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REVIEW OF RECENT DESALINATION DEVELOPMENTS FOR MORE EFFICIENT DRINKING WATER PRODUCTION ACROSS THE WORLD

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Abstract. This review paper aims to summarize the recent developments of desalination as an efficient method for drinking water production in water scarce areas. The main desalination technologies are discussed and big focus is given in the energy costs of desalination as well as to the parameters affecting the overall process costs. The review goes further in describing several case studies in some of the more characteristic water scarce areas around the globe and then it describes some representative recent developments, in the direction of novel membranes developments such as inorganic membranes, application of ceramic membranes, use of layer by layer technology. The main outcome is that desalination has a bright future. A big number ot plants are expected to be installed in the next decade and the improved technologies will enable the reduction of cost to values much below the 1 kwh/m^3.

Keywords: *desalination, energy, forward osmosis, layer by layer technology.*

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1. Introduction

Water is fundamental for the existence of life on Earth. Although water covers two thirds the surface of earth, only a small portion of this water is suitable for human consumption and use. With the increasing world population and the changing climate, the scarcity of fresh water resources has become a critical issue (Mekonnen & Hoekstra, 2016). Currently, one fifth of the world's population is facing scarcity in water resources. Another one quarter do have access to water, however they lack proper treatment methods to make it potable. By 2030, this water shortage is expected to affect up to 40% of world inhabitants (Mekonnen & Hoekstra, 2016).

Until recently, seawater desalination has been limited to the desert climate dominated regions of the World (Deliyannis, 2003). Dramatic improvements in membrane technology and energy recovery equipment over the past 20 years have allowed two-fold reduction of power needed to desalinate seawater (Elimelech & Philip, 2011; Voutchkov, 2018). Such advancements have rendered desalination more affordable and attractive alternative for sustainable water supply. The use of desalination for production of fresh drinking and industrial water has gained a significant momentum over the past two decades. In the present review study, we summarize the historical advancements of desalination, we report on case studies that have been accomplished and solved pressing societal problems and we finally focus on the forward osmosis and other recent developments for desalination to highlight the modern direction in order to improve efficiency and reduce costs.

2. Desalination: Past and Present

Ever since desalination was originally invented in antiquity, different technologies have been developed. Back in the 4th century BC, Aristotle, the Hellenic philosopher, described a desalination technique by which non-potable water evaporated and finally condensed into potable liquid. Likewise, Alexander of Aphrodisias in the 200 AD described a technique used by sailors, as follows: seawater was boiled to produce steam, and that steam was then absorbed by sponges, thereby resulting in potable water. In the past decades, the technology of seawater desalination for the production of potable water evolved rapidly and has become quite popular (Deliyannis, 2003).

Desalination is growing so fast globally that it is more than certain that it will play a significant role in water supply in the years to come. Desalination is growing particularly in parts of the world where water availability is low. Annual desalination capacity increases rapidly as years go by (Elimelech & Phillip, 2011, Voutchkov, 2018).

A sharp increase in the number of desalination projects to supply water is indicated. This rose from 326 m^3 /d in 1945 to over 5,000,000 m^3 /d in 1980 and to more than 35 million m^3 /d in 2004. In 2008, the total daily capacity was 52,333,950 m^3 /d, from some 14,000 plants in operation globally. In 2011, the total capacity was about 67 million m^3 /d, while in 2012 it was estimated at about 79 million m^3 /d from around 16 thousand plants worldwide. As of June 30, 2016 the total number of desalination plants worldwide was 18,983 and these plants have cumulative fresh water production capacity of 95.6 million m^3/day (Voutchkov, 2018).

The global capacity of desalination plants is expected to grow at an annual rate of more than 9% until 2030. The market is set to grow in both developed and emerging countries such as the United States, China, Saudi Arabia (SA) and the United Arab Emirates (UAE). A very significant potential also exists in rural and remote areas, as well as on islands, where grid electricity or fossil fuels to generate energy may not be available at affordable costs. About 54% of the global growth is expected to occur in the Middle East and North Africa (MENA) region, where from the 21 million m^3 /d of desalinated water in 2007, the capacity is expected to reach 110 million m^3 /d by 2030, of which 70% is in SA, the UAE, Kuwait, Algeria and Libya (Albawaba, 2018).

The majority of the largest desalination plants (in operation or under construction) use seawater and are located in the Middle East. The biggest desalination plant is the Ras Al-Khair in the city of Ras Al-Khair (also called Ras Al-Zour or Ras Azzour) SA, which uses both membrane and thermal technology with a capacity over 1,000,000 m^3/d, in operation since 2013. The Ras Al-Khair plant supplies Maaden factories with 25,000 m^3 of desalinated water and 1350 MW of electricity. It also supplies with water the capital city of Riyadh and several central cities with a total need of 900,000 m^3/d. Another example is the 880,000 m^3/d MSF Shuaiba 3 desalination plant that is located along the east coast of SA and supplies with potable water the cities of Jeddah, Makkah, and Taif. SA also hosts the Ras Al-Zour unit, producing 800,000 m^3/d of water.

3. Desalination technologies

Desalination is a process by which dissolved salts are removed from seawater or brines water thereby converting it into potable water. There are two classes of desalination: thermal or, distillation process, heats the saltwater to boiling, collects and condenses the steam producing purified water; the membrane class Reverse Osmosis (RO) and Electro-Dialysis reversal (EDR) method involves forcing salt water across a semipermeable membrane that separate the salts from the water leaving a saline solution or brine on one side and a “de-saline” solution (drinkable water) on the other (El-Dessouky & Ettouney, 2002). The following are the most frequently used types of desalination:

Multi-Stage Flash Distillation (MSF) is a type of thermal desalination. Salt water is heated under extreme pressures and lead through a series of chambers. The first chamber is under a lower pressure than the salt water that enters it allowing a portion of the salt water to vaporize and be collected. Upon leaving the first chamber the salt water enters several more chambers each with a lower pressure than the previous one allowing even more of the pressurized salt water to vaporize. The sum of the vaporized water is collected and re-condensed into distilled water. The water that did not vaporize leaves the system with a higher saline concentration than when it entered; this is discarded properly as waste while the distilled water is put into the municipal water supply as drinkable water (Water for all, 2017).

Multiple Effect Distillation (MED) is a type of thermal desalination. Salt water is heated under pressure and and forced through a chamber. A portion of the salt water evaporates leaving behind a slightly more saline solution than the original salt water. However, in this system the water vapor from the first chamber is used to heat the water in the next chamber (that is under a lower pressure than the previous chamber). Though this pattern repeats throughout several chambers to increase the efficiency of the overall system, the underlying process is trying to use the heat of condensation to heat the next batch of salt water; this produces distilled water (the condensed water vapor) and more water vapor (the cycle repeats) (Water for all, 2017).

Reverse Osmosis (RO): is a type of membrane desalination. Here salt water is forced under high pressures through a semipermeable membrane that produces relatively pure water on the downstream side and leaves saline-rich water on the source side. Because membrane cleanliness is crucial to the efficiency of this mechanism, salt water is treated with some initial filters to remove particulate matter. Additionally, after the water passes through the designated membrane, a post treatment generally occurs to kill any microbes in the water as well as adjustment of the water’s pH back to normal. (Water for all, 2017).

4. Energy consumption – Cost

4.1. Energy consumption

Technological advances of membrane seawater desalination have propelled its worldwide use. Despite the twofold reduction of its power demand over the past 20 years, seawater desalination remains the most energy intensive alternative for production of fresh drinking water at present. Table 1 shows the average energy costs for conventional water treatment, as compared with desalination.

Table 1. Average energy consumption per cubic meter of water produced of various water treatment technologies. Data obtained from Voutchkof, 2018 and reference therein

Water supply alternative	Energy use (kWh/m^3)
Conventional treatment of surface water	0.2 to 0.4
Water reclamation	0.5–1.0
Indirect potable reuse	1.5–2.0
Brackish water desalination	1.0–1.5
Desalination of Pacific Ocean water	2.5–4.0

As it can be demonstrated in table 1, salt separation from seawater requires a significant amount of energy to overcome the naturally occurring osmotic pressure exerted on the reverse osmosis membranes. Seawater reverse osmosis (SWRO) desalination uses several times more energy intensive than conventional treatment of fresh water resources. Analysis of this table indicates that the energy needed for seawater desalination is approximately eight to ten times higher than that for production of fresh water from conventional sources such as rivers, lakes, and fresh water aquifers. It should be pointed out however, that such resources are limited to less than 2.5% of the water available on the planet, and that in large urbanized centers of most developed countries worldwide traditional fresh water resources are near depletion, while new sources are not readily available to sustain long-term population growth, industrial development and quality of life.

A breakdown of energy consumption within a typical seawater desalination plant using Pacific Ocean water of total dissolved solids (TDS) concentration of 33,500 mg/L as source seawater is 3.57 kWh/m^3 and the SWRO system's energy demand is 2.54 m^3/day (71% of the total plant energy use) (Voutchkov, 2018).

Table 1 also highlights, that desalinated water is produced by either using brackish water (water with salt content of less than 10,000 mg/L), or seawater which salinity in a range of 30,000 to 44,000 mg/L. While desalination of brackish water offers opportunities to produce lower cost water, it’s unlikely to be a main source of alternative water supply in the future. The total volume of brackish water worldwide is limited (less than 1% of the world’s water) and, in most arid regions of the world, it is almost fully utilised.

4.2 Energy savings

4.2.1. Collocation of desalination and power plants

Desalination of warmer source seawater usually requires less energy for membrane separation than using seawater of ambient temperature. This potential energy reduction benefit could be applied by using warm water discharges from coastal power plants as source water for desalination. Coastal power generation plants often use seawater of ambient temperature for cooling of their electricity generation units. The cooling water discharged from a typical power generation station is usually 5 to 15 °C warmer than the ambient ocean water. Taking under consideration that energy needed for salt separation is reduced with 5 to 8% for every 10 °C of elevated seawater temperature in the temperature range of 12 to 40°C, using warmer seawater can result in measurable energy reduction (Voutchkov, 2019).

4.2.2. Use of lower salinity source water

In reverse osmosis membrane desalination systems energy demand for salt separation is proportional to the salinity of the source water. Therefore, desalination of lower salinity source water results in lower energy demand for fresh water production. From this prospective, desalinating brackish water is preferable if such saline water source is readily available as it is shown in table 1. If brackish water sources at a given location are not adequate to produce a desired volume of fresh water, then the available brackish water could be blended with seawater to reduce the source water salinity of a seawater desalination plant and thereby to decrease the overall energy used for desalination. While this approach is not commonly practiced at present, if holds significant potential benefits under the right circumstances (Voutschkov, 2019).

Besides brackish source water, concentrate from brackish water desalination plants (desalter brine) could also be used as feed water to a seawater desalination plant in order to reduce feed water salinity. Such approach has already found practical implementation at a 10,000 m^3/day desalination plant located in City of Eilat, Israel and is under consideration for implementation in Orange County and San Diego County, California, USA (Voutchkov, 2019).

4.2.3. Alternatives for reducing RO system energy use

The optimum design of a given RO system in terms of energy use is strongly dependent on a number of site-specific factors such as: source and product water quality specifications; cost of construction labor and materials; O &M labor and chemical costs; unit power costs; Membrane element costs; plant size, location and type of power supply; etc. Therefore, a universal optimum plant design does not exist, and plant design optimization always needs to be completed based the site-specific project requirements and constraints. Depending on certain prevailing site-specific factors, there are a number of different practical approaches for minimization of RO system energy which have found industry-wide acceptance and use (Atam & Roskilly, 2016; Voutchkov, 2019):

- High productivity/low energy membrane elements;
- Hybrid membrane configuration;
- Low-recovery plant design;
- Split-partial two-pass RO system design;
- Three-center RO system design;
- Large size high efficiency pumps;
- Energy recovery by pressure exchangers.

Table 1. Key desalination plant energy use factors (Voutchkov, 2018)

Factor	Energy saving technology trends	Potential for energy savings (as percentage of industry average)
Source water temperature	Use of warmer source water (collocation with power generation plants	3 to 5%
Source water salinity	Use of lower-salinity source water or blend of seawater and brackish water	Over 50%
Membrane element and system energy and productivity losses	Use of higher productivity elements. Application of lower-energy & cost RO system configurations	5 to 15%
High pressure RO feed pump efficiency	Maximizing pump and motor efficiency by the use of large pumps serving multiple RO trains	5 to 10%
Recovery of energy from RO concentrate	Use of isobaric chamber type technologies	10 to 15%

5. Forward osmosis

Unlike reverse osmosis (RO) that needs external pressure to function, forward osmosis (FO) is driven by osmotic pressure difference across a semipermeable membrane. FO as a new membrane separation technology has gained wider attention in many applications such as desalination, power generation, food processing and wastewater treatment. For seawater desalination, the energy requirement of a standalone FO process is much higher than that of RO. However, FO hybrid systems can be used for the desalination of high-salinity waters, which is not possible using standalone RO process. FO hybrid systems using thermolytic draw solutions consume less total energy for desalting high-salinity waters, and can be economically more feasible than other desalination technologies. As a general definition, FO involves two major steps: the osmotic dilution of the draw solution and the generation of fresh water from the diluted draw solution. When salty feed water and highly concentrated solute (draw solute) are separated by a semipermeable membrane, there is movement of water from the salty water to the draw solution due to osmotic gradient, while retaining solute on both sides of the membrane.

The reason for the call for widespread applications of FO is due to its advantages over RO such as low energy consumption, minimal fouling problems, and considerably high water recovery. These advantages are not without some accompanied challenges such as limited choices of draw solutes. An ideal draw solute should be characterized by the ability to ensure high osmotic gradient, substantial water flux, and efficient recovery at minimal energy consumption. For osmosis-driven desalination, an ideal draw solute should have zero toxicity and low cost as some of its characteristics. Researches have been conducted for creating suitable draw solutes for desalination processes. Industrial impracticability is cited as the major barrier for the deployment of this technology. (Akther *et al.*, 2015)

5.1 Cost

Table 3 provides typical ranges for cost of fresh water production and energy use of reverse osmosis membrane systems of medium and large seawater desalination plants (i.e., plants with fresh water production capacity of 40,000 m^3/day, or more). This table is based on actual data from over 20 SWRO plants constructed between 2005 and 2010. As seen from Table 2, SWRO systems of best-in-class seawater desalination plants use between 2.5 and 2.8 kWh of electricity to produce 1 cubic meter of fresh water, while the industry average energy use is approximately 3.1 kWh/m^3. The industry-wide cost for production of fresh drinking water from seawater at present is approximately US$1.1/$m^3$. Energy expenditure typically contributes 25 to 40% of this cost depending on the unit power rate and the SWRO plant design, and equipment efficiency. (Voutchkov, 2018)

However, there are cases where the cost of water produced is much lower. For example, the Sorek desalination plant in Israel, which is producing around 624.000 m3/d has a cost of treated water at much less than 1 Kwh/m^3, based on calculations by Voutschkov (2013). The main parameters affecting the cost of desalination are the following: (a) the Source Water Quality (TDS, Temperature, Solids, Silt and Organics Content), (b) the demand for the product water quality (TDS, Boron, Bromides, Disinfection Compatibility) (c) Concentrate disposal method (d) Power Supply & Unit Power Costs (e) Project Risk Profile (f) Project Delivery Method & Financing. Other factors affecting the final cost are the intake and discharge system type, the pretreatment & RO System Design.

Table 2. Typical cost and energy use for medium and large size SWRO systems (Voutchkov, 2018)

Classification	Cost of water (US$/m^3)	SWRO system energy use (kWh/m^3)
Low-end bracket	0.5-0.8	2.5-2.8
Medium range	0.9-1.5	2.9-3.2
High-end bracket	1.6-3.0	3.3-4.0
Average	1.1	3.1

For example, the Sorek plant uses chemical dosing and a flocculation basin for the pretreatment/ pre-filtration process. The chemical dosing station consists of two pumps, each supplied with a frequency converter device. The flocculation basin facilitates the process to separate suspended solids. Remaining impurities are removed through dual media gravity filtration. The filtered seawater is then pumped by the low pressure feed booster pumps to the reverse osmosis section for desalination. Post-treatment involves re-mineralization of the desalinated water followed by final disinfection.

6. Brine disposal

Brines are liquid concentrates of salts produced as waste from industrial production processes, oil and gas fracturing or desalination of saline groundwater, seawater or wastewater recycling. Brine concentrate management presents a challenge because of the waste product's composition, the mass of liquids that need to be managed and the solids that are generated. Disposal options are limited depending on the origin of the brine, its composition, location and potentially substantial costs (Cotruvo, 2018). The main technology applied for discharging brine is to do it into surface bodies of water or sewer systems. If the brine meets regulatory requirements, brine discharge into the nearest body of water or to sanitary sewers is usually the lowest cost option for disposal. Discharge regulations or guidelines vary widely from region to region, or are sometimes determined on a project-specific basis.

Regulations may prohibit discharge based on any of the following:

- Concentrations of certain constituents of concern (e.g., maximum limits for metals, salinity, or compounds)
- Total mass per day of certain constituents of concern
- Specific properties, such as temperature and pH
- Volumetric flow rates
- Discharges only during certain time of day

One option to comply with regulatory discharge requirements may be to dilute the brine stream with other waters requiring discharge. With sufficient dilution, this may reduce the controlled constituents to below the allowable concentration limits. If the brine stream has only one or two constituents of concern that exceed the discharge limits, you should consider selective treatment or removal of those constituents. There are low cost solutions available for removing certain constituents, such as using green sand for iron removal. While discharging brine directly into surface water systems or sewers is often the most cost-effective solution, your organization should consider how it will impact the local environment. If regulations do not exist, studying the potential impacts of discharging the brine on local flora and fauna will help identify the benefits of treatment to protect the ecosystem or prepare for impending regulations.

6.1 Other ways of brine disposal

Brine Disposal in the Ocean: Like discharging brine into surface bodies of water, ocean discharge is another brine disposal method that tends to be very cost effective. In southern California, there is a 'Brine Line' that allows inland plants to discharge their brine to the ocean rather than to sewer or surface waters.

Figure 1. Discharging brine pump in the ocean (Saltworks, 2017)

Deep Well Injection of Waste Brine: Waste brine can be disposed by injecting it into deep wells. These injection wells are installed thousands of feet deep into the ground, away from the upper aquifers that feed drinking water sources.

Brine Evaporation Ponds: Evaporation ponds are the artificial solution to inland surface water discharge of waste brine. Under the right climatic conditions, the water evaporates, allowing you to discharge more brine to the ponds. One limitation of ponds is that they require large areas of land to increase the surface area where the water can evaporate, and can represent a future environmental liability due to either animal entry or future decommissioning.

Brine Incineration: Waste brine can be sent to an incinerator facility, where it is typically mixed with other solid wastes for processing. Incineration evaporates the water, while the salts in the brine become part of the residual ash that requires further management. Incineration is popular in countries with limited availability of land for landfills (Saltworks, 2017).

7. Applications Worldwide

In response to increasing water scarcity, over the last 30 years desalination has evolved into a viable alternative water supply. It allows us to tap non-traditional water resources with great potential to provide a sustainable, drought-proof water supply. Desalination provides only around 1 percent of the world's drinking water, but this percentage is growing year-on-year. An expected US$10 billion investment in the next five years would add 5.7 million cubic meters per day of new production capacity. This capacity is expected to double by 2030.

The ocean has two unique features as a water source – it's drought-proof and is practically limitless. Over 50 percent of the world's population lives in urban centers bordering the ocean. 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.

At the end of 2015, there were approximately 18,000 desalination plants worldwide, with a total installed production capacity of 86.55 million m^3/day or 22,870 million gallons per day (MGD). Around 44% of this capacity (37.32 million m^3/day or 9,860 MGD) is located in the Middle East and North Africa. While desalination in that region is projected to grow continuously at a rate of 7 to 9 percent per year, the "hot spots" for accelerated desalination development over the next decade are expected to be Asia, the US and Latin America (Voutchkov, 2016)

Saudi Arabia

Saudi Arabia is the largest producer of desalinated water in the world. In 2011 the volume of water supplied by the country's 27 desalination plants at 17 locations was 3.3 million m^3/day (1.2 billion m^3/year). 6 plants are located on the East Coast and 21 plants on the Red Sea Coast. 12 plants use multi-stage flash distillation (MSF) and 7 plants use multi-effect distillation (MED). Both MSF and MED plants are integrated with power plants (dual-purpose plants), using steam from the power plants as a source of energy. 8 plants are single-purpose plants that use reverse osmosis (RO) technology and power from the grid. By far the largest plant in 2012, Jubail II on the East Coast, is a MSF plant built in subsequent stages since 1983 with a capacity of almost 950,000 m^3/day that supplies Riyadh. The largest RO plant in 2012 was located in Yanbu on the Red Sea. It supplies the city of Medina and has a capacity of 128,000 m^3/day. The MED plants are much smaller. Mecca receives its water from plants in Jeddah and Shoaiba, just south of Jeddah.Ras al Khair, the largest plant of the country with a capacity of 1 million m^3/day was opened in 2014, using RO technology. (Global water intelligence, 2016)

Solar desalination. The first contract for a large solar-powered desalination plant in Saudi Arabia was awarded in January 2015 to a consortium consisting of Abengoa from Spain and Advanced Water Technology (AWT), the commercial arm of the King Abdulaziz City for Science and Technology (KACST). The $130 million reverse osmosis plant, co-located with a photovoltaic plant in Al Khafji near the Kuwaiti border, was planned to have a capacity of 60,000 m^3/day. The plant would rely on grid power at night and its operator expected to sell electricity to the grid in the future. However, Abengoa filed for bankruptcy at the end of 2015, putting the future of the plant in jeopardy.

Once the first plant is commissioned, a plant ten times larger is due to be built at a hitherto undisclosed location. Both plants are part of a national plan, launched in 2010 and called the King Abdullah Initiative for Solar Water Desalination, to massively expand solar desalination (Al-HarbiOmar *et al*, 2011).

*Floating desalination.*Desalination barges have operated since 2008 to meet high seasonal demand for potable water along the Red Sea coast of the Kingdom. In 2010 the largest floating desalination plant in the world, with a production capacity of 25,000

m^3/day (9 million m^3/year), was launched on a barge in Yanbu. It is sufficient to supply a city with more than 100,000 inhabitants with drinking water. (Rasooldeen, 2010)

Figure 2. This group of plants in Marafiq covers the water needs for the city of Al Jubail and can also distribute water to other parts of Saudi Arabia's Eastern Province. With capacity of 100,000 m^3/d using the reverse osmosis process (Acciona United States, n.d.)

In January 2018 Minister of Environment, Water and Agriculture Abdulrahman, Al-Fadhli Saudi, announced that Arabia plans to build nine desalination plants for more than SR2 billion ($530 million) on the Red Sea coast. The plants will have capacity of 240,000 cubic meters (c.m.) of water per day and will be completed in less than 18 months, Al-Fadhli wrote in a Twitter post. The project, which the minister said was ordered by Custodian of the Two Holy Mosques King Salman in a royal decree, will help government-owned Saudi Saline Water Conversion Corp (SWCC) raise production efficiency and cut operating and capital costs (Albawaba Business, 2018).

Greece

In Greece, and particularly in several southeastern regions, there is a very low water availability, which is exacerbated by the high water demand for tourism and irrigation in summertime. Therefore, the integration of desalinated water, treated wastewater and other marginal waters into water resources and the management of master plants are of paramount importance to meet future water demands.

The problem seems to be more evident in the Aegean Islands (particularly the Dodecanese and Cyclades), Thessaly in Central Greece, eastern Continental Greece (Sterea Greece), eastern Crete and the southeastern Peloponnese. More specifically, in central Greece (Thessaly and Sterea Greece), there is a high water demand for agricultural irrigation, while on the islands the problem is mainly attributed to the increased demand in potable water during the summertime. Both the population density of the Region of Crete (Prefectures of Chania, Rethymno, Iraklio and Lasithi) and the Regions of North and South Aegean (Prefectures of Lesvos, Chios, Samos, Dodecanese and Cyclades) are below the population density of Greece. Both regions receive large numbers of visitors during the summer. Nonetheless, that high water demand is also attributed to over-exploitation of groundwater aquifers, as well as to groundwater contamination, including seawater intrusion in coastal areas. In addition, the small size of the islands and their geography does not allow other possible cost-effective technologies to increase water availability.

According to the IDA Worldwide Desalting Plants Inventory in Greece, there are currently 157 operating desalination plants, with a total capacity of 109,115 m^3 /d, while another 35 are expected to soon be operational, with a total capacity of 40,135 m^3 /d. Moreover, five more desalination plants were under construction, with a capacity reaching 32,800 m^3 /d. As for the feed water, 56% is seawater, while 41% is brackish water. Regarding the use of the produced desalinated water, 48.08% is to supply the municipalities, 31.07% goes to the industry, 15.94% covers touristic demands, and 4.24% and 0.16% are directed to power production and water supply of military camps, respectively. RO is the most popular desalinating technology in Greece, as it produces 74.41% of the desalinated water. ED is used for the desalination of 10.20% of the total desalinated water produced, whereas MED is used for 8.47% of the produced water and MSF is used for the 6.75%. (Zotalis *et al.,* 2014).

There are 35 RO plants operating in the Hellenic island municipalities with a total capacity of 22,860 m^3/d and operating costs ranging from 0.13 €/m^3 to 2.70 €/m^3. The newest desalination plant in Almyros (Iraklion, Crete), with a capacity of 2,400 m^3/d, has been in operation since January 2014. This project is the first one whereby the produced water will be sold by the contractor to the Municipality of Iraklion, at a guaranteed price of 0.27 €/m^3 for five years. Also, a future upgrading of its capacity up to 20,000 m^3/d is planned. Note that the Almyros brackish spring, from where the plant will be fed, has a capacity more than 620,000 m^3/d. The average operating costs of 30 RO plants of seawater desalination in the Hellenic islands has been estimated at 0.85 €/m^3. More precisely, the 4800 m^3/d capacity plant in Leros has a minimum operational cost of 0.13 €/m^3, while the 500 m^3/d capacity in Sifnos reaches the highest registered value of 3.5 €/m^3.

Modern desalination processes of utilizing solar, wind, or wave energy, instead of fossil fuels, are under development. Desalination plants utilizing renewable energy sources have also been operating in Greece. Such plants are:

- A vapor compression plant charged with a 750 kW wind turbine is located on the island of Symi, producing 450 m^3/d, has been operating since 2009.
- A MED plant using geothermal energy was built on the island of Kimolos in 2000. This unit has a 188 m well and is considered to be a low enthalpy one (61°C), capable of producing 80 m^3/d.
- A hybrid RO was constructed on Keratea in 2002, combining wind turbines with photovoltaic panels. The capacity of this hybrid plant reaches 3 m^3/d, while the wind turbines and photovoltaic cells are of 900 W and 4 kWp nominal power, respectively.
- Another plant of today’s capacity 3,360 m^3/d is on the island of Milos. It is a RO plant which used the electrical energy needed from an 850 kW wind turbine operating at 600 kW.
- Finally, on Irakleiaisland, there is a removable RO desalination plant, which uses both wind and solar energy through a 30 kW wind turbine and a backup photovoltaic panel system (Zotalis *et al.,* 2014).

Cyprus

Cyprus an island with a semi-arid climate, and with its water resources already intensely utilized is suffering from structural and temporary water shortages. With a high level of utilization of its natural water resources, water demand increasing rapidly and water availability decreasing due to repeated droughts, the Government of Cyprus has decided to construct a number of desalination plants. In table 4 are presented the three existing desalination plants. (Manoli, 2010)

The new 15,000 m^3/d desalination facility at Kouklia, Paphos, will make use of an existing water intake structure and conveyance to the island's main water distribution network that were put in place to serve a temporary desal facility that has now been removed. The contract will be for design, construction, and operations and maintenance over 25 years. The country aims to produce 30 per cent of water from desalination by 2020, while the goal for reuse water is 20 per cent by 2020, and 30 per cent by 2025 (Manoli, 2010).

Table 3. Existing desalination plants in Cyprus (2010). (Manoli, 2010)

	Dhekelia	Larnaka	Moni
Start of production	2007	2001	2008
Period	20 years	10 years	3
Capacity (m^3/day)	60.000	62.000	20.000
Minimun daily production (m^3)	54.000	55.800	18.000
Mnimum yearly production (m^3)	19.770.000	21.352.500	6.570.00
Selling price (euro/m^3)	0.82	1.08	1.39

8. Recent trends in membranes processes for desalination

Many recent and important improvements in desalination technologies are in RO systems. The total desalination capacity worldwide using RO technology is continuously increasing, even in the Arabian Gulf region where energy is cheap and raw water quality is less suitable for RO technology, requiring an advanced pretreatment scheme to protect RO membranes mainly from fouling and biofouling. The total global capacity (sea and brackish waters) of RO is the highest compared to any other process. The tremendous reduction in desalinated water cost by RO has enabled many countries to implement desalination to supply potable water for domestic and industrial use and even for agriculture purposes in some countries such as Spain.

There have been many developments over the last three decades that have contributed to a reduction in unit water cost of RO desalination, particularly membrane performance and reduction in energy consumption caused by more efficient energy recovery systems. The performance of the membrane materials and modules has improved with respect to increased salt rejection, increased surface area per unit volume, increased flux, improved membrane life, and capacity to work at higher pressure, and has also a decreased membrane cost. The recovery ratio increased considerably over the years due to improved salt rejection (Ghaffour *et al.*, 2013).

8.1 Inorganic membranes for desalination

Membrane technology based on polymeric membranes is one of the most important and widely recognized technologies for desalination and wastewater treatment. While polymeric membranes are known to be plagued with some bottlenecks, the technical progress and the accompanying knowledge in inorganic membrane development have grown inexorably to solve some of the underlying issues. Aside from the conventionally used ceramic membranes which based on metal oxides, nanostructures such as zeolites, metal organic frameworks and carbon based materials have sparked enormous interest in the preparation of inorganic membranes owing to their tunable nanoscaled structural properties that can render excellent rejection and/or ultrafast water transport (Goh & Ismail, 2018).

8.2 Graphene-based nanofiltration membranes for improving salt rejection, water flux and antifouling

Recent studies reveal that nanoporous single layer graphene and stacked graphene oxide (GO) membranes with desired spacing between layers are capable of rejecting monovalent ions, and are promising materials for future nanofiltration-based desalination. GO has antifouling properties that are highly advantageous for improving membrane properties. The basic understanding of the mechanism of graphene-based nanofiltration have been reported mainly based on computational studies. Hence, a great deal of experimental research is essential to develop efficient graphene membrane-based desalination methods for practical use. (Anand *et al.*, 2018)

Computational studies suggest that graphene can be used in two ways for desalination, specifically, i) using nanopores as sieves in single layer graphene, and ii) using pores and interlayer spacing in multilayer graphene membranes as nanochannels for water flow and salt rejection. The interlayer distance between the graphene layers, their hydrophobicity, and the interaction of polar functional groups with water molecules all influence the flux. In addition, incorporation of GO with existing polymer NF membranes significantly improves their desalination properties. GO has antibacterial properties that can withstand fouling and improve the durability of membranes. A systematic understanding of the surface hydrophilicity, porosity, pore size, functional groups at the pores, and charge density is essential to evaluate the performance of graphene-based membranes. To date, limited data are available on the use of standalone graphene-based membranes for desalination. For commercial applications, graphene sheets would need to be manufactured in large, defect-free areas with the desired pore sizes. Thin, single sheets of graphene need to be produced in mechanically stable forms that can withstand the applied pressures in order to realize extreme flux enhancements, which remains a hurdle. However, recent reports on stacked GO sheets with desired interlayer spacing suggest that they are practically feasible for salt removal applications. But, nearly 100% rejection of monovalent ions has to be achieved to compete with reverse osmosis membranes. In addition, the materials should be resistant to fouling and scaling. Only then it will be possible to operate the membranes at higher than normal fluxes, leading to savings in both operating and capital expenses. The release of nanomaterials from the membrane and their toxicity have to be studied in detail for practical desalination applications (Anand *et al.,* 2018).

8.3 Carbon nanotube in membranes technology

Carbon nanotube in membranes technology CNTs are composed of cylindrical graphite sheets (allotropic form of carbon) rolled up in a tubelike structure with the appearance of latticework fence. Single-walled carbon nanotubes (SWCNTs) have cylindrical shape consisting of a single shell of graphene. On the other hand, multi-walled carbon nanotubes (MWCNTs) are composed of multiple layers of graphene sheets. Both SWCNTs and MWCNTs have been used for direct water desalination or indirectly to remove trouble making compounds that complicate the desalination processes. CNTs are fascinating in advanced membrane technologies for water desalination since they provide low energy solution for water treatment. CNT membranes provide near frictionless water flow through them with the retention of a broad spectrum of water pollutants. The inner hollow cavity of CNTs provides a great possibility for desalinating water. The high aspect ratios, smooth hydrophobic walls and inner pore diameter of CNTs allow ultraefficient transport of water molecules. Some prototypes of CNT based membranes are shown in Fig. 10 and the fundamental aspects of CNTs are discussed in the subsequent subsections.

The smooth and hydrophobic inner core of the hollow CNTs can allow the unit errupted and spontaneous passage of water molecules with very little absorption. The specially aligned CNTs are of special interest for the construction of CNT membranes. The pore diameter has special effects on the water passages through the membranes consisting of aligned CNTs. Majumder et al. observed frictionless movement of water molecules with high velocities from 9.5 to 43.0 cm s^{-1}/bar speed through a 7 nm diameter membrane pore. The flow rates were four to five times faster than those of conventional fluid flow of between 0.00015 and 0.00057 cm s^{-1}/bar) (Das *et al.,* 2014)

8.4 Layer-by-layer assembly of anion exchange membrane by electrodeposition of polyelectrolytes for improved antifouling performance

Layer-by-layer (LbL) assembly polyelectrolyte technique is a promising way to control membrane fouling because of its simplicity and it allows the gradual and controlled build-up of electrostatically crosslinked layers on the surface of the membrane. Various LbL modified membranes have recently been developed for different specific purposes by selecting various polyelectrolyte species, adjusting fabrication conditions and altering surface functionalities.

Zhao et al. studied the antifouling performance of a Layer-by-Layer assembly of anion exchange membrane. The top PSS layer on the AEM endows the surface with negative charges and higher hydrophilicity, contributing to the improvement of antifouling performance of AEM to organic foulant in electrodialysis. Both the surface negative charge density and surface hydrophilicity increased with the increase of the number of PSS/PDADMAC bilayers. SDS (75 mg/L) in the initial solution caused the desalination rate of the pristine AEM during 180 min decreasing to 24.0% and the SDS fouling layer was formed at the dilute side of the pristine AEM. The area electrical resistance of the SDS-fouled AEM exhibited a sharp increase and the ion transport through the SDS-fouled AEM was restricted completely. Electrodeposition of 5.5 PSS/PDADMAC bilayers made the desalination rate of the modified AEM during 180 min increasing to 30.5% with 75 mg/L SDS in the initial solution and prevented the formation of the SDS fouling layer. The area electrical resistance of the SDS-fouled AEM exhibited a very slight increase and the ion transport through the SDS-fouled AEM was almost unaffected. With higher SDS in the initial solution, LbL assembled

AEM also showed better antifouling performance than the pristine AEM. (Zhao *et al.*, 2018)

9. Conclusions

Desalination is growing so fast globally that it is more than certain that it will play a significant role in water supply in the years to come. Desalination is growing particularly in parts of the world where water availability is low. Annual desalination capacity seems to increase rapidly as years go by.

There are two classes of desalination: thermal or, distillation process, heats the saltwater to boiling, collects and condenses the steam producing purified water; the membrane class Reverse Osmosis (RO) and Electro-Dialysis reversal (EDR) method involves forcing salt water across a semipermeable membrane that separate the salts from the water leaving a saline solution or brine on one side and a “de-saline” solution (drinkable water) on the other.

Seawater desalination remains the most energy intensive alternative for production of fresh drinking water at present. Some ways for energy savings are: collocation of desalination and power plants, use of lower salinity source water and forward osmosis. Practical approaches for minimization of RO system energy which have found industry-wide acceptance and use: high productivity/low energy membrane elements, hybrid membrane configuration, low-recovery plant design, split-partial two-pass RO system design, three-center RO system design, large size high efficiency pumps, energy recovery by pressure exchangers. The brine is often discharged into the surface bodies of water or sewer systems and in the ocean according to the regulations.

At the end of 2015, there were approximately 18,000 desalination plants worldwide, with a total installed production capacity of 86.55 million m^3/day or 22,870 million gallons per day (MGD). Around 44% of this capacity (37.32 million m^3/day or 9,860 MGD) is located in the Middle East and North Africa. While desalination in that region is projected to grow continuously at a rate of 7 to 9 percent per year, the “hot spots” for accelerated desalination development over the next decade are expected to be Asia, the US and Latin America.

Polymeric membranes are known to be plagued with some bottlenecks, the technical progress and the accompanying knowledge in inorganic membrane development have grown inexorably to solve some of the underlying issues. The performance of the membrane materials and modules has improved with respect to increased salt rejection, increased surface area per unit volume, increased flux, improved membrane life, and capacity to work at higher pressure, and has also a decreased membrane cost.

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