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Renewable energy powered membrane technology: A review of the reliability of photovoltaic-powered membrane system components for brackish water desalination

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HIGHLIGHTS

- Review of photovoltaic-powered membrane systems for brackish water desalination.
- 20-year lifetime for small-scale systems (= lowest cost for water) possible via:
- 1) Smart component selection based operating range, reliability and lifetime.
- 2) System design optimized to enhance performance under fluctuating conditions.
- 3) Correct choice of membranes as well as system operation and maintenance strategy.

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ABSTRACT

Photovoltaic-powered membrane filtration (PV-membrane) systems are of interest for the provision of clean drinking water in small communities, especially in remote areas. In order to deliver clean water at the lowest cost over the lifetime of the system, a reliable and robust design is paramount. This paper provides a comprehensive review of the operating range and reliability of all components of a small-scale PV-membrane system for brackish water desalination. The failure and degradation modes, as well as lifetime and robustness issues associated with field operation are discussed and best-practice recommendations made. The outcomes of this paper suggest that a small-scale (power rating < 1.5 kW) PV-membrane system – based on a helical rotor pump driven by a direct-current brushless motor and powered by silicon photovoltaic modules – may achieve a lifetime of 20 years, while operating with a specific energy consumption of 1.5–3 kWh/m^3. Possible methods for mitigating the effects of membrane fouling and damage are also discussed. To maximize membrane lifetime, such systems ought to be operated with a recovery of less than 30% and limit the rate of change of pressure (induced by fluctuations in solar irradiance) to less than 0.7 bar/s. The analysis is useful for identifying the optimal combination of components, system operation and possible reliability improvements. The investigation into component and system failures allows the weakest links to be avoided and enable the optimization of future systems. This review is intended as valuable reference for engineers engaged in the field of renewable-energy-powered membrane filtration technologies.

1. Introduction

The lack of potable water is one of the most serious problems in developing countries, especially in remote areas [1]. The desalination of brackish groundwater is often a practical solution for the provision of clean drinking water where insufficient surface water is available. Brackish water is typically defined as exhibiting a salinity between 1000 and 10,000 mg/L in total dissolved solids (TDS) [2]. Amongst the many available technologies, nanofiltration (NF) and reverse osmosis (RO) have gained a high level of acceptance due to their low specific energy consumption (SEC, units: kWh/m^3) [3], which represents the energy input required to treat 1 m^3 of water [4,5]. In addition, since an electricity grid is often non-existent in remote areas, powering NF/RO systems with photovoltaics (PV) is a practical powerful way of overcoming this lack of infrastructure. Such photovoltaic-powered membrane filtration (PV-membrane) systems are attractive due to strong

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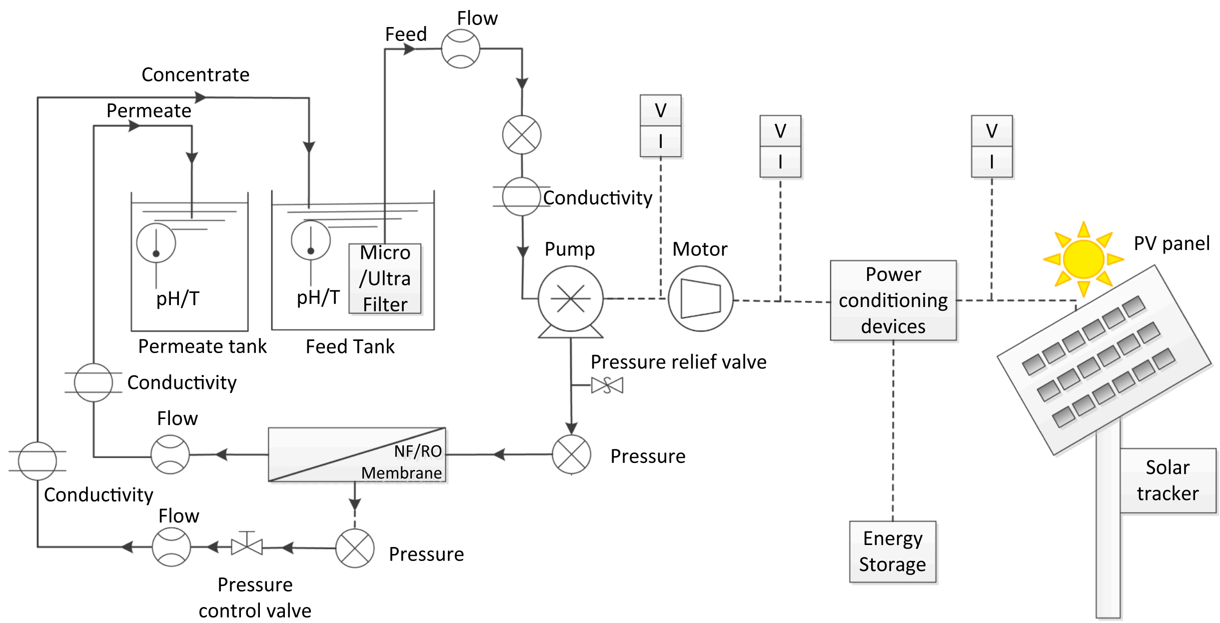

Fig. 1. Schematic diagram of the PV-membrane system, showing the main system components – PV modules, solar tracker, power conditioning devices, energy storage, motor, pump, pre-treatment filters (in this case submerged), nanofiltration (NF) or reverse osmosis (RO) membrane, pressure control valve – as well as the required sensors for measuring pressure (⊗) sensors, conductivity (), flow (), voltage (V), current (I), as well as pH and temperature sensors (). The solid arrow lines represent water pipes, and the dotted lines are electrical connections.

synergies between the two technologies [6]. Firstly, both PV panels and NF/RO membrane elements are modular and can be scaled to meet the desired clean water demand. Secondly, the demand for drinking water is higher in arid regions of the world and these same regions typically exhibit an excellent solar resource [7]. Thirdly, the prices for PV modules have been dropping steadily and reached US$0.21 per Watt-peak ($W_p$) by the end of 2018 [8], while the RO module market has been rapidly growing at a compound annual growth rate of 10.5% by 2019 [9], with costs decreasing accordingly. Indeed, a recent study concluded that the cost of clean drinking water from small-scale decentralized membrane systems can be less than local water vendors charged for *untreated* water in several locations in sub-Saharan Africa [6]. In addition, even within Europe, the cost of delivering drinking water via tanker to Greek and Italian islands has been reported to cost as much as €7–11/m^3 [10,11], while the cost of water in Qatar now exceeds that of diesel [12]. While this paper does not focus on cost analysis, it should be noted that certain geographic locations that have an abundance of sunshine represent obvious potential markets for PV-membrane technology and that price is not a barrier to the further deployment of the technology. The use of renewable energy (RE) provides a long-term sustainable power supply option that is cost-competitive with fossil fuels, while also offering important environmental benefits, such as reduced greenhouse gas emissions and preservation of the limited fossil-fuel resources [13]. The combination of RE and desalination technologies can meet the requirements for sustainable development and the water demands of society [14], in particular in developing countries.

For the purpose of this work, a “small-scale” PV-membrane system is defined as having a motor power rating less than 1.5 kW and a daily clean water production capacity of less than 3 m^3. While small-scale PV-membrane systems have received significant attention in recent years and a considerable number of demonstration systems have been established [8], the total number of systems deployed worldwide remains relatively low [6]. Many different system design configurations exist that offer choice. This makes it difficult to gain trustworthy data regarding long-term performance as well as information regarding the robustness and reliability of such systems. Many small-scale PV-membrane systems are being targeted for deployment in remote areas of developing countries, where the technical skills required for operation and maintenance (O&M) are initially not present and a supply chain for spare parts is not in place [6,15]. Several reports of renewable-energy-powered membrane filtration (RE-membrane) systems – driven by either PV and/or wind energy – have been published [10,11,16,17]. To evaluate the reliability of such systems, different aspects have been studied, including the choice of system components, system degradation, O&M, as well as the impact of environmental conditions. Schäfer et al. investigated the effects of selected different membranes and operating parameters on PV-membrane system performance [18], noting that careful membrane selection (suited to water quality) leads to a robust system with a respectable SEC [17]. An analysis by Bilton et al. mentioned that the performance characteristics of RO-based PV-membrane systems degrade significantly with the deposition of retained materials on the membranes, which is typically defined as fouling or scaling due to the dissolved organic and inorganic salts in the raw water [19]. This remains a general issue for all membrane filtration systems, including RE-membrane systems. Moreover, environmental conditions such as high ambient temperature, humidity and dust play an important role in the performance of PV-membrane systems, especially for the PV panels. This indicates how the successful deployment of PV-membrane systems depends on, amongst other things, the reliability of the components and robust system design. However, to date, a systematic study on the reliability of PV-membrane systems is lacking. Filling this knowledge gap regarding the robustness and reliability of PV-membrane systems is paramount to ensure that long-term operation can be achieved and that poor system design does not tarnish the ability of a relatively “high-tech” water treatment solution being successful deployed in a developing country.

In order to fill this gap, this paper provides an extensive assessment of which PV-membrane system components allow operation over the widest possible power input range (relevant for a fluctuating energy source), and with the highest reliability. For the sake of clarity, the following terms are defined:

- Robustness: refers to the ability of tolerating perturbations that might affect the functionality of the system.
- Reliability: defined as the ability of a system (or a component

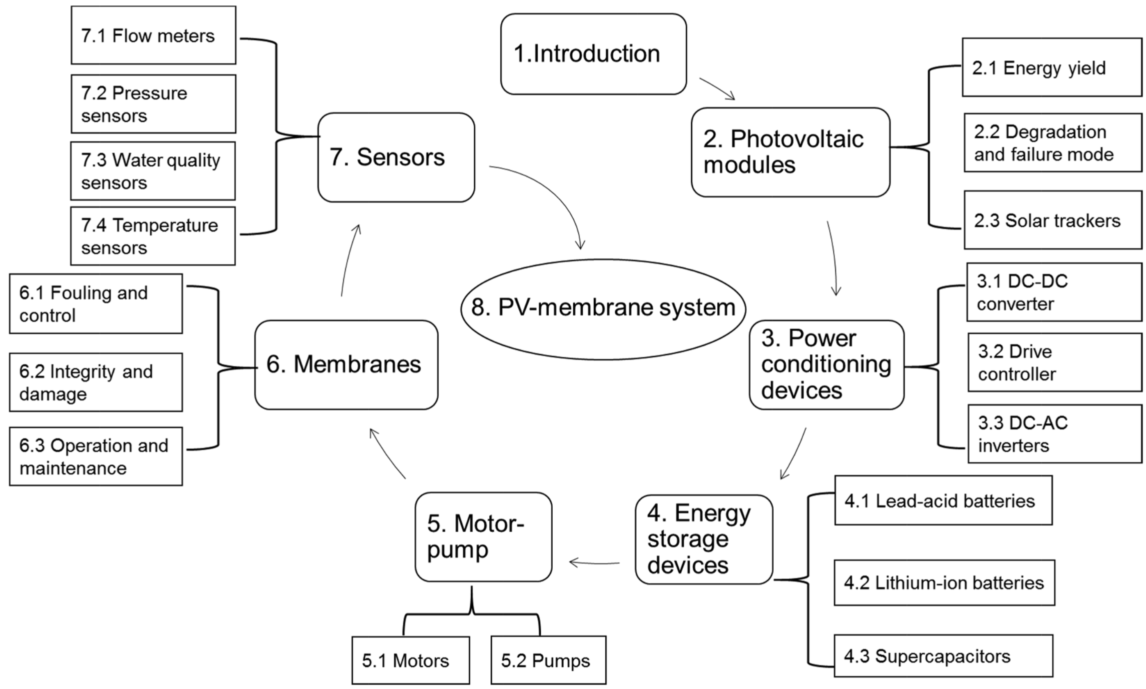

Fig. 2. Overview of the structure of the paper and the contents that will be discussed within each section and sub-section.

within) to successfully perform the task for which it was designed, in a defined environment and over a specified time range.

- Lifetime: implies the expected lifetime of a product, or the acceptable period of use in service.

The main components of a typical PV-membrane system are illustrated in Fig. 1. The power from the PV modules is required to drive the pump, which sucks water through a micro- or ultra-filter (in this case) from the feed tank, and increases the feed water pressure to force it through the NF/RO membrane. A portion of water becomes permeate (clean) water, leaving behind the concentrate water to be used for washing or other purposes. The details of each component are discussed in later sections, with Fig. 2 providing the reader with a graphical overview of the paper's structure. Recommendations by the authors are given at the end of each section.

2. Photovoltaic modules

Solar cells are made of semiconductors that generate direct-current (DC) electricity by electromagnetic means when exposed to sunlight. Many individual solar cells are connected in series and parallel within a PV module to build the output voltage and current, respectively. Within the PV module, the solar cells are sealed between layers of glass or transparent polymers to protect the electrical circuit from the environment. One or more modules are then connected and mounted on the supporting structure to form a PV array.

2.1. PV module degradation and failure modes

PV modules possess no moving parts, which are a major source of unreliability in many other types of electrical generating systems. Instead, the operating life expectancy is primarily determined by the stability and corrosion resistance of the materials from which the PV module is fabricated. Manufacturers' guarantees of up to 30 years indicate the proven nature of the market-dominant silicon PV modules, while thin-film technologies such as cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) are being covered by 25 years of warranty [20,21]. Extensive environmental testing of the PV modules before they leave the factory ensures their robustness to temperatures ranging from −40 °C to +85 °C, relative humidity up to 85%, and that they survive 25 mm diameter hailstones impinging at 23 m/s [22]. However, there are still several failure modes and degradation mechanisms that may lead to decreased power output or cause module failures. A study carried out by Quintana and King [23] on field-aged PV modules suggested that there are five main modes of degradation that are responsible for performance loss and failure: (i) degradation of the polymeric encapsulation; (ii) loss of adhesion within the PV module laminate due to high temperature and moisture intrusion; (iii) degradation of cell/module interconnects caused by segregation of the metals in the soldering alloy; (iv) degradation caused by moisture intrusion; and (v) degradation of the semiconductor itself. Jordan and Kurtz published an extensive review of nearly 2000 degradation rates measured on individual PV modules during field testing over the last 40 years [24], with the key results plotted in Fig. 3. Comparing installations from "pre" and "post" year 2000, it can be seen that some thin-film PV technologies, notably CdTe, have been made significant gains in reducing the degradation rates. CIGS, which exhibits a susceptibility to water vapor, has also made good progress towards more stable devices. The post-2000 degradation rates of wafer-based silicon PV modules – both crystalline silicon (c-Si) and multicrystalline silicon

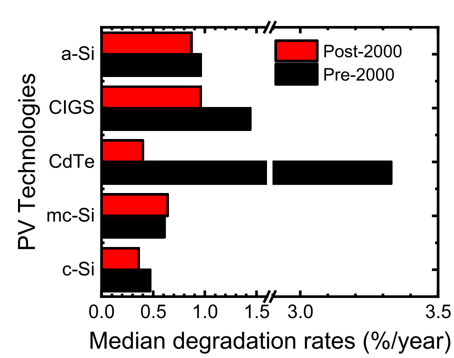

Fig. 3. Summary of the median degradation rates of different PV technologies (data from [24]). "Pre" and "Post" refer to installations prior to and since the year 2000, respectively.

(mc-Si) – as well as CdTe ranged from 0.4 to 0.6%/year, while both CIGS and amorphous silicon (a-Si) thin-film technologies exhibited a higher degradation rate of 0.9–1.0%/year [24]. This suggests that the latter two technologies are less suitable for application in PV-membrane systems. Also, CdTe PV modules should not be operated for long periods of time under open-circuit conditions – the period of time when no photocurrent is being generated by the PV module. Sinapis et al. [25] observed degradations on a CdTe PV array of eight modules operated outdoors in open-circuit conditions. The power, open-circuit voltage (V_{oc}) and fill factor (FF) degraded 12%, 6% and 7%, respectively, after outdoor exposure of 650 kWh/m^2 within 7 months. The performance drop under these conditions resulted from the CdTe semiconductor itself (a decreased doping concentration close to the junction) and increased series resistance encountered in the transparent conducting oxide (TCO). Ultimately, damage to the TCO layer impedes current flow throughout the device [26]. In contrast, similar arrays of grid connected CdTe PV panels operated at the maximum power point (MPP) – the operating point at which the maximum power is extracted from the PV module – did not exhibit any degradation over the same period of time.

2.2. Solar trackers

A solar tracker is an actuator-driven system that enables the PV panels to follow the path of the sun across the sky, mimicking what nature does with a sunflower. Significantly more solar energy can be harvested if the PV array is mounted onto a solar tracker. There are two different types of mechanisms that are used: (i) active trackers; and (ii) passive trackers. Active trackers are directed toward the sun by electrical circuitry in the form of either photodetectors or global positioning systems (GPS). In contrast, passive trackers apply a hydraulic mechanism responding to the heat of the sun, and hence avoiding electrical power consumption. Typically, active trackers exhibit a higher accuracy than passive trackers, but this is usually not critical for non-concentrating PV applications.

In the 1980s, solar trackers were regarded as the weakest link in a PV system [27], however tracking systems today have a 10-year system warranty and a 25-year design life [28]. Reliability problems may arise from the failure of timer integrated circuit, or from failure to an actuator, position sensor, or controller due to disturbances or noise [29]. Previous work on a PV-membrane system in Tanzania showed a GPS-based single-axis (east-west) tracker [30] constantly lagging the actual position of the sun by around 40 min. Although five satellites were found by the GPS system – more than the minimum number to reliably locate its position – the time-lag resulted in reduced system performance and the problem could not be repaired in the field.

2.3. Recommendations

From the above analysis, the following recommendations of choosing PV panels in the RE-membrane system are proposed:

- Silicon-based PV panels – either mc-Si or c-Si – are available worldwide and present the lowest risk option, supported by > 25-year warranties and overall technical maturity;
- With regard to the thin-film PV technologies: a-Si is a low efficiency product that exhibits higher degradation rates, CIGS (if available) exhibits a similar degradation rate, while CdTe is not recommended for use in an off-grid system;
- While a solar tracker can be employed, a more robust option might be simply to instead include more PV panels to generate additional power in the morning or afternoon.

3. Power conditioning

Power conditioning refers to devices that serve to deliver a desired voltage to an electrical load. Examples include: DC-DC converters; maximum power point tracking (MPPT) devices; inverters that enable alternating current (AC) loads to be supplied; as well as drive controllers for motors. In a PV-membrane system, the electric motor which drives the pump is the key load. Electric motors operate most effectively within a certain voltage and current range, however, the power output of a PV panel varies throughout the day with the availability of solar irradiance. Therefore, in order to optimize the power coupling between the PV panels and the pump motor, power conditioning devices are required. Energy conversion always comes at an energetic cost and power losses will be incurred by the power conditioning devices, however, this is typically 5% or less [31]. Perhaps more significant is the increased number of additional components in the system that will incur additional failure modes. Thus, it is important to ensure that the losses incurred are compensated for by having an overall net benefit to both the performance and reliability of the PV-membrane system. Each of these is discussed in detail below. Note, the MPPT is primarily based on the DC-DC converter that continually searches the for the MPP of the PV module [32], therefore, the details of the former will not be discussed.

3.1. DC-DC converter

A DC-DC converter is a device that converts the DC input voltage to a desired output voltage. Typically, dozens of c-Si solar cells (0.6 V) are connected in series to build voltage. For example, a c-Si PV module will be most efficient when operating at its MPP, where the MPP ranges from $V_{mp} \sim 18\ V_{DC}$ for a smaller PV module (typically used for charging 12 V_{DC} batteries) up to $V_{mp} \sim 60\ V_{DC}$ for a larger PV module. It is often required to match the output of the PV panel to the required voltage for the pump motor, which could lie in the range V_{pump} = 30–300 V. A DC-DC converter can either achieve an increase or decrease in the output voltage via "boost" or "buck" operation, respectively. Both of these circuits require the combination of a switch and an inductor, in conjunction with capacitors to smooth and reduce the ripple in the converted DC output [33]. According to one manufacturer, DC-DC converters are typically designed and built for a life expectancy of 20–30 years in harsh environments [34], equaling that of the PV module. Problems with DC-DC converters mainly result from: (i) electrical overstress causing the failure of key components such as the metal-oxidesemiconductor field-effect transistors, which are used for power conversion; (ii) resistor failures being caused by the sulfur corrosion of silver electrode due to environmental stress, such as high temperature and moisture; and (iii) poor wetting of the solder to the printed circuit board (PCB). Thus, in order to prevent or decrease the failure rates of DC-DC converters, high quality components should be chosen, professionally assembled (achieving good soldering process control), with good environmental controls present [35,36] and the electronics mounted within dust- and water-proof housings (for example, satisfying the IP65 code).

3.2. Drive controller

A drive controller is required to meet the particular current requirements of the pump motor, particularly for positive displacement pumps. The motors for such pumps requires a high start-up current – around 6–10 times the normal operating current of the motor for a period of seconds [37,38] – followed by a constant current to provide a given torque, which is proportional to the pumping pressure [39]. The lifetime of drive controllers has been reported to be as long as 15 years [40]. In order to improve the reliability, some additional features can be applied such as robust sensorless control for safety critical applications, rugged packaging suitable for high vibration locations, small footprint suitable for cold-wall or heat-sink mounting, and highly qualified PCB screening [41]. The elimination of Hall (current) sensors and feedback devices traditionally located inside the motor housing for detecting the position of permanent magnet has highly improved the

Table 1
Comparison of the energy storage technologies that are suitable for application in small-scale PV systems.

Type	Charge/ Discharge cycles (–)	Lifetime (years)	Self- discharge rate (%/d)	Energy density (Wh/kg)	Power density (W/kg)	Operating temperature range (°C)	Ref.
Lead-acid battery	1200–1800	5	0.1–0.3%	30–50	75–300	−20 to +45	[59,60]
Lithium-ion battery	1000–10,000	5–15	0.03–0.17%	90–200	500–2000	−25 to +45	[60,61]
Supercapacitor	> 500,000	8–10	5–40%	~5	100,000	−40 to +60	[60,62,63]

reliability of the controller. Sensorless control technology avoids the needs of these components, which in turn reduces motor size and cost, as well as improving overall reliability [41].

3.3. DC-AC inverters

Inverters are required to convert the DC output from a PV module when powering an AC load, for example, if an AC motor is present in the PV-membrane system. The main functions of an inverter include inverting the DC voltage of a PV array output into AC output, wave shaping the AC voltage output, and regulating the effective value of the voltage output. Often, capacitors are required to smooth the power output at varying levels of current and MPPT circuitry is integrated within the inverter. Manufacturers report that today's inverters exhibit an mean time between failures (MTBF) of greater than 10 years [42,43]. However, a number of reliability problems have been reported with inverters [44]. Firstly, inverter failures occurred due to the electromechanical wear on capacitors. The electrolytic capacitors are widely used due to their high capacitance and low cost, however these wet-type capacitors have a limited lifetime and age faster than dry components. Secondly, over-current and over-voltage can cause inverter failures due to the excess heat generated by current or voltage spikes, most frequently damaging the inverter bridge. Thirdly, the mechanical stress caused by ultrasonic vibrations contributed to inverter failures. Such ultrasonic vibrations arise from the cores of inductive components and cause friction, adding to the excess heat and further damaging components in the inverter. To keep the inverters reliable, consistent maintenance schedules and occasional replacement of capacitors prevent most failures caused by wear and tear. The failure rates of inverters investigated as part of PV pumping systems will be discussed in Section 8.

3.4. Recommendations

Power conditioning devices play an important role in optimizing the power coupling between the PV panels and pump motor and the following recommendations are given:

- A DC-DC converter is required to match the PV output with required voltage for the pump motor with a design lifetime of 20 years;
- MPPTs must be included to assure the PV modules are operated at the MPP, thus extracting the highest power from the system at all times of the day;
- A drive controller is required to supply the necessary current to the pump motor, especially for starting positive displacement pumps, with a reported lifetime of 15 years;
- DC-AC inverters are not recommended due to the additional risk of one more component failing, especially considering the good availability and high performance of DC-powered pumps (see Section 5).

4. Energy storage

RE resources are by nature both fluctuating and intermittent. In the case of a PV system, the amount of power generated can fluctuate due to passing clouds, while there are periods of intermittency – for example, at night – where the power output is zero. Traditionally, the resulting variations in power supply have been regarded as detrimental to membrane systems that were designed to operate under constant flow and pressure conditions [45,46]. A lack of power can result in both reduced permeate quality as well as daily permeate production. In addition, a performance deterioration is likely to be caused by the constant on/off cycling of the system, increasing the potential wear on the pump and motor [47]. Therefore, it is typical to rely on an energy storage device to balance demands from the electrical load with the power available from the PV system. In order to reduce the cost and maintenance requirements associated with batteries, several RE-membrane systems stored the permeate water in the tank to overcome the challenge of longer-term fluctuations and intermittency [48,49]. While water is easier and cheaper to store than electricity, this does not address the influences of reduced water quality and frequent system shut down [50] that may occur, or potential damage to the pump motor and membrane (such as delamination) [46,51–53] due to the short-term variability of the RE resource.

For energy storage in small-scale PV-membrane systems, several different storage technologies can be used and a comparison of these is given in Table 1. Important selection criteria include efficiency, charging/discharging cycles, self-discharging rate, cost and lifetime. These must be considered to allow efficient and reliable system operation, particularly during fluctuations and periods of intermittency [54,55]. The discussion here focuses on two types of batteries (lead-acid and lithium-ion) as well as supercapacitors, which will be discussed detail in the following sub-sections to enable an appropriate choice to be made. Although other novel battery technologies such as metal-air and sodium-sulfur (Na-S) batteries are being developed, their performance is not yet up to the standard required for applications in RE systems. For example, metal-air batteries exhibit a limited number of charge/discharge cycles (~300) [56,57], while Na-S batteries require a high operating temperature (350 °C), thus, making Na-S batteries more suitable for industrial applications [58].

4.1. Lead-acid batteries

The most common storage technology employed in off-grid RE systems is lead-acid (LA) batteries as they are a mature technology, exhibiting a low cost, relatively low level of maintenance, and widespread availability [37,59]. The low self-discharge rates for LA batteries make them suitable for longer-term storage applications [64]. Self-discharge is a phenomenon that whereby the internal chemical reactions can reduce the stored charge without a load being connected across the electrodes. However, the main disadvantages associated with LA batteries are the limited number of cycles and the reduced lifetime caused by deep discharging or operation at high temperature (with the upper limit of 45 °C) [5,37,65,66]. When connected to a RE system to supply a daily load, incomplete battery charge/discharge can introduce battery degradation mechanisms such as electrolyte stratification, gas bubble entrapment, excessive sulfation, and degradation of the positive electrode, all of which shorten battery life [67,68]. Hence, it is critical to maintain a high average state-of-charge (SOC) of > 50% to achieve expected battery performance and cycle life in small-scale RE systems [37,69]. In a RE system, LA batteries exhibit a lifetime of 3–5 years [37], although sometimes as low as 2 years under extreme circumstances [70,71]. Typically, the capital cost of a residential LA battery is in the range of ~$600/kWh [72]. For a typical PV-membrane system with a 300–500 W motor, 1 kWh of battery storage would allow an additional 2–3 h of full operation.

4.2. Lithium-ion batteries

Lithium-ion (Li-ion) batteries exhibit the highest energy density and power density among all commercial battery technologies, making them favored candidates for implementation in transportation applications. Currently, Li-ion batteries have been applied in on-grid PV solar systems, boasting up to 4000 charge/discharge cycles and 10 years of lifetime [73]. Additionally, Li-ion batteries also exhibit a very low self-discharge rate and are relatively maintenance-free compared to LA batteries [74]. However, similar to LA batteries, Li-ion batteries age much faster at high temperatures, and their lifetime can be severely shortened due to deep discharges. In addition, due to special packaging and internal overcharge protection circuits, Li-ion batteries typically presently cost 1.2–2 times more than a similar capacity LA battery (2018 data) [75], although this is expected to reduce over time as the technology matures.

4.3. Supercapacitors

Supercapacitors (SCs) store energy by building up positive and negative charge within an electrolytic solution and are recognized as a promising device for energy buffering during short-term fluctuations from RE resources [55,76,77]. SCs exhibit a lifetime of 8–10 years [63,78], and can be charged/discharged > 500,000 times [63,65,66,79]. SCs can be charged substantially faster than conventional batteries and are thus appropriate for applications that need to be charged/discharged over periods of 1–2 min [80]. The main drawback of SCs is the relatively high self-discharge rate compared to batteries and depends on the SOC [63]. Degradation in SCs is accelerated at high thermal cycles between 40 °C and 60 °C due to the increase of internal reaction, resulting in an increase of the degradation rate and a decrease of the capacitance. [81]. SCs cost significant more than batteries, estimated as five times that of a LA battery with similar capacity [82]. Notably, if the benefits of energy buffering – minutes as opposed to hours of storage – are significant then SCs could be a potentially cost effective solution.

Park et al. reported their RE-membrane system equipped with SCs resulted in an 85% increase in the average flux and 40% increase in permeate quality when tested under fluctuating conditions, compared to the system performance without SC bank [79,83]. The SCs were able to offer sufficient energy during periods of intermittency and enhance the power quality delivered to the membrane by smoothing out fluctuations, hence avoiding system shut downs. Interestingly, SCs have also been used in conjunction with batteries to extend battery operating life via reducing the charge/discharge cycles and buffering the peak currents in the battery [37,59,84,85]. Thus, the SC-battery is a synergy between both technologies where high power or current pulses are buffered by the supercapacitors while long-term energy requirements are supplied by the battery [37]. These applications demonstrate that it is advantageous to couple SCs with RE-membrane systems, such that the system performance with the inherent short term fluctuations and intermittency of the resource was improved [86].

4.4. Recommendations

The recommendations for energy storage devices for PV-membrane systems are:

- Energy storage can enhance system performance due to the reduced number of system shut-down events – affording energy buffering between the intermittent solar/wind source and the power requirements – as well as allowing autonomous system operation;
- Li-ion batteries offer better performance than LA batters – long lifetime (up to 15 years), more charging cycles, low self-discharge, and minimal maintenance – while their price is becoming steadily cheaper, such that these should be considered when medium-term storage is required;
- SCs are favorable due to high efficiency, 8–10 years lifetime and an extremely high number of charge/discharge cycles, making them good candidates for buffering fluctuations and periods of short-term intermittency efficiently.

5. Motor-pump subsystem

5.1. Pump motors

There are three types of motors commonly used for RE-powered water pumping applications: (i) brushed permanent magnet DC motors; (ii) brushless permanent magnet DC motors; and (iii) AC motors. Normally, the choice of a motor for a RE-powered system depends on the size required and the availability of electronics that go with it. DC motors are attractive for low power demand (< 5 kW) [87] and hence can be paired with PV modules directly. For higher power demand applications (> 10 kW) AC motors are typically used (in conjunction with an inverter). The reason being that the range of AC motors available is much greater and the prices are generally 20% lower than DC motors with a similar power rating [87]. The associated disadvantage of increased failure risk of inverters was addressed above.

The DC motors used for RE applications are generally of the permanent magnet (PM) type. The rotation of the PM brushed DC motor is caused by the brushed commutator without inducing the surrounding magnetic field electrically. For submersible DC pumps, maintaining and replacing the brushes periodically every 2000–4000 h or 2 years require the pump to be removed, which is undesirable as it increases both the system downtime and the O&M costs [88,89]. Brushed DC motors typically last 4–8 years, depending on usage, while the exact maintenance requirements depend on the type of coupling (direct, drive, gear) [88]. With brushless DC motors, the PM is the central rotor, and the field windings are electronically switched by means of a rotor position sensor. They are commonly used for small-scale RE applications as they require very little maintenance apart from preventing ingress of water and dust, and provide a service lifetime of 10–20 years [88,89]. The typical operating power range, the advantages and disadvantages of different motor technologies are summarized in Table 2.

5.2. Pumps

The pump is one of the key components of the PV-membrane system as it produces the feed flowrate and pressure required for the membranes, and determines the power requirements from the PV panels. For a NF/RO brackish water desalination system equipped with a PV array of 1.0–1.5 kW and treating brackish water with a salinity of up to 10 g/L, the typical operating pressure and flowrate required for the pump are in the range of 3–14 bar and 300 – 600 L/h (assuming 25% of the feedwater being recovered as permeate), respectively [94,95]. Note that while the discussion here focusses on high-pressure pumps for driving the membrane filtration system, the discussion is also relevant for situations where pumping of the feed water from a borehole to the surface. The main difference being that membrane system pumps require a higher pressure at lower flow than for pumping application.

Generally, pumps can be divided into two categories: (i) dynamic pumps; and (ii) positive displacement pumps. These two types of pumps have inherently different characteristics and are suited to different operating conditions, as discussed below. In order to be distinguished with motor efficiency, the pump efficiency, η_{pump} is defined in Eq. (1),

$$\eta_{pump} = P_{hydraulic}/P_{shaft}, \tag{1}$$

Table 2
Comparison of motors in terms of power, advantages and disadvantages that are suitable for powering pumps in PV systems.

Pump motors	Power	Advantages	Disadvantages	Ref.
AC induction motor	> 10 kW	Larger range available Diversity of control strategies Maintenance free ~20% cheaper than DC motor 15–20 year lifetime	Requires inverter, incurs increased risk of failure (~10 years MTBF)	[87,90]
DC brushed PM motor	< 5 kW	Simple for small loads No complex control circuits needed	Maintain and replace brushes every 2000–4000 h or 2 years Shorter service time 4–8 years	[88,90]
DC brushless PM motor	< 5 kW	10–20 year lifetime Little maintenance	Extra electronic circuit for the rotor position sensor offers double the price of motor	[88,91–93]

where $P_{hydraulic}$ represents the hydraulic power possessed by the fluid and P_{shaft} represents the mechanical shaft power supplied by the pump motor to the pump. Different pumps exhibit large variations of efficiency which will significantly affect the RE-membrane system performance.

5.2.1. Dynamic pumps

A dynamic pump relies on fluid velocity and the resulting momentum to produce pumping power, move fluid through the system and generate the required pressure. The main type is the centrifugal pump, which has long been the most commonly used pump worldwide due to the robustness, simplicity and cost-effective design [89]. Centrifugal pumps are designed for fixed head applications and the output increases with rotational speed. The principle of operation is that water is sucked by the centrifugal force created by the impeller and the water is thrown towards the outlet as the impeller rotates at high speed. A pump with a single impeller is referred to as single-stage. However, most borehole pumps are multi-stage, where the discharge from one impeller feeds into the next inlet, with each one adding a further pressure difference. Centrifugal pumps exhibit a relatively high hydraulic efficiency (30–60%), with larger capacity pumps achieving higher efficiencies. However, the efficiency decreases significantly as the operating pressure departs from the design specification, which results in a limited operating range [96]. Centrifugal pumps are most economical when used with large flowrates (25–100 m^3/day) and low to medium pressure (1–3 bar) requirements when compared to positive displacement pumps [87]. For these reasons, centrifugal pumps have largely been replaced by positive displacement pumps for more efficient pumping in small-scale PV-membrane systems [97].

5.2.2. Positive displacement pumps

The operating principle of a positive displacement pump is to force a fixed amount of water from the inlet to the discharge side of the pump for each revolution/stroke [89]. Due to the fixed volume of water displaced during each pump stroke, the flowrate is directly proportional to the speed of oscillation. Higher operating pressures are achieved at the expense of lower flowrates when compared to centrifugal pumps of the same power rating. Positive displacement pumps are capable of operating with higher efficiency over wider speed and pressure ranges, which is particularly useful for coupling with PV panels that provide a greatly varying power supply [96]. Positive displacement pumps can be divided into two categories in terms of their operation: (i) reciprocating; or (ii) rotary pumps. Reciprocating pumps use a crankshaft to transfer the rotational drive power to a plunger, piston or diaphragm oscillating within a cylinder, whereas rotary pumps use rotating screws, lobes, gears or rollers that are directly connected to the drive shaft from the motor. In particularly, helical rotor pumps have been widely employed in PV-powered water pumping applications over the last few decades [98]. These pumps use an eccentric single-helix-shaped metal rod as a rotor sealed within a thick rubber stator and the small gap between these forms the progressive cavity, resulting in water being expelled.

5.2.3. Pump performance comparison

Protogeropoulos and Pearce performed a detailed study comparing the performance of several different types of pumps designed for PV-powered water pumping systems [97]. The present review expands on this original work to highlight the efficiency improvement of positive displacement pumps as well as extending the analysis to encompass a larger range of pumps, namely piston, diaphragm, helical rotor and rotary vane pumps, as well as single- and multi-stage centrifugal pumps. The pumps reviewed here all have a power rating of less than 1.5 kW and were tested over their full range of operation in terms of pressure and flowrate by manufactures. The results are plotted in Fig. 4, which plots the water flowrate, efficiency and pumping SEC versus head (pressure) of eight different pump types. The graph in Fig. 4C shows the dependence of the SEC – which in this case represents how much energy would be consumed by pumping (not treating) 1 m^3 of water – as a function of absolute head.

The specified pumps represent a variety range of different pump manufactures and pump types. Looking at Fig. 4, it can be seen that the single-stage centrifugal pump has a larger capacity but a very low operating pressure, the latter which also results in a low pumping SEC (Fig. 4C). By using stacked impellers, the multi-stage centrifugal pump achieved a much higher pressure (18–25 bar) once coupled to a much higher power motor (1.5 kW). It is then able to achieve a maximum efficiency of 56% (Fig. 4B). This efficiency deviates quickly (25–56%) when moving away from the design pressure, and the pumping SEC was 7.5 kWh/m^3 at the maximum pressure of 25 bar (Fig. 4C). Comparatively, the positive displacement pumps have higher operating pressure and lower flowrates (Fig. 4). The reciprocating pumps (diaphragm and piston pumps) exhibit a lower pressure and efficiency than the rotary pump (helical rotor and rotary vane pumps), as shown in Fig. 4B. Fig. 4C shows that the pumping SEC of reciprocating pump is relatively low (< 1 kWh/m^3) as it was calculated by the ratio of power rating to the flowrate, which is due to the low operating pressure (up to 7 bar) and power rating (100 W). The 600 W helical rotor pump was the most efficient pump in this study (75% maximum) and at a head of 100–150 m (pressure of 10–15 bar), the pumping SEC was at a minimum at about 0.5 kWh/m^3, while it increased up to 5.5 kWh/m^3 at a pressure of 25 bar. At pressures higher than 20 bar, the SEC increased rapidly because very little water is pumped with the motor power. Although the 600 W pump is more efficient than others, PV-membrane systems reported in the literature have typically used 4–12 bar [7,16,50,105] for treating brackish water with a TDS in the range of 1000–10,000 mg/L). For this reason, the smaller helical rotor pump (285 W) is the best choice, with a reasonable pumping SEC of 1.5 kWh/m^3 at high pressure (20 bar), while operating over a wide power range. The pumping SEC contributes to 70–80% (assuming 20–30% recovery) of the final SEC for a small-scale PV-membrane system.

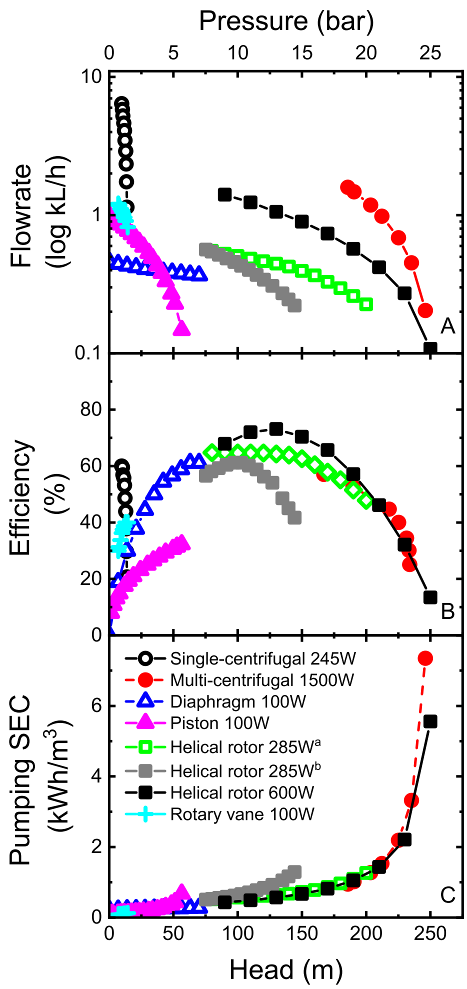

Fig. 4. Flowrate, efficiency and pumping SEC as a function of the head (pressure) for a range of powered pumps. The pumps were arranged in the sequence of dynamic (single-centrifugal 245 W [99], multi-centrifugal 1500 W [100]), reciprocating (diaphragm 100 W [101], piston 100 W [97]) and rotary pumps (helical rotor 285W[a] [102], helical rotor 285W[b] [103], helical rotor 600 W [102] and rotary vane 100 W [104]). The numbers in the legends represent the motor power. It should be noted that the multistage centrifugal pump has an AC motor, while all the rest are DC powered pumps.

5.2.4. *Pump reliability*

Apart from the performance of pumps over the widest possible operating range, reliability is an important criterion to determine the pump selection. Lifetime testing of diaphragm and helical rotor pumps has been performed [106], with the pumps being tested until failure at their maximum rated pumping head. It needs to be noted that these tests are distinguished from the normal tests, indicating the highly accelerated life test (HALT) to estimate the lifetime and determine the safety margins of the design beyond specification levels, hence can be used to evaluate the reliability and failure analysis. The diaphragm pumps were powered by a 160 W PV array and achieved a lifetime of 0.75–2.4 years with a maximum design pressure of 7 bar. All the diaphragm pumps failed resulting from the worn diaphragm seals. The diaphragm pumps with a significant amount of metal demonstrated better lifetime (2.4 years) than the ones made from plastics (< 1.5 years), indicating the possible reasons were the higher weight reduced the movement of pump during commissioning [106]. Overall, it was found that the operating lifetime can be extended to over 6 years by limiting the maximum operating pressure to 3 bar [107], however it should be noted that such pressures are not relevant for brackish water desalination. Highlighted were the requirements of regular servicing of

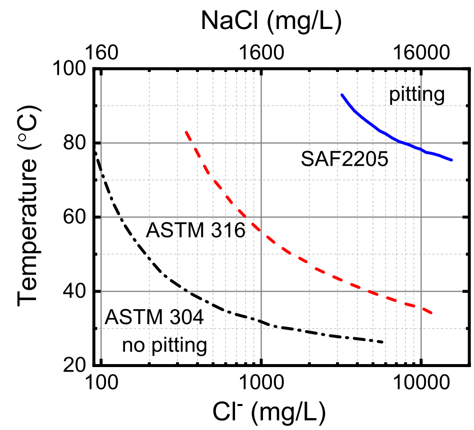

Fig. 5. Critical pitting temperatures for ASTM 304, ASTM 316 and 2205 duplex stainless steel, at varying concentrations of sodium chloride with a pH of 6.0 (data taken from [109]). Pitting occurs above the curve areas.

diaphragm pumps, replacing the diaphragms (2–3 years) and seals (3–5 years) as well as regular maintenance being carried out every 1–2 years to enable a long service life [88,98,106]. In contrast, helical rotor pumps powered from PV arrays (320, 480 and 640 W) operated within a pressure range of 5–10 bar showed no measurable degradation in performance over a 3 year period. Furthermore, one pump was tested for over one year at a maximum design pressure of 15 bar, and this showed no measurable signs of degradation as well. These test results further highlight the better capability of helical rotor pumps over diaphragm pumps with respect to longer operational lifetime and higher operating pressures. However, no information about other pumps regarding to reliability can be found in the literature.

Clearly, the materials of the pumps play an important role in the robustness, especially the wetted parts of the pumps – mainly including the rotor, stator, and torsion shaft – have a big influence on the lifetime. In general, the wetted parts can be made of thermoplastics, thermosetting plastics, elastomers, stainless steel, ceramics, and other materials [108]. For RE-membrane applications, it is critical to consider the chemical resistance of the wetted parts in saline-containing corrosive waters and the ability to handle higher operating pressure to improve the reliability. Thus, the majority of metallic materials for the wetted parts used now are stainless steel (SS), such as ASTM304, ASTM316, duplex 2205 and super duplex. Fig. 5 illustrates the corrosion resistance of the three types of stainless steel (ASTM 304, ASTM 316 and duplex 2205) as a function of NaCl concentration and temperature [109]. Pitting is defined as a form of localized corrosion caused by aggressive water, such as salty water, which produces attacks in the form of spots or pits. As can be seen from Fig. 5, if the feed water temperature remains below 20 °C then no pitting problems are expected with either ASTM 304 or 316 SS. However, at a temperature of 30 °C corrosion problems can be encountered with ASTM 304 at a NaCl concentrations of > 2000 mg/L. For ASTM 316, such pitting problems are typically only observed at temperature > 40 °C and for concentration > 5000 mg/L. More can be learnt by examining the situation with seawater desalination systems, where pitting problems occur with ASTM 304 and 316 at temperature > 20 °C and for NaCl concentrations > 10,000 mg/L. In this scenario, duplex 2205 or super duplex are applied to greatly improve the reliability of the pumps for applications in aggressive environments [110]. Fig. 5 illustrates that duplex 2205 exhibits significantly better performance at higher temperatures and chloride (Cl^-) and NaCl concentrations than either ASTM 304 or ASTM 316 without pitting. The typical groundwater temperature that can be found in regions with a tropical climate at a depth to 50 m is remained at 25 °C [111]. Thus, ASTM 316 SS is expected to be a satisfactory for the vast majority of brackish water RE-membrane applications. However, to avoid corrosion, duplex or super duplex SS would be more appropriate for use at at higher ambient temperature (> 40 °C) and concentrations (for example, seawater) applications.

Other factors can also increase the probability of pitting corrosions, such as low pH, and the addition of oxidative chemicals. Schäfer et al. [112] identified a number of physico-chemical water quality problems during an extensive sampling trial in Ghana, showing natural waters with pH values in the range of 3.69–8.88. Research has shown that as the pH decreased (increasing acidity), the corrosion rate also increased [34]. This is due to the low pH solutions accelerate corrosion by providing hydrogen ions, resulting in attacking and damaging the surface of steel, as well as increasing the weight loss.

5.3. Recommendations

For small-scale RE membrane system applications, the authors recommend the following:

- Brushless DC motors are preferred, since they exhibit 15–20 years of lifetime and less maintenance compared to brushed motors;
- Helical rotor pumps are the most suitable pumps for small-scale systems as they combine the characteristics of high efficiency and pressure with low flowrate over a wide operating range, which are difficult to achieve with other pumps;
- The combination of helical rotor pumps with brushless DC motors are found to provide the most reliable and efficient pumping system that fulfils: (i) the pressure and flowrate requirements with low maintenance and (ii) the target system lifetime of 20 years;
- The wetted parts of pumps made of ASTM 316 stainless steel can satisfy the majority of brackish water PV-membrane applications.

6. Pressure-driven membrane processes

Membrane technologies have become very important tools in drinking water production, wastewater treatment and reclamation, and industrial process water treatment. The efficiency has been proven from a technical and economical, as well as an ecological point of view [113]. Pressure-driven membrane processes, such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) – listed in order of decreasing membrane pore size – are standard components in RE-membrane systems. Transmembrane pressure (TMP) provided by a pump is the driving force for water permeation through the membranes.

MF and UF are classified as low-pressure processes, typically requiring a TMP of less than 3 bar. MF (pore size 0.1–1.0 μm) can remove most finely suspended solids turbidity, while UF (pore size 2–50 nm) can remove viruses, colloids and organic macromolecules [114]. The permeation mechanism of MF and UF membrane is mainly based on a pore flow model, whereby contaminants are separated by pressure-driven convective flow through tiny pores [115,116]. The pore size of NF is typically < 1 nm, corresponding to a molecular weight cut-off (MWCO, defined as the molecular weight of a solute corresponding to a 90% rejection coefficient for a given membrane) in the range of 100–500 g/mol [117,118]. Typically, NF exhibits a high retention of multivalent inorganic salts such as calcium (Ca^{2+}) and magnesium (Mg^{2+}) – that contribute to water hardness – and small organic molecules at modest applied pressures (typically with a TMP of 5–15 bar) [119]. RO membranes are dense membranes without predefined pores and typically require high pressures in the range of 30–60 bar, depending on the feed water osmotic pressure [120,121]. RO membranes are able to reject most dissolved solids including monovalent ions, such as sodium and chloride. For NF/RO membranes, the well-established solution-diffusion model is used to explain and describe the permeation process, whereby permeants dissolve into the membrane material and then diffuse through the membrane following a concentration gradient [116]. Separation is achieved between different solutes due to the difference in solubilities and mobilities in the membrane [115,116]. MF/UF is commonly used as a pre-treatment for NF/RO to reduce fouling of the NF/RO membranes [122].

From the reliability point of view, fouling and control, membrane integrity and damage, as well as O&M are key issues. Details of those aspects are discussed in the following sections.

6.1. Membrane fouling and control

The main challenge associated with effective pressure-driven membrane is fouling [123]. This results in a loss of membrane performance (permeability and retention) due to the deposition of suspended or dissolved substances (foulants) on the external surfaces of the membrane, at the pore openings, or within the pores [118,124]. Fouling can shorten the membrane lifetime and severely affect the performance of a membrane system, such as, the decline of permeate flux and product water quality. The increased TMP is required to maintain constant permeate flow, resulting in a rise of SEC. Moreover, fouling will increase the frequency of cleaning, leading to an increase of maintenance cost.

Membrane fouling is typically classified into inorganic fouling, organic fouling, and biofouling on the basis of biological and chemical characteristics of foulants in the feed water. Inorganic fouling, including scaling and colloidal fouling, results from the precipitation of insoluble salts and/or deposition of colloidal solids or particles on the membrane surface [125]. Organic fouling is caused by organic molecules and/or dissolved organic matter, such as natural organic matter (NOM), synthetic organic compounds, disinfection by-products and soluble microbial products that typically form gels on the membrane surface [126,127]. Biofouling occurs due to microbial attachment to membrane surfaces followed thereafter by their growth and multiplication [122,125].

For MF and UF, the fouling mechanisms are pore-clogging/blocking and adsorption, as well as cake formation on the membrane surface, which all lead to an increase in hydraulic resistance to permeate flux [128]. For NF and RO, in addition to the increase of hydraulic resistance, fouling layers may enhance the salt concentration polarization (CP) layer on the membrane surfaces, leading to enhanced osmotic pressure and significant flux decline [129,130]. Obviously, membrane fouling is determined by the coupled influence of physical and chemical interactions between foulants and membrane. In the case of complex water sources, different types of foulants will form a mixed fouling layer. Moreover, in the case of the PV-membrane systems, the TMP and permeate flux will vary with the fluctuations and intermittency of solar energy supply, which further affects the physical and chemical conditions on the membrane surface. Consequently, the fouling behaviors/mechanisms may differ from constant operational conditions. Therefore, further research involves the fouling behaviors/mechanisms in RE-membrane system is needed to improve the system reliability.

The complexity of membrane fouling determines the various possible approaches to mitigate its effects [128]. Here, these approaches are categorized under four main topics: (i) pre-treatment of feed water; (ii) membrane selection; (iii) optimization of operating parameters; and (iv) regular and periodic cleaning. The first three approaches focus on the prevention or mitigation of membrane fouling, whereas the fourth topic focuses on dealing with the consequences of membrane fouling [122,127,131]. These will be discussed in detail below.

6.1.1. Pre-treatment of feed water

Adequate pre-treatment prior to membranes filtration is very important to minimize membrane fouling and increase life expectancy of the membrane. Pre-treatment can greatly reduce potential of different foulants attached to the membrane surface [132]. To examine the fouling potential of feed water for NF/RO systems, many indices of feed water fouling potential have been developed. For instance, the silt density index (SDI), modified fouling index (MFI) and turbidity of permeate from pre-treatment, which are the indirect measures of the

Table 3
Overview of potential pre-treatment options for pressure-driven membranes and their fouling removal targets.
Adapted from [128,143,145,146].

Membrane type		Pre-treatment technique	Target foulants
MF/UF	Conventional process	Media prefiltration (such as sand filtration) Pre-coagulation Pre-flocculation	Suspended particles Colloidal particles, organic matter
	Adsorption	Powdered activated carbon	Organic matter, particles
	Pre-oxidation	Ozone Chlorine	Large organic molecules Biological activities
	Biological treatment	Bio-filter	Organic matter, colloids
	Other process	Magnetic ion exchange (MIEX)	Organic matter
NF/RO	Conventional processes	Pre-screens Cartridge filter Media filtration	Large particles such as sand Particles, suspended solids Particulates, suspended solids, organic matter
	Chemical	Addition of scale inhibitors/acids Addition of bisulfites Addition of coagulants (such as alum, $FeCl_3$) and flocculants	Scale Dechlorination Colloidal particles, suspended solids
	Disinfection	Chlorination Ultraviolet light Ozonation	Organic and biological activities biofouling potential
	Adsorption	Activated carbon	Organic matter and dechlorination
	Membrane processes	MF UF NF for RO	Particulates, bacteria and organic matter
	Other process	MIEX	Organic matter

content of colloids and particles in the feed water, are common colloidal fouling potential indices [133]. A MFI value of < 1 corresponding to a SDI value of < 3 can be considered sufficiently low to control colloidal and particulate fouling [133]. Dissolved organic carbon (DOC) and total organic carbon (TOC) are common organic fouling potential indices, while assimilable organic carbon (AOC) and adenosine-triphosphate (ATP) are common biofouling potential indices [134]. Supersaturation index (SI) and scaling potential index are common scaling potential indices. Scaling could occur when the SI is > 1 [133].

Table 3 summarized the main potential pre-treatment options for pressure-driven membranes and foulant removal targets. Usually, a combination of different pre-treatment technologies is adopted to ensure the best membrane system performance due to the complexity of the feed water quality, potential foulants, and treatment targets [135]. For MF/UF membranes, the common potential pre-treatment options include conventional processes (such as coagulation, flocculation, and media filtration), adsorption, pre-oxidation and biological treatment and other pre-treatment such as magnetic ion exchange (MIEX). Those techniques have been demonstrated effective for reducing colloidal fouling, organic fouling and biofouling of MF/UF membrane. For instance, the effects of pre-coagulation (aluminum-based coagulant) on removal of NOM for UF membrane was investigated. The conclusion was that the highest NOM substances separation was achieved with alum at a pH of 6, and the pre-coagulation can reduce the organic fouling for UF [136].

On the other hand, membrane-based processes (MF, UF) is increasingly common pre-treatment for NF and RO systems due to the advantages compared to conventional pre-treatment processes while NF is commonly used as pre-treatment for RO system [122,137]. Firstly, it can ensure a consistent and excellent RO feed water quality (typically SDI < 2.5). This can improve RO performance and increase lifetime of membranes by 20–30%. Recovery and permeate flux can be increased by about 22% compared to conventional processes, regardless of the fluctuations in raw water quality [138,139]. Secondly, it can greatly reduce land footprint by 40–70% due to the modular design, which facilitates the integration with RE-membrane systems where space is limited [34]. Thirdly, MF/UF modules are easy to transport and install, low-pressure operation and simple maintenance to save O&M cost [135,140]. Based on a study of cost comparison between UF and conventional pre-treatment for a 90,000 m^3/d RO desalination plant, the total water cost using UF is 0.52 \$/m^3. This is comparable to the water cost of conventional pre-treatment at 0.51 \$/m^3 [141]. Hence, membrane-based processes are recommended to apply as pre-treatment for RE-membrane systems. Among those membranes, Schäfer et al. [142] found UF is superior to MF, and NF is superior to tight UF. This assessment was based on the estimation of membrane costs as a function of water quality parameter (WQP), which was defined in terms of colloid, organics and cation rejection when feed water contained NOM. They concluded that when considering chemicals and energy costs, additional energy required to operate NF is cheaper than the chemicals required achieving same level organic removal with MF. Therefore, for small-scale RE-membrane systems in remote areas, the economic potential to apply NF membrane instead of UF or MF combined with chemical pre-treatment.

Chlorination has been applied to reduce the biofouling potential as it can inactivate most pathogenic microorganisms with a reaction time of 20–30 min [46,143]. In addition, free residual chlorine concentration of 0.5–1.0 mg/L should be maintained through the whole pre-treatment line [46]. However, a dechlorination process of upstream is required to prevent the oxidation damage of polyamide (PA)-based NF/RO membranes. The addition of a scaling inhibitor, such as sodium hexametaphosphate (SHMP), organophosphonates and polyacrylates, or antiscalant and acidification are commonly applied to reduce scaling potential due to their ability to increase the solubility of sparingly soluble salts, such as calcium carbonate, magnesium sulfate, and calcium

Table 4
Overview of design and simulation software illustrating the supplier and application range for membrane system.

Software name	Supplier	Application range
Winflows 3.3.2	SUEZ Co.	RO system design and simulation
ROSA 9.0	DOW Co.	NF and RO membrane system
WAVE	DOW Co.	UF, RO and ion exchange system design
Q+2.4	LG Chem. Co.	RO system
ROPRO 8.0	KMS Inc.	UF and RO design and simulation
IMSDesign 2018	Hydranautics Co.	NF and RO design and simulation
LEWAPLUS	Lanxess Co.	RO and ion exchange membrane

fluoride [126]. A scale inhibitor is recommended to be applied at system recovery > 20% to prevent membrane scaling although this depends on the raw water quality [144].

6.1.2. Membrane selection

Appropriately chosen membranes can effectively remove contaminants and ensure good product water quality and reduce fouling potential and cleaning frequency. It ultimately improves system performance, extends the membrane lifetime and saves O&M costs [147]. For instance, in Scotland, tubular cellulose acetate (CA) membranes [148] were applied to replace the initial Magnum 8231LP cellulose triacetate membranes [149] with proper cleaning methods for a small scale NF system. Consequently, the membrane lifetime was extended from the initial 1 year to 3 years due to the change of membrane modules. The ideal membrane should be selected and considered based on the following factors: feed water quality, target water production, target water quality, membrane characteristics, and membrane cost.

Naturally such selection requires the analysis of the physical-chemical-biological characteristics of the feed water. Common design and sizing processes for large-scale (grid-powered) RO membrane system are already well established by membrane manufacturers [150], so the details are not discussed here. However, membrane system design and simulation software available by membrane suppliers is a useful and important tool for selecting membranes [151]. Table 4 summarizes the commonly used membrane system design and simulation software from different suppliers. The simulation results including the permeate quality and SEC of different potential membranes (NF or RO) show whether the local drinking water guideline or World Health Organization (WHO) guideline can be met [152], for example, passing the palatability test for good drinking water requiring a TDS < 600 mg/L. It needs to be noted that the seasonal variation of feed water quality and quantity must be considered. When NF can achieve the target water quality, it is recommended to use NF due to its lower energy consumption, reduced fouling tendency and higher water production compared with RO. As an example, Katie and Korak [151] employed the DOW Chemicals Reverse Osmosis System Analysis (ROSA) software to identify the membranes used in the PV-membrane system. The results indicated that NF90 required lower feed pressure and still met the target water quality compared to BW30 RO membrane and other NF/RO membranes. However, design and simulation tools cannot replace pilot scale testing with specific water. Especially when water contains contaminants such as arsenic, iron or heavy metals, the removal of those contaminants with potential membranes should be tested at least in the lab scale using methodologies that can attain comparable results to real applications [153].

Other membrane properties, such as fouling resistance, permeability, as well as robustness which can be obtained to some extent from membrane manufacturers should be taken into consideration. For instance, the operational experience (more than 3 years) of a river water RO plant in Infra-Zeitz (Germany) has been proven successful and no biofouling detected due to a well-selected fouling-resistant membrane (BW30-365FR) in combination with a weekly low dose of biocide [154].

When selecting membranes, the total cost including the capital costs and O&M costs is important, yet often difficult to establish up front. Ang et al. [155] combined cost modelling, membrane performance, fouling propensity and energy consumption to provide a comprehensive evaluation to determine the potential of NF (NF270, NF90, and TS80) and low pressure RO (XLE) membranes to replace a typical brackish water RO membrane (BW30). The authors concluded that for very low TDS (400 mg/L) brackish water, NF90 and XLE membranes could be used as an alternative to BW30 since both encountered reduced fouling issues, consumed less energy and offered cost savings. For medium TDS (4000 mg/L) brackish water, the NF90 membrane was shown to be the preferable candidate. Compared to XLE, it showed robust performance, and a 21% and 17% cost savings for total costs and operation costs per cubic meter treated water. For the small-scale RE-membrane systems in remote area, it is suggested to use simulation tools to select appropriate membranes, thereafter pilot testing is recommended to evaluate the long term performance of the system.

6.1.3. Optimization of operating parameters

Membrane manufacturers normally recommend operation ranges for membranes to minimize the rate of fouling and eliminate the potential for mechanical damage to the system [46]. Operating parameters include many aspects, such as, cross-flow velocity, recovery, TMP and initial permeate flux. In directly coupled PV-membrane system operation, many of those parameters are variable with energy supply availability, resulting in the optimization of those parameters becoming very complex.

For MF/UF membranes, Grozes et al. [156] investigated the impact of several operating parameters on NOM fouling, including permeate flux, concentrate velocity, backwash frequency and TMP. It was found that NOM fouling can be reduced by decreasing flux, increasing concentrate velocity and backwash frequency. By doing so, the shear at membrane surface increased and concentrate velocity should be adjusted to maintain the increase of TMP below a certain limit (in this case 1 bar). In 1995, Field et al. [157] firstly proposed the “critical flux” concept for membrane fouling control. The critical flux was defined as the point at which flux ceases to increase linearly with TMP. Critical flux depends on the hydraulic conditions of the membrane process. For the long-term MF/UF membrane process, operation at critical flux greatly reduces membrane fouling, especially colloidal fouling [156].

Generally, increasing feed flow rate will increase cross-flow velocity, consequently it can enhance shear stress and reduce CP/fouling. Slight changes in recovery can significantly affect the overall cost of the membrane system, as well as the extent of typical membrane performance limiting factors, such as fouling propensity and mineral scaling potential [158]. With an increase of system recovery, TMP and flux will increase accordingly, leading to higher fouling/scaling potential due to enhanced CP on membrane surface, which may increase O&M cost due to increase of membrane cleaning frequency. In small-scale RE-membrane systems, it is recommended to maintain the maximum recovery of each NF/RO element at 10–25% to minimize maintenance and reduce the requirement for using antiscalants [46,159]. The operational experiences in Norway showed the recommended system design with a moderate flux (< 20 L/m^2h) and recovery (< 70%). System were operated with daily cleaning to control fouling [160], and this operation resulted in a typical membrane lifetime of 6–10 years [161].

The TMP is an important indicator to monitor the fouling of the membrane system in constant flux operation. The hydrodynamic driving force toward the membrane surface increases permeate flux, causing enhanced CP. High pressure/permeate flux enhance deposition of foulants. For NF/RO membranes, the understanding of critical flux needs to be further improved, because fouling composition of these membranes is more complex than MF/UF. In particular, osmotic pressure can’t be ignored and solubility limits [162]. In addition to optimized operation parameters, the start-up strategies also influence the fouling control. For example, Chen et al. [163] found that the gradual

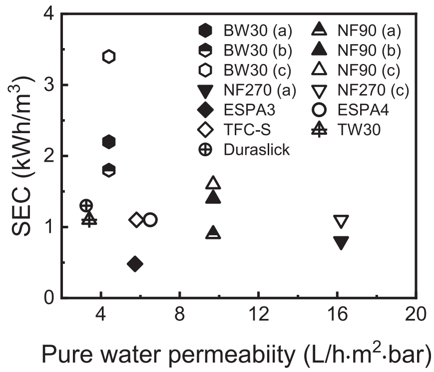

Fig. 6. SEC as a function of water permeability for different membranes applied under different operational conditions as described in Table 5 (data taken from [18,164,167–170]).

Table 5
Examples of operational conditions in terms of TMP, feed flowrate, recovery and feed TDS concentration for different NF and RO membranes. Note (a), (b) and (c) represent different operational conditions.

Membrane	TMP (bar)	Feed flowrate (L/h)	Recovery (%)	Feed TDS concentration (mg/L)	Ref.
Duraslick	13	—	50	3500	[167]
TFC-S	10	300	55	5300	[18]
ESPA4	10	300	58	5300	[18]
ESPA3	9.5	—	70	4000	[168]
TW30	14	728	70	2000	[169]
BW30$^{(a)}$	4.5	600	17.3	282	[164]
BW30$^{(b)}$	11	400	40	5300	[18]
BW30$^{(c)}$	5	550	13.4	3632	[170]
NF90$^{(a)}$	4.3	600	45	282	[164]
NF90$^{(b)}$	9	300	40	5300	[18]
NF90$^{(c)}$	4.8	567	27.8	3632	[170]
NF270$^{(a)}$	4.3	600	45	282	[164]
NF270$^{(c)}$	4.8	567	39.7	3632	[170]

Note: "—" denotes information not provided.

pressure start-up from low to high values every 30 min produced a smaller fouling rate than the direct start-up directly to the full operational value.

Different operational conditions have significant impact on the SEC of the PV-membrane systems. Fig. 6 summarized typical SEC of commercial NF/RO membranes under different operational conditions (provided in Table 5) as a function of permeability. The results generally show that lower permeability membranes exhibit significantly higher SEC. Despite NF270 appearing to be the most energy-efficient membrane, the salinity removal may fail to meet the guideline [164]. For the BW30 membrane operating under condition (a) and (b) (see Table 5), the higher SEC was caused primarily by the higher feed flowrates due to additional energy required by the pump. For NF90 at condition (c) (see Table 5), the higher SEC was caused by the low TMP (4.8 bar) with high feed concentration resulting in very little permeate being produced. At condition (a) with very low feed concentration and high recovery, less energy is required at low pressures resulted in low SEC. Finally, although the SEC was low, TFC-S and NF270 membranes were not capable of fulfilling the recommended drinking water guidelines due to lower salt retention. Many studies showed that RO membranes with high permeability lead to lower energy consumption in desalination [165,166].

6.1.4. Membrane cleaning

Although adequate feed water pre-treatment, appropriate membrane selection and optimal operating parameters can minimize fouling, membrane cleaning remains an essential step in maintaining the performance of the membrane process [171]. It is recommended to clean the RO membrane when the normalized permeate flow drops by 10%, or the normalized salt rejection decreases by 5–10%, and/or the normalized pressure drop (the differential between feed and concentrate pressure) increases by 10–15% [172]. For full-scale groundwater treatment NF systems, the typical cleaning frequencies range from once per 3 months to once per 2 years, with an average of 6 months. For treating surface water the cleaning frequencies may vary from once per week to once per 3 months [171]. There are a variety of cleaning methods, both physical- and chemical-based, and their cleaning efficiency can be evaluated by resistance removal and flux recovery [122].

Fig. 7 summarizes common physical cleaning methods for pressure-driven membranes. For MF/UF membranes, hydraulic cleaning methods use strongly changing hydrodynamics of membrane system to force foulants to leave the membrane surface. This includes forward flushing, backwashing, and backpulsing. In general, backwash is conducted for 30–60 s every 5–15 min of filtration. The backpulsing time is typically much shorter ($<$ 1 s) at a higher frequency [162]. Pneumatic methods such as water/air flushing clean the membrane by means of producing turbulence and flow in vicinity of the membrane surface and instable bubbles thus, sweeping away foulants. Mechanical cleaning, such as sponge ball wiping can be used to clean the large diameter tubular membrane [148], which increases energy consumption and cost. Comparatively, osmotic backwash (OB) processes are becoming promising methods for cleaning NF/RO membranes due to low maintenance cost and lower chemicals consumption [173]. Rolf and Eckehard patented it as a 'suck back effect' in 1997 with the potential to exploit OB for self-cleaning of membranes in the second stage of NF/RO membrane system operation [174,175]. This OB processes are driven by osmotic pressure difference when the feed pressure drops below osmotic pressure in the feed side. In RE - membrane systems without energy storage, OB process occurs when operating pressure is reduced below the osmotic pressure. Foulants deposited on the membrane are consequently removed during brackish water desalination. This suggests a RE-membrane system could potentially benefit from operation under fluctuating energy [176,177], but no detailed investigations have been carried out to date. Chen et al. [178] identified the key factors affecting both physical and chemical cleaning of UF and RO membranes as being the production interval between cleaning, duration of backwash and pressure during the forward flush. The UF physical cleaning protocol, namely 1 min backwash followed by 1 min forward flush at 1.7 bar using RO permeate once every 30 min of operation was developed. Meanwhile, the RO physical cleaning protocol 5 min backwash followed by 1 min forward flush at 6.2 bar using RO permeate once every 6 h of operation was proposed. Higher flux recovery was achieved by increasing the production interval between cleaning. Those protocols may vary due to different feed water qualities and membrane types. Even though the physical cleaning methods are environmentally friendly and more effective, application of these methods may result in more complex system control and design [171,179].

For chemical cleaning, it is important to select proper chemical agents by means of distinguishing the fouling types and foulants, as well as the chemical properties and economic factors [122]. The optimal (the least membrane damage and maximal effectiveness of cleaning) choice of the cleaning agent depends on type of fouling [171]. Table 6 summarized common chemical cleaning agents and fouling removal targets for pressure-driven membranes. Alkaline solutions such as sodium hydroxide are more effective in removing organic fouling and biofouling while acids, such as hydrochloric acid, nitric acid, and sulfuric acid are effective in removing membrane scaling [171]. A commonly used chelating agent is ethylene diamine tetraacetic acid (EDTA), which was found to be able to effectively remove scaling and organic foulants associated with calcium ion [171]. Sodium dodecyl sulfate (SDS) is a commonly used surfactant in cleaning, which has also been used for effectively removing colloidal fouling and organic fouling [182]. When NF/RO membranes suffer from colloidal, organic fouling

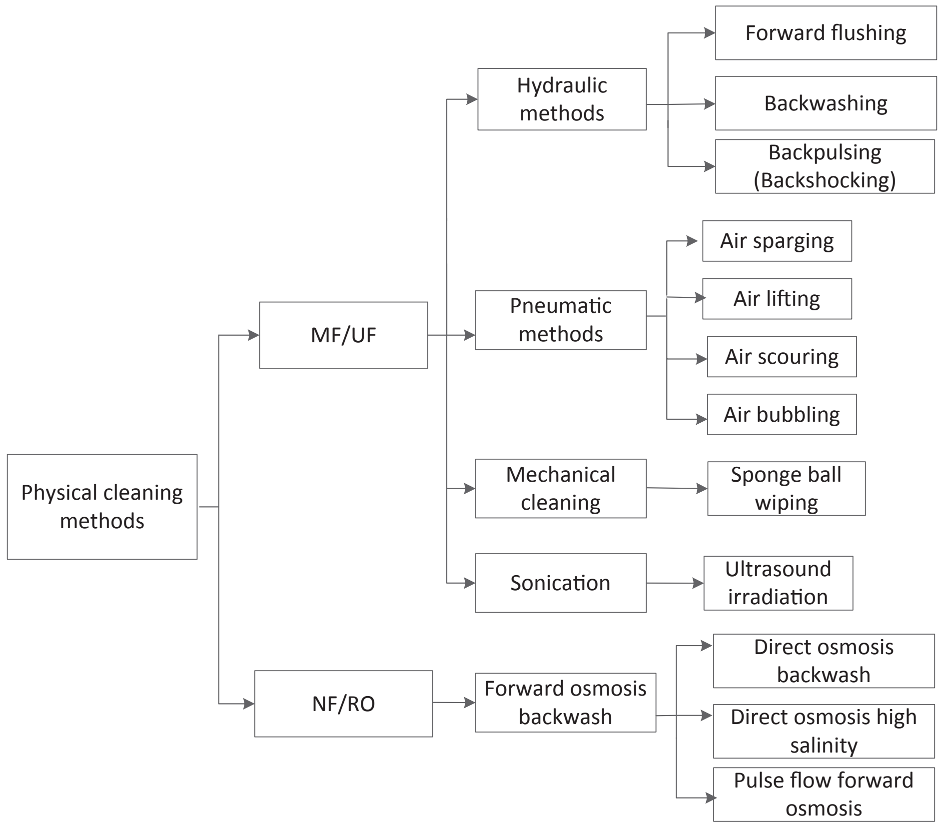

Fig. 7. Overview of physical cleaning methods for pressure-driven membranes [162,180,181].

Table 6
Overview of common chemical cleaning agents for pressure-driven membrane process [119,180,184].

Category	Examples	Fouling removal targets
Acids	HCl, HNO_3, H_3PO_4, citric acid, oxalic	Inorganic fouling (scaling)
Alkalis	NaOH, KOH, Na_2CO_3	Organic fouling
Chelants	EDTA	Scaling
Oxidants	H_2O_2, NaClO, $KMnO_4$	Biofouling, organic fouling
Surfactants	SDS, CTAB, Tween 20, Aakyl sulfate	Colloidal fouling
Enzymes	Lipases, proteases	Organic fouling (e.g., proteins, lipids), biofouling

or biofouling in combination with calcium carbonate, then alkaline cleaning followed by an acid cleaning is required [172]. Typically, there are six steps in cleaning procedure of membrane module *in situ*: (i) prepare cleaning solution; (ii) low-flow pumping; (iii) recycle; (iv) soaking; (v) high-flow pumping; and (vi) flush out the cleaning solution [37]. The physical and chemical cleaning methods are usually both applied to enhance the cleaning effectiveness [171]. Besides, according to a study on cost analysis of large scale groundwater RO desalination system (100,000 m^3/day, sand filtration as pretreatment), the chemicals cost for cleaning was reported to be about 35% of the total operation cost [183].

6.2. Membrane integrity and damage

6.2.1. Membrane integrity and monitoring

The membrane system performance can be further deteriorated by membrane integrity loss [124]. As discussed previously, the MF and UF can effectively remove pathogens; however, pathogens may pass through membranes if the integrity is compromised, such as, broken fibers, fiber degradation, or O-ring failure [185]. The failures of membrane fiber or sheets maybe caused by (i) chemical corrosion such as oxidation; (ii) faulty installation and maintenance; (iii) membrane stress and strain under operating conditions, such as backwash or excessive movement due to bubbling; (iv) damage by sharp residuals from pre-treatment [185,186]. Zondervan et al. [187] performed a systematic study of factors that affect UF membrane lifetime – including the fouling status of the membrane; cleaning agent concentration, magnitude of the back pulse and number of applied back pulses. The integrity of membrane was evaluated via permeability testing, pressure decay test and bubble tests. It was concluded that the membrane fouling status in combination with the number of applied pressure pulses were significant aging factors and eventually contributed to membrane failure [187]. The integrity of the NF/RO membranes might be compromised during commissioning and operation of the system, such as the inter-connector, or end connector O-rings, as well as membrane element glue lines [188].

Therefore, it is important to perform accurate and efficient integrity tests and monitoring to ensure the quality of filtered water [185]. The purpose of membrane integrity tests include verification of filtered water quality, demonstration of regulatory compliance, and the detection of equipment/filtration problems [185]. Membrane integrity monitoring techniques are classified into direct and indirect methods. Direct methods refer to tests directly applied to the membrane element. In spiral wound NF/RO elements those tests can only be applied before loading elements into the system or after disassembling the elements from the system. Indirect methods refer to tests applied to water quality parameters in the permeate solution, such as particles (turbidity), salinity (conductivity), organic matter (TOC and DOC) and microorganisms, which is possible during system operation. Among these methods, the pressure decay test (PDT) and diffusive air flow (DAF) test are the most frequently used *in situ* direct methods for MF/UF due to simplicity, low maintenance, reliability and high sensitivity to detect membrane breaches [185]. Such tests can be carried out for about 30–60 min, thus minimizing system downtime [189]. Besides, particle counting, turbidity monitoring, and routine microbial analysis are the most frequently used indirect methods for MF/UF. For NF/RO membrane integrity monitoring, vacuum tests and pressure tests are common direct methods, while in-line conductivity monitoring for the permeate, conductivity probing for each membrane element, in-line TOC/DOC monitoring and microbial seeding of the permeate solution are the most common indirect methods [188,190]. Importantly, the use of more than one monitoring method may be necessary to ensure the reliable operation of the NF/RO system [190]. Those available integrity monitoring methods are applied at different levels and different stages during O&M of membrane systems depending on integrity testing goals [151].

TOC/DOC monitoring is being implemented in large scale water treatment plants, such as the wastewater reclamation plants in Singapore [191]. For small-scale RE-membrane systems in remote areas, they are expensive and complicated. Schäfer et al. [18] have shown that conductivity is a good surrogate parameter for RE-membrane systems. Hence, the in-line conductivity monitoring is recommended to apply during the system operation, due to their simplicity, low maintenance and sensitivity. While the direct methods like PDT and vacuum tests are recommended to be applied during RO element delivery, system assembly and troubleshooting stages by a qualified operator. Alghoul et al. [169] applied in-line conductivity sensor monitoring of permeate salinity (less than 50 mg/L TDS) as an integrity method for a small-scale PV-membrane system for brackish water desalination.

6.2.2. Membrane damage

During start-up, shut-down, cleaning or other sequences, abrupt pressure or flow variations on the membrane elements is possible to cause membrane damage [46]. Generally, pressure-driven membrane damage can be classified into physical and chemical damage. Such damage is causing membrane failure or membrane integrity loss, consequently, leading to decrease of permeate quality.

Physical damage – such as abrasion by large particles, sharp precipitates, spacer rubbing/moving protrusion or spacer material and membrane element telescoping (the longitudinal unravelling of the spiral wound membrane elements) – is mainly due to loss of function in the pre-treatment, to membrane cleaning process or to operational problems [192]. Physical damage could occur when some particulate matter enters or is generated in the membrane module and then physically abrades or penetrates the membrane layer, finally compromising product water quality [193]. Even particles in the size range of 10–50 μm have been known to cause membrane damage. Therefore, it is important to maintain the pre-treatment in good conditions, ensuring that no bypassing occurs. On the other hand, the operation of the membrane system itself plays an important role in physical damage. According to one membrane manufacturer [46], telescoping could occur due to excessive pressure drop from feed to concentrate when the system is operating beyond the recommended maximum feed flow rates or the feed pressure builds up too fast during the start-up stage. As a result, the membrane module can be mechanically damaged. Therefore, the manufacturer suggests a soft start-up to increase the feed pressure and feed flow rate slowly [46]. For this reason, the rate of feed pressure increase should be less than 0.7 bar/s to realize a soft start [46]. Besides, the excessive TMP or major loss of TMP can cause a pressure differential, leading to the membrane damage. Excessive permeate backpressure is one of the most common causes of mechanical damage to NF/RO during operation [194]. To avoid membrane damage from backpressure, the static permeate backpressure must not exceed 0.3 bar at any time [46]. The closing permeate valve during operation also cause high permeate backpressure. Such backpressure may causing the delamination of the active thin film PA layer from its support layer [194]. Membranes are expected to undergo plastic creep at constant pressure and temperature, hence in RE-membrane systems, the combination of fluctuating pressure and flowrate with cycling on/off may cause material fatigue [195].

Chemical damage occurs mainly due to the presence of chlorine (such as hypochlorite, hypochlorous acid, or chlorate) or some oxidants in the feed water. Oxidants may compromise the active PA layer of NF/RO membranes, resulting in higher salt passage and permeability. The damage is irreversible and continues as long as the membrane is exposed to such chemicals [193]. Kang et al. [196] determined that the hypochlorite degradation reaction of an aromatic PA membrane involved a reversible N-chlorination and an irreversible ring-chlorination. It was suggested that the use of PA membranes should be absolutely avoided in acidic environments with residual active chlorine, while the short-time treatment with alkaline hypochlorite solution could improve membrane performance somewhat. Oxidants are often used for disinfection of the feed water prior to the NF/RO system to reduce biofouling potential, leaving the system exposed to a higher risk of chemical damage [197]. Therefore, it is recommended to select chlorine-resistant PA-based NF/RO membranes, while ensuring no oxidants are present in the feed water prior to NF/RO. Physical adsorption (activated carbon adsorption) or chemical neutralization (bisulphites neutralization) can be implemented in order to reduce the chemical damage risks of PA-NF/RO membranes. Tin et al. [198] assessed the chlorine resistance and separation performance of a prototype chlorine-resistant NF membrane compared to a commercial NF membrane. It was found that the prototype NF membrane could retain the stable performance with the exposure of a 1000 g/L NaOCl solution up to the cumulative chlorine exposure of 50,000 g/Lh. For RE-membrane systems, it is critical to select a robust membrane that can cope with operator errors and harsh conditions. New membrane materials are being developed providing further choices in the future.

Overall, for avoiding physical damage of membranes, transportation, installation, O&M process should be handled with care [199]. To prevent chemical damage of membranes, specific chemicals such as chlorine should be prevented to contact with PA-based NF/RO membranes during operation.

6.3. Operation and maintenance

6.3.1. System operation with fluctuations and intermittency

As discussed in Section 6.1.1, MF/UF membranes are typically used as pre-treatment for PV-membrane systems to protect NF/RO from fouling [200]. Fluctuations and intermittency will result in pressure and feed flow rate variation that such membrane can withstand and size exclusion of contaminants would not be affected. NF/RO membranes experience fluctuations and intermittency in term of pressure and flow variations that may cause osmotic backwash and variation of contaminants retention. To minimize the potential of excessive mechanical stresses on the membrane module, membranes are typically anticipated to operate at constant operating conditions without abrupt pressure or crossflow variations [46]. However, due to the transient nature of RE resources, any system that is directly coupled to membranes is subjected to fluctuations and intermittency. Richards et al. observed that system shut-downs due to the lack of energy during periods of severe energy fluctuations, ranging from 20 to 800 Wh/m^2 for two hours. This can cause the retention of the NF/RO membrane drop significantly to gather with low water production [201]. Besides, variable operation caused by the fluctuating solar resource could lead to mechanical fatigue of NF/RO membrane and thus reduce both the performance and lifetime [202].

Shen et al. [164] compared the performance of three different membranes (BW30, NF90, and NF270) under fluctuating solar energy. The results from short-term fluctuations (up to 10 min, resulting from passing heavy clouds) showed that the tight BW30 and NF90 membranes exhibit high abilities to produce good quality drinking water, but the NF270 exhibited decreased performance due to its looser structure. Richards et al. [201] compared the performance of a PV-membrane system at six remote field locations to evaluate the effect of fluctuating energy on inorganic contaminant removal using a BW30 membrane. The results showed that the retention of ions such as Ca^{2+} and Mg^{2+} was above 95% with each groundwater during continuous operation. The retention dropped to between 40 and 50% for one sample due to severe fluctuations (thunderstorms), while at another location the retention dropped to temporarily low levels (< 30%) due to system shutdowns when significant cloud cover occurred. The poor performance was typically not significant for overall water quality as not much water was produced at low power. Freire-Gormaly and Bilton [203,204] performed experimental investigations of the effect intermittent operation characteristic of PV membrane systems has on membrane performance. The results showed the average normalized permeability (ratio of membrane permeability and an average of the first 5 min of collected data) declined to 87 ± 9% for intermittent operation with antiscalant and rinsing over six days, while the continuous operation with antiscalant declined to 30 ± 4%. These results were intended to be used to develop robust design algorithms for RE-membrane systems in the future [205]. Richards et al. [176] used solar irradiance step-response testing to investigate the impact of solar irradiance fluctuations on the performance of PV-membrane system. It was found that the operating conditions during the first couple of minutes following a system shutdown event are very important with: (i) shorter off-periods resulting in good performance being achieved quicker, and (ii) short-term power availability dramatically improving system performance.

Additional research such as the issue of robustness of membranes operating under fluctuating energy condition in small-scale PV-membrane system – particularly a long-term study – is needed to evaluate the performance and improve the reliability of these systems in remote locations.

6.3.2. Safe operating window (SOW)

The concept of a safe operating window (SOW) was proposed to examine the factors that resolve the optimum operating strategy for variable operation of RE-membrane systems [206]. SOW is used to determine the safe operation (both physically and performance wise) with main constraints to enable maximum water production at minimal cost, as well as reducing the performance degradation risk due to high recovery operation [207]. Directly-coupled RE-membrane systems are required to operate over a very wide power range – for example from as low as 10% and up to the maximum power rating – due to the transient nature of the RE resource and the lack of energy storage components. The hydraulic inputs such as feed pressure and flowrate have to be controlled to optimize the system performance based on the available power range. Experimental investigations of operating strategy for a wind-powered-membrane system within a SOW were conducted [207]. The performance was determined using a RO membrane module (BW30), brackish (5500 mg/L NaCl) feed water and 24 h of real (fluctuating) wind speed data (average wind speed 6.1 m/s; interval of 1 s). An example of the improvement that can be realized via adding a large SC energy buffer to a system is illustrated in Fig. 8. The operating point of the system throughout the day is plotted in terms of pump motor power and TMP. It can be seen that the time spent within the SOW over the 24 h period increased from 16 h 47 m with a 10 bar set point under the operating conditions up to 19 h 56 m with the larger SC energy buffers [207]. The SOW method can be used to evaluate the performance of RE-membrane systems, help with the system design and determine energy buffering components.

6.3.3. Membrane maintenance

The small-scale powered PV-membrane systems applied in remote areas must be well operated and maintained by qualified personnel, which is not usually available on site. General maintenance guidelines provided by manufactures are not always suitable for specific system and site conditions. The model-based maintenance schedules under determined conditions proposed by Kelly et al. can help inexperienced operators to perform the maintenance in a proper time in a small-scale PV-membrane system [208]. The results indicated the potential to use model-based methods to permit non-experts to operate a RE- membrane system under uncertain, changing conditions, while still meeting the community water demand [208]. Predictive tools and remote sensing technologies for small-scale RE-membrane system are needed to carry out to improve the system operation and maintenance. Initially, qualified personnel must operate such systems, ideally under service contracts. This will ensure reliable operation when such technologies are established and actual operation & maintenance needs are determined. As small-scale RE-membrane systems are to be operated with minimal maintenance or chemicals, the operational lifetimes of NF/RO membranes were reported as relatively low in the range of 1–3 years [16,209,210], with one membrane manufacturer quoting an operational lifetime of 1–2 years for membranes operated at low recovery in the range of 25% with preventative cleaning [46]. The MF/UF membranes used as pre-treatment in RO seawater applications were typically replaced every 5–10 years [211]. For brackish water desalination, MF/UF lifetime is expected to be longer. Additional research of the understanding and knowledge on the membrane lifetime and O&M methods suitable for remote regions for small-scale RE-membrane systems is required. In fact, this is the biggest remaining challenge for such technologies.

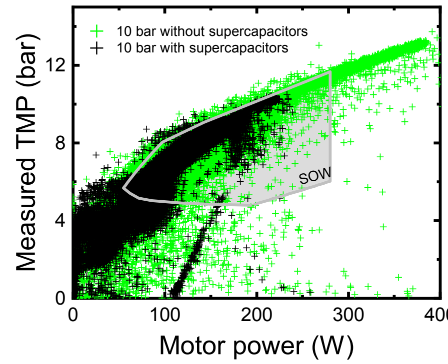

Fig. 8. Performance comparisons of RE-membrane system with/without SCs at each second of the 24 h period plotted on top of the SOW.
Adapted from [207].

6.4. Recommendations

Concluding from the above discussions, the following recommendations for a small-scale PV-membrane system in remote areas are given:

- UF as a pre-treatment process to control and minimize NF/RO membrane fouling is a good precaution and a dual barrier to pathogenic water contaminants;
- Lower retention NF membranes likely to be adequate to satisfy the drinking water guideline requirements, thus saving energy;
- To reduce the probability of fouling: i) optimize the TMP and initial permeate flux (critical flux) such that the recovery is low; and ii) use simple and low-cost daily physical cleaning methods to maintain the membrane performance;
- To target 20 years of system lifetime: i) choose correct NF/RO membrane to aim for 6–10 years of membrane lifetime; then ii) replace NF/RO membrane 1–2 times throughout system life;
- In-line conductivity monitoring of the permeate stream can be applied to evaluate the membrane integrity;
- Employ a constant set-point operation strategy to provide a more robust and effective solution in remote areas, while ensuring the

system to operate within the SOW;

7. Sensors

The location of sensors for measuring the instantaneous system performance was shown in Fig. 1 for an example PV-membrane system developed by Schäfer and Richards. For research and development purposes, the number of sensors is high but for systems implemented in commercialization, the number of sensors can be greatly reduced and most important selection criteria to be established individually. Based on previously published works [7,50,79,212,213], the selection criteria of sensors, such as operating range, accuracy, response time, chemical resistance are chosen according to the application purposes. The failure modes and effects analysis of components are now discussed individually.

7.1. Flow meters

Flow meters are used to measure the flowrates of the water (feed, permeate, concentrate) in PV-membrane system, and they are the most susceptible to failure than other sensors as they often contain moving parts. There are various types of flow meters. Positive-displacement flow meters measure flow by accumulating a fixed volume of fluid and then taking count of the number of times when the volume is filled. Other flow meters can indirectly calculate flow relying on forces created by the flowing stream as it overcomes a known constriction. For instance, a differential pressure flow meter calculates the flow via measuring the pressure drop over an obstruction inserted in the flow. Turbine flow meter measures the rate of spin of the turbine to calculate the flow. Electromagnetic flow meter measures the voltage that is directly proportional to the flow rate, while the voltage is induced when the water moves through a magnetic field that is created by energized coils.

The flow meters used in the authors PV–membrane system utilize a Pelton wheel-like rotor whose motion is converted by a pickup coil into frequency output that is proportional to flow. This flow sensor was chosen as it presented a wide operating range, and it was capable of measuring the very low flowrate (down to 16.5 L/h). During three field trials – in the Australian outback in 2002 and 2005, and northern Tanzania in 2013–2014 – greatest challenges with flow meters were encountered. As the sensors were designed to for clean water [214], they are prone to fail due to the corrosive brackish water. In particular, the ball bearings in the flow meter were severely corroded – the corrosion resistance of 440C stainless steel is similar to that of 304 in many environments [215]. Later, this was replaced with a hybrid bearing, consisting of a stainless steel bearing race together with ceramic balls (such as silicon nitride), which was a more effective solution in the presence of brackish water, as well as possible cleaning chemicals [216]. The flow sensor was reported to have a lifetime of 15 years [217].

7.2. Pressure sensors

Pressure sensors are used for pressure measurement of water in both the feed and concentrate streams in PV-membrane system. It has a sensing element of constant area and reacts to the force applied by water pressure. It must respond fast enough to notify the operators or initiate automatic safety actions during transient states, such as abrupt pressure changes. For pressure sensors, the response time degrades mostly due to blockages and voids in the sensing lines [218]. They typically fail due to mechanical damage, electrical overload, over pressure, pressure spikes or ingress of moisture/chemicals into the product [219]. In commercial RE-membrane systems, analog pressure gauges are commonly installed at or near the pump's pressure port to indicate the pressure in the process [220]. The gauges fail mainly due to pipe vibration, overpressure and pressure spikes, corrosive media, clogging and water condensation [221,222]. Excessive vibration is the main cause of pressure gauge failures, the gauges cannot accurately read a pointer on a dial during vibration, and incremental damage to the pointer mechanism can ultimately move the pointer off zero, hence creating inaccurate readings. A surge of media flows through the pipe and affects pressure gauge due to power cycling of pumps or switching on/off of valves, causing pressure spikes which can damage the gauge. The gauge pointer can be bent due to frequent pegging against the stop pin and ruptured ultimately. Corrosive liquids (such as salty water) can damage the sensing material in gauges if inappropriate construction materials are used; Suspended particles in the not properly pretreated water can clog the gauges and make readings unreliable; while intrusion of humid ambient air such that the water can accumulate and condense can damage the internal parts of gauges [221]. High reliability of commercial gauges are attributed to reduced wearing parts, ultrasonically cleaned and lubricated process to minimize the effect of harsh environments, protect internals from corrosive atmospheres and provide continuous lubrication in the mechanism. Pressure sensors are reported to have a lifetime of 5–15 years [219].

7.3. Water quality sensors

Common sensors used for determining water quality are electrical conductivity (EC), pH sensors, ion selective electrodes (ISE), TOC analyzer and turbidity meter. The EC sensors measure the electrical conductivity, which is determined by using the distance between the electrodes with a known surface area. TDS is normally used to calculate the concentration of water, hence indicating the purity of water. The conductivity sensors may have problems of electrical wiring, such as open circuit, short circuit, and plugging that reduces ion contact with the electrodes [223]. Moreover, they are prone to fail to conduct ions across plates (voltage collectors) due to collector plate fouling or scale buildup, which results from material degradation such as corrosion, abrasion, or cracking [223]. EC sensors are reported to have a lifetime of 10 years [224].

A pH sensor measures the hydrogen ion concentration in a liquid and a difference in potential is formed between the electrode and solution, which is directly proportional to the pH value. The possible failure modes of pH sensors can be brittle glass lead to sensor probe crack or break, as well as breakage (open circuit) of electrodes caused by material flaws or short circuits due to insulation flaws. The expected lifetime of pH sensor is 1–3 years [225]. An ISE that responds selectively towards one or several specific ions is used for measuring the concentration of specific ion in water, such as fluoride, silver ion (Ag^+) [226]. ISE could be far more sensitive to the interfering ion rather than to the primary ion, causing measurement errors, hence the interfering ion should be removed firstly to ensure accuracy [226]. The ISE typically has a lifetime of 2–5 years [227]. TOC analyzer detects CO_2 produced by organic matter oxidation at high temperature by means of catalytic oxidation combustion technique. It is applied for measuring organic matters, mainly contributed by NOM, like humic substances and animal partially degrade matters [228]. This can also be one of indirect methods to monitor the membrane integrity. The TOC analyzer may report false negative TOC results if too much dissolved oxygen is removed [229]. TOC can last 10 years of lifetime with regular replacement of ultraviolet lamp every 2 years [230]. Turbidity meter is used to determine true turbidity and suspended solids in water, using a nephelometer or absorptiometer to measure the scattered light or absorption of light intensity [231]. The LED has a typical lifetime of 10 years [232].

7.4. Temperature sensors

The two most common temperature sensors used in commercial RE-membrane systems are resistance temperature detector (RTD) and thermocouple. They are used to monitor the temperature of the feed water, as the membrane flux changes with temperature up to 3%/°C [233]. The typical failure modes of RTD are open circuit and short circuit due to its structure [223]. The short circuit to ground can be occurred when a metallic or conductive sheath is applied. RTD can have calibration shifts due to oxidation, metal ion migration from the sheath to the sensing element with high temperature (> 500 °C), and electrical insulation resistance changes caused by moisture [234]. Other failures such as drift, which is more of a problem for thermocouples than RTDs, caused by a change in the metal chemistry, excessive heat, work hardening of the wire (by vibration or bending), contamination (from chemicals or moisture), or ionizing radiation. Chemical or moisture contaminations can lead to corrosive attack on the wires, and pass through the sheath by osmosis, thus penetrating cracks in the sheath, or by cross contamination between the sheath and the individual wires.

In the RE-membrane applications, rapid changes in temperature are not expected, the temperature sensors reach a lifetime of 10–20 years [218].

7.5. Recommendations

To accurately determine the transient nature of PV-membrane system when subjected to fluctuating power, the following suggestions are given:

- Pay careful attention to the selection criteria of the sensors – in an order of operating range, accuracy, response time, chemical resistance and cost – to ascertain system performance at any point in time;
- Flow, pressure and EC sensors are critical to ensure reliable system operation;
- With regard to flow sensors, the magnetic inductive type is recommended due to fewer moving parts, low maintenance, 15 years of lifetime and high reliability. This comes at the disadvantage of slightly higher cost.

8. PV-membrane brackish water desalination systems

8.1. System performance

The desalination of brackish water to provide clean drinking water is an established and promising industry [235]. Details of selected outdoor small-scale (motor power rating < 1.5 kW, permeate capacity < 3 m^3/d) PV-membrane systems for brackish water desalination (1000–10,000 mg/L) are summarized in Table 7.

In the PV-membrane systems, the SEC is one of the most important criteria to determine the feasibility of these systems, which indicates the required PV power to achieve the permeate water flux. Although both membranes and PV panels have become very cheap, the SEC needs to be as low as possible to provide the maximum water production with minimum energy requirements. Therefore, it is one of the key figures-of-merit for comparing the overall system performance. As shown in Table 7, the SEC exhibits a very wide range, for example, Joyce et al. [239] used a 12″ long spiral-wound RO membrane (MP-TA50-J4) coupled to a 12 V_{dc} diaphragm pump connected with a 100–150 W_p PV array, the system exhibited an extremely high SEC at 25.6 kWh/m^3. The high SEC resulted from the super small size and non-optimized construction of the PV-membrane system. In addition, high SEC associated with small-scale membrane systems can be caused by the energy losses of components throughout the systems. A significant reduction in the SEC can be achieved by scaling up the size of the system components, going from a system based on ¼″ diameter tubing [7] to ½″ diameter stainless steel pipe [18,212].

Another important step in the design process is to determine the most appropriate membrane in terms of the feed water quality versus required permeate quality. This fact was already highlighted by a performance comparison of four 4″ diameter NF/RO membranes (BW30,

Table 7
Overview of some existing outdoor small-scale (motor power rating < 1.5 kW, permeate capacity < 3 m^3/d) PV-membrane brackish desalination systems for drinking water, illustrating the different configurations, operating conditions and system performance.

Location	Feed Water TDS (mg/L)	Production (m^3/d)	PV Size (kWp)	Battery Capacity (kWh)	Pump Type	Motor Power (kW)	TMP (bar)	SEC (kWh/m^3)	Salt Retention (%)	Recovery (%)	Ref.
White Cliffs, Australia	3500	0.5	0.34	No	Rotary vane	0.15	5–10	2–8	93–95	20–22	[7]
Perth, Australia	5000	0.4	0.12	No	Piston	–	2–12	–	84	16 or 25	[236,237]
Pine Hill, Australia	5300	1.1	0.3	No	Helical rotor	0.3	4–12	2.3	98	28	[18,212]
Perth, Australia	2000–4000	0.5–1.0	1.20	3.4	Positive displacement	0.25	–	4.0–5.8	83–88	17–20	[238]
Lisbon, Portugal	1200 –3200	0.02	0.1–0.15	–	Diaphragm	–	3.3–4.2	25.6	94	< 2.4*	[239]
Bangi, Malaysia	2000	5.1	2	2.4	Rotary vane	0.6	15	1.1	97*	–	[169]
La Mancalona, Mexican	2100	1	400	—	High pressure	75	6	0.2–2	99	33	[240]
Amman, Jordan	400	0.1	0.07	No	High pressure	0.025	–	–	96	–	[241]
Hammam Lif, Tunisia	2800	0.05	0.59	No	–	–	–	22.8	–	–	[242]
Marseille, Mexico	8000–22,000	~1	1.025	No	High pressure	–	–	4.3*	95	–	[86]
Jordan	1700	0.28	433	2.76	Diaphragm Centrifugal		6	16	94	54	[243]
Coite-Pedreiras, Brazil	1200	6	1.10	9.6	High pressure	1.5	8.3	3.0	85–99	27	[244]
Cairo, Egypt	2000	1.0	1.07	10.9	Booster	0.375	–	4–5.2	–	50	[245]
Saudi Arabia	400–500	0.4–0.7	0.25	No	High pressure	–	–	–	75*	–	[246]
Tanzania	3000 µS/cm	2.4	2.25	2.2	Helical rotor Centrifugal	0.75	6	4.4	83	12	[247]
Jordan	7000	2–7	1.1	7.7	High pressure	–	–	2	–	–	[248]
St. Dorcas, Tanzania	3632	1.3–1.6	0.3	No	Helical rotor	0.3	4.8	1.6–1.9	> 97	23.1–27.8	[170]

* Calculated by current authors; (–) Not specified results.

ESPA4, NF90, TFC-S) on a brackish (5300 mg/L) bore in a PV-membrane system [18]. For this specific test site with 5300 mg/L feed water, the ESPA4 membrane was the best choice. Other membranes were able to produce better quality water but with a higher SEC (BW30, NF90), whereas the TFC-S membrane was not able to fulfill the recommended drinking water guidelines. Such a selection process assists in performance optimization, while performance degradation over time must be considered.

The operating pressure has a significant impact on the energy consumptions as well. The higher operating pressure requires larger pump and PV power supply. This indicates that the design criteria of PV-membrane systems operating in remote areas are different from typical membrane plants. The most important factors are energy requirements and robust long term operation, other than designing for maximum water production in terms of pressure, recovery and retention.

In summary, Table 7 shows that diverse system combinations result in very different system performance, the SEC in particular exhibits the most important criteria to evaluate the system performance. With good system design, the SEC of small-scale PV-membrane system can be achieved in the range of 1–3 kWh/m^3 for the small-scale PV- membrane system.

8.2. System reliability

As new technological developments occurred in the past few years, including the improvement of pump performance and efficiency, the use of brushless DC motors, and power conditioning components, the reliability and robustness of PV-membrane systems have been improved significantly [31]. Although statistics on reliability and failure modes are rarely reported, some useful information can be drawn from PV-powered water pumping programs that have been implemented worldwide. For example, in an early PV water pumping program in Mali [31] from 1983 to 1989, 66 systems were monitored and there were 37 recorded failures. This corresponded to a mean of 1 failure in 139 pumping months, or a MTBF of over 30,000 h. In another pumping program in Thailand, 1000 rural villages had PV-powered water pumping systems installed in 1999, 45% of the systems (489 units in total) were either damaged or broken down after 5 years of installation [249]. After completing the 3 year survey, over half of the failures were attributed to inverter failures (19%) and motor-pump failures (32%).

The wide range of possible failures is indicated in Fig. 9. Apart from inverter failures and pump motors breaking down, the remaining failure modes were typically structural or infrastructure problems including leakages (water tanks and taps) and drying-up of seasonal water

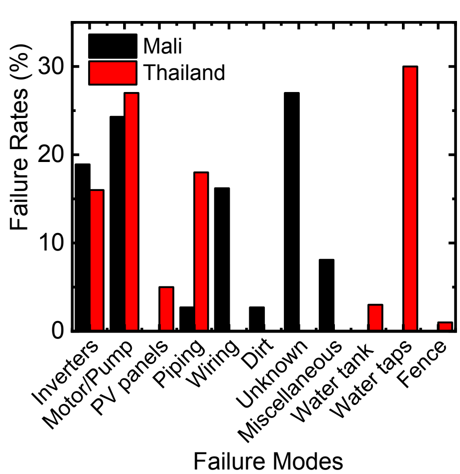

Fig. 9. Failure rates and mechanisms of PV water pumping programs in Mali (1983–1989) and Thailand (1999).
Data adapted from [31,249].

sources. The cause of a relatively high amount of failures (27%) in Mali remains unknown, thus emphasizing the importance of accurate monitoring and data collection.

8.3. System operation & maintenance

The levels of maintenance for PV-membrane water pumping systems range from preventive maintenance, predictive maintenance and corrective maintenance [88]. Preventive maintenance based on the manufacturer's recommendations is crucial for efficient and trouble-free operation as it aims at preventing unexpected component failures. A suitable program of preventive and routine maintenance will reduce component failures, extend the system lifetime and reduce the overall operating costs. The following is a list of possible preventive maintenance procedures for PV-membrane system, indicating some of the periodic procedures that a system may require [31,250,251].

(i) Maintenance of PV modules requires periodic cleaning of dust, the frequency of which depending on the location. The glass covers of PV modules as well as the frames need to be checked regularly to avoid damage and corrosion, and seasonal tilt adjustments might be needed.
(ii) With the rising of PV panel theft (at least €50,000 worth of PV modules and inverters) [252,253], anti-theft strategies might be needed, such as special fasteners, locking end-clamps [254], or control system to issue an alarm [255].
(iii) The pivots of solar tracker (if included) should be lubricated once a year. The pivot points and tracking mechanism should also be inspected for rust and painted as required.
(iv) Pump may require periodic replacement of filters, diaphragms, piston seals, cylinder leathers, bearings, casing wear rings or DC motor brushes depending on the type of pump, and monthly check of packing and seals for wear and tear.
(v) Batteries (if included) should be stored in a dry and cool atmosphere and recommended to recharge periodically (typically every six months). The terminals must be checked and cleaned if necessary.
(vi) All cable connections and seals, the suction and delivery hoses or pipes should be checked for water tightness.
(vii) Membranes require preventative cleaning by regular flushing, chemical cleaning to prevent fouling, scaling as well as unpredictable deteriorations due to cycling on/off during periods of fluctuating power.
(viii) Water storage and distribution networks also need to be regularly examined for water leaks. Steel tanks need regular check-ups for rust and should be coated periodically, and have to be cleaned and disinfected regularly.
(ix) The sensors need to be calibrated periodically and the calibration verified.
(x) Systems protection from weather exposure (high temperature, sandstorms) might be needed.

Predictive maintenance is performed based on the analysis of data collected during the monitoring of the system performance, noise, vibrations, and temperature of motors. For example, water leakage may indicate that the mechanical parts might need replacement; bad bearings and shafts are non-alignment; vibration is an indication of the beginning of a failure; overheating of motors may indicate the bad bearings, mechanical overload or insulation failure of the motor windings.

Corrective maintenance can be highly reduced if preventive and predictive maintenance are well implemented. Nevertheless, some common corrective activities can be scheduled, such as: correction of small leakages at the pipes or connections especially where high pressure or screw connections exist; replacement of membranes due to fouling; replacement of damaged power conditioning devices, or rusted surfaces of metallic components.

8.4. Recommendations

A key final recommendation for a well-designed small-scale PV-membrane system is provided in below, it indicated that a target 20 year lifetime may be achievable by selecting very reliable components:

- Silicon-based PV panels – supported by a warranty of 25 years;
- Brushless DC motor - with limited O&M, a lifetime of 20 years can be realized;
- Helical rotor pump - with O&M, the target 20 year lifetime can be achieved.

The less reliable components should be avoided or replaced periodically:

- DC-AC inverters are avoided – with consistently O&M, occasionally replacement of components (such as capacitors, transistors) to reach 10 year lifetime;
- NF/RO membrane are replaced – operate the system with recovery less than 30% and realize soft start with the increase of feed pressure less than 0.7 bar/s to target a lifetime of 6–10 years;
- Sensors are replaced- with O&M, such as cleaning of the electrode or wet parts to achieve 5–15 years lifetime.

9. Conclusions

PV-membrane technology is an effective solution for the supply of clean drinking water, especially for small-scale systems deployed in remote, off-grid areas. In this paper, a review of major components of small-scale PV-membrane systems for brackish water desalination including components selection, operating range and reliability is presented. It indicated that the small-scale PV-membrane system could achieve a lifetime of 20 years by selecting robust and reliable components, and a strong operation and maintenance plan. As a power supply, silicon-based PV panels are favored due to their market dominance and 25 year performance warranty. Helical rotor pump along with brushless DC motors are found to be the most efficient and robust combination to enable a lifetime of 20 years. NF/RO membranes are expected to target a lifetime of about 5 years with proper pre-treatment and when operating at a recovery of $< 30\%$, while longer lifetimes have been reported. Constant set-point strategy is recommended for the operation of such systems to provide more effective and robust solutions in remote areas with minor reduction in performance. With the motor power rating less than 1.5 kW, it is anticipated that a SEC in the range of 1.5–3 kWh/m^3 can be achieved, depending on the feed water characteristics. Overall, the challenges discussed serve as a guide to aid designers or operators to enhance the reliability of PV-membrane systems.

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