 43% of these plants are powered using solar photovoltaic (PV), 27% are powered using solar thermal, and 20% are powered using wind energy; while the remaining 10% are based on hybrid renewable energy sources [4]. At present, desalination RO systems have proved their commercial penetration by integrating solar and wind energy systems, while desalination RO systems powered by wind turbines can provide water with better costs [62]. However, wind power may fluctuate if the wind turbine is not built in suitable locations having high wind speed, for example on shore. This gives the solar energy, which is much more available in tropical regions, a special competence to present as a potential source to desalination units [4, 63, 64].

Solar energy can be used in the form of thermal or electrical energy. Thermal energy can be converted from radiance heat of the sun, while solar electrical energy involved direct conversion of solar light using solar cells made from crystalline silicon or other semiconductor materials [65, 66]. Many solar cells are connected together to form PV modules that could drive membrane desalination units. Due to its lower price compared to solar thermal plants, more than 50% of RO plants around the world are using PV systems [67, 68]. In addition, since both PV and RO are modular and easily scalable, the integration of PV technology to power RO systems could be a promising option in remote areas. Particularly, given that small-scale BWRO systems consumed relatively low energy, studies suggested that small-scale BWRO systems could be suitably integrative with PV energy [34, 69]. For the last decade, there are several small-scale PV-BWRO units around the world (Table 4).

**Table 4.** Representative small-scale PV-BWRO systems for drinking water in the last decade

| Location | Feed Water TDS (mg/L) | Production (m³/day) | Salt rejection (%) | Recovery (%) | SEC (kWh/m³) | PV Capacity (kWp) | Battery | Source |
|----------|----------------------|---------------------|-------------------|--------------|--------------|-------------------|---------|--------|
| Malaysia | 2000                 | 5.1                 | 97                | -            | 1.1          | 2                 | Yes     | [70]   |
| Mexico   | 2100                 | 1                   | 99                | 33           | 0.2 – 2      | 400               | -       | [60]   |
| Jordan   | 1700                 | 0.28                | 94                | 54           | 16           | 433               | Yes     | [71]   |
| Arabia   | 400 - 500            | 0.4 – 0.7           | 75                | -            | -            | 0.25              | No      | [72]   |
| Tanzania | 3632                 | 1.3 – 1.6           | > 97              | 23.1 – 27.8  | 1.6 – 1.9    | 0.3               | No      | [73]   |
| India    | 1500 - 3500          | 0.205 - 0.934       | 78.5 – 89.2       | 19.25 – 35.75| 5.02 – 17.6  | 3                 | Yes     | [49]   |

The PV-BWRO system could operate independently or in the hybrid with other energy storage plants such as batteries and traditional electrical grid to deal with the local high intermittence of solar radiation [70, 74, 75]. The scheme of a PV-BWRO system in hybrid network is shown in Figure 5. Typical practices to modify the operational efficiency of PV-BWRO units include solar tracking, tilt angle adjustment, and autonomous cleaning for PV panel system [70, 76]. A previous study reported the increases of permeate gain, 43% and 62% for single and double axis tracking PV panels as compared to flat PV panels [77]. Optimization of the PV module for a BWRO unit in Malaysia showed that the tilt angle between 5° and 15° was optimal to allow rain washing of the panel surface [70]. Using feed water for cooling the PV panel could save energy and increase the productivity [78].

Using batteries together with the PV module makes PV-BWRO system more efficient, especially at night and low solar radiation condition [31, 79]. Unfortunately, batteries are expensive, short-lived in
hot climate, hazardous to environments, and lose energy during charging and discharging. Therefore, 
the need to use batteries should be considered according to the operational duration of PV-BWRO 
systems to minimize initial and maintenance costs. Continuous operation requires large battery bank to 
power at night or cloudy climate. According to previous studies, batteries were not necessary to small-
scale PV-BWRO systems with production capacities below 5 m$^3$/day [80]. Alternative solution is the 
grid integration of PV-BWRO, which can sell extra produced electricity to grid or import electricity 
from grid during insufficient periods of solar radiation. In overall, the system is relatively complicated 
and strongly relies on distribution grid [75].

![Diagram of a PV-BWRO system with battery](image)

**Figure 5.** A scheme of a PV-BWRO system with battery

4. Socio-economic feasibility of PV-BWRO systems

The combination of solar energy and BWRO system has proved to be a promising solution to preserve 
environmental integrity and sustainability. It has also presented challenges in term of operational 
requirement of integrated systems. The problem of unpredictable fluctuations in energy production of 
PV units can be solved with quick start units to cover the shortfall or absorb the unscheduled energy 
generation [81]. The hybridization of solar energy with other renewable sources was suggested to 
regulate the energy supply to the RO system. One study also showed that independent PV-BWRO 
system required the highest initial capital cost, but produced the lowest operating cost as compared to 
PV-BWRO hybrid with other energy source such as diesel or grid [82, 83].

Studies have confirmed the techno-economic feasibility of discontinuously operated PV-BWRO 
systems [48, 74]. Discontinuous operation is defined for a range of 5-10 hours per day, which is 
adequately suitable for small water demands in remote areas. Using of water storage tanks could help to 
reduce costs [84]. An independently operated PV-BWRO system was able to produce high quality water 
effectively under low and variable solar radiation [74].

The disposal of reject water is one of important issues that affects the feasibility of RO desalination 
plants and total cost [31]. High salt concentrations of reject water would disturb the ecosystem [85]. 
Studies have discussed on factors that affect the disposal methods including 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 [86]. The quality and quantity of reject water, the availability and
physical or geographical location of the discharge site, public acceptance, capital and operating cost, and the expandability of facility are all important factors to determine disposal methods [87].

Total production cost of PV-BWRO system generally accounts for energy consumption, equipment and membrane, maintenance costs. However, feed water quality, product water quality, plant location, cost of land, disposal system, and others can highly influence the actual production cost. In overall, studies have confirmed the significant socio-economic contribution of PV-BWRO systems in provision of drinking water to improve human life, mitigation the dependence on conventional resources of vulnerable communities, and reduction of carbon footprint [88].

5. Conclusions
Success deployment of PV-BWRO systems depends on the integrative optimization of water and energy, which are the most essential pillars for a sustainable life. In this review, we have discussed the critical and urgent need for small-scale PV-BWRO systems with suitable productivity and low energy demand to increase drinking water supply for vulnerable communities in remote areas. We have showed that proper configuration of small-scale PV-BWRO systems to fit water characteristics would be useful to achieve high efficiency and reasonable costs. Remarkably, batteries were not recommended at production capacities below 5 m³ because of their high cost and short lifetime. The hybrid with a backup source of renewable energy or conventional grid, as well as using storage tanks, can be implemented to enhance system productivity.

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