Desalination; a comprehensive and practical assessment on challenges and opportunities ahead

Abstract

Water scarcity becomes more severe and there will need to be a concerted effort to ensure that water supply remains secure. To mitigate the danger of water scarcity using an energy efficient method for water desalination is crucial. This review objectively compares the most practical thermal and reverse osmosis desalination technologies and the latest energy recovery opportunities for each process. This analysis reveals that thermal and reverse osmosis desalination should not be considered as a competitor since (mostly) the feed water quality and the final permeate water standards are the main parameters that impose choosing either of the most appropriate desalination method or hybridization of both approaches. Desalination of seawater using improved thermal desalination in which pre-heated helium gas instead of air is used to increase evaporation efficiency up to 3 times, is a promising technique that could make this sub-boiling thermal desalination approach the future of thermal desalination. The effect of Renewable energy resources, BCE, multiple stage units and optimizing liquid height in the dehumidifier were particularly evaluated in the HDH process which could perfectly handle the sub-boiling thermal desalination approach. Results of this comprehensive review can aid decision-makers by manifesting the main developments in desalination techniques to a reasonable degree of accuracy.

Abbreviations

BCE, Bubble Column Evaporators; BCH, Bubble Column Humidifiers; CCGT, Combined Cycle Gas Turbine; ERD, Energy Recovery Device; ERT, Energy Recovery Turbine; FO, Forward Osmosis; GE, General Electric; GHG, Green House Gas; HDH, Humidification Dehumidification; IPR, Indirect Potable Reuse; ISS, International Space Station; MED, Multi Effect Distillation; MF, Micro Filtration; MSF, Multi Stage Flash; NASA, the National Aeronautics and Space Administration; NF, Nano Filtration; ORC, Organic Rankine Cycle; PPM, Parts Per Million; PX, Pressure Exchanger; RO, Reverse osmosis; SEC, Specific Energy Consumption; SWRO, Sea Water Reverse Osmosis; TBT, Top Brine Temperature; UF, Ultra Filtration; VCD, Vapor Compression Distillation; WRS, Water Recovery System;

Keywords

Desalination, Thermal desalination, Bubble column evaporator, Desalination energy efficiency, Desalination technologies

1. Introduction

Water scarcity is a significant global challenge that affects human beings' life profoundly. Economic, social, and demographic development has globally led to an increased demand for water, consequently forcing some countries to face the shortage of water resources (Dadmand et al., 2020, p. 123812). The global water consumption has been increasing dramatically as a result of the growing world population. By 2030, the world water scarcity is anticipated to reach 2700 billion m^3/year (Shahzad et al., 2014, p. 293) and the population that will suffer from water deficit will surpass 1.6 billion (Ferroukhi et al., 2015). The surface water resources scarcity and rising demands for potable water led to the improvement of desalination technologies which generate fresh water from seawater (Woo et al., 2019).

Desalination is the process in which salts and other minerals are removed from a fluid (U.S. Department of Energy, 2019). The aim of this process is to produce industrial scale potable water mainly from seawater or brackish water. Desalination techniques can be categorized into the thermal and membrane-based separation technologies. Reverse osmosis (RO), multi-stage flash (MSF), and multi-effect distillation (MED) are the main commercial desalination technologies, with RO being the fastest growing, MSF being historically the most popular in the Middle Eastern region, and recently MED gaining popularity over MSF due to technological advancements (Fritzmann et al., 2007, p. 48).

The key challenges and recent advances in desalination are directly, or indirectly, related to the high energy cost of desalination (Ghobeity & Mitsos, 2014, p. 65). Energy efficiency often serves in favor of reducing the final cost (Ahmadvand et al., 2019, p. 696). There are several approaches to improve desalination energy efficiency. "Co-production approaches" and "performance improvement" which are mentioned in sections 2.2.1 and 2.2.2 aim to evaluate the latest measurements to enhance desalination energy efficiency. As the power costs continue to increase globally, using energy recovery devices (ERDs) has turned to be a necessary part of the RO plants. ERDs have been the largest contributor and breakthrough to reduce the specific energy consumption since the last three decades. Technically to reduce energy consumption of desalination plants, ERDs harness the concentrate stream energy of the system and transfer it to the feed side using several methods (Kadaj & Bosleman, 2018, p. 438).

In this review, the most important thermal desalination technologies i.e. MSF, MED, VCD and HDH as the main competitors for Reverse Osmosis are assessed and the main developments in each technique are discussed. Herein, the focus is on assessing the latest condition of different desalination methods and in particular more recent advances resulting from new findings and optimization opportunities. Since thermal desalination techniques are more efficient in terms of desalination of very salty water than the membrane technologies (Antonyan, 2019, pp. 1–3), producing less GHG (Skuse et al., 2021, p. 114844) and chemicals-containing brine, the question is what can be done to bring the cost of thermal energy closer to RO? The manuscript framework is around these opportunities/ challenges.

2. Literature review

By 2050, up to 5.7 billion people could be living in areas where water is scarce for at least one month a year. With seawater making up 97.5% of the world's water resource, low energy desalination solutions will be a vital component of providing sufficient levels of good-quality drinking water for a growing population (CORDIS, 2020). Physical process of separating soluble salt from different water resources such as brackish, seawater or any other water-based salt solution for collecting desalinated water, that could be suitable for industrial, municipal, pharmaceutical and drinking consumption called desalination. Desalination Cost could be dependent on many factors such as intake and outfall techniques, the location of the plant, local electricity price, desalination technology, energy recovery techniques, product water quality requirements, post-treatment methods, storage, distribution and environmental regulations. For example, the cost of desalination is more loss-making than the very amount of natural water to be transported from short distances. However, either pumping of fresh water or transportation from remote areas, could be more costly compared to setting up a new desalination plant nearby (Belessiotis et al., 2016, p. 10). Advances in technology and equipment have resulted in a reduction of 80 percent of the energy used for water production over the last 20 years. Today, the energy needed to produce fresh water from seawater for one household per year (2,000 kW/yr.) is less than that used by the household's refrigerator (Voutchkov et al., 2016). Saudi Arabia, the United Arab Emirates, and the U.S. are the top three desalination producers of drinking water by capacity in the world, followed by Australia, China, and Kuwait (Nicholas, 2019).

2.1 Desalination methods

It is predicted that by 2025, about 14% of the world's population will have to consume desalinated water (Chandrashekara & Yadav, 2017, p. 1319). Desalination methods are divided into two general groups i.e., thermal and nonthermal (membrane) processes. Almost 95 percent of the installed desalination capacity today is either thermal (35 percent) or membrane based (60 percent) technology (Ghaffour et al., 2013, p. 206). The energy required for unit freshwater product is expressed as 'Specific Energy Consumption' (SEC) with units of kWh m^{-3} (Gude, 2011, p. 251).

2.1.1 Thermal desalination

The thermal desalination technique utilizes energy to evaporate saline water and subsequently condense it again to the form of distilled water. Thermal desalination is an effective and suitable solution when there is attainable surplus heat or electricity from adjacent refineries and power plants (IDE Technologies, 2020). To treat large volumes of highly saline water, in locations where energy costs low or when a waste heat source is available, thermal desalination is still the most practical technique. High energy consumption and CO_2 production are two major downsides of this approach (Ahmadvand et al., 2019, p. 696). At the moment, about 75% of thermal desalination sites are installed in Arab countries, and half of them are active in Saudi Arabia (Esmaeilion, 2020, p. 1). The most important thermal desalination technologies mainly include MSF, MED, VCD and HDH.

Multi Stage Flash distillation (MSF)

Multi-stage flash (MSF) units are widely used in the Middle East such that it accounts for 34% of the world's seawater desalination (Morin, 2020, pp. 1–3). Multi-stage flash distillation (MSF) is a desalting water technique that distills salinity by flashing a fraction of the water into vapor in multiple stages that are necessarily forms of countercurrent heat exchangers. Nearly 26% of all desalinated water in the world are generated by MSF units but currently most of the new built desalination units utilize RO due to its much lower energy consumption (Ghaffour et al., 2013, p. 198). The MSF method is most appropriate when the feedwater conditions (temperature, salinity, insoluble matters and high percentages of contaminations) are unfavorable. The typical energy consumption of MSF units is 250–330 kJ/kg of freshwater, and the amount of electricity required for processing is in the range of 3–5 kWh/m^3 (Esmaeilion, 2020, p. 1). Large MSF units are often combined with gas or steam power plants. The generated steam at high temperature and high pressure is first expanded in the turbine of the power plant to generate electricity, and then, the intermediate to low-pressure steam leaves the turbine to be used in the thermal desalination unit. MSF units are usually located at the bottom of steam power plants with a temperature range of 90–120 °C to be used to heat the saline water in the unit. In this combined system by using heat loss as an energy resource in the desalination process, the requirement for condensers in these power plants is eliminated due to the use of turbine exhaust steam for desalination (El-Ghonemy, 2012, p. 6592).

Since the 1960s, the cost for Multi-Stage Flash Distillation (MSF) to desalinate water has decreased approximately by a factor of 10 (Advisian, 2017). Most installations of MSF plants are operated in cogeneration with a power plant. MSF plants can be combined with other desalination technologies such as Nano filtration and Reverse osmosis (RO) in new installation. (El-Ghonemy, 2018, p. 2402). Also, results of the research from El-Ghonemy shows that (2018, p. 2402), running the thermal desalination MSF plant in cold regions is more economic than hot regions for energy saving from pumping power. This is to be considered in future large-scale plants.

Multi Effect Distillation (MED)

Similar to the MSF-method the MED-method relies on the separation of salinity and fresh water with the help of thermal distillation. MED process is applied in various industries such as sugar, paper production, dairy industry and desalination (Esmaeilion, 2020, p. 1). MED units may have horizontal or vertical tubes in which vapor is condensed on one side and heat transfer occurs to the salt water on the other side. Pressure is reduced in each stage (effect) as the temperature declines and additional heat is provided (Water Technology, 2016). In MED processes, using oval shaped corrugated tubes have increased the heat transfer coefficients by 70% in comparison to flat surface round tubes (Desportes et al., 2019, p. 38). The major challenge for the pumps used in MED desalination process is low NPSH available. To overcome this problem, end suction, low NPSH pumps are normally used. Moreover, for larger capacities axial split casing pumps are also applied (SULZER, 2020).

Vapor Compression Distillation (VCD)

VCD units work by compressing water steam that is applied to change the boiling point of water. Compressing water steam use as an evaporating heat source. Recycling crew members' urine in the International Space Station (ISS) is a good example of using VCD technology. According to the data from NASA (2020), VCD is used as plan B for the Water Recovery System (WRS) for NASA astronauts. In case of an unexpected accident for WRS, VCD comes to operation. To generate water steam, the pre-treated urine evaporates at a low pressure and then is compressed to elevate its condensation pressure and temperature. The produced compressed vapor will be directed to the condenser subsequently.

HDH

Humidification-dehumidification (HDH) system consists of a heater, a humidifier, a dehumidifier, and the pumps and piping necessary to move fluid between components. Desalination using the HDH process is an encouraging technology to settle water shortage in rural areas. However, this process suffers from low efficiency of humidifier. Bubble column humidifier (BCH) is a turning point for the HDH process, as it supplies strengthened heat and mass transfer as well as having low maintenance demands (Eder & Preißinger, 2020, p. 110063). In research from Abdelmoez et al. (2013, p. 4635), under one type of classification, HDH systems are based on the form of energy used such as solar, thermal, geothermal, or hybrid systems. This classification brings out the most promising merit of the HDH concept: the promise of water production by use of low-grade energy, especially from renewable resources. Another classification of the HDH systems is based on the type of heating used: water- or air-heating systems. The performance of the system depends greatly on whether the air or water is heated.

In HDH process, the superheated gas is injected into the liquid phase through submerged orifices of a distribution system. The gas forms bubbles that grow at the orifices until reaching a critical volume, at which point they detach. After the formation stage, the bubbles ascend in the liquid column. Transferring Heat and mass occurs during both stages. Part of the exchanged energy is used to vaporize the liquid and the other portion is used to heat the liquid phase. The vapor is removed from the system by the bubbles that reach the top of the liquid column (Campos & Lage, 2001, p. 285). The performance of the system is mainly influenced by the dehumidifier effectiveness. In research from Tow and Lienhard V (2013, pp. 1–3), for efficiency enhancement, capital cost reduction and higher energy recovery in dehumidifier performance, the height of liquid should be minimized as the efficiency is not dependant on liquid height for covering the single loop coil.

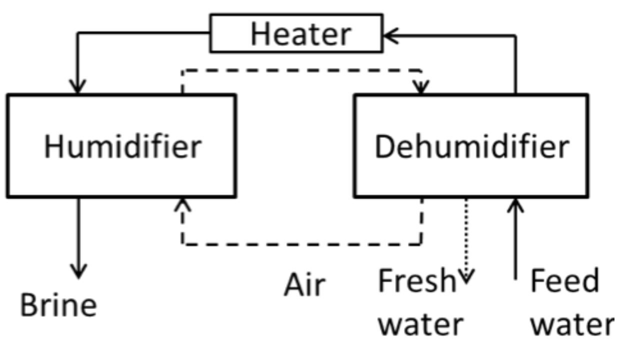

Figure 2.1. Schematic diagram of a typical humidification dehumidification desalination cycle

Source: (Lienhard Research Group, 2016)

Traditional thermal desalination methods are easy to operate and effective but requiring heat to the boiling point for collecting water vapor is an energy consuming process. In research from Schmack et al. (2015, p. 77), to improve the energy efficiency of the thermal method, bubble column evaporators (BCE) could be introduced, as a piece of equipment which has a simpler working mechanism, low construction costs, reduced scaling deposit issues and operates under sub-boiling conditions. BCE works via a process that continuously generates fine bubbles in a column filled with seawater. The bubbles produce by pumping heated dry gas through specific porous sinters under the column. The BCE process offers an improved, more controllable, non-boiling method for thermal desalination, and is able to perform excellent desalination efficiency at high salt concentrations (Wei & Pashley, 2020, p. 8).

Interesting results from Wei and Pashley (2020, p. 3) shows that, pre-heated helium inlet gases can facilitate the evaporation process. The increased evaporation efficiency of about 3.1 times with 75 °C heated Helium inlet illustrates its potential for future seawater desalination because of its relatively low energy consumption compared with other commercial desalination methods. The Helium carrier gas can be recycled during the condensation process to reduce the commercial cost.

2.1.2 Membrane desalination

The pressure-driven membrane separation is divided into four main categories including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). Reverse osmosis (RO) and nanofiltration (NF) that are classified as high-pressure membrane processes, typically include a relatively smaller membrane pore size in comparison with low-pressure membrane i.e. microfiltration (MF) and ultrafiltration (UF). Moreover, membranes can be generally classified into three groups: inorganic, polymeric, or biological membranes. These three types of membranes differ significantly in their structure and functionality (El-Gendi, 2015, p. 58). Over the past three decades, consumption of energy in membrane desalination technologies has decreased remarkably. The main reason for this includes enhancement of high-performance membranes with higher flux and improvement of salt rejection capabilities that automatically decrease high-pressure requirements. Improving membrane characteristics has also led to utilizing more efficient fouling-resistant membranes.

Reverse Osmosis

Using mechanical energy in the pressure form, make RO being able to separate salts from water. Unlike thermal desalination, RO process does not need thermal energy and all processes could be done using merely electricity. In a typical seawater reverse osmosis plant, 3 to 10 kWh of electric energy is required to produce one cubic meter of freshwater (Dashtpour & N. Al-Zubaidy, 2012, p. 340). The pretreatment in the RO process known as a crucial stage in which fouling caused impurities are removed to protect the system membranes (Shevah, 2017, p. 243).

During past decades, while membrane cost has decreased significantly, at the same time, membrane life has risen, mainly owing to development of pretreatment processes and also increasing knowledge for operating RO systems. The amount of freshwater that could be obtained from a sea water ranges between 30 and 75% of the volume of the feed water, depending on the initial water quality, the quality of the product needed, and the technology and the membranes that is applied (Cipollina et al., 2014, p. 3). Seawater reverse osmosis process (SWRO) requires about 3 kWhe m^{-3} for the Mediterranean Sea, Atlantic and Pacific oceans, and 4 kWhe m^{-3} for the Persian Gulf including pre- and post-treatment. Brackish water desalination processes (for salinity in the range of 5000-20000 ppm) require 1.5- 2.5 kWhe m^{-3} (Hanshik et al., 2016, p. 685). Theoretical minimum energy requirement for desalination as a function of percent recovery has been shown in the Figure 2.2. However, it should be noted that the actual energy consumption is larger in practice and additional energy is spent because desalination systems are finite and do not operate as a reversible thermodynamic process (Elimelech & Phillip, 2011, p. 713).

Desalination of saline water via reverse osmosis (RO) could also be driven by Organic Rankine cycle (ORC) engines, exploiting readily available low-grade heat (e.g solar or waste heat). However, the specific energy consumption (SEC) of conventional ORC-RO systems is quite high while its efficiency is significantly low at low temperatures (Igobo & Davies, 2018, p. 741). RO suffers from three fundamental issues: (1) it is very sensitive to high-salinity water, (2) it is not suitable for zero liquid discharge and is therefore environmentally challenging, and (3) it is not compatible with low-grade energy (Ahmadvand et al., 2019, p. 696).

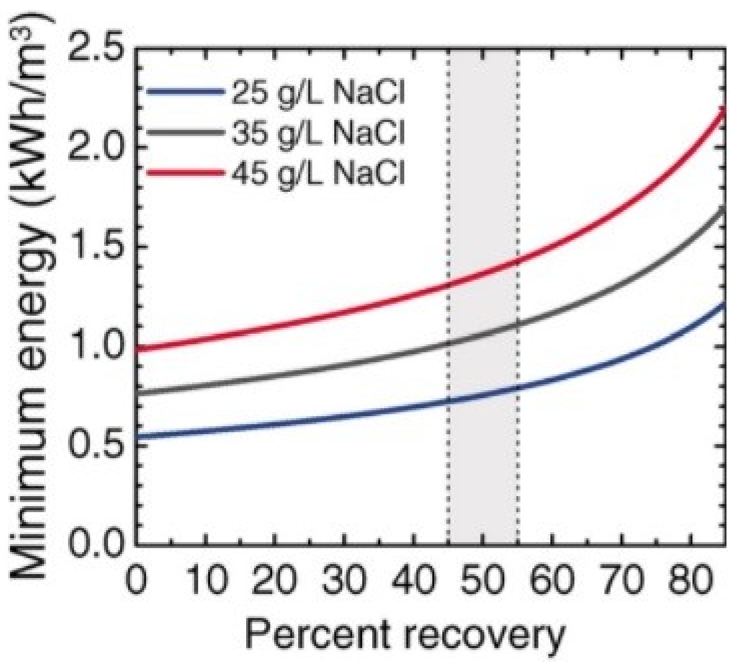

Figure 2.2. Theoretical minimum energy for desalination as a function of percent recovery.

Source: (Elimelech & Phillip, 2011)

2.2 Desalination energy efficiency opportunities

There are several approaches to improve desalination energy efficiency. "Co-production approaches" and "performance improvement" which are mentioned in sections 2.2.1 and 2.2.2, look into the opportunities for increasing energy efficiency of a desalination plant.

2.2.1 Co-production approaches

Desalination plants are often built close to thermal power plants since large quantities of heat are needed to evaporate the seawater. Waste heat produced as a byproduct during the generation of electricity can therefore be recovered by the desalination plant (Planète Energies, 2019). As mentioned by Lee and Younos (2019), from a water-energy nexus point of view and for providing chances for energy consumption efficiency in desalination plants, three attitudes including co-located plants, cogeneration plants and hybrid plants could be utilized to improve desalination process. In the co-located approach, a desalination facility is co-located with a power plant usually in a coastal area in which the power plant uses seawater as its cooling water. In fact, power plant cooling water is used as feed water for desalination that subsequently requires less energy for heating. Co-located desalination plants with power generation stations may yield measurable improvement in the economics of seawater and brackish water desalination and offer cost-reduction advantages as a result of use of shared intake and discharge facilities, and reduced desalination power costs (Voutchkov, 2007). In the cogeneration approach, high temperature steam which is normally considered as the power plant waste is utilized as an additional source of energy during the desalination process. In research from Shahzad et al. (2019, p. 1), the co-generation of electricity, steam and desalinated water via improved combined cycle gas turbines (CCGTs) have recorded high energy efficiency. General Electric (GE) with the partnership of ENGIE (formerly known as Electricity De France or EDF) set a world record by achieving a 62% efficiency of the most advanced CCGT power plant operating in Japan. In the third approach i.e. hybrid plants, for enabling the plant to optimize performance and energy reuse, a combination of treatment technologies is applied. Hybrid desalination processes that are resulted by combining membrane filtration and thermal desalination technologies, help reduce energy consumption expenses as well as the carbon footprint emission of the project impressively. For some special cases, reducing these unwanted items had been reported to be up to $400 million per annum (Awerbuch, 2014).

2.2.2 Performance improvement potentials

There are several approaches to enhance desalination technologies, and in particular to decrease the desalination energy cost. According to the research from Wei and Pashley (2020, p. 4), the bubble column evaporator (BCE) process is a promising method for thermal seawater desalination with improved evaporation efficiency. Using pre-heated helium gas instead of air can increase evaporation efficiency up to 3 times. This dramatically low energy consumption could make this sub-boiling thermal desalination technique as future of seawater desalination compared with other commercial desalination techniques. In MED processes, using oval shaped corrugated tubes increases the heat transfer coefficients by 70% in comparison to flat surface round tubes (Desportes et al., 2019, p. 38). In the MED process, low NPSH is the major problem for the pumps. To overcome this problem, end suction pumps with lower NPSH are usually utilized. Moreover, axial split case pumps are applied for higher production capacities (SULZER, 2020).

According to LennTech (2020), the concentrate effluent has relatively high pressure as it only lost 1.5-2 bar of its initial pressure due to passing through membranes. This pressure drop is relevant to the number of membranes in each pressure vessel. Energy Recovery Device (ERD) enables reusing the energy from the concentrate flow. The concentrate is directed to the ERD where it directly transfers its energy to part of the incoming feed water. Energy Recovery Turbine (ERT) and Pressure Exchanger (PX) are two main energy recovery systems. ERT and

PX provide up to 30-40% and 50-60% energy saving respectively. Energy Recovery devices have reached high development to the extent that the latest devices gained up to 97% efficiency that let some desalination facilities achieve specific energy consumption of 3 kWh m^{-3} (Schunke et al., 2020, p. 3).

Time-variable operation is another approach for improving performance of the RO process. As energy costs comprise the major operating costs of a RO process so that could be considered as a main reason for moving toward time-variable operation of RO. Most of the early work on optimization of RO, assume constant operation and constant electricity costs (Ghobeity & Mitsos, 2014, p. 65). Using the variable operation approach for increasing efficiency of RO has led to valuable results. The optimization results show that winter operation requests the RO process to utilize more membrane modules than in summer. On the other hand, summer operation requires less pressure compared to that in winter season to meet the variable demand of freshwater leading to lower power consumption (Sassi & Mujtaba, 2013, p. 107).

3. Discussion

Abundant seawater and brackish water sources as well as fast-developing desalination techniques and researches will provide significant opportunities to address current and future water scarcity problems (Lee & Younos, 2019). In many arid parts of the world such as the Middle East, Australia, Northern Africa and Southern California, the population concentration along the coast exceeds 75 percent. Seawater desalination provides a logical solution for the sustainable, long-term management of growing water demand (Voutchkov et al., 2016).

Thermal methods are more expensive than membrane ones because of the large quantities of fuel required to vaporize salt water. However, they are more efficient in terms of desalination of very salty water than the membrane technologies (Antonyan, 2019, pp. 1–3). Thermal desalination technologies rely on both electricity and heat for separation of salt from water while conventional membrane desalination technologies need electrical energy to be converted to mechanical energy for separating freshwater from saline water. Thermal energy, especially when obtained by solar and waste heat sources, should be considered as an important component in reducing water desalination costs (Omar et al., 2020, p. 109609). If there is a thermal power plant nearby, building a thermal desalination plant such as MSF could be more efficient in comparison with a Reverse Osmosis one. However, one major barrier that hinders the wider application of MED and MSF is the high initial plant cost, which limits them to large-scale operations (Chen et al., 2020, p. 1). Using the SWRO method is very economical in terms of operating costs (0.47 USD/m^3) followed by the MED (0.54 USD/m3). The cost of using the MSF method is 0.65 USD/m3 that puts it at the bottom of the selection queue, and this will make many obstacles to construct new units (El-Ghonemy, 2012, p. 6592). While the final costs of desalination by the thermal methods are higher than reverse osmosis, it requires much less preparation and preprocessing in which the obtained water has a higher quality and does not require post-treatment processes such as boron, chloride or bromide removal. The reverse osmosis membrane is sensitive to changes in pH, oxidizers, a wide range of organic matter, algae and bacteria, as well as other particles and sediments. Moreover, in mining industries and refineries such as alumina refineries, thermal desalination processes such as MED and MSF are more suitable than RO processes, which cannot handle the process streams because of significant fouling (Rahimi & Chua, 2017, p. 5). Therefore, there are several precautions to prevent extra charges in a RO system performance (Esmaeilion, 2020, p. 1). In comparison with MSF desalination, Reverse Osmosis needs more maintenance and seawater pretreatment procedures. MSF can run with cheaper and low-grade waste heat which makes it a win card against RO. In research from El-Ghonemy (2018, p. 2411), new MSF plants are recommended, where large amounts of cheap or waste energy are available.

In research from Rahimi and Chua (2017, p. 4), the main difference between MED and MSF is related to the difference between boiling and flashing evaporation phenomena. Flashing technique (MSF process) requires much more feed water and pressure difference compared to the boiling technique (MED process) for producing the same amount of vapor. This means that the flashing technique consumes much more pumping power. The other difference is related to the top brine temperature (TBT) and scaling issue. Because of the design of MED processes, some cleaning procedures that can be applied to MSF cannot be used in MED, thus, the best way to manage scaling is to keep the TBT to around 65-70 C. Also, in comparison with the MED process, MSF has higher resistance against scaling but it has a disadvantage of lower recovery ratio. MSF and MED processes consume both thermal and electrical energy. For typical MSF plants with the maximum live steam (as heat source) temperature of 120 C, the thermal energy consumption is around 12 kWh/m3 of produced freshwater, while it is around 6 kWh/m3 for an MED plant, which operates at lower temperatures of less than 70 C (Lattemann & Höpner, 2008, p. 6). In contrast, RO processes only consume electrical energy in a range between 3 and 7 kWh/m3 for seawater application. Thus, the overall energy consumption of RO processes is closer to the minimum theoretical consumption threshold compared to MED and MSF processes. However, it does not mean that the RO’s unit product cost is necessarily cheaper than the thermal processes. As it mentioned earlier, in addition to energy consumption, there are many other issues that can influence the product costs (Rahimi & Chua, 2017, p. 5).

Humidification-dehumidification (HDH) is suitable for small-scale operation (Chen et al., 2020, p. 1). However, the productivity of HDH is limited by the small vapor-carrying capability of air, and the footprint size is relatively large due to small heat and mass coefficients between wet air and condenser surface (Chen et al., 2018, p. 1004). Cost of water production using HDH cycles is still high. However, this high cost could be lessened to a more suitable level by applying a renewable source of energy for water and air heating. Also, for more heat recovery having the right choice between single or multiple stages in which the air before the humidifier is heated is quite effective. The results of an experiment performed by Zamen et al. (2014, p. 2) showed that a two-stage desalination unit had 20% more production than a similar single-stage unit and the improvement was negligible when more than two stages were used. Considering the cost of unit production, the results suggest the best choice would be a two-stage unit. Assessing the latest research related to thermal desalination also shows, minimizing liquid height in the dehumidifier is also influential for energy recovery of the HDH system. The most important, novel and promising improvement technique that could work for all thermal desalination processes in which water vaporizing is applied, is utilizing pre-heated helium inlet gas that could increase evaporation efficiency up to about 3 times. Unlike its counterpart RO, the feed solution in the

BCE process can be highly contaminated without pre-treatment because the water-air interface is the natural membrane (Wei & Pashley, 2020, p. 8). The HDH system advantages become more highlighted for smaller scale decentralized water production systems that include much simpler pretreatment of brine, disposal requirements and simplified maintenance and operation (Abdelmoez et al., 2013, p. 4626). In this regard, this could be similar to VCD technique where it is mostly used for small- to medium-scale desalination plants (Al-Karaghouli & Kazmerski, 2011, p. 183). VCD technique often used in industries where freshwater is not readily available (Buros et al., 1999, pp. 1–3).

Energy recovery is a main challenge for all desalination techniques as they consume a high amount of energy. Although the energy recovery tactics are different, all of them pursue a common goal which is total energy reduction of the system. RO is the fastest growing desalination process compared to other desalination technologies due to the reduction in membrane costs and developments of energy recovery devices (Ghobeity & Mitsos, 2014, p. 63). Energy Recovery Devices (ERDs) enable reusing the energy from the concentrate flow. Applying ERDs do not necessarily mean energy recovery for all the systems. For example, Model calculations revealed that FO–RO is more energy efficient than RO when no ERD was employed (Altaee et al., 2016, p. 80). Time-variable operation is another promising approach toward increasing efficiency of RO technology. optimization of time-variable operation in desalination can offer significant advantages, particularly in cogeneration concepts. However, there are multiple challenges with the time-variable operation of desalination systems, including the increased potential in membrane fouling, the need for back-washing, sensitivity of membranes to frequent start-stops and membrane degradation (Ghobeity & Mitsos, 2014, p. 65).

It must be mentioned that one of the main disadvantages of ROs is not having the compatibility with low-grade energy. For overcoming this issue many endeavors including applying ORC engines for using low-grade heat have been made. However, the specific energy consumption of conventional ORC-RO systems is quite high while its efficiency is significantly low at low temperatures. Cogeneration scheme has enabled low-cost energy input to desalination processes and the overall economics are significantly favorable compared to stand-alone desalination and power generation units (Gude & Fthenakis, 2020). Also, Hybridization of different thermal and membrane processes has also been considered for energy utilization. These include MSF-RO combination and MSF-MED-RO configuration among others (Gude & Fthenakis, 2020). The largest hybrid MED-RO plant which is constructed by SIDEM and Veolia is the second phase of UAE’s Fujairah project, capable of generating 2000 MW of electricity and 591,000 m3/d of freshwater.

5. Conclusion

Desalination of seawater is an attractive choice for producing fresh water mainly for those regions where there is no adequate water supply alternative. As desalination procedures are energy consuming, there have been tremendous endeavors to improve energy efficiency of the desalination units.

This review shows that Reverse Osmosis and Multi-Effect Distillation technologies are the leading techniques in the desalination market. Using either thermal or Reverse Osmosis desalination methods is depending on many factors. When there is waste heat or sufficient electricity available, as is often the case with refineries and power plants, thermal desalination is an efficient and viable solution. As reverse osmosis technology is very sensitive to high-salinity water, thermal desalination is more efficient in terms of desalination of very salty water than the membrane technologies. In MED processes, using oval shaped corrugated tubes as well as utilizing low NPSH pumps increases system efficiency dramatically. However, Reverse osmosis is the most extensively applied desalination technique now. Today energy-recovery devices that use pressure drop over the RO membranes recover up to 97% of the waste energy released in the time of depressurization of the brine. Even so, Reverse Osmosis raises environmental fears over production of substantial amounts of chemicals-containing brine as well as the high greenhouse emissions.

Thermal and reverse osmosis desalination should not be considered as a competitor since (mostly) the feed water quality and the needed permeate water standards impose choosing either of the most appropriate desalination method or hybridization of both approaches. Desalination of seawater using improved thermal desalination in which bubble column evaporator (BCE) process is applied to generate fresh water, is a promising technique that consumes less energy to boil water compared to traditional thermal desalination process. Using pre-heated helium gas instead of air can increase evaporation efficiency up to 3 times. This dramatically low energy consumption, could make this sub-boiling thermal desalination technique the future of seawater desalination compared with other commercial desalination techniques. Bubble column humidifiers (BCH) are favorable for HDH, as they provide enhanced heat and mass transfer as well as having low maintenance requirements. However, the cost of water production using HDH cycles is still high but this could be reduced to a more suitable level by applying a renewable source of energy for water and air heating, using a two-stage desalination unit and minimizing liquid height in the dehumidifier. Now, knowing the fact that pre-heated helium gas bubble column is dramatically reduce energy consumption of thermal desalination is one thing, and industrializing it is another. Therefore, more research strongly needed to be done for the industrialization of this process.

This review confirms that applying a suitable hybrid system for desalination is a trusted option that increases efficiency as well as reducing investment costs. Cogeneration approach allows water desalination by use of low-grade energy that save operation costs in comparison with stand-alone desalination units. Also, Co-located power generation stations and desalination plants improve desalination efficiency remarkably as well as cost reduction due to shared intake and discharge facilities. Time-variable operation is another approach for improving performance particularly for the RO process. Although it still faces some challenges, optimization of time-variable operation in desalination can offer significant advantages, specifically in cogeneration concepts.

Credit authorship contribution statement

Babak Akram: Conceptualization, Data curation, Investigation, Formal analysis, Writing - original draft, review & editing

Conflict of interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abdelmoez, W., Mahmoud, M. S., & Farrag, T. E. (2013). Water desalination using humidification/dehumidification (HDH) technique powered by solar energy: a detailed review. *Desalination and Water Treatment*, *52*(25–27), 4622–4640. https://doi.org/10.1080/19443994.2013.804457

Advisian. (2017). *The Cost of Desalination*. Advisian. https://www.advisian.com/en/global-perspectives/the-cost-of-desalination#

Ahmadvand, S., Abbasi, B., Azarfar, B., Elhashimi, M., Zhang, X., & Abbasi, B. (2019). Looking Beyond Energy Efficiency: An Applied Review of Water Desalination Technologies and an Introduction to Capillary-Driven Desalination. *Water*, *11*(4), 696. https://doi.org/10.3390/w11040696

Altaee, A., Millar, G. J., Zaragoza, G., & Sharif, A. (2016). Energy efficiency of RO and FO–RO system for high-salinity seawater treatment. *Clean Technologies and Environmental Policy*, *19*(1), 77–91. https://doi.org/10.1007/s10098-016-1190-3

Antonyan, M. (2019). *Energy Footprint of Water Desalination*. LAP LAMBERT Academic Publishing.

Awerbuch, L. (2014, December 24). *Hybrid Desalination: The Best of Both Worlds?* Water World. https://www.waterworld.com/international/desalination/article/16200955/hybrid-desalination-the-best-of-both-worlds

Belessiotis, V., Kalogirou, S., & Delyannis, E. (2016). Desalination Methods and Technologies —Water and Energy. *Thermal Solar Desalination*, 1–19. https://doi.org/10.1016/b978-0-12-809656-7.00001-5

Buros, O. K., International Desalination Association (IDA), Corporation, S. W. C., International Desalination Association (IDA), & Saline Water Coversion Corporation (SWCC). (1999). The ABCs of Desalting (2nd ed.). International Desalination Association.

Campos, F. B., & Lage, P. L. C. (2001). Modeling and simulation of direct contact evaporators. *Brazilian Journal of Chemical Engineering*, *18*(3), 277–286. https://doi.org/10.1590/s0104-66322001000300007

Chen, Q., Kum Ja, M., Li, Y., & Chua, K. J. (2018). Evaluation of a solar-powered spray-assisted low-temperature desalination technology. *Applied Energy*, *211*, 997–1008. https://doi.org/10.1016/j.apenergy.2017.11.103

Chen, Q., Burhan, M., Wakil Shahzard, M., Alrowais, R., Ybyraiymkul, D., Hassan Akhtar, F., Li, Y., & Choon Ng, K. (2020). A Novel Low-Temperature Thermal Desalination Technology Using Direct-Contact Spray Method. Desalination - Challenges and Opportunities, 1. https://doi.org/10.5772/intechopen.92416

Cipollina, A., Tzen, E., Subiel, V., Papapetrou, M., Koschikowsk, J., Schwantes, R., Wieghaus, M., & Zaragoza, G. (2014). Renewable energy desalination: performance analysis and operating data of existing RES desalination plants. *Desalination and Water Treatment*, 1–21. https://doi.org/10.1080/19443994.2014.959734

Dadmand, F., Naji-Azimi, Z., Motahari Farimani, N., & Davary, K. (2020). Sustainable allocation of water resources in water-scarcity conditions using robust fuzzy stochastic programming. Journal of Cleaner Production, 276, 123812. https://doi.org/10.1016/j.jclepro.2020.123812

Dashtpour, R., & N. Al-Zubaidy, S. (2012). Energy Efficient Reverse Osmosis Desalination Process. *International Journal of Environmental Science and Development*, *3*, 339–345. http://www.ijesd.org/papers/243-B20001.pdf

Desportes, I., Mandefro, H., & Hilhorst, D. (2019). The humanitarian theatre: drought response during Ethiopia's low-intensity conflict of 2016. *The Journal of Modern African Studies*, *57*(1), 31–59. https://doi.org/10.1017/s0022278x18000654

Eder, E., & Preißinger, M. (2020). Experimental analysis of the humidification of air in bubble columns for thermal water treatment systems. Experimental Thermal and Fluid Science, 115, 110063. https://doi.org/10.1016/j.expthermflusci.2020.110063

El-Gendi, A. T. A. E.-A. (2015). Phase Diagram and Membrane Desalination. Desalination Updates, 38–72. https://doi.org/10.5772/60419

Elimelech, M., & Phillip, W. A. (2011). The Future of Seawater Desalination: Energy, Technology, and the Environment. *Science*, *333*(6043), 712–717. https://doi.org/10.1126/science.1200488

El-Ghonemy, A. M. K. (2018). Performance test of a sea water multi-stage flash distillation plant: Case study. *Alexandria Engineering Journal*, *57*(4), 2401–2413. https://doi.org/10.1016/j.aej.2017.08.019

El-Ghonemy, A. M. K. (2012). RETRACTED: Future sustainable water desalination technologies for the Saudi Arabia: A review. *Renewable and Sustainable Energy Reviews*, *16*(9), 6566–6597. https://doi.org/10.1016/j.rser.2012.07.026

Esfahani, I. J., Rashidi, J., Ifaei, P., & Yoo, C. K. (2016). Efficient thermal desalination technologies with renewable energy systems: A state-of-the-art review. *Korean Journal of Chemical Engineering*, *33*(2), 351–387. https://doi.org/10.1007/s11814-015-0296-3

Esmaeilion, F. (2020). Hybrid renewable energy systems for desalination. *Applied Water Science*, *10*(3), 1. https://doi.org/10.1007/s13201-020-1168-5

Fan, C., Shahid, M., & Pashley, R. M. (2017). The energy balance within a bubble column evaporator. *Heat and Mass Transfer*, *54*(5), 1313–1321. https://doi.org/10.1007/s00231-017-2234-x

Ferroukhi, R., Nagpal, D., López-Peña, Á., Hodges, T., Mohtar, R., Daher, B., Mohtar, S., & Keulertz, M. (2015). *Renewable Energy in the Water, Energy & Food Nexus*. International Renewable Energy Agency (IRENA). https://www.researchgate.net/publication/277565584

Fritzmann, C., Löwenberg, J., Wintgens, T., & Melin, T. (2007). State-of-the-art of reverse osmosis desalination. *Desalination*, *216*(1–3), 1–76. https://doi.org/10.1016/j.desal.2006.12.009

Ghaffour, N., Missimer, T. M., & Amy, G. L. (2013). Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability. *Desalination*, *309*, 197–207. https://doi.org/10.1016/j.desal.2012.10.015

Ghobeity, A., & Mitsos, A. (2014). Optimal design and operation of desalination systems: new challenges and recent advances. Current Opinion in Chemical Engineering, 6, 61–68. https://doi.org/10.1016/j.coche.2014.09.008

Gude, V. G., Nirmalakhandan, N., & Deng, S. (2010). Renewable and sustainable approaches for desalination. Renewable and Sustainable Energy Reviews, 14(9), 2641–2654. https://doi.org/10.1016/j.rser.2010.06.008

Gude, V. G. (2011). Energy consumption and recovery in reverse osmosis. Desalination and Water Treatment, 36(1–3), 239–260. https://doi.org/10.5004/dwt.2011.2534

Gude, V. G., & Fthenakis, V. (2020). Energy efficiency and renewable energy utilization in desalination systems. *Progress in Energy*, *2*(2), 022003. https://doi.org/10.1088/2516-1083/ab7bf6

Hanshik, C., Jeong, H., Jeong, K.-W., & Choi, S.-H. (2016). Improved productivity of the MSF (multi-stage flashing) desalination plant by increasing the TBT (top brine temperature). *Energy*, *107*, 683–692. https://doi.org/10.1016/j.energy.2016.04.028

IDE Technologies. (2020). *Thermal Desalination (MED & MVC)*. IDE-Tech. https://www.ide-tech.com/en/solutions/desalination/thermal-desalination-med-mvc/?data=item_1

Igobo, O. N., & Davies, P. A. (2018). Isothermal Organic Rankine Cycle (ORC) driving Reverse Osmosis (RO) desalination: Experimental investigation and case study using R245fa working fluid. *Applied Thermal Engineering*, *136*, 740–746. https://doi.org/10.1016/j.applthermaleng.2018.02.056

Kadaj, E., & Bosleman, R. (2018). Energy Recovery Devices in Membrane Desalination Processes. Renewable Energy Powered Desalination Handbook, 415–444. https://doi.org/10.1016/b978-0-12-815244-7.00011-8

Lattemann, S., & Höpner, T. (2008). Environmental impact and impact assessment of seawater desalination. Desalination, 220(1–3), 1–15. https://doi.org/10.1016/j.desal.2007.03.009

Lee, J., & Younos, T. (2019, September 10). *Desalination: Opportunities and Challenges*. Water World. https://www.waterworld.com/home/article/14071194/desalination-opportunities-and-challenges

LennTech. (2020). *Sea water desalination*. https://www.lenntech.com/industries/sea-water-desalination.htm

Li, W., Hai, X., Han, L., Mao, J., & Tian, M. (2020). Does urbanization intensify regional water scarcity? Evidence and implications from a megaregion of China. Journal of Cleaner Production, 244, 118592. https://doi.org/10.1016/j.jclepro.2019.118592

Lienhard Research Group. (2016). *Schematic diagram of a typical humidification dehumidification desalination cycle* [Illustration]. MIT. https://lienhard.mit.edu/wp-content/uploads/2016/10/Picture1.png

Morin, O. J. (2020). *THERMAL DESALINATION PROCESSES* (Vol. 1). EOLSS Publications.

NASA. (2020). *LSDA Hardware - Backup Water Recovery System (WRS)*. NASA Life Sciences Data Archive. https://lsda.jsc.nasa.gov/Hardware/hardw/1096

Nicholas, N. (2019, August 29). *Pros and Cons of Seawater Desalination Using RO for Drinking Water*. Water Online. https://www.wateronline.com/doc/pros-and-cons-of-seawater-desalination-using-ro-for-drinking-water-0001

Omar, A., Nashed, A., Li, Q., Leslie, G., & Taylor, R. A. (2020). Pathways for integrated concentrated solar power - Desalination: A critical review. *Renewable and Sustainable Energy Reviews*, *119*, 109609. https://doi.org/10.1016/j.rser.2019.109609

Rahimi, B., & Chua, H. T. (2017). Introduction to Desalination. *Low Grade Heat Driven Multi-Effect Distillation and Desalination*, 1–17. https://doi.org/10.1016/b978-0-12-805124-5.00001-2

Sassi, K. M., & Mujtaba, I. M. (2013). Optimal operation of RO system with daily variation of freshwater demand and seawater temperature. *Computers & Chemical Engineering*, *59*, 101–110. https://doi.org/10.1016/j.compchemeng.2013.03.020

Schmack, M., Ho, G., & Anda, M. (2015). A bubble column evaporator with basic flat-plate condenser for brackish and seawater desalination. *Environmental Technology*, *37*(1), 74–85. https://doi.org/10.1080/09593330.2015.1063706

Schunke, A. J., Hernandez Herrera, G. A., Padhye, L., & Berry, T.-A. (2020). Energy Recovery in SWRO Desalination: Current Status and New Possibilities. *Frontiers in Sustainable Cities*, *2*, 1–7. https://doi.org/10.3389/frsc.2020.00009

Shahid, M., & Pashley, R. M. (2014). A study of the bubble column evaporator method for thermal desalination. Desalination, 351, 236–242. https://doi.org/10.1016/j.desal.2014.07.014

Shahzad, M. W., Ng, K. C., Thu, K., Saha, B. B., & Chun, W. G. (2014). Multi effect desalination and adsorption desalination (MEDAD): A hybrid desalination method. *Applied Thermal Engineering*, *72*(2), 289–297. https://doi.org/10.1016/j.applthermaleng.2014.03.064

Shahzad, M. W., Burhan, M., & Ng, K. C. (2019). A standard primary energy approach for comparing desalination processes. Npj Clean Water, 2(1), 1. https://doi.org/10.1038/s41545-018-0028-4

Shevah, Y. (2017). Challenges and Solutions to Water Problems in the Middle East. Chemistry and Water, 207–258. https://doi.org/10.1016/b978-0-12-809330-6.00006-4

Shon, H. K., Phuntsho, S., Chaudhary, D. S., Vigneswaran, S., & Cho, J. (2013). Nanofiltration for water and wastewater treatment – a mini review. Drinking Water Engineering and Science, 6(1), 47–53. https://doi.org/10.5194/dwes-6-47-2013

Skuse, C., Gallego-Schmid, A., Azapagic, A., & Gorgojo, P. (2021). Can emerging membrane-based desalination technologies replace reverse osmosis? *Desalination*, *500*, 114844. https://doi.org/10.1016/j.desal.2020.114844

SULZER. (2020). *Multi Effect Distillation MED | Sulzer*. https://www.sulzer.com/en/shared/applications/multi-effect-distillation-med

Tow, E. W., & Lienhard V, J. H. (2013). *HEAT FLUX AND EFFECTIVENESS IN BUBBLE COLUMN DEHUMIDIFIERS FOR HDH DESALINATION*. The International Desalination Association World Congress on Desalination and Water Reuse, Tianjin, China. http://web.mit.edu/lienhard/www/papers/conf/TOW_IDA_Tianjin_2013.pdf

Planète Energies. (2019, March 5). What are the different methods used for seawater desalination? https://www.planete-energies.com/en/medias/close/what-are-different-methods-used-seawater-desalination

U.S. Department of Energy. (2019, April). Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Martime Markets. Energy.gov. https://www.energy.gov/sites/prod/files/2019/03/f61/Chapter%207.pdf

Voutchkov, N. (2007, January 1). *Power Plant Co-Location Reduces Desalination Costs, Environmental Impacts*. Water Tech Online. https://www.watertechonline.com/home/article/14171329/power-plant-colocation-reduces-desalination-costs-environmental-impacts

Voutchkov, N., Trommsdorf, C., Veras, R., & Miller, A. (2016, August 17). *Desalination – Past, Present and Future*. International Water Association. https://iwa-network.org/desalination-past-present-future/

Water Technology. (2016). *Desalination basics*. WaterTechOnline. https://www.watertechonline.com/processwater/article/15550278/desalination-basics

Wei, R., & Pashley, R. M. (2020). An improved evaporation process with helium inlet in a bubble column evaporator for seawater desalination. *Desalination*, *479*, 1–9. https://doi.org/10.1016/j.desal.2020.114329

Winter, T., Pannell, D. J., & McCann, L. (2013, June 16). *The Economics of Desalination and its Potential Application in Australia*. University of Western Australia. https://dpannell.science.uwa.edu.au/dpap0102.htm

Woo, Y. C., Kim, S.-H., Shon, H. K., & Tijing, L. D. (2019). Introduction: Membrane Desalination Today, Past, and Future. Current Trends and Future Developments on (Bio-) Membranes, xxv–xlvi. https://doi.org/10.1016/b978-0-12-813551-8.00028-0

World Water Day 2020: Desalination technologies provide safe and sustainable drinking water. (2020, March 23). Cordis European Commission. https://cordis.europa.eu/article/id/415568-world-water-day-2020-desalination-technologies-provide-safe-and-sustainable-drinking-water

Zamen, M., Soufari, S. M., Vahdat, S. A., Amidpour, M., Zeinali, M. A., Izanloo, H., & Aghababaie, H. (2014). Experimental investigation of a two-stage solar humidification–dehumidification desalination process. *Desalination*, *332*(1), 1–6. https://doi.org/10.1016/j.desal.2013.10.018