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Reverse Osmosis (RO) Membrane Desalination driven by Wind and Solar Photovoltaic (PV) Energy: State of the Art and Challenges for Large-Scale Implementation

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Abstract

The use of Reverse Osmosis (RO) desalination has grown considerably in response to water scarcity. Despite steady improvements in efficiency, RO desalination remains an energy-intensive process. Numerous studies focussed on using mature Renewable Energy Sources (RES), such as wind and solar photovoltaic (PV) energy, to drive RO plants on a small scale. However, RES have not been used to drive large plants, except with a grid connection, due to the intermittency and fluctuation of such sources. Direct coupling of the RO plant to a RES requires variable-speed operation and/or modular operation to match the load to the available power. This review presents the state-of-the-art in wind and solar-PV powered RO to identify technical challenges and potential solutions regarding large-scale implementation. Recent studies using wind and solar-PV to drive RO are analysed while considering the plant configuration, operational strategy, control system and methods used to improve the plant adaptability to the RES. Technical challenges may include shortened membrane life and reduced performance of energy recovery devices. Potential strategies for incorporating modular and variable-speed operation in commercial RO plants are presented. Control strategies are reviewed, including Model Predictive Control, Neural Networks and classical Proportional-Integral-Differential feedback control. Recommendations are made on future research necessary for operation of commercial RO plant operation from renewable energy.

Keywords

Desalination; reverse osmosis; renewable energy; wind energy; solar PV energy; variable operation; membranes; control system.

Nomenclature

DMC	Dynamic matrix control
DWEER	Dual work exchange energy recovery
ED	Electro-Dialysis
EPA	Environmental protection agency
ERD	Energy recovery device
Exp.	Experimental study
HPP	High-pressure pump
MED	Multi-effect distillation
MIMO	Multiple inputs/multiple outputs
MPC	Model predictive control
MPPT	Maximum power point tracking
MSF	Multi-stage flash desalination

MVC	Mechanical vapour compression
NN	Neural network
PID	Proportional, integral and differential control
PPM	Part per million
PV	Photovoltaic
RE	Renewable energy
RES	Renewable energy source
RO	Reverse osmosis
ROSA	Reverse osmosis system analysis
SEC	Specific energy consumption
SWRO	Seawater reverse osmosis
Theo.	Theoretical study
TVC	Thermal vapour compression
WHO	World health organization

1 Introduction

1.1 Growth of the desalination industry

Global water consumption is growing at more than twice the rate of population due to improving standards of living and increasing demand from the industrial and agricultural sectors [1, 2]. It is expected to increase by 50% by the year 2030 [3]. Currently, two-thirds of the world population suffers from water shortage for at least one month per year [2]. This situation is expected to escalate to the point where half will suffer from water stress by the year 2025 [4].

Although 71% of the Earth is covered by water, 97% of this is unpotable seawater [5]. Desalination is a water treatment process that involves removing salt from saline water thus making it suitable for drinking. Growing water security challenges have led to intensive research and investments in desalination, spurring its rapid growth over the last 40 years [6]. The global online desalination capacity has been constantly increasing since 1965, especially throughout the last decade [6]. It increased significantly from 66.4 million m^3/day in 2012 to 99.7 million m^3/day by 2018 [7-9]. The sector continues to grow, with a yearly contracted capacity of about 4 million m^3/day from 2015 to 2017 [9]. A number of countries, such as Qatar and Kuwait, already rely on desalination as their sole water supply [7].

Reverse osmosis (RO), a membrane-based desalination technology that depends on applying hydraulic pressure to force water through a semipermeable membrane, currently dominates the industry [10-12]. In 2016, RO represented 65% of the globally installed desalination capacity (Fig. 1) [13, 14]. A typical configuration for large-scale RO plants is presented in Fig. 2. The predominance of RO stems from a number of advantages. Firstly, RO is able to provide a wide range of production capacities, from small standalone installations delivering less than 1 m^3/day, to large-scale plants delivering over 500,000 m^3/day [13]. Secondly, RO can handle a wide range of feed water salinity including, brackish water and seawater. Thirdly, RO plants can provide continuous and reliable operation without shutdown for extended periods. Fourthly, RO plants operate at low specific energy consumption (SEC) ranging from 2 to 4 kWh/m^3, not far from the thermodynamic limit of about 1 kWh/m^3 for seawater [15, 16]. Consequently, the CO_2 emission from seawater RO (SWRO) plants is the lowest compared to other desalination processes, ranging from 1.7 to 2.8 kgCO_2/m^3 [17]. In contrast, the CO_2 emission for Multi-Stage Flash desalination (MSF) ranges from 15.6 to 25 kgCO_2/m^3 and from 7 to 17.6 kgCO_2/m^3 for Multi-Effect Distillation (MED) [17]. Lastly, RO is considered cost-effective due to constant fall in water production costs [8]. For large RO plants, with production capacity over 40,000 m^3/day, costs ranged from 0.8–1.2 \$/m^3 in 2017 and are expected to decrease further by 60% to reach 0.3–0.5 \$/m^3 within the next 20 years [16].

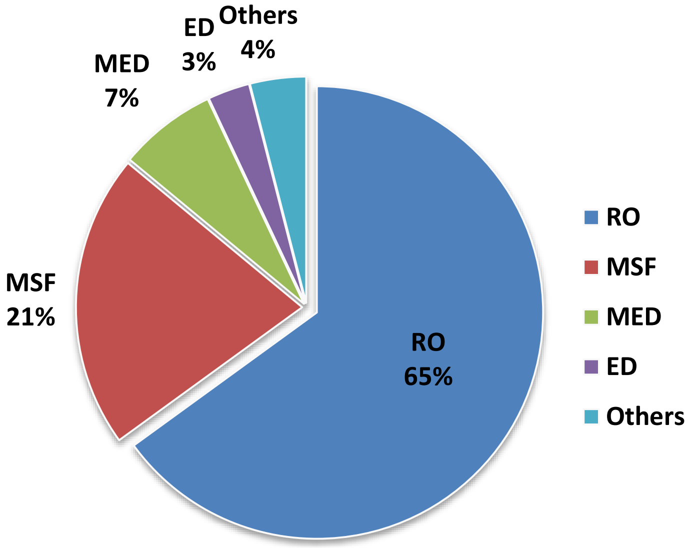


Fig. 1. Contribution of desalination processes to global production (redrawn from [14]).

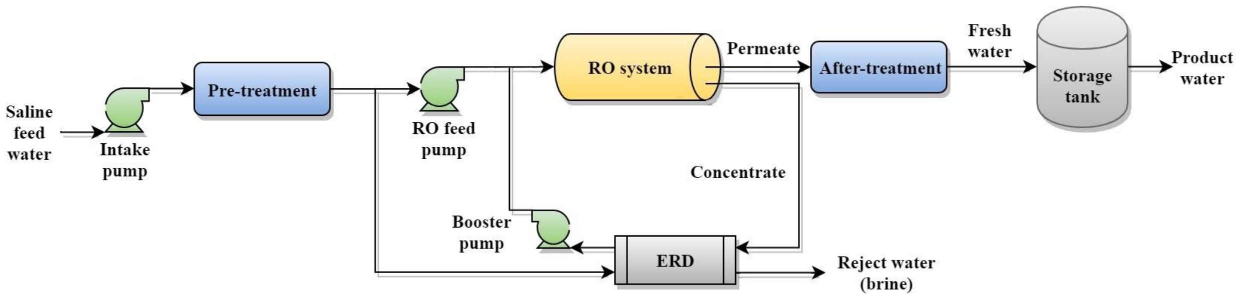


Fig. 2. Standard reverse osmosis plant configuration.

Nevertheless, there are two major concerns about the impact of RO desalination on the environment. First, despite improvements, RO desalination remains energy intensive compared to other modes of water supply [18, 19]. Second, the discharge of highly saline brine and chemicals from large plants represents a threat to the marine environment [20]. Finding alternative energy sources to drive commercial RO desalination plants is key to improving their sustainability, decarbonizing water production, and making them accessible to countries with limited natural and financial resources [15, 21, 22].

1.2 Renewable energy desalination (RED)

Renewable energy (RE) is an attractive solution to reduce RO plants' carbon footprint, decrease their running costs and eliminate the link between water prices and fuel costs [18]. In general, RE is a sustainable alternative to using fossil fuels due to its abundant availability. During the period of 2014 to 2015, the global installed capacity of wind power plants and solar PV increased from 370 to 433 GW and from 177 to 227 GW, respectively [23]. Meanwhile, the price of RE is constantly decreasing; for example, the price of solar photovoltaic modules decreased from 33.44 $/watt in 1979 to just 0.35 $/watt in 2017 [24, 25]. As for wind turbines, their price in the United States decreased by one third from 2008 to 2011 [26]. Possible combinations between various RESs and desalination processes are presented in Fig. 3.

Desalination by RO is widely considered for RED applications due to its low SEC compared to other processes [11, 27-29]. The SEC is made up of two components. Firstly, the energy required for the RO process itself, which depends on factors including water quality, membrane efficiency, pump efficiencies, recovery rate and the ERD used. It can range from 1.7 to 2.5 kWh/m^3. Secondly, the energy required for secondary processes, such as feedwater pumping, pre-treatment and the plant electrical services, typically ranges from 0.3 to 1.5

kWh/m^3 [22]. The SEC can vary based on plant location, size and design efficiency. While 2-4 kWh/m^3 is typical for larger plants, for smaller standalone systems values tend to be higher, from 3 to 7 kWh/m^3, due to unusual operating conditions, inefficiencies of scale, or sub-optimal design and operation [30].

Electrical energy to drive the RO plant, which constitutes 44% of the water cost [31], can be generated directly from RE by solar-, wind- or wave-energy converters, as shown in Fig. 3. Other important RE sources include hydro- and bio-energy, but these are mostly unsuitable as they rely on natural water resources that are inherently scarce in regions where desalination is needed [32]. Wind and wave energy can be used directly to produce mechanical movement to drive the High-Pressure Pump (HPP). However, directly-driven wind-RO systems are not recommended for SWRO due to the high osmotic pressure [33-35]. In addition, a separate electrical energy source is needed to drive the control system and data logging [36]. Another approach would be to couple a thermal energy source, such as solar-thermal or geothermal energy, to a Rankine cycle to produce mechanical energy and drive an electric generator [37]; however, this is more expensive than solar-PV or wind turbines, except in specific locations where high-grade geothermal resources are available [14, 32].

The use of wind and solar-PV to drive RO plants has been recommended by several studies, due to their affordability, availability, technological maturity, and zero water consumption compared to other RESs [11, 38-41]. PV-RO and wind-RO are the most widely deployed technologies for RED contributing 32% and 19% of the field respectively (Fig. 4) [42].

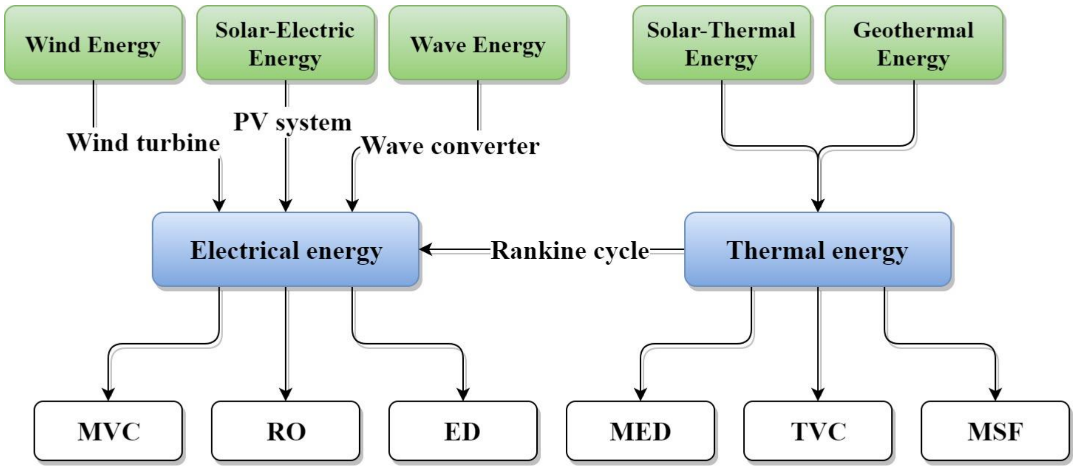


Fig. 3. Overview of renewable energy desalination.

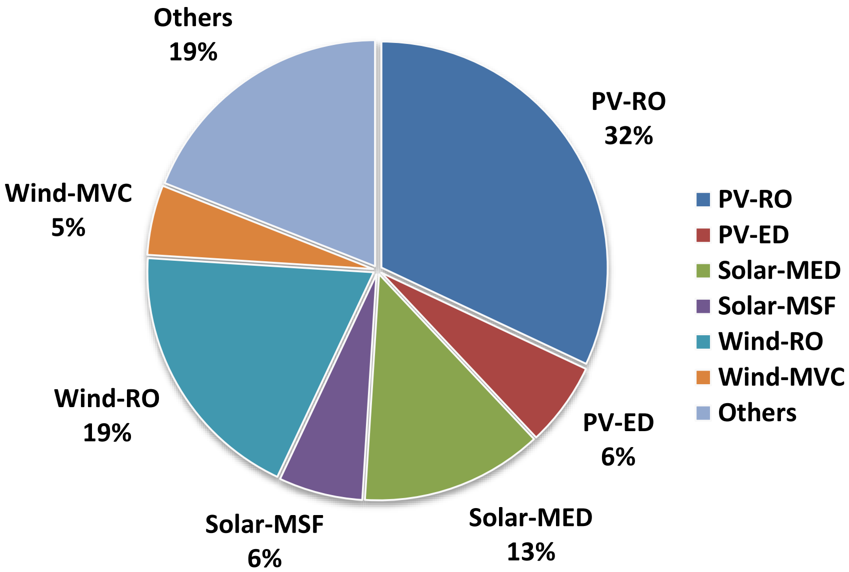


Fig. 4. Current landscape of renewable energy desalination worldwide (data adapted from [42]).

1.3 Limitations of steady-state operation

Whereas the power output of solar-PVs and wind turbines is intermittent and fluctuating, commercial RO plants are designed to work at constant flow, pressure and power level. Steady-state operation is considered economical for grid-powered RO plants, as it maximizes production capacity and makes good use of invested capital. In addition, it is easier to maintain the product water quality and manage the membrane fouling. As such, earlier studies of renewable energy-driven RO plant often included a backup, such as a direct connection to an electric grid, an energy storage system, or a Diesel generator to operate the RO plant with constant power [43, 44].

Current large-scale RE powered RO plants are grid-connected to ensure a constant water production, such as the Al Khafji solar-PV powered RO plant in Saudi Arabia which has capacity of 60,000 m^3/day [45]. Such plants are considered more economical than conventional fossil-fuel powered RO plants, especially when the RES availability and the feed-in tariff are high [48]. However, grid-connected RO plants place a high load on national grids and affect grid stability. For example, in the Gulf Cooperation Council countries, desalination is estimated to consume 4–12% of the total electricity consumption, [46, 47]. It would require a high penetration of RE into the electricity grid to support these desalination plants. Such penetration would decrease the electric grid's reliability and power quality by introducing voltage rise, flicker and harmonics [48, 49]. The transition to fully renewable RO plants is desirable to allow a high fraction of RE while maintaining stable grids.

As for energy storage systems, these have been somewhat impractical for large-scale applications, as they require a large area, increase capital cost and can complicate the system due to requiring additional equipment, such as charge controllers [50]. Specifically, batteries tend to be expensive, have a short lifetime and require regular replacements, all features that cripple their economic feasibility and increase water production cost [11, 28, 50]. In [43] and [51], water production cost was compared for a SWRO system with and without battery storage. In one study it increased from 7.8 to 8.3 €/m^3 [43] , and in another from 10 to 13 \$/m^3 [51]. Accordingly, energy storage is limited to small standalone installations and is not favourable for large-scale applications [35, 52, 53].

To address these difficulties, recent advances have included variable operation to directly couple the RO plant to the RES, without backup systems [27, 29, 54-58]. Firstly, directly-coupled RO plants operate with a variable production rate and recovery ratio that follow the available power [29]. The operating pressure and flow rate are controlled to change the production rate and recovery ratio, respectively. This procedure is referred to in this review as ‘variable-speed operation’, as it uses a variable frequency drive to change the HPP speed according to the available power. Normally, positive displacement pumps are suitable for variable-speed operation, as they offer consistent efficiency at varying flowrates. Secondly, RO trains (sets of identical modules that constitute the RO plant) can be connected/disconnected based on the available energy [59]. This procedure is referred to in this review as ‘modular operation’. Variable operation, using the variable speed and/or modular approach, is interesting for renewable energy-driven RO plants as it omits the need for energy storage, backup systems and associated costs. It is especially attractive for islands, remote areas and countries with low energy availability from fossil fuels and lacking a regional grid interconnection to neighbouring countries.

1.4 Problem definition and review methodology

The combination of RE and RO is a vital move towards sustainable desalination. In the last decade, extensive research was performed to efficiently drive RO systems by RESs without backup systems, which led to employment of RESs in many small-scale systems [11, 28, 38, 42]. However, the fluctuation and intermittency of RESs to date presented technical and economic challenges that prevented large-scale commercial RO plants (i.e. plants with production capacity over 40,000 m^3/day) from operating independently using RESs [16, 28, 35].

Several reviews covered progress in driving RO plants with RE. However, the technical challenges for the direct operation of large-scale RO plants using wind and solar-PV energy were not discussed specifically. For instance, Abelkareem et al. [14] assessed from a general perspective different RESs, including solar, wind, geothermal and wave energy, for powering desalination plants. Koroneos et al. [37] and Gude et al. [38] presented selection criteria for an efficient combination of RE with desalination processes. N.Ghaffour et al. [42] and Eltawil et al. [11] investigated the potential application, technologies and challenges for RED from a techno-economic perspective.

This review aims to capture the current state-of-the-art and technical challenges in using wind, solar and hybrid wind-solar energies as main drivers of large-scale RO plants. Initially, studies of RO plants driven by wind and/or solar-PV will be presented and analysed, to assess the current status of the technology. The technical challenges of variable operation and potential solutions will then be discussed, focussing on key elements of the RO plant – namely the membranes and energy recovery devices. Strategies for operation and control will be analysed and discussed. We conclude with recommendations for the future development of RE-RO to satisfy the world's growing water demand.

2 State of the art in renewable energy-driven RO

Over the last two decades, several research papers have discussed the variable operation of renewable energy-driven RO plants. Theoretical studies covered mostly small or medium plants (<40,000 m^3/d) and experimental studies covered plants rarely exceeding 1000 m^3/d. This section reviews studies of specific plants (some constructed and some only taken to the theoretical stage) that aimed to efficiently integrate RO with wind, solar or hybrid wind-solar energy. The studies are reviewed with regard to the plant configurations and the operational strategies adopted. Lessons learnt for improving the plant adaptability to fluctuating energy will be useful for application in commercial plants.

2.1 Wind-energy RO desalination

Wind turbines are playing a major role in achieving sustainability goals in many countries [60]. Their low operating cost, high efficiency and energy availability, especially for coastal areas, make wind turbines a successful and clean choice to power RO plants [5, 61, 62], reducing both carbon footprint and water production costs [54, 63]. However, further deployment of wind turbines requires certain challenges to be addressed [64]. For example, wind turbines have to gain social acceptance and improved public perception due to their aerodynamic noise and visual impact. Wind measurement and forecasting should be enhanced for accurate prediction of power generation, which would improve the control of wind farms and their integration with local grids. Availability of lightweight materials will allow larger turbines with improved efficiencies to be developed [65]. The fluctuating energy input of wind-powered RO plants could affect the daily production capacity and have negative effects on the plant's performance [61, 63]. Numerous studies considered the design of wind-RO plants and presented different approaches to accommodate the variable nature of wind power, as summarised in Table 1.

2.1.1 Stabilization of wind power output

Short-term energy storage devices were suggested for wind-RO plants to smooth wind power fluctuations and improve system stability [11]. They are usually selected based on their storage capacity, mode of coupling and charging/discharging rate. Common options include flywheels, compressed air storage, hydraulic accumulators and supercapacitors [52, 61, 66]. Batteries were not included in this list, as they are not suitable for stabilizing wind power output due to limitations on their charging/discharging rate [52]. Flywheels and supercapacitors are promising as short-term energy storage devices as they offer high energy density and higher roundtrip efficiency of 89% and 86%, respectively, compared to 63% efficiency of lead-acid batteries [52]. Fast rotating flywheels have advantages of instantaneous response, ability to stabilize system frequency and low energy cost compared to supercapacitors [11, 29, 35, 52, 57]. For instance, Rahal [67] used a flywheel connected to a synchronous generator integrated into the wind-RO system to overcome wind power input fluctuation for a 84 m^3/day RO plant. The flywheel inertia smoothed the wind turbulence and improved the stability of system frequency, which was beneficial for the RO plant as it decreased pump pressure fluctuations.

Another approach for smoothing the plant operation is by connecting it to a microgrid that includes backup systems such as Diesel generators and electricity storage. Bognar et al. [68] compared two different operation scenarios for a RO plant powered by a microgrid. The constant and variable operation of the microgrid and RO plant were compared. For constant operation, a Diesel generator and electricity storage were used to maintain steady operation. However, for variable operation, water storage was used to meet the required production demand. Variable operation and water storage lowered electricity usage and water production costs by avoiding fuel use of a Diesel generator.

2.1.2 Variable operation of wind-RO plants

Several studies have used variable operation to directly couple the RO plant to a wind turbine. Both modular and variable-speed operation have been used. Modular operation for wind-RO plants uses a high-power wind turbine to operate multiple RO units, such that, matching between available power and load is achieved by switching on and off RO units and trains [57]. Several research teams used this approach. Peñate et al. [35] presented a variable capacity plant, displayed in Fig. 5, that consists of three switchable RO trains. The variable capacity plant was compared to a fixed capacity system that operated when enough energy was available to achieve full production capacity. The variable capacity plant produced 2 – 8% less than the fixed capacity plant, which operated at a higher recovery ratio. However, the variable capacity plant operated for more hours of the year, as it adapted better to the available energy using variable-speed operation. Moreover, Carta et al. [57] presented an operational analysis of an autonomously operating RO plant in the Canary Islands. The plant, shown in Fig. 6, was directly coupled to a wind farm without any backup system. It consisted of 2 wind turbines and a flywheel to operate 8 identical RO units. A control strategy for modular operation was developed to match the load to the available power. However, no other method, i.e., variable speed operation, was used to adjust the RO plant capacity to the transient power supply. Also, an ERD was not included, which reflected a high SEC of 6.9 m^3/day. In another study, Carta et al. [27] designed a small-scale wind–RO plant, with a rated production capacity of 18 m^3/day, using a combination of variable-speed and modular operation. A comprehensive control system was developed, presented in Fig. 7, to control the number of operating pressure vessels, the operating pressure and feed flow rate according to a predetermined operation strategy. Due to the inertia and sensitivity of the desalination plant towards changes in the control parameters, a perfect fit between power generated by the wind turbine and power consumed by the desalination plant was not achieved, even with constant wind speed over 2-minute intervals. This was caused by the slow response of the system in reaching reference control variables for feed flow rate and pressure. The aforementioned mismatch would have been more prominent if the RO plant included an ERD, if the constant wind speed intervals were reduced, or the wind turbine was represented by a dynamic model. A later study [56] presented the use of Artificial Neural Networks (NNs) for controlling and managing the wind-RO system mentioned in [27]. The NN control system generated infrequent feed flow and pressure set points that tended to drive the permeate recovery ratio over the acceptable limit. This was caused by shortcomings in the algorithms controlling the frequency converter and the proportional-solenoid throttle valve, which controlled the feed flow rate and pressure respectively. Moreover, Lai et al. recommended developing advanced control system and strategy for directly coupled wind-RO [61]. Control systems selection, tuning and performance have a significant effect on plant performance (see Section 3.4).

For directly coupled wind-RO plants, the wind turbine is connected to the plant through an isolated electric grid. The grid frequency depends on the wind turbine power and plant load. A decrease in grid frequency will indicate lower power delivered by the wind turbine and the RO plant load must be decreased accordingly. On the other hand, an increase in grid frequency indicates an increase in wind turbine power, requiring activation of the blade pitch control system [29]. The creation of an isolated electric grid and load connection for a wind-powered RO plant was described in detail by Subiela et al. [29] and Carta et al. [57]. The main difficulties occurred during plant start-up, as the loads could not be connected until the frequency reached a specified range between 48 – 50 Hz.

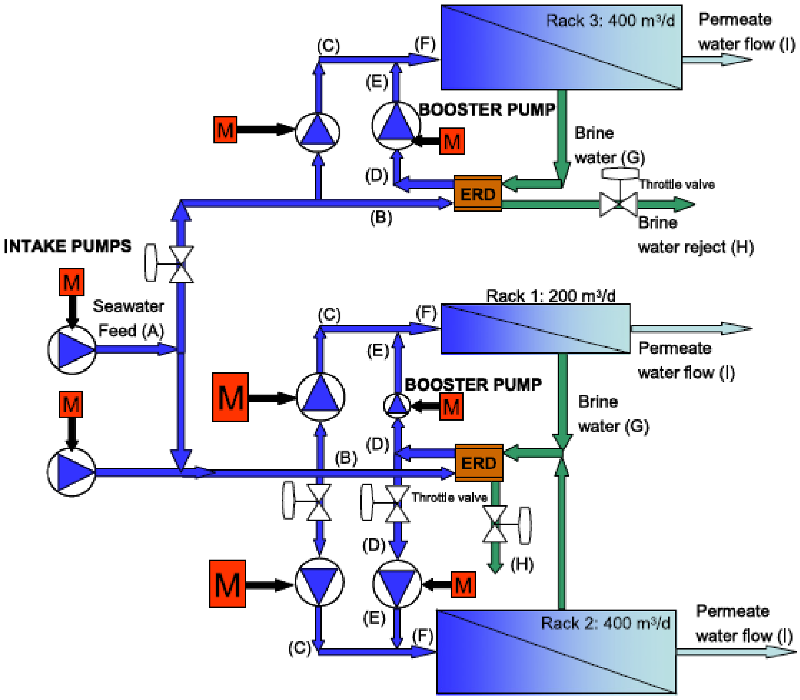


Fig. 5. Diagram of the variable capacity plant presented by Peñate et al. (reproduced with permission from [35]).

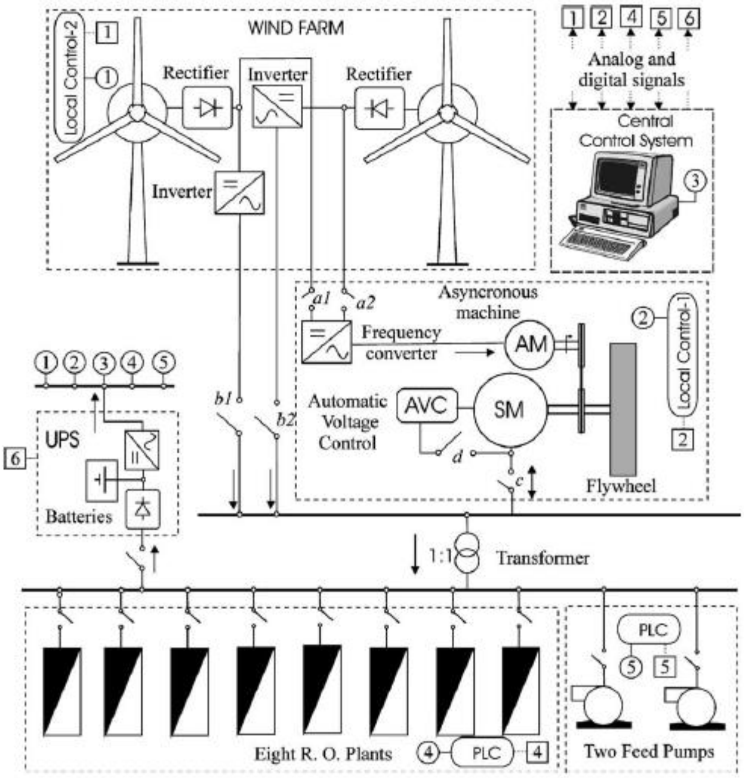


Fig. 6. Connection diagram for the plant presented by Carta et al. (reproduced with permission from [57]).

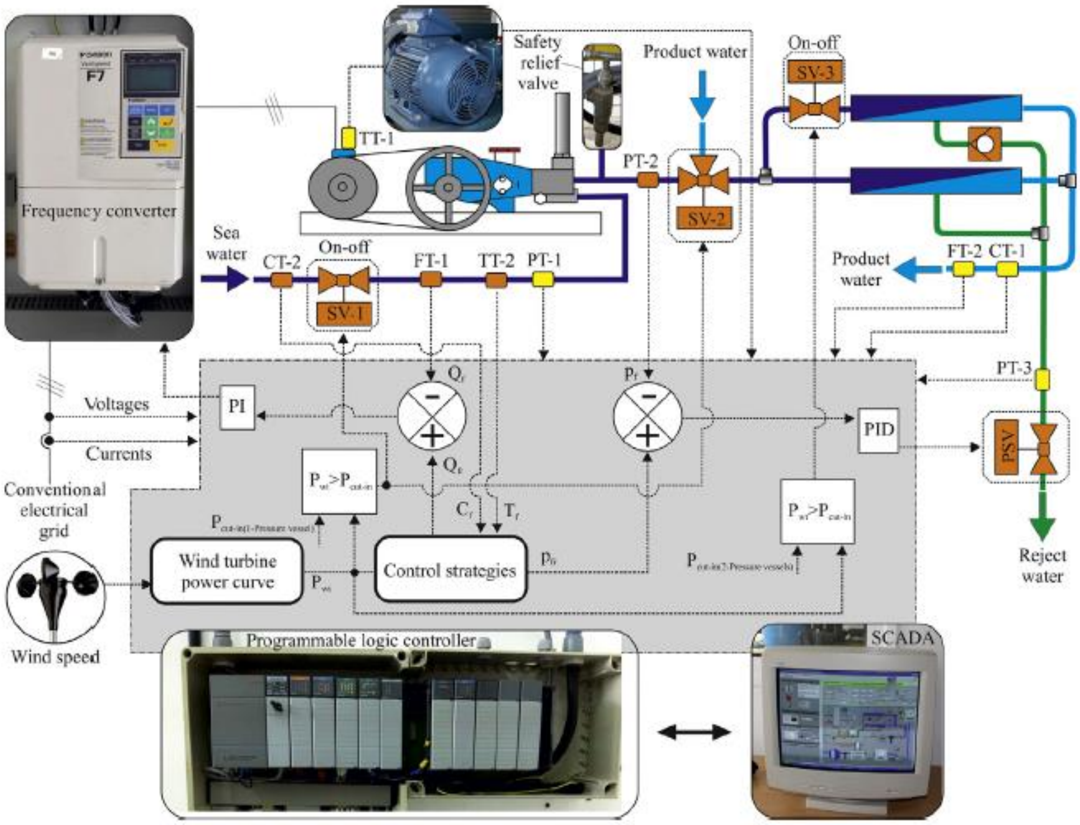


Fig. 7. Control system layout for the plant presented by Carta et al. (reproduced with permission from [27]).

Table 1.
Summary of previous literature discussing wind-RO desalination.

Author(s)	Year	Location	Study	Energy storage	Wind turbine power (kW)	Production capacity (m^3/day)	S.E.C (kWh/m^3)	Feed salinity (mg/L)	Production cost	Energy recovery	Plant description
Miranda and Infield [69]	2002	Red Sea	Exp.	None	2.2	8.5	3.4	40,000	0.8 – 3 (£/m^3) [70]	Clark pump	-
Carta et al. [57]	2003	Canary Islands	Exp.	Battery and UPS for control system	2 x 230	25 x 8	6.9	Seawater	-	None	Eight identical plants connected in parallel. Each plant has three pressure vessels with three RO membranes each.
Moreno and Pinilla [71]	2004	Colombia	Exp.	None	1.5	0.4	-	35,000	-	None	One RO membrane.
Pohl et al. [72]	2009	Not based on wind data	Theo.	None	Power from main: 12.5	30.5	3.2 – 4.22	35,646	-	Presented by an 85% efficiency	Four RO membranes in series.
Peñate et al. [35]	2011	Canary Islands	Exp.	Flywheel - batteries	225	1000	2.7	38,170	-	RO Kinetic®	Three RO trains. Each train has 2, 6 and 10 pressure vessels, respectively. Each pressure vessel includes seven RO membranes in series.
Bognar et al. [68]	2012	Cape Verde	Theo.	None	275	200 - 600	4.3	Seawater	1.09 (€/m^3)	Hydraulic turbocharger	Two RO trains.
Carta et al. [27]	2015	Canary Islands	Theo	None	15	5.2 – 19.4	10 – 14.5	35,200	-	None	Two pressure vessels connected in parallel. Three modules per PV.
							11.3 – 16.9	39,800			

Gökçek and Gökçek [5]	2015	Turkey	Theo.	None	30	24	4.38	43,528	2.96 – 6.46 **($/m^3)**	None	Six RO membranes in series.
Bilstad et al. [63]	2015	Norway	Exp.	None	5	7.5	4.24	35,000	-	None	Eight RO membranes in series.
Latorre et al. [55]	2015	Canary Islands	Exp.	None	Power from main 5.5 - 21.5	45.6 - 120	4 – 5.5	32,237 ppm	-	None	One pressure vessel with six RO membranes connected in series.

2.2 Solar-PV RO desalination

Solar-Photovoltaic (PV) powered RO plants are considered very promising for providing fresh water in isolated, arid and remote regions [44]. The success of solar-PV as a driver for RO plants is attributed to four factors [73]. Firstly, the modularity of PV systems offers implementation with RO on different scales and their capacity can be increased after initial installation. Secondly, PVs require low maintenance and offer a long lifetime of 20 years [44]. Thirdly, areas that demand high water consumption usually have high solar radiation intensity which makes PVs well matched to the application. Fourthly, the somewhat predictable bell-shaped diurnal solar irradiance curve, compared to the random variation of wind power, makes it easier to schedule the plant operation during daytime and use water storage instead of energy storage to meet night-time demand. Table 2 presents a summary of previous studies discussing solar-PV powered SWRO plants. With the decrease in PV costs, PV-RO systems have become more feasible, depending on solar resource availability, RO system demand, water characteristics and local government policies [74]. Hence, water production cost from PV-RO systems is highly site dependent. Numerous studies [43, 44, 74-77] discussed the feasibility of PV-RO systems and suggested different configurations that may offer high feasibility. Mohamed et al. [43] compared the performance of a RO plant using batteries for energy storage against another plant that is directly coupled to a PV array. The directly coupled plant offered less complexity since there is no need for batteries or a charge controller. Another approach to ensure a full-day operation is to assist the PV system with a conventional energy source such as a Diesel engine. This scheme was tested by Helal et al. [44] within a comprehensive techno-economic analysis for different configurations of autonomous PV-RO plant. The RO plant was alternatively driven fully by a Diesel engine, directly coupled to a PV array, or operated by both the PV array and Diesel engine. The directly coupled PV-RO plant produced water at the most competitive price. In general, PV-

RO systems were found to be economically more feasible than Diesel-powered systems provided there is sufficient solar resource [74, 76, 77]. The economic feasibility of a RO plant operated by an organic-solar Rankine cycle was compared to that of a directly coupled PV-RO system by Manolakos et al. [75]. Water production cost for the PV-RO system was significantly lower than that of the organic-solar Rankine-RO system at 7.77 €/m^3 compared to 12.53 €/m^3.

2.2.1 Enhancing the PV array performance

PV array performance holds an important role in the PV-RO integration, as maximizing the PV power output would lead to higher freshwater production. In previous studies, several approaches for improving the PV system performance were considered. For example, collection of solar irradiance during daytime can be maximised by using solar trackers [78]. Richards and Schäfer suggested using single- or dual-axis trackers, which could increase water production by nearly 30% [79]. Similarly, Thomson and Infield [80] used a Matlab-Simulink® model to assess whether a single or dual axis tracker should be used for their PV-RO system. The single- and dual-axis trackers increased annual water production, by 33% and 36% respectively, when used together with a Maximum Power Point Tracking (MPPT) algorithm [80-84]. MPPT adjusts the RO plant load so that the voltage across the PV cell is equivalent to the voltage required to achieve the maximum power at the corresponding solar irradiance and cell temperature [84]. A drawback for PV-RO, which is especially marked in arid regions, is the noticeable degradation of power output due to dust and sand accumulation [85]. Scattering by dust in the atmosphere and dust accumulation over the panels can lead to an increase in panel temperature, attenuation of incoming solar radiation and may lead to physical damage [86]. Several PV cleaning techniques were suggested in the literature that includes mechanical methods, PV coating or electrostatic methods [87, 88].

Ambient temperature has a significant effect on the PV panel performance, as their conversion efficiency decreases with increasing PV temperature [82, 86]. In certain studies [82, 89], the RO system feed water was circulated in heat exchangers to cool the PV array and increase the feed water temperature before entering the RO system. This modification was based on the fact that solar panels' open circuit voltage and output power increase at lower temperatures, whereas RO membranes allow more permeate at higher feed temperatures [82]. A similar procedure was used by Kelley and Dubowsky [82] to improve PV-RO system productivity. However, concentration mirrors were installed to increase the solar irradiance collected by the solar panel, which alongside the solar panel cooling and feed water heating, improved water production by 57% (see Fig 8). The concentrating mirrors could not have been used without such cooling, as the panels would have overheated and their efficiency degraded.[82].

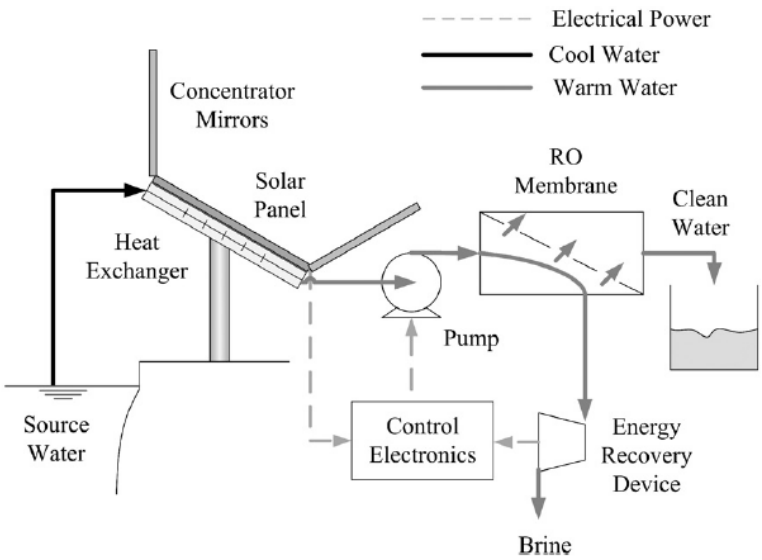


Fig. 8. PV-RO system with panel cooling and concentrator mirrors (reproduced with permission from [82]).

2.2.2 Variable operation of PV-RO plants

For PV-RO systems to transition to large-scale applications, a reliable operation strategy and control system is needed to allow efficient energy use despite variation in solar power.

As with wind powered-RO, both modular and variable-speed operation have been used. Thomson and Infield [80] presented a variable operation PV-RO system, shown in Fig. 9, that can adapt to a PV array power output without using batteries. Variable-speed operation was enabled by a controller that delivers two functions. Initially, it applied MPPT, which controls the current drawn from the PV array to maximize the PV array power output at varying solar irradiance and array temperature. Then, it executed a control algorithm for two variable-speed feed pumps to operate the plant at optimum recovery ratio and minimum SEC. In another study, Ntavou et al. [91] analysed the performance of a RO plant that consists of three identical sub-units, as presented in Fig. 10. The RO sub-units were operated using a combination of variable-speed and modular operation. They were operated by a variable power input using a frequency inverter to control the HPPs. In addition, the number of operating units was varied depending on the available PV array power. This strategy would produce, in some cases, 4 m^3/day more than a conventional system. However, a wider operation range could have been achieved by using an isobaric ERD. The ERD used was an axial piston motor coupled to an axial piston HPP that did not allow independent variation in feed pressure and flow rate, due to the linear relationship between flow rate and pump speed for positive displacement machines. In addition, both the pump and motor had fixed volumetric displacement. These factors resulted in a linear relation between feed pressure and flow rate under varying pump speed. Therefore, the recovery ratio was fixed, which is not ideal in a variable-speed system.

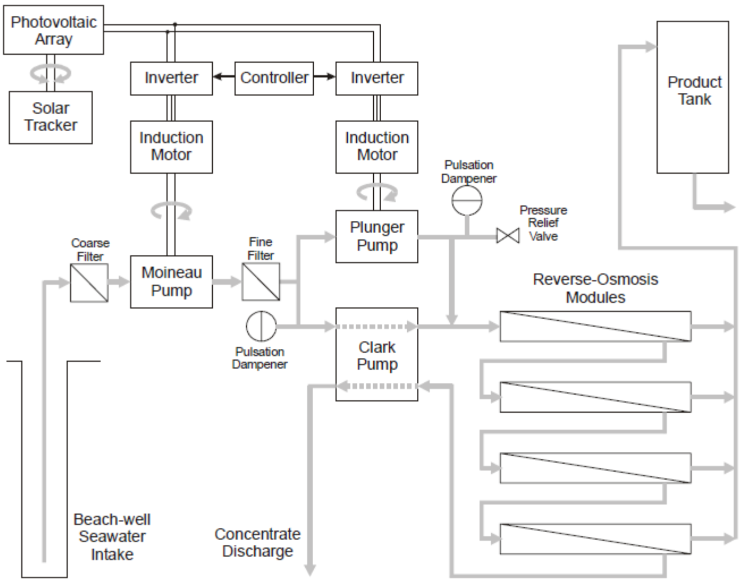


Fig. 9. Layout of the plant presented by Thomson and Infield (reproduced with permission from [80]).

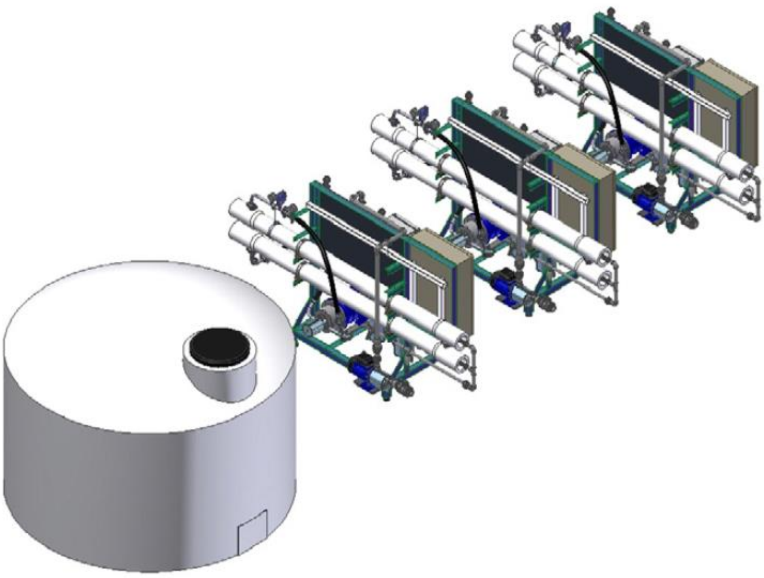


Fig. 10. Configuration of the RO plant used by Ntavou et al. (reproduced with permission from [91]).

Table 2.
Summary of previous literature discussing PV-RO desalination.

Author(s)	**Year**	**Location**	**Study**	**Energy storage**	**PV power** (kW)	**Production capacity** (m^3/day)	**S.E.C** (kWh/m^3)	**Feed salinity** (mg/L)	**Production cost**	**Energy recovery**	**Plant description**
Thomson and Infield [80]	2002	Massawa, Eritrea	Theo.	No	2.4	3	3.5	40,000	2 £/m^3	Clark pump	Four RO membranes in series
Mohamed et al. [43]	2007	Athens	Exp.	No	0.85	0.35	4.6	32,738	7.8 €/m^3	Clark pump	Two RO membranes in series.
Helal et al. [44]	2008	United Arab Emirates	Theo.	No	17.9	20	7.33	45,000	7.34 $/$m^3$	yes	Two-stage system with booster pump between stages. Two RO membranes in series per stage.
Manolakos et al. [75]	2008	Thirasia island, Greece	Exp.	No	0.846	2.4	3.8 - 6	22,000	7.77 €/m^3	Clark pump	Two RO membranes in series.
Bilton et al. [74]	2011	USA	Exp.	Batteries to power the control electronics	0.23	0.3	4 – 2.5	35,000	4.7 – 6.62 $/$m^3$	Clark pump	One RO membrane.
Soric et al. [92]	2012	Marseille, South of France	Exp.	No	0.5	0.75 – 1.02	-	25,000	-	Clark pump	Two RO membranes in series.
Clarke et al. [93]	2012	Australia	Theo.	Compare with/without batteries	0.7	With Battery: 0.054 Without battery: 0.047	-	Seawater	-	No	One RO membrane (Commercial unit).
Kelley and Dubowsky [82]	2013	USA	Exp.	No	0.23	0.3 – 0.45	-	Seawater	-	Dual-piston pressure exchanger	One RO membrane.

Kumarasamy et al. [84]	2015	India	Theo.	No	0.667	0.7	-	35,000	-	No	One RO membrane.
Ntavou et al. [91]	2016	Greece Spain UAE	Exp.	No	10 - 20	Single unit 12 – 16.8 3 identical units	5.2 – 5.8	37,500	-	Axial piston motor	Three identical units connected in parallel. Four RO membranes in series each.

2.3 Hybrid wind-PV RO desalination

Hybrid renewable energy systems can improve the feasibility and stability of RE-RO by exploiting the strength of one RES to overcome the weaknesses of others. For instance, wind turbines can be used with solar-PV to extend energy availability to include night time and overcast days, providing more consistent output [40]. This will help improve system reliability and economic feasibility, as it will provide better use of capital invested in the RO plant [14]. Table 3 summarises previous studies of hybrid RE-powered SWRO plants, giving an overview of the current status and trends.

The selection and sizing of the hybrid RES components are not straightforward and have a significant effect on economic feasibility. Oversizing its components to overcome the intermittent power supply can lead to a wasteful increase in capital cost [44]. Hybrid RES and RO plant sizing should be based on cost optimization as the investment cost of RESs are still high compared to conventional grid power systems [43, 94]. Several studies presented sizing models for hybrid RESs that power RO plants [95-99]. Hossam-Eldin [97] developed an optimization procedure to optimally select and size the hybrid RES for operating a RO plant. The optimization considered the capital cost and the excess energy generated by the hybrid RES. Similarly, Weiner et al. [98] developed a simulation code that helps in component selection and sizing of hybrid wind-PV system and RO plant. Also, a control algorithm was developed to determine if wind and solar energy are sufficient to supply the plant load or additional energy is needed from the batteries and Diesel generator. Mokheimer et al. [99] studied the optimum component sizing for a hybrid RES-RO plant while considering the RO system performance, capital and operation costs. The optimized system achieved water production costs less than the range mentioned in literature.

The majority of studies discussing hybrid RE-RO systems focused on the theoretical aspects of sizing and performance without discussing practical operation [97, 99-101]. For, this reason the RO plant was often very simplified. In some cases, the plant was only represented by its average SEC and production capacity [95, 96, 102]. Additionally, as presented in Table 3, the majority of systems included energy storage to ensure the RO plant is operating at constant conditions. For example, Smaoui and Krichen [103] presented a control and energy management algorithm for a RO plant powered by a hybrid RES that includes wind turbines, PVs, a fuel cell and electrolyzer for providing hydrogen energy storage. The control algorithm optimized plant operation by considering the energy circulation among all components. Similarly, Spyrou and Anagnostopoulos [100] operated a RO plant in Greece by a hybrid RES that included a pumped storage system. The plant, presented in Fig. 11, was found to be economically feasible despite having high-energy rejection.

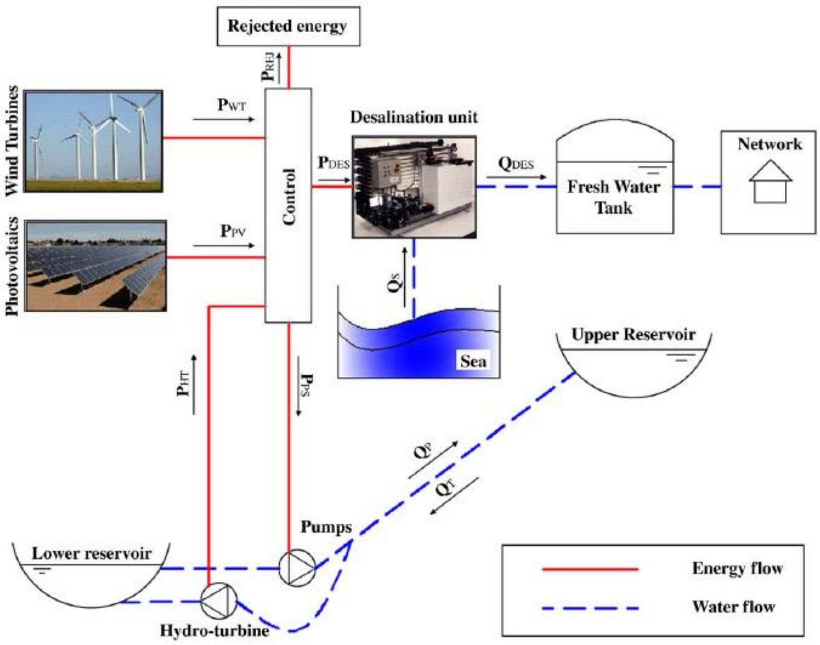


Fig. 11. Configuration of RO plant presented by Spyrou and Anagnostopoulos (reproduced with permission from [100]).

Table 3.
Summary of previous literature discussing hybrid Wind-PV RO desalination.

Author(s)	**Year**	**Location**	**Study**	**Backup system**	**Hybrid system**	**Production capacity** (m^3/day)	**S.E.C** (kWh/m^3)	**Feed salinity** (mg/L)	**Production cost**	**Energy recovery**	**Plant description**
Weiner et al. [98]	2001	Israel	Exp.	Battery + DE	WT PV	3	-	3500 - 5000	-	None	Two RO membranes in series.
Kershman et al. [101]	2002	Libya	Theo.	Grid-connected	WT PV Grid	300	5.6	Seawater	2.3 €/m^3	None	Two RO trains.
Spyrou and Anagnostopoulos [100]	2010	Greece	Theo.	Pumped storage	WT PV Hydro.	3840 Based on hourly average	3	Seawater	2.53 €/m^3	-	-
Hossam-Eldin et al. [97]	2012	Egypt	Theo.	Battery	WT DG	150	7.3	33,000	1.6 $/$m^3$	None	Four pressure vessels with Three RO membranes each.
					WT PV DG	300	4.6	34,000	1.25 $/$m^3$	Yes	Five pressure vessels with four RO membranes each.
Mokheimer et al. [99]	2013	Saudi Arabia	Theo.	Battery	WT PV	5	8 - 20	-	3.693 – 3.812 $/$m^3$	-	-

- **Acronyms:** DG: Diesel generator - Grid: a connection to local grid - Hydro.: Hydropower - PV: Photovoltaic - WT: wind turbine.

3 Technical challenges and potential solutions for RE driven RO plants

The above studies revealed numerous challenges regarding RE-RO plants, especially for the main components, operational strategy and control system design. This section analyses these aspects in detail, starting with the critical components namely membranes and energy recovery devices.

3.1 Membranes performance and lifetime

RO membranes are the heart of the desalination process. These semi-permeable membranes allow fresh water but not salts to pass, creating a concentrate (brine) and a permeate stream. Their operation depends on delivering feed water at a pressure above the osmotic pressure for the separation process to occur. In conventional RO plants, the HPP supplies feed water at constant pressure and flow rate. However, for variable operation, feed water pressure and flow rate will vary according to the available RE power.

Manufacturers normally guarantee a lifetime of 5 years, if the RO membranes are operating under recommended steady conditions [57]. According to Cabrera et al. [104], continual start-ups, shutdowns, flow variation and pressure fluctuations present unusual operating conditions for the RO membranes, causing mechanical fatigue with a negative impact on the membrane lifetime and performance. Also, membrane compaction, which is the plastic deformation that leads to membrane deterioration, is expected to accelerate under variable operating conditions [105]. Accordingly, water production cost could be affected by variable operation, as it is influenced by the membrane replacements costs [57]. Hence, the economic viability of variable operation is dependent on the extent to which it affects membrane performance and lifetime.

Several studies discussed membrane performance and lifetime in plants operated with variable RE power [54, 55, 57], as summarized in Table 4. The study of Carta et al. [57] using 8 switchable RO units (Fig. 12) developed an operation strategy to examine the effect of modular operation on component lifetime. Units were connected and disconnected in reverse order, which meant that some units underwent fewer start-ups and shutdowns than others. In contrast to the claims presented by Cabrera et al. [104], Carta et al. [57] concluded that no physical deterioration was observed in the main components. Similarly, Pestana et al. [54] and Latorre et al. [55] operated a RO plant for 7000 and 6000 hours respectively, at variable flow and pressure under variable-speed operation. In both studies, no membrane deterioration was noted. However, these test periods were insufficient to give a definitive conclusion when compared to the average 5-year (43,800 hr) lifetime of a RO membrane [57].

Improvements in performance were reported in several studies [106-109] when testing the membrane performance against fluid instabilities and pulsating trans-membrane pressure. For instance, Al-Bastaki and Abbas [109] reported a maximum permeate flux improvement of 13% when testing against square wave pressure pulses at an average pressure of 50 bars. The reason for this improvement is the increased turbulence caused by the fluctuating pressure and flow instabilities. This turbulence improved the diffusion through the membrane and decreased the effect of concentration polarization which led to increased permeate flux and quality [61]. In summary, there are mixed views about the effects of variable operation on membranes, with some authors reporting shortened lifetimes and others highlighting improvements in performance.

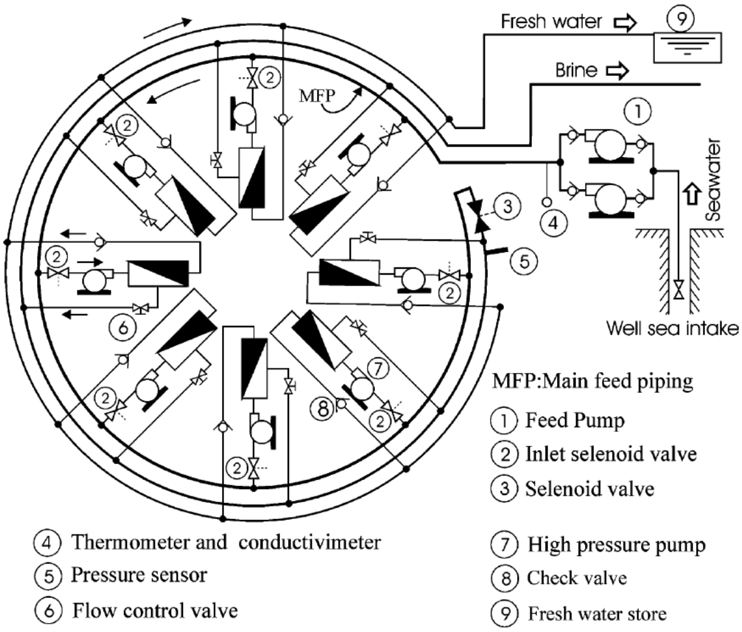


Fig. 12. Schematic diagram of the test rig used by Carta et al. (reproduced with permission from [57]).

Table 4.
Studies analyzing membrane deterioration in variable operation.

Study	Methodology	Outcome
Carta et al. [57]	Modules had a different number of start-ups and shutdowns.	No membrane deterioration was noted.
Pestana et al. [54] **Latorre et al.** [55]	Operated the plant for 7000 and 6000 hrs. at variable conditions.	
Rodger et al. [106] **Winzler et al.** [107] **Al-Bastaki and Abbas** [108, 109]	Effect of fluid instabilities and pulsating trans-membrane pressure.	Improvement in performance was reported.

3.2 Energy recovery device (ERD)

A significant amount of the pumping energy still resides in the brine stream as it exits the membrane at high pressure [110]. This energy may be recovered by a hydraulic ERD that transfers the brine energy to the feed stream, thus reducing the SEC by decreasing the HPP power. ERDs can help decrease the power consumption by as much as 60% when compared to systems operating without energy recovery [111]. Their introduction in RO desalination allowed for a SEC below 5 kWh/m^3 [110, 112]. ERDs are generally classified as either centrifugal or isobaric devices. Further sub-classification of ERDs is presented in Fig. 13 [111]. In the early eighties, when ERDs were first introduced, centrifugal machines like the Pelton wheel or Turbocharger were mostly used, requiring system configurations as shown in Fig. 14 (a, b) respectively [110]. Centrifugal ERDs are characterised by their suitability for high flow rates, limited range of capacity and maximum energy transfer efficiency of around 82% [111]. On the other hand, isobaric ERDs are gaining popularity because of their higher energy transfer efficiency of nearly 97%, low power requirement, decoupled operation from the HPP and smaller size compared to centrifugal devices [111]. Many commercial RO plants that used centrifugal devices have now been retrofitted with isobaric ERDs, providing increased plant production capacity for the same power consumption [113, 114]. Two common types of isobaric ERDs are the Dual Work Exchange Energy Recovery DWEER™ and the Pressure Exchanger PX® [115-117]. Both devices are presented in Fig. 14 (c, d) respectively. For commercial RO plants, the sizing and selection of ERDs are based on the plant's optimum operating point, to ensure that the ERD will operate at its optimum efficiency during normal operation [118]. The use of RE to drive RO desalination introduces new challenges regarding the variable operation of ERDs.

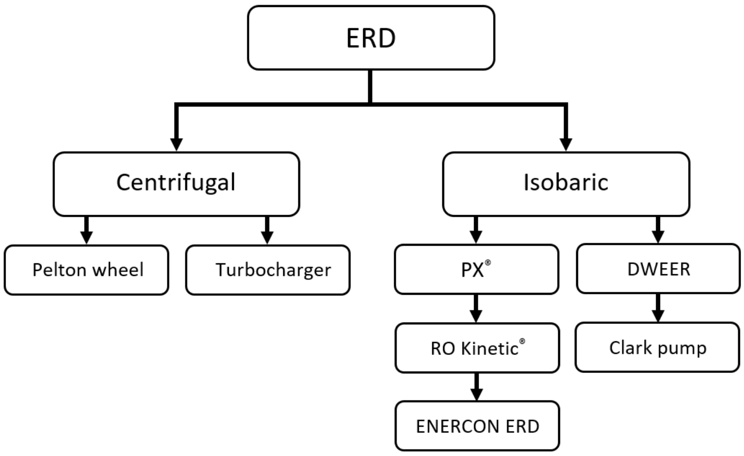


Fig. 13. Classification of energy recovery devices discussed in this article.

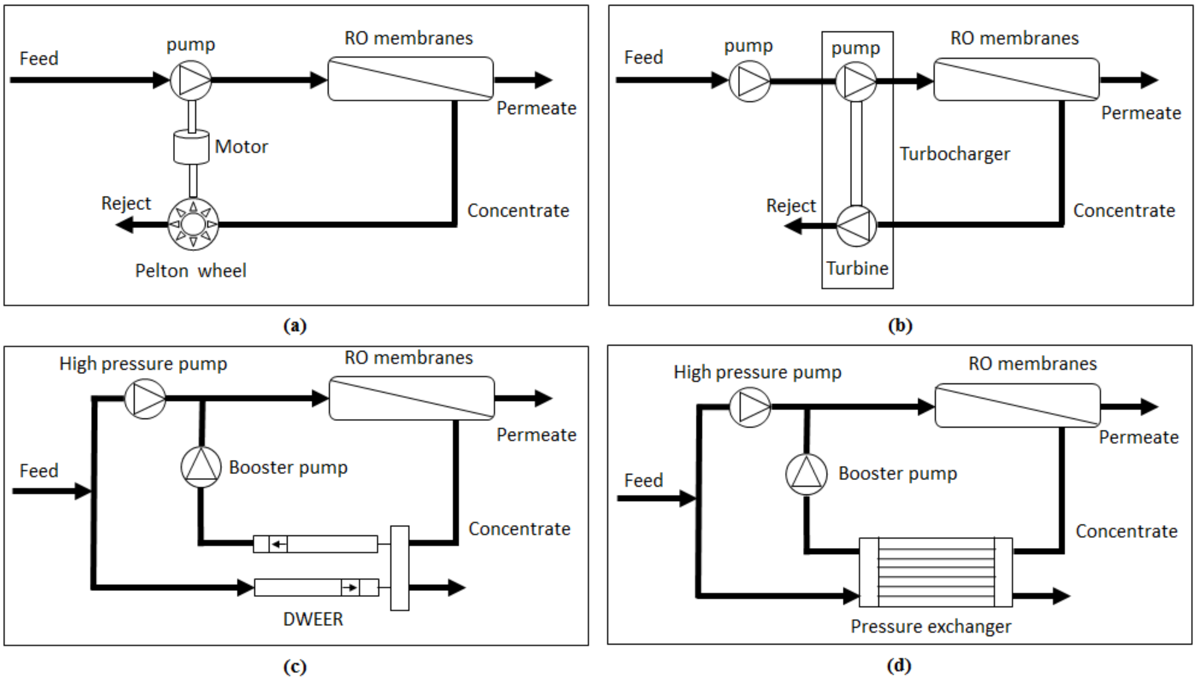
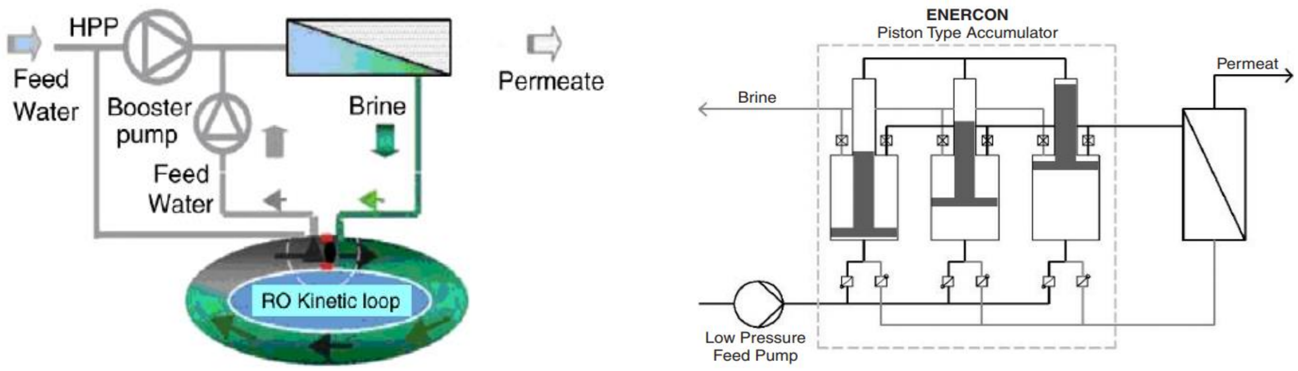


Fig. 14. RO plant configuration for using a) Pelton wheel, b) Turbocharger, c) DWEER and d) Pressure exchanger.

3.2.1 ERD performance in variable operation

In case of variable operation, the ERD should offer the flexibility to operate with acceptable efficiency at different flow rates, to allow for independent variation in membrane flux and recovery ratio [35]. Centrifugal devices cannot deliver this performance because their efficiency varies with changing flux and recovery ratio [35]. On the other hand, isobaric devices can operate at nearly constant efficiency with a varying flow rate which makes them more suitable for variable operation [111, 119]. Additionally, the decoupled operation of isobaric ERD from the HPP offers a great advantage for variable operation, as it allows the independent variation of membrane flux and recovery [119]. Several studies introduced isobaric ERDs that are suitable for variable operation. Peñate et al. [119] described the theory of operation and operational data of a patented isobaric ERD called RO Kinetic®, presented in Fig. 15 (a). The RO Kinetic® is designed in the form of a closed loop, in which, the pressure is exchanged between the brine and feed water. The process of distributing the input feed water and output brine is done by servo-controlled valves. The ERD delivered a robust, low maintenance operation and achieved a SEC of slightly higher than 2.2 kWh/m^3. The RO Kinetic® was recommended for RO plants operating with variable conditions [35]. In another study, Paulsen and Hensel [118] presented an ERD developed by ENERCON specifically for RO plants operated by wind energy. The ERD, displayed in Fig. 15 (b), only uses a single low-pressure pump to drive the desalination process, without the need for a HPP. The ERD is a "piston type accumulator" that operates within a range of 12.5 – 100% of plant capacity while maintaining a SEC between 2 – 2.8 kWh/m^3. A follow-up study was presented in [120]. For small-scale standalone applications, the Clark pump was used by several studies, as it delivers high efficiency at low flow rate [43, 69, 74, 80, 121]. The Clark pump, manufactured by Spectra Watermakers Inc. [122], is described as a "positive displacement reciprocating pressure intensifier" ERD. It is referred to as a pressure intensifier because it has two pistons that allow energy from the feed to be added to the energy of the concentrate such that the output pressure is higher than that of the concentrate [123].



(a) (b)

Fig. 15. a) RO Kinetic® working principle (reproduced with permission from [119]), b) ENERCON piston-type accumulator (reproduced with permission from [118]).

3.2.2 Technical challenges for isobaric devices

The main disadvantage of some isobaric ERDs is mixing between the brine and feed streams [111]. Mixing increases feed salinity thus increasing feed water osmotic pressure and required pumping power [124]. The increase in feed salinity can range between 3 – 5%, requiring additional pressure of about 2 bar [125]. Stover [111] presented equations to describe the salinity increase due to mixing in a rotary isobaric pressure exchanger. Similarly, leakage flow occurs between the high-pressure and low-pressure sides of the brine stream. This leakage is estimated at 1 – 2.5 % of the brine flow [125]. Mixing and leakage flows depend on system pressure, temperature, feed and brine flow rate and device characteristics [111, 125]. Variable operation can lead to an increase in brine mixing and leakage due to increased fluid instabilities, resulting from changes in flow and pressure. This is especially true for the pressure exchanger (PX®), as there is no physical barrier between the brine and feed streams. A study was performed by Xu et al. [126] to analyse the effect of rotor speed, brine and feed flow velocities on the mixing rate for a rotary pressure exchanger. The analysis was performed using a computational fluid dynamics simulation, presented in Fig. 16, and an experimental model. The simulation showed clear signs of mixing.

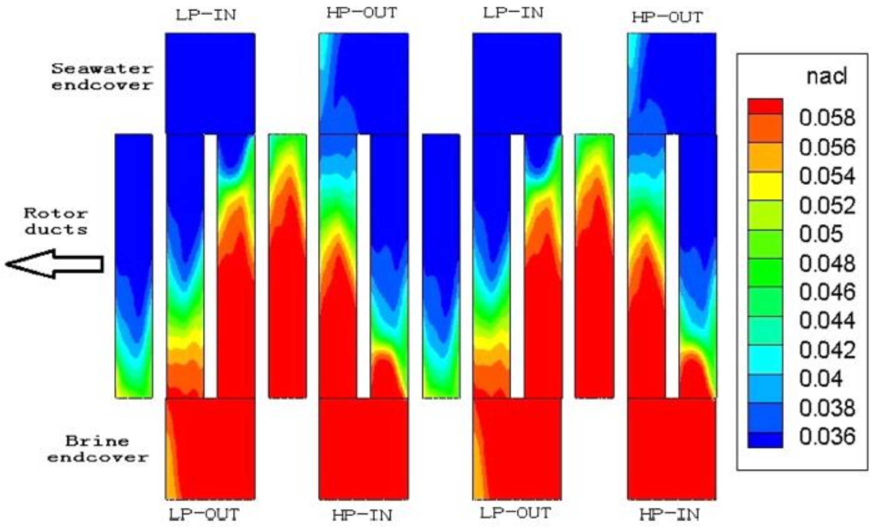


Fig. 16. Two-dimensional salinity contour of the central cylindrical surface of the ERD (reproduced with permission from [126]).

3.3 Strategies for variable operation of RO system

As mentioned earlier, RO plants are designed to operate at constant flow, pressure and power level and with all modules working continuously. Specific strategies are required for the RO plant to enable variable operation. This section will review different strategies to adapt large-scale RO plants to modular and variable-speed operation.

3.3.1 Start-up and shut down under modular operation

For the purpose of routine maintenance in standard (non-RE) plant, manufacturers have defined operating procedures for start-up, shutdown and steady operation. With RE, modular operation will demand much more frequent start-up/shutdown of RO trains to modulate the plant according to the available power. This section will discuss the standard membrane flushing procedures during the start-up/shutdown cycle, as recommended by membrane manufacturers to deliver their claimed water quality and output and to prevent membrane fouling and damage under sudden mechanical loading [127]. The implications for variable operation are then discussed.

According to the DOW Filmtec™ Technical Manual [127], for a typical start-up, the system should be flushed with low-pressure clean water, between 2 to 4 bar, at a low flow rate, to purge air out of the RO elements and the pressure vessels. The concentrate and permeate should be discarded during this procedure [127]. After flushing, the feed pressure is increased gradually to reach the operation set point. Feed pressure ramping should be limited to 0.7 and 0.5 bar per second for FILMTEC™ and TORAY modules respectively, to complete a soft start [127, 128]. Otherwise, the element housing might be damaged by shock force acting in the radial or flow direction [127]. Once the set point is reached, it is suggested to disregard the permeate until it reaches the desired quality [128].

During a typical shutdown, it is recommended to flush the membrane with fresh water to prevent scaling, salt deposition and (forward) osmosis from occurring across the membrane, which can cause the membrane to swell and rupture [105, 127]. Flushing is done using low-pressure water, approximately 3 bar, at a high flow rate, to remove the brine completely from the pressure vessel [127]. Permeate water or high-quality feed water can be used for flushing [123, 127]. This procedure should continue until the concentrate conductivity matches the feed conductivity. TORAY recommends flushing the membranes every 12 hours for shutdowns between 1 to 4 days and adding a preservative solution for shutdowns exceeding 4 days [128]. Modular operation can involve several start-up and shutdowns of RO trains in a single day depending on RE power variation [27]. The unpredictability of RE variation can be problematic because, to flush the membrane prior to shutting down, there must be enough energy to operate the flushing pumps and enough permeate water to flush the membranes [59, 123]. In terms of energy requirement, operating the flushing pumps for PV-RO systems can be scheduled at the end of peak radiation hours during the day. However, it is more challenging for wind-RO plants, as wind speed changes randomly during the day. An efficient approach would be to store water in an elevated tank for gravity-driven flushing [27]. Moderate elevation is sufficient since the pressure requirement is low. Flushing water can be obtained by storing the first batch of permeate for this purpose [59]. Feed water is sometimes used for flushing if it is of sufficient quality [59, 123, 128].

3.3.2 Variable speed operation and safe operating window

Modular operation by switching units on and off may not be enough to accommodate the frequency and pattern of RES variation. Variable-speed operation can be used to achieve a faster and finer response. To operate a RO plant with variable speed, firstly, a safe operation window should be defined to set boundaries for the operation parameters. Secondly, an operation strategy is needed to change the operation parameter within the boundaries of the safe operation window.

The operational window defines the acceptable parameter variation range for safely operating the RO plant, providing an important guideline in control system design. The operational window is set based on operation parameters subject to hydraulic limitations such as the feed pressure and flow rate, permeate and concentrate flow rate. In several studies [69, 71, 72], the operational window was based on five parameters: 1) maximum feed pressure that the membrane can withstand based on its mechanical resistance; 2) maximum allowed feed/brine flow that is based on the membrane mechanical loading; 3) maximum permeate flow per element and the maximum recovery per element were constrained as they directly affect the concentration polarization; 4) minimum concentrate flow to avoid precipitation and membrane fouling, as the concentrate flow is responsible for clearing the salt out of the membranes; and 5) maximum product concentration based on the recommendations of the EPA and WHO [72]. Table 5 includes the hydraulic limitation for a common proprietory membrane.

Table 5.
Hydraulic limitations for 8-inch /37 m^2 DOW-FILMTEC SW membranes with generic conventional pretreatment [127].

Maximum recovery per element	13 %
Maximum permeate flow per element	1.4 m^3/h
Minimum concentrate flow	3.4 m^3/h
Maximum feed/brine flow rate	14 m^3/h

The operational limits are determined by simulating the membrane hydraulic performance while holding specific parameters constant. After defining the plant operational window, an operational strategy is used to vary the feed flow and feed pressure, according to the set boundaries. Miranda and Infield [69] established an operational window for a variable operating small-scale RO plant operating by a 2.3 kW wind turbine. Afterwards, a control strategy was developed to operate the system within the operational window. Two positive displacement pumps enabled the independent control of feed pressure and flow, to allow operation at any point within the operational window. Likewise, in [71, 72], an operational window was defined using Reverse Osmosis System Analysis (ROSA) software to vary feed flow rate and operating pressure while holding specific membrane parameters constants. The operational window set by Pohl et al. [72], for four series SW30-HR400i DOW Filmtec™ elements using feed water at 35,646 mg/l, is displayed in Fig. 17.

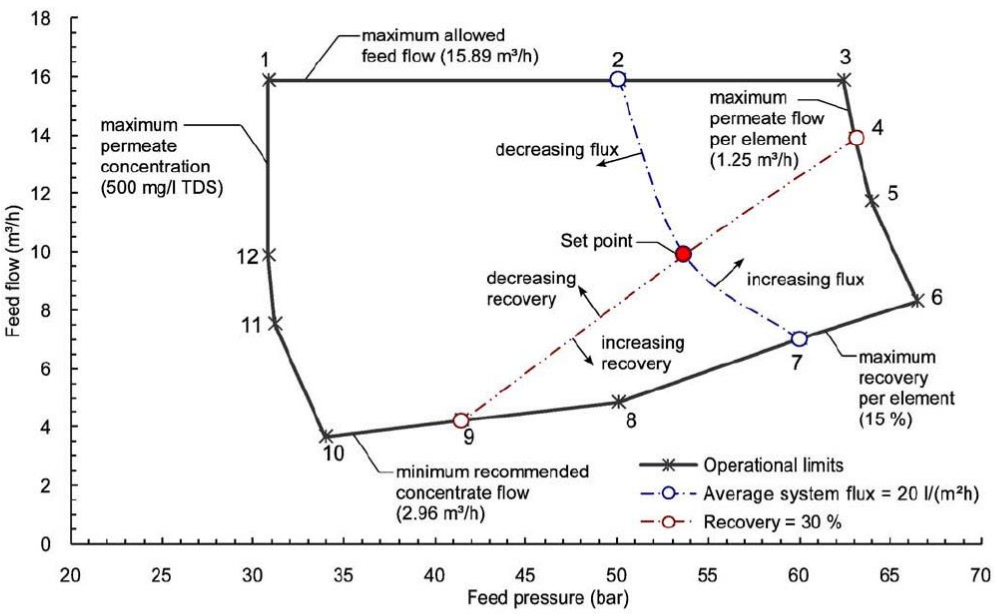


Fig. 17. Operational window presented by Pohl et al. (reproduced with permission from [72]).

Variable-speed operation requires definition of an operation strategy for the plant to respond to changes in available power while remaining within the safe operation window. The operation strategy should result in feed pressure and flow rate combinations that achieve maximum water production and desired water quality while operating at the lowest SEC. Operating at the lowest SEC ensures full utilization of available power and maximum water production [123]. The relation between feed pressure, feed and permeate flow rate, permeate recovery and SEC can be described as follows [37]:

$$Q_p = A * S * (\Delta P - \Delta\pi) \tag{3.1}$$

$$Q_s = B * S * \Delta C \tag{3.2}$$

$$Recovery = \frac{Q_p}{Q_f} \tag{3.3}$$

$$SEC = \frac{Power}{Q_p} \tag{3.4}$$

where Q_f, Q_p and Q_s are the feed flow rate, permeate flow rate and salt transport, respectively, A is the membrane permeability, B is the salt transfer coefficient and S is the membrane surface area. $(\Delta P - \Delta\pi)$ is the net driving pressure and ΔC is the concentration difference across the membrane.

Thomson [123] used two pumps to vary the feed pressure and flow rate individually to operate a RO plant at the lowest SEC during power fluctuation from a PV array. Pohl et al. [72] compared four different operation strategies to operate a simple RO plant connected to a wind energy source. The operation strategies relied on controlling the feed pressure, feed flow rate and permeate recovery, to operate the plant at either constant feed pressure, constant permeate recovery, constant feed flow or constant concentrate flow. Maintaining constant permeate recovery by changing feed pressure and flow rate delivered the best performance regarding SEC, permeate quality and wider load range. A study by Kumarasamy et al. [84] compared varying either the pressure or the flow rate while keeping other parameters constant. While maintaining constant pressure and varying flow rate, the recovery ratio could increase and cause increased salt diffusion through the membrane. Alternatively, operating at a constant flow rate and variable pressure increased production capacity by 5%; however, this introduced a risk of the pressure decreasing below the osmotic pressure. In general, when selecting any operation strategy, the safe operational window must be observed to ensure that there is no conflict between achieving maximum production and operating within safe limits.

Meeting the daily water demand and ensuring a suitable product water concentration are important objectives in formulating the operation strategy. Several studies suggested permeate storage to satisfy a stable water demand and allow monitoring of product water quality [44, 80, 84]. Kumarasamy et al. [84] compared operating a directly-coupled PV-RO system with and without permeate storage. For the system without permeate storage, the permeate water should meet the specified maximum concentration of 500 mg/L at all times; however, for the system using permeate storage, permeate concentration could increase above the limit temporarily as long as the concentration inside the storage tank remains below 500 mg/L. Permeate production increased significantly by 28% when using permeate storage due to a wider range of acceptable permeate concentration. In general, permeate storage is beneficial for providing a balance between water supply and demand [44, 80, 84].

3.4 Control system performance

Process control is an integral part of the RO plant operation and productivity. The control strategy for grid-connected RO plants aims to fulfil a daily production demand under constant operating conditions and is relatively straightforward when compared to variably operating RO plants, which should maximize the RES power output while managing the RO plant load against energy fluctuation [35].

The control procedure for large-scale plants can be simplified into three states: start-up, shutdown, and maintenance of setpoint parameters against any disturbances. Disturbance variables – such as changes in feed temperature or concentration, reduction in permeate flow, increase in permeate concentration, increase in fouling resistance and changes in permeate demand – can interfere with the plant operation. Sensors throughout the plant monitor these disturbances and send a signal to the controller. A control signal is generated to change the manipulated variables according to the difference between the measured and the set values. The control action guides the plant towards the desired reference or set point. Systems that include supervisory control can perform an optimization procedure to reach certain goals such as maximising daily output and water quality [129].

3.4.1 Control actions for variably-operating RO plants

The control system for variably-operating plants is a Multiple-Input Multiple-Output (MIMO) system that can handle different manipulated variables such as feed pressure, feed flow rate and recovery ratio in order to control target variables such as permeate flow rate and permeate concentration. The control is based on the available power from the discontinuous RES and water demand, in a manner that ensures proper plant operation and water quality [29, 113]. Additionally, the controller should provide fast response, high stability and minimum disturbances to adapt the RO plant against the discontinuous energy source [113].

Advanced control systems are recommended for variable operating RO plants for their ability to provide adequate control performance against the plant time-varying dynamic behaviour and RES fluctuation [27, 74]. Unfortunately, the number of studies discussing specifically RED plants control system is low [130]. The following will introduce control systems used for RO plants control in general, which can be used for RO plants operated by RES.

3.4.2 Advanced control techniques for RO plants

Proportional-Integral-Differential (PID) control and Model Predictive Control (MPC) have been frequently described in the literature for controlling RO plants [131, 132]. A PID controller, presented in Fig. 18, is a common and traditional approach to process control as a result of its simplicity and effectiveness [132]. On the other hand, MPC, presented in Fig. 19, is an advanced optimization-based control technique that is applicable to multivariable control problems, specifically for MIMO systems [133]. It relies on currently measured outputs from the process and future predicted outputs supplied by a dynamic model to calculate the required change in the input variable, so the measured output reaches the set point in an optimal manner [134].

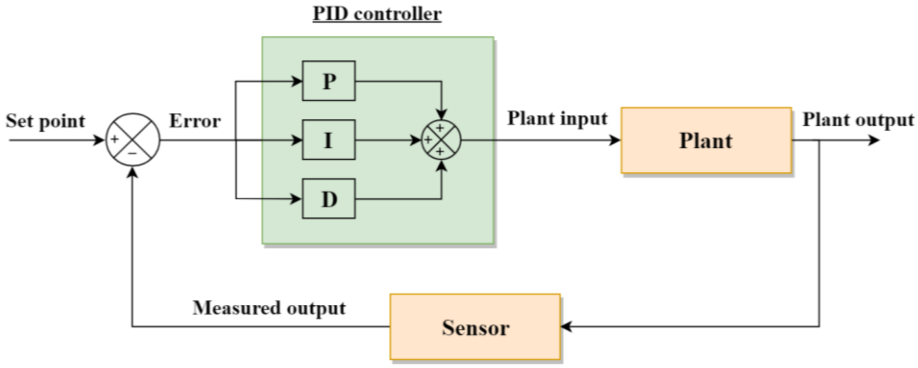


Fig. 18. Proportional-Integral-Differential controller block diagram.

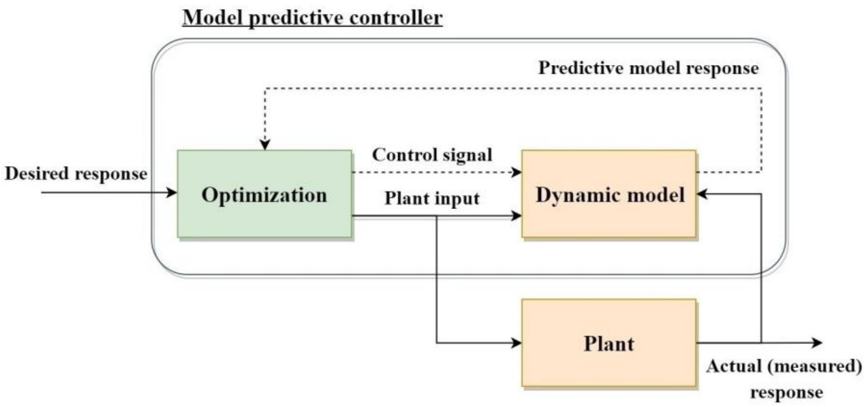


Fig. 19. Model predictive controller block diagram.

Abbas [135] used Dynamic Matrix Control (DMC), a common MPC strategy [136], to control a RO plant. The controller based on DMC was compared to a PI controller and tested against process disturbances. MPC showed faster response and robust performance as it delivered adequate response despite a ±30% change in the pressure-permeation rate gain. A similar study, performed by Robertson et al. [137], concluded that MPC based on DMC control algorithm offered better response and flexibility than the PI controller. The two studies used Ziegler–Nichols rule for PID tuning [135, 137]. However, another study performed by Esfahani et al. [133] used Internal Model Control (IMC) to tune a RO plant PID controller and compared it to the performance of a MPC that uses DMC and a PID controller tuned by the Ziegler–Nichols rule. The study found that the PID tuned by IMC presented better performance than both MPC and the Ziegler-Nichols tuned PID controller. This indicates that the controller performance is dependent on its design, tuning and the control problem.

A supervisory control system based on MPC was presented by Qi et al. [138] to manage the operation of a wind-PV-RO plant. The MPC coordinated the power flow among the wind turbine, PV array, battery bank and the RO plant in order to satisfy water demand. Weather forecasts were used to predict the maximum power available from the RESs. Similar studies were presented by Palacin [130] and Salazar et al. [139] for a MPC that solves an optimization problem at each sample step, to adjust water production based on water demand and energy available from hybrid RESs.

The application of NNs in desalination was first described by El-Hawary in 1993. Since then, NNs have been used for the RO plant modelling and performance prediction by several studies [140-144]. However, the first use of NNs to control the operation of a standalone wind-RO plant was reported by Cabrera et al. [56] in 2017. Cabrera et al. [56] implemented a NN in the control system of a wind-powered RO plant, to adapt the plant energy consumption to changes in available energy by generating feed flow rate and pressure set points while considering the wind power, feed temperature and conductivity.

4 Summary and conclusions

The integration between RE and RO promises a cost-effective and sustainable solution to decarbonize water production. The use of RE, specifically wind and solar-PV, in driving large-scale RO plants has, however, been hampered by the inefficiency and high cost of energy storage systems with larger RED systems remaining dependent on grid connection. This review has discussed recent studies that provide innovative approaches to RED and identified technical challenges and potential solutions for the commercialization of RED in large-scale plants. The main conclusions and future research directions are:

- Variable operation has been implemented in several studies by using modular 'on-off' operation and/or variable-speed operation. It has proven to be a successful strategy to operate small-scale RO plants and holds promise for large-scale plants with RE.
- Maintaining membrane performance and lifetime while using variable operation is economically crucial for proving RE-powered RO plants feasibility. Previous studies tested the membrane performance only for short periods compared to membrane lifetime. Further testing should be performed to analyse any degradation in membrane performance or lifetime due to variable operation.
- Centrifugal ERDs are not recommended for variable operation, as their efficiency varies with fluid pressure and flow. On the other hand, isobaric ERDs have a stable efficient performance with varying flow and pressure which makes them preferable for variable operation. However, the negative effects of mixing and leakage on overall performance could worsen under variable operation due to increased pressure and velocity fluctuations. Additional testing should be performed to determine the extent that pressure and velocity fluctuations will affect the ERD overall performance.
- The execution of the RO operational procedure during modular operation is crucial for maintaining the lifetime and performance of the RO modules. However, if the start-

up/shutdown procedures for RO trains were performed randomly based on energy availability, it would be wasteful of energy and product water, both of which are valuable during variable operation. Forecasting and prediction of RES availability has a promising role in scheduling by reducing the unnecessary repetition of the start-up/shutdown cycle.

- Several studies compared advanced control systems such as MPC to classical techniques, e.g., PID control, for controlling RO plants. Different conclusions were made as to which delivers the best performance, considering response time and performance robustness. However, the number of studies discussing specifically RE driven RO plants, as opposed to fossil-fueled RO plants, is low. More research that considers the RES fluctuations in analyzing the control system response would accelerate the move towards large-scale implementation.
- Hybrid RESs can play an important role in stabilizing the operation and enhancing energy availability for RE-driven RO plants. Current studies presenting hybrid RESs to drive RO plants lack the comprehensive representation and analysis of the RO plant performance against variable power. The focus should be guided towards the RO plant performance and the benefits and challenges of using hybrid renewable energy.
- Current academic progress has led to the successful operation of RO plants from RE without any backup systems. Future research and development should aim to transfer the technology to commercial plants by ensuring components are able to deliver adequate performance and presenting operation strategies to accommodate the variable power input. This requires collaboration between academia and the desalination industry to address research and developments needs, provide data for large-plant modelling and validation and possibly involving testing of new technologies on large-scale plants.

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