Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2020.25686

193 (2020) 1–10
July

Towards sustainable desalination industry in Arab region: challenges and opportunities

Mohamed A. Dawoud[a,*], Saleh O. Alaswad[b], Hatem A. Ewea[c], Rokia M. Dawoud[d]

[a]*Water Resources Advisor, Environment Agency – Abu Dhabi, P.O. Box: 45553, UAE, email: mdawoud@ead.gov.ae (M.A. Dawoud)*
[b]*Nuclear Science Research Institute, King Abdulaziz City for Science and Technology, Box 6086, Riyadh 11442, KSA, email: aswad77@hotmail.com (S.O. Alaswad)*
[c]*King Abdul Aziz University, Jeddah, KSA, email: hewea1136@gmail.com (H.A. Ewea)*
[d]*Joiner Civil Engineer, Abu Dhabi, UAE*

Received 6 December 2019; Accepted 12 February 2020

ABSTRACT

The scarcity of freshwater sources and the increasing gaps between supply and demand are major challenges facing the economic and social development in the Gulf Cooperation Council (GCC) countries. Desalination technology is finding new outlets in supplying freshwater to meet growing demands for future development in the domestic, agricultural, industrial, and economical sectors. More than 8,950 desalination plants in GCC countries have a cumulative capacity of about 38.1 million $m^3\ d^{-1}$. Desalination is energy and capital intensive industry, though technological innovations have reduced production costs. Investments in infrastructure and R&D in innovative technologies and renewable energies can lower desalination costs and make it more sustainable in the future. While desalination can help reducing pressure on conventional water resources, they have negative environmental impacts. The cost of desalted water depends on energy input, depreciation and interest, infrastructure cost, and O&M cost. Desalinated water cost is coming down due to continued technological improvement and innovations in both thermal and membrane desalination processes. In thermal desalination processes, R&D efforts are directed towards utilizing low-grade heat and waste heat as energy input; lowering the chemicals use and the advantage of scale up to higher capacity as a cost reduction strategy. In membrane desalination, new pre-treatment methods like the use of ultrafiltration, energy reduction using energy recovery devices, and higher membrane life from better quality membranes are the future target of R&D programs. The main objective of this paper is to assess several desalination innovative technologies for reducing energy and produce sustainable desalination processes based on renewable energies. The assessment was based on the results of four pilot projects implemented and monitored for two years in Abu Dhabi. Preliminary results indicated that the energy consumption in forward osmosis (FO) membrane technology is only 3.6 kWh m^{-3}, which means that FO membrane technology can make the desalination industry more energy efficient in the near future. Membrane distillation technology is also a thermally driven low-energy that utilizes a hydrophobic microporous membrane to separate freshwater by liquid-vapor equilibrium. Both two technologies can help to improve the sustainability of the desalination industries in the future lowering energy consumption, minimizing environmental impacts, and reducing desalination water cost.

Keywords: Desalination; Forward osmosis; Sustainability; RO; Innovations; Water scarcity

* Corresponding author.

Presented at the 4th International Water Desalination Conference: Future of Water Desalination in Egypt and the Middle East, 24–27 February 2020, Cairo, Egypt

1. Introduction

Gulf Cooperation Council (GCC) countries facing the challenges of renewable freshwater scarcity due to their location in arid and hyper-arid regions with permanent surface freshwater bodies. GCC started its desalination industry in the early 1960s to produce freshwater to fill the gaps between water supply and demand mainly in the domestic sector. Recently, other Middle East countries started also to increase their desalination capacities such as Egypt with at present capacity of 630,000 $m^3\ d^{-1}$ and planned capacity of 1,650,000 $m^3\ d^{-1}$ by 2037 [1]. Recent desalination statists indicating the about 45% of global desalination capacities are produced in GCC countries as shown in Fig. 1 [2]. Due to the need for energy, 77% of desalination plants are thermal co-generation systems for power and water production and only 23% are RO. The plan is to increase RO desalination capacities to be more than 35% by 2030. 2018 GCC statistics show that there are about 200 plants with a plan to add another 38 by 2030 as shown in Tables 1 and 2. The total seawater desalination capacity is about 5,000 million $m^3\ y^{-1}$, which means a little less than a half (45%) of the worldwide production as shown in Table 3. The annual total GCC countries desalination capacity was increased from 3,000 million m^3 in 2000 to about 5,500 million m^3 by 2018 and it is expected to be more than 9,000 m^3 by 2030 as shown in Fig. 2.

The rapid social development across the GCC in the face of highly arid conditions has been enabled by the introduction of large-scale desalination technology. The first desalination plant in the GCC was introduced, on the Red Sea coast, in Jeddah in 1907, and the first desalination plants on the Gulf coast were built in Kuwait and Qatar in 1953 with a combined output of 5,000 $m^3\ d^{-1}$ [3]. Desalination now provides over 20% of the total water used in all of the GCC countries and over 50% of the water used in Bahrain, Kuwait, Qatar, and UAE [4] as well as providing up to 100% of drinking water in GCC states [5]. Furthermore, despite being located in a highly arid region the proportion of the population with access to safe drinking water and improved sanitation is above the global average in each of the GCC states. The volume of water produced through desalination by GCC states drawing water from the Arabian Gulf has increased from 0.03 million $m^3\ d^{-1}$ in 1970 (GCC 2014) to over 21 million $m^3\ d^{-1}$ in 2018 [6] and it is expected continue to rapidly increase over the coming decades. The development of desalination has been and will continue to be, essential to social and economic development in the Gulf. However despite these huge benefits desalination is not without costs. Costs in terms of the direct economic cost of generating desalinated water, but also environmental costs from CO_2 emissions and environmental impacts on the source and receiving waters [7–9]. In the case of the desalination plants operating on the east coast of the Arabian Peninsula the source and receiving waters are the Arabian Gulf. The Arabian Gulf is a shallow semi-enclosed basin located in the north-western Indian Ocean. The Arabian Gulf is naturally exposed to extreme conditions due to its location, bathymetry, and restricted circulation [10,11]. Average summer sea surface temperatures are 33°C, and salinities over 43 ppt are common in parts of the Gulf. Yet despite this, the Gulf is important for biodiversity conservation, including species and habitats of global conservation significance. Arabian Gulf is also of social and economic importance to GCC states providing food, supporting a growing tourism industry, and providing a location for recreation and leisure. The GCC states have formally recognized the societal importance of, and the need to protect, the Gulf marine

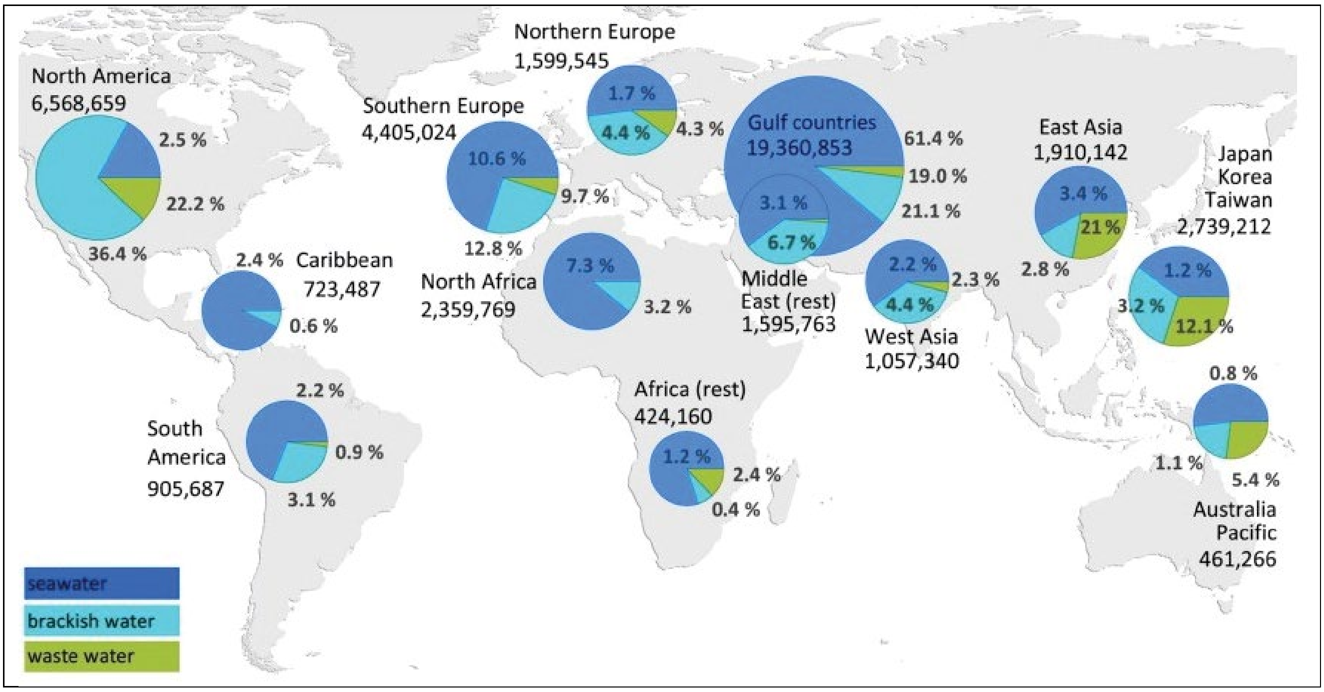


Fig. 1. Global desalination production (2017).

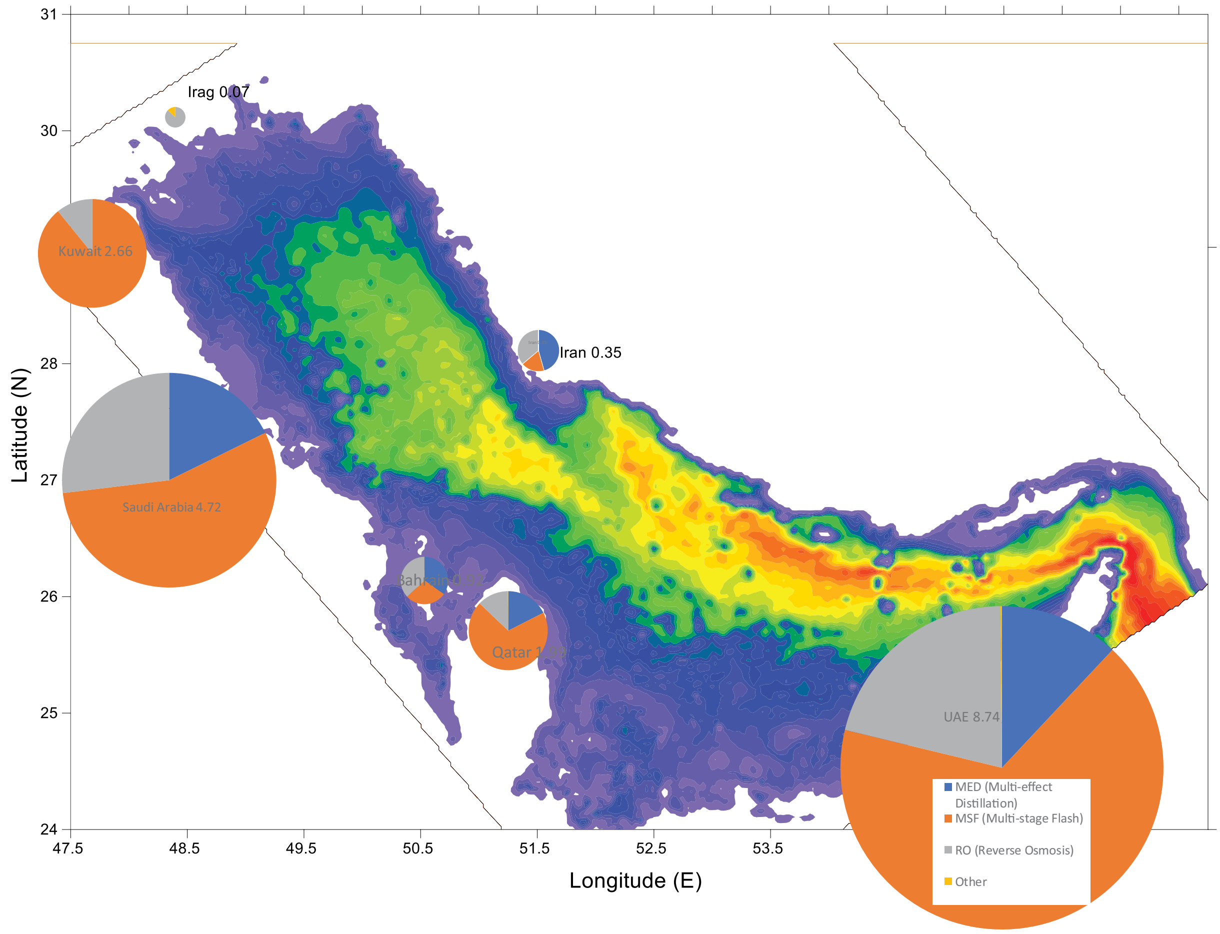


Fig. 2. Total desalination capacity by different desalination technologies in GCC countries.

Table 1
Existing desalination plants in GCC countries (2017)

Technology	GCC countries (desalination capacities in million m^3)						Total
	KSA	UAE	Kuwait	Qatar	Oman	Bahrain	
MSF	1,078	1,307	702	387	158	91	3,723
MED	3	315	0	3	0	111	432
RO	1,054	153	0	1	10	44	1,262
VC	0	0	0	0	0	0	0
ED	0	0	0	0	0.01	0	0
Total	2,135	1,776	702	391	168	246	5,417

Source: GCC Cooperation Council, Desalination Statistics 2017

ecosystem through international commitments under the United Nations Sustainable Development Goals, and the Convention on Biological Diversity and the United Nations Convention on the Law of the Sea in addition to regional and national commitments. The overarching concept of 'sustainable development' is to enable development that meets the needs of the present without compromising the options of future generations. But beyond this the international commitments mentioned above include a range of more specific commitments achieve sustainable development including protecting marine species and habitats, building climate resilience in marine ecosystems, maintaining fisheries productivity, and avoiding adverse effects of land-based sources of pollution as shown in Table 2.

Given that desalination is known to have adverse impacts on the marine environment, that semi-enclosed sea or more susceptible to impacts [12], that environmental status of the Gulf has wider importance to GCC states,

Table 2
Future planned desalination capacities in GCC countries (2030)

Technology	GCC countries (desalination capacities in (million m^3)						Total
	KSA	UAE	Kuwait	Qatar	Oman	Bahrain	
MSF	1,078	1,307	702	387	158	91	3,723
MED	3	315	0	3	0	111	432
RO	1,054	153	0	1	10	44	1,262
VC	0	0	0	0	0	0	0
ED	0	0	0	0	0.01	0	0
Total	2,135	1,776	702	391	168	246	5,417

Source: GCC Cooperation Council, Desalination Statistics 2017

Table 3
Growth of the installed desalination capacities in GCC (2000–2017)

Country	2000	2002	2004	2006	2008	2010	2012	2014	2017
UAE	773	943	1,116	1,352	1,775	1,833	1,833	1,833	1,776
Bahrain	140	140	140	246	246	246	246	246	246
KSA	1,500	1,515	1,533	1,678	1,721	1,742	1,742	1,742	2,135
Oman	70	104	104	104	168	236	236	236	168
Qatar	188	188	217	279	391	391	391	391	391
Kuwait	476	524	520	612	702	702	702	702	702
Total	3,146	3,413	3,630	4,274	5,004	5,151	5,151	5,151	5,417

Source: GCC Cooperation Council, Desalination Statistics 2017

and that the significant increases in the desalination capacity in the Gulf are predicted, this paper asks the question of whether the development of desalination in the Gulf is compatible with the sustainable development of the Gulf. The paper draws together knowledge on the state of the Gulf marine environment and the marine environmental impacts of desalination with scenarios of the development of desalination in the Gulf to consider the potential nature, extent, and implications of desalination impacts on the Gulf marine ecosystem. The extent of potential environmental impacts is considered in terms of intensity and spatial extent. This paper does not intend to provide exhaustive reviews of the state of the Gulf marine environment or the impacts of desalination on the Gulf marine environment as these topics have already been addressed by a number of studies and reviews. Rather this paper seeks to synthesize available information to provide a regional scale evaluation of the potential issues associated with the development of desalination in the Gulf and to identify priority mitigating measures and knowledge gaps.

2. Marine environmental impacts of desalination

The construction, operation and decommissioning of seawater desalination plants can have a variety of impacts on the marine environment which can be considered in relation to general construction and decommissioning impacts similar to any coastal development project, atmospheric CO_2 emissions due to the energy requirements of the desalination process, and impacts associated with the intake of seawater and discharge of concentrated brines, and these impacts have been discussed and reviewed by a number of authors [13–15]. This summary of the impacts of desalination plants focuses on impacts on the marine environment that are specific to desalination operations and hence does not address general coastal construction impacts nor atmospheric emissions of CO_2 due to power generation [16]. This does not mean that general coastal construction impacts and emissions are irrelevant, but rather that they are not the focus of this study.

Lattemann and Höpner (2008) provide an extensive list of the potential impacts of desalination on the marine environment, however, the main impacts can be broadly grouped into four categories:

- Impingement and entrainment in seawater intakes: this is large organisms being drawn into intakes and caught on screens and filters (impingement) as well as smaller and unicellular organisms passing through the initial screening and entering the water stream within the plant (entrainment),
- Thermal discharges of heated water either directly from thermal desalination plants or the cooling water from power plants that generate power for reverse osmosis plants,
- Brine discharges are the discharge of concentrated brines in the residual outflow water following the removal of purified water,
- Chemical discharges; various chemical treatments are used to condition water to control biofouling, remove

suspended solids, antiscalants, foam control additives (not required for RO), and cleaning. Additional chemical contamination of discharges can be due to the corrosion of metal parts within the system. Chemical contamination of discharges varies between plants due to plant-specific process controls and different chemical composition of commercial treatment products [17].

The evidence on the biological and ecological impacts of desalination is based on a mixture of experimental, field, and modeling studies. However, it is noted that the impacts are location, desalination plant, and species-specific. Discharge plumes that are released into a confined water body, or an area with bathymetric topography that leads reduces dispersal, can lead to a concentration and build-up of brines that would otherwise be rapidly dispersed in an open coastline. Similarly, the impact of intakes and outfall varies depending on both the configuration and design of intakes and outlets and on the type and amount of water preconditioning chemicals used in a given desalination plant [17]. Species-specific responses have been identified in a variety of taxa, but for example have been shown in corals and seagrasses [18,19]. Therefore, although there is an increasing body of evidence given the location, desalination plant, and species-specific nature of impacts that have been reported the overall body of evidence is patchy which limits the ability to draw out general conclusions on the ecological impacts of desalination plants on marine ecosystems. Despite this it has been noted that impacts of elevated salinity are rarely observed for salinity elevations below 2–3 ppt but some species and communities are robust to salinity increase >10 ppt. In terms of the physical scale of impacts salinity increases >2 ppt are rarely seen beyond a 400 m radius of outfalls [20] although increases have been observed over several km [21], however, using modern diffuser systems in unconfined systems salinities can drop to just above ambient levels over short distances. It should be noted that short term observations usually associated with observation campaigns around power stations or desalination plants cannot detect uplifts to the whole environment for either temperature or salinity. It is only by the use of modeling where reference scenarios can be run that the true extent of the potential impact can be estimated. However, when evaluating the ecological effect of desalination in relation to sustainable development goals it is important to consider how physiological or local effects that have been observed in studies relate overall population and ecosystem dynamics. The direct impacts of desalination plants will impact physiological processes in marine organisms at a local scale, but policy objectives typically relate to population and ecosystem-level processes at a national or regional scale, and there is not a direct relationship between a physiological impact and corresponding higher-order population or ecosystem-level effects [22]. Evaluating population and ecosystem-level effects is challenging as these processes operate at spatial and temporal scales that are not amenable to experimental studies. However, despite the challenge associated with scaling from observed physiological or local impacts to population or ecosystem-level impacts is necessary to constrain the range of predictions on the possible impacts of desalination to allow for the development of informed policy and management.

3. Current and future desalination in the Gulf

The first desalination plants on the Gulf coast of the GCC were built in Kuwait and Qatar in 1953 with a combined output of 5,000 $m^3\ d^{-1}$, by 1970 the total desalination capacity installed on the Gulf coast of the GCC was 40,500 $m^3\ d^{-1}$, these early plants nearly all used multi-stage flash distillation other than the very early plants that used a submerged tube distillation process [23]. A variety of different desalination techniques have been applied in the Gulf as desalination technologies have developed and recovery efficiency and energy efficiency improved as shown in Table 3. The three main technologies used in the Gulf are multi-stage flashing (MSF), multi-effect distillation (MED), and reverse osmosis (RO). MSF and MED are both based on thermal evaporation processes and produce heated brine as the discharge, whereas the RO process is based on applying pressure to drive low ion concentration water through a semi-permeable membrane. The brine discharge produced by RO desalination is not heated.

From an early capacity of 40,500 $m^3\ d^{-1}$ in 1970 the total desalination capacity across the Gulf has increased rapidly to over 567 plants operational in the Gulf with a combined capacity in excess of 21,180,000 $m^3\ d^{-1}$ in 2018 [6]. The single largest plant in the Gulf, a MED plant at Al Jubail in Saudi Arabia has a capacity of 800,000 $m^3\ d^{-1}$. MSF desalination was the dominant technology used by newly installed plants in the Gulf until 2010, but since 2010 RO has become the dominant technology for newly installed desalination capacity, although MSF is still the dominant technology used by operational plants in the Gulf at the time of writing as shown in Fig. 2. The UAE was the country with the largest desalination capacity on the Gulf coast, in 2018 the UAE had 45% of the total Gulf desalination capacity and Saudi Arabia was the second-largest producer contributing 24% of the Gulf desalination capacity [6]. Although there are over 560 desalination plants operating around the Gulf the large majority of the desalination capacity is produced by a small proportion of extra-large desalination plants; the 81 largest plants on the Gulf account for over 85% of the total desalination capacity in the Gulf, whilst the 360 smallest plants account for less than 5% of the total desalination capacity. With continuing population growth and economic development total desalination capacity in the Gulf region is expected to continue to grow. As of 2018 an additional 2 million $m^3\ d^{-1}$ of capacity is under construction of which >80% is RO [6]. The actual capacity based on plants drawing on Gulf waters in 2050 will be determined by multiple factors including population growth, per capita water usage, power and desalination costs, regulation and technological development.

To estimate the possible increase in desalination capacity in the Gulf three different scenarios is considered. Two of them use simplifying assumptions to project current desalination capacity forward to 2050 based on either current capacity growth rate or predicted population growth rate under the assumption of constant per capita desalination supply. The third scenario is based on a more complex projection that includes the estimated population growth rate and the proportion of national water supply generated by desalination compared to groundwater supplied [24]. Although the Abu Dhabi Global Environmental Data Initiative (AGEDI)

[24] projection is based on a more detailed set of assumptions the projection is based on older base data for desalination capacity in the Gulf that has already been 'outgrown' by actual capacity increases in the Gulf. The three scenarios estimate desalination capacity in the Gulf will have increased from 19.5 million $m^3 d^{-1}$ in 2018 to between 25 and 44 million $m^3 d^{-1}$ by 2050 based on the population growth or constant increase scenarios respectively. The AGEDI scenario also estimates that desalination capacity will have increased to over 40 million $m^3 d^{-1}$ by 2050. The AGEDI scenario has the highest growth rate but starts from a lower starting point. Given that 2 million $m^3 d^{-1}$ additional desalination capacity is already under construction in the Gulf it seems reasonable to assume, based on current expectations for population and technological development, to assume that desalination capacity will exceed 40 million $m^3 d^{-1}$ by 2050.

4. Impact of desalination on sustainable development of the Gulf marine environment

Observational and experimental data have demonstrated that desalination directly impacts species, habitats, and communities that are the focus of international commitments to sustainable development and environmental conservation (Table 1), and therefore that desalination acts as a source of pollutants to the marine environment. The indirect food web impacts of desalination may also impact environmental status with respect to international commitments, for example, seagrasses have been demonstrated to be sensitive to salinity increases, and seagrasses are a predominant food source for dugongs and green turtles both of which are species listed as threatened by the International Union for Conservation of Nature [25]. Therefore, and given the significant increase in desalination capacity expected in the Gulf over the coming decades, it is reasonable to question whether the development of desalination in the Gulf will compromise the sustainable development of the Gulf. However, studies on the environmental impacts of seawater desalination note that the observed impacts only occur over limited areas in close proximity to desalination plans [20], so although local effects have been observed these may not impact species, habitats, and communities at the population and ecosystem-scale which is the primary scale at which sustainable development goals and environmental commitments are evaluated.

5. Future of using new innovative technologies

Ever since desalination was originally invented in antiquity, different technologies have been developed. 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. Since then, the seawater desalination technologies for potable water production were developed rapidly and has become quite popular and usable. The most reliable sweater and brackish water desalination technologies that can currently be exploited at the commercial scale can be classified in two main categories:

- *Thermal technologies*: including MSF, MED, thermal vapor compression, and mechanical vapor compression process as shown in Fig. 3.
- *Membrane technologies*: including RO and electro-dialysis (ED) processes as shown in Fig. 4.

Over the last few years, a large number of desalination plants began to operate globally. Moreover, the production cost of desalinated water has been considerably decreased and is expected to decrease even further. This is mostly due to the recent improvements in membrane technology, but also due to the increase of the energy conversion efficiency for desalination processes.

The selection of suitable and proper desalination methods used in Egypt depends on many factors such as capacity, row water salinity, and quality, energy source, land use, available alternative water resources (conventional resources), and operational characteristics as shown in Fig. 5. In general, the following prevailing desalination technologies could be used in the Southern and Eastern Mediterranean Region region: ion exchange, thermal systems, electrodialysis reversal, and RO [26]. In recent years, numerous large-scale seawater desalination plants have been built in water-stressed countries to augment available water resources, and the construction of new desalination plants is expected to increase in the near future. Despite major advancements in desalination technologies, seawater desalination is still more energy-intensive compared to conventional technologies for the treatment of freshwater. There are also concerns about the potential environmental

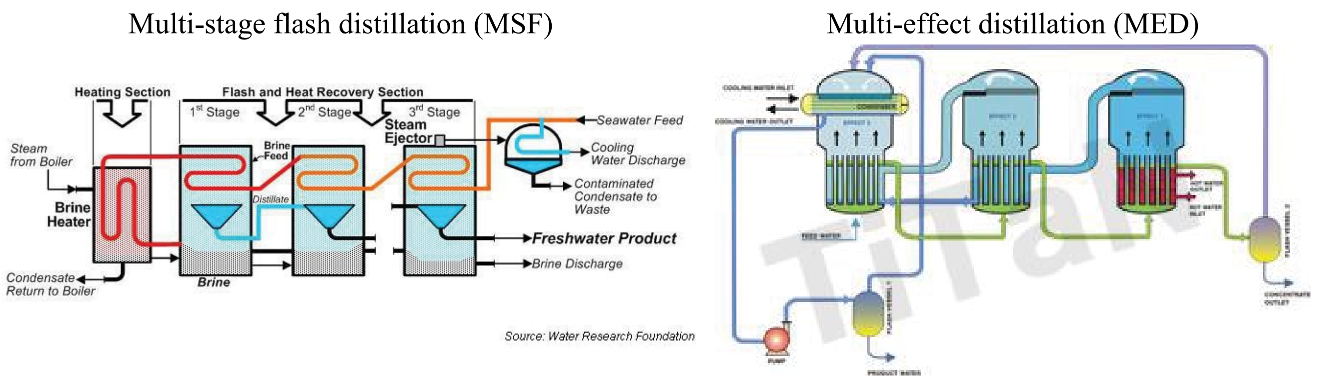
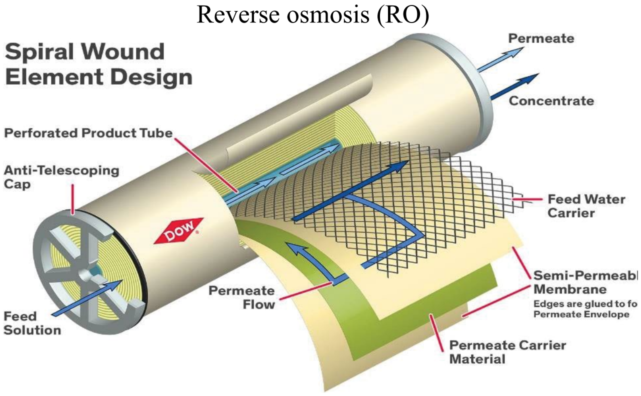


Fig. 3. Thermal desalination technologies.



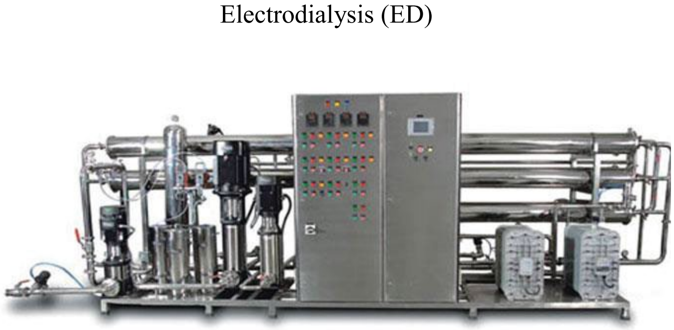


Fig. 4. Membrane desalination technologies.

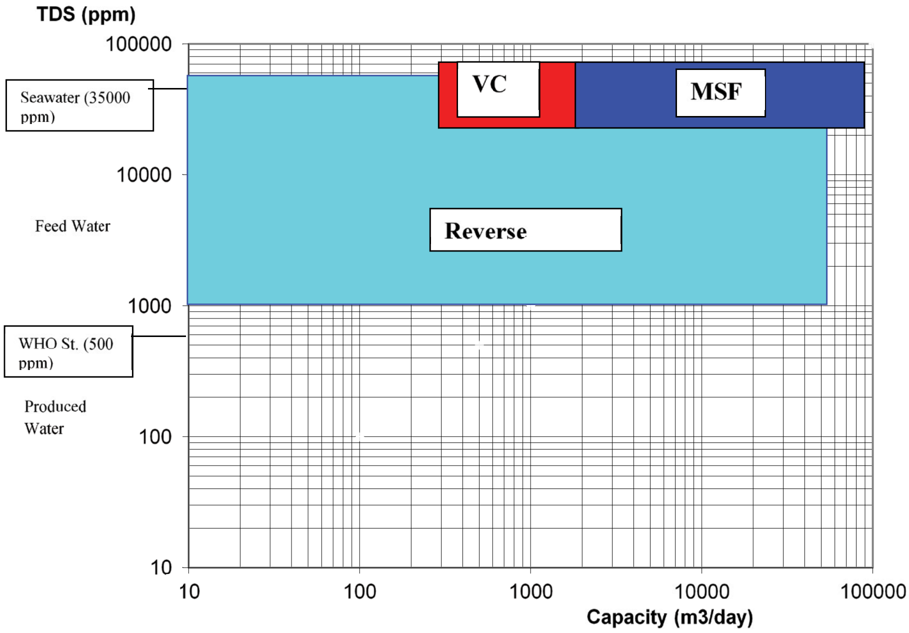


Fig. 5. Ranges of applicability for desalination technologies.

impacts of large-scale seawater desalination plants. Here, we review the possible reductions in energy demand by state-of-the-art seawater desalination technologies, the potential role of advanced materials and innovative technologies in improving performance, and the sustainability of desalination as a technological solution to global water shortages. All over the world now the use of RO trend is increasing against thermal technology due to many reasons including energy consumption, environmental impacts and Capex and Opex costs as shown in Fig. 6. However, and due to the availability of energy sources (electrical source), marine water quality as shown in Fig. 7 and cost breakdown analysis, the most promising desalination technology in Egypt is RO. Fig. 8 shows the schematic diagram for various desalination technologies classified into the main three categories:

- Established (working efficiently on a commercial scale for a long time)
- Emerging (tested on small scale and not yet produced on a commercial scale)
- Developmental (in the research phase and not yet tested)

6. Future of using renewable energy sources

6.1. Energy use in desalination

Desalination is the energy consumption industry. The thermal desalination process still consumes too much energy with adverse environmental impacts. Energy consumed from one desalination plant with a capacity of 300,000 $m^3\ d^{-1}$, is equivalent to the energy consumed by a jumbo jet. In the RO desalination process, billions of gallons of water are forced through the pressure treatments, consuming an average of 4–6 kWh per every one cubic meter of produced freshwater. To reduce the footprint of desalination energy consumption should be minimized, which allows to produce of more freshwater with the same amount of energy used now.

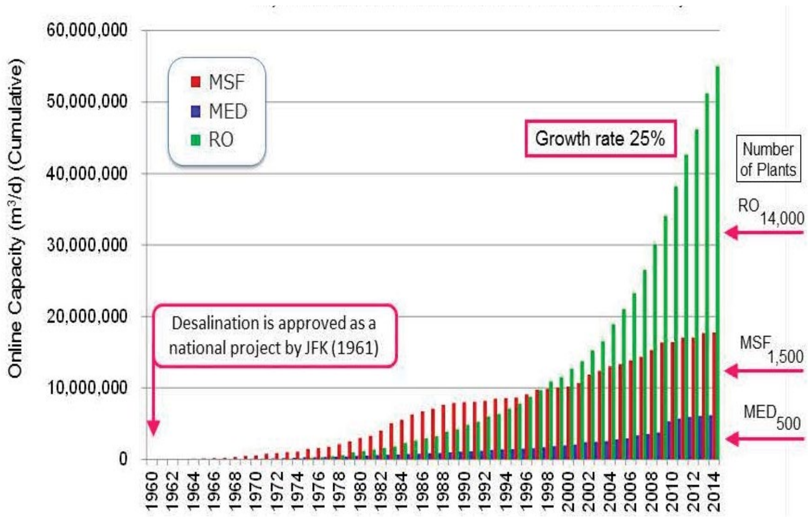


Fig. 6. Transition of the technology from distillation to membrane and expansion of the global desalination market.

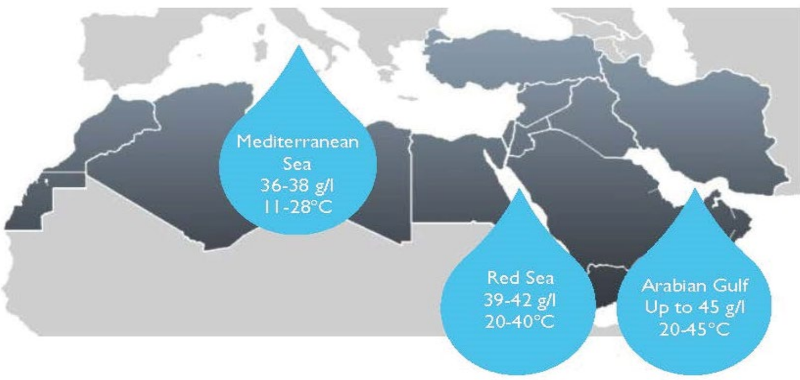


Fig. 7. Salinity of seawater in the GCC region.

By increasing the membrane to graphene, salts can be separated from seawater with no need for more energy. Desalination requires a considerable amount of energy as shown in Table 4. Using fossil fuel in desalination is not environmentally friendly. Coupling renewable energy sources with membrane technologies are recommended in GCC countries in the future. These energy sources include:

- Solar energy
- Wind energy
- Geothermal energy
- Waves and tidal energy
- Hydro-electric

The economics of using the renewable energy sources in desalination depends on the cost of energy as the cost of desalination is largely determined by the energy costs, which contribute by more than 30%. Feasibility studies done by researchers or developers in Egypt indicated that in general, the cost of desalination using renewable energy is still higher compared to the cost of conventional desalination based on fossil fuels. However, the costs of renewable energy technologies are quickly decreasing and renewable energy-based desalination can compete with conventional desalination in remote areas, where the transmission cost of energy and distribution is higher than the cost of distributed generation.

6.2. Green possibilities

To reduce the amount of carbon emitted into the atmosphere, desalination plants can make environmentally friendly choices. One plant sets the bar high with its solar-powered desalination. This plant located just outside of Santa Monica, California, uses sustainable energy for the process of electromagnetic desalination. It was even given a nickname — "the pipe" — due to its architectural design. Any desalination plant has the possibility to use sustainable energy. Solar power is a great source of energy, for example, although desalination plants are already extremely costly, solar panels are becoming more and more affordable. Offshore wind power plants provide clean energy and should be considered a viable power source for desalination plants. The best way for desalination plants to minimize

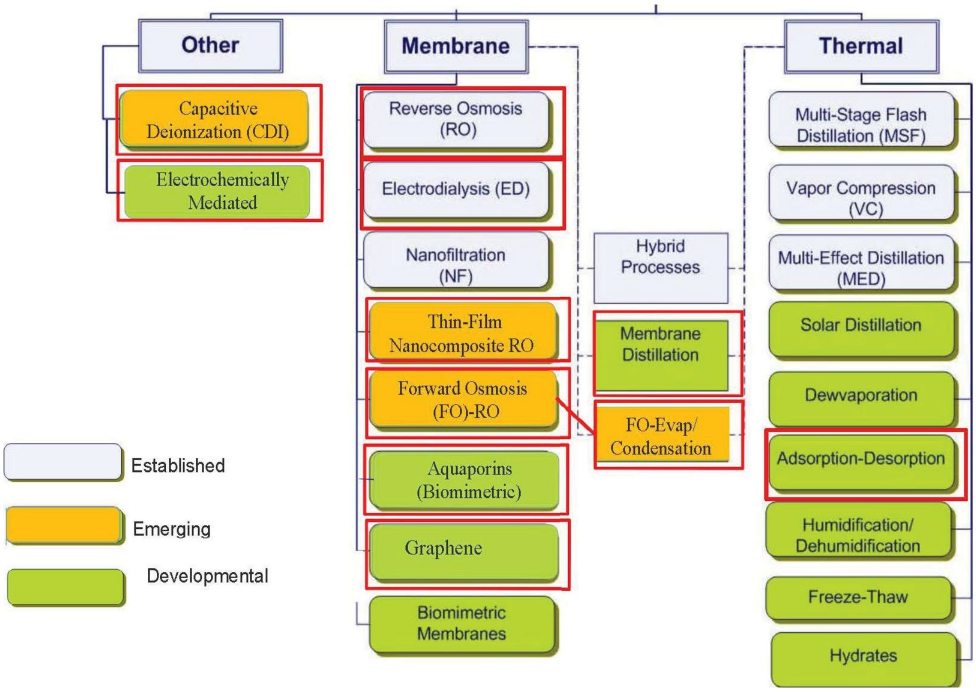


Fig. 8. Desalination technologies classification.

Table 4
Energy requirements of desalination

Process	Total energy (kW h⁻¹ m⁻³)	Capital cost ($ m⁻³ d⁻¹)	Unit water ($ m⁻³)
MSF (without waste heat)	55–57	–	–
MSF (with waste heat)	10–16	1,000–1,500	0.8–1.0
MED (without waste heat)	40–43	–	–
MED (with waste heat)	6–9	900–1,200	0.6–0.8
SWRO	3–6	800–1,000	0.5–0.8
SWRO (with energy recovery)	2–3	<800	0.45–0.6
BWRO	0.5–2.5	<800	0.1–0.3
Innovative technologies/hybridization	<2.0*	<800	<0.5

*Assumed the value of 1.58 (kW h^{-1} m^{-3}) for 42% recovery at 36,300 ppm feed and 1.87 (kW h^{-1} m^{-3}) for 53% recovery at 33,900 ppm feed.

their energy consumption is by using renewable energy to power the facility. Although it carries a huge cost, desalination benefits people by providing them with freshwater. High-speed electrical pumps on desalination plants consume more energy than is needed. If desalination plants focused on sustainably using renewable energy, it would be a major step toward a greener environment.

7. Conclusions or results

Seawater desalination plants cause a range of impacts on the marine environment, and although these are typically considered to only have a local effect operating over 10's m to a few 100's m from a plant the predictions for the expansion of desalination capacity across the Gulf indicates that the impacts of multiple individual desalination plants in combination will lead to impacts at a regional scale which individually or as part of the cumulative impact of multiple-human activities impacting the Gulf could compromise the objectives for sustainable development of the Gulf marine environment. However, the introduction and expansion of desalination in the Gulf region has been fundamental to enabling the development of the Gulf societies that has been observed since the 1950s and the further expansion of desalination is inevitable despite concerns over the potential environmental impacts of desalination.

References

[1] M.A. Dawoud, Egypt's Non-conventional Water Resources: Desalination Sector Analysis and Proposed Development, African Development Bank, 2019, pp. 1–99.
[2] E. Jones, M. Qadir, M.T.H. Van Vliet, V. Smakhtin, S. Kang, The state of desalination and brine production: a global outlook, Sci. Total Environ., 657 (2019) 1343–1356.

[3] GCC, Gulf Cooperation Council Secretariat, Desalination Statistics, Water Resources Committee, GCC Secretariat, Riyadh, KSA, 2017.
[4] World Bank, The Role of Desalination in an Increasingly Water-Scarce World, World Bank, Washington, DC., 2019, pp. 1–135.
[5] World Bank, A Water Sector Assessment Report on the Countries of the Cooperation Council of the Arab States of the Gulf, Water, Environment, Social and Rural Development Department, MENA Report 32539-MNA, Washington DC, USA, 2005.
[6] GWI, Desalination Markets 2019, Global Water Intelligence, Media Analytics, Ltd., Oxford, U.K., 2019.
[7] S. Lettemann, T. Höpner, Environmental impact and impact assessment of seawater desalination, Desalination, 220 (2008) 1–15.
[8] M.A. Dawoud, M.M. Al Mulla, Environmental impacts of seawater desalination: Arabian Gulf case study, Int. J. Environ. Sustainability, 1 (2012) 22–37.
[9] K.L. Petersen, H. Frank, A. Paytan, E. Bar-Zeev, Impacts of Seawater Desalination on Coastal Environments, V. Gnaneswar Gude, Ed., Sustainable Desalination Handbook, Plant Selection, Design and Implementation, Butterworth-Heinemann, California, USA, 2018, pp. 437–463.
[10] P.F. Sale, D.A. Feary, J.A. Burt, A.G. Bauman, G.H. Cavalcante, K.G. Drouillard, B. Kjerfve, E. Marquis, C.G. Trick, P. Usseglio, H.V. Lavieren, The growing need for sustainable ecological management of marine communities of the Persian Gulf, AMBIO, 40 (2011) 4–17.
[11] C.R.C. Sheppard, The Gulf: a young sea in decline, Mar. Pollut. Bull., 60 (2010) 13–38.
[12] J.F. Caddy, Toward a comparative evaluation of human impacts on fishery ecosystems of enclosed and semi-enclosed seas, Rev. Fish. Sci., 1 (1993) 57–95.
[13] T.M. Missimer, R.G. Maliva, Environmental issues in seawater reverse osmosis desalination: intakes and outfalls, Desalination, 434 (2018) 198–215.
[14] K.L. Petersen, A. Paytan, E. Rahav, O. Levy, J. Silverman, O. Barzel, D. Potts, E. Bar-Zeev, Impact of brine and antiscalants on reef-building corals in the Gulf of Aqaba - potential effects from desalination plants, Water Res., 144 (2018) 183–191.
[15] S. Jenkins, J. Paduan, P. Roberts, D. Schlenk, J. Weis, Management of Brine Discharges to Coastal Waters Recommendations of a Science Advisory Panel, Southern California Coastal Water Research project, State Water Resources Control Board Technical Report 694, Coasta Mesa, CA, 2012, pp. 1–101.
[16] A.G. Pervov, A.P. Andrianov, Assessment of the effectiveness of new "green" scale inhibitors used in reverse-osmosis seawater desalination, Pet. Chem., 57 (2017) 139–152.
[17] S. Jamaly, N.N. Darwish, I. Ahmed, S.W.Hasan, A short review on reverse osmosis pretreatment technologies, Desalination, 354 (2014) 30–38.
[18] J. Sánchez-Lizaso, J. Romero, J. Ruiz, E. Gacia, J. Buceta, O. Invers, Y. Torquemada, J. Mas, A. Ruiz-Mateo, M. Manzanera, Salinity tolerance of the Mediterranean seagrass *Posidonia oceanica*: recommendations to minimize the impact of brine discharges from desalination plants, Desalination, 221 (2008) 602–607.
[19] P.L.A. Erftemeijer, D.A. Shuail, Seagrass habitats in the Arabian Gulf: distribution, tolerance thresholds and threats, Aquat. Ecosyst. Health Manage.,15 (2012) 73–83.
[20] D.A Roberts, E.L. Johnston, N.A. Knott, Impacts of desalination plant discharges on the marine environment: a critical review of published studies, Water Res., 44 (2010) 5117–5128.
[21] S. Uddin, A.N. Al Ghadban, A. Khabbaz, Localized hyper saline waters in Arabian Gulf from desalination activity—an example from South Kuwait, Environ. Monit. Assess., 181(2011) 587–594.
[22] W.J.F. Le Quesne, J.K. Pinnegar, The potential impacts of ocean acidification: scaling from physiology to fisheries, Fish Fish., 13 (2012) 333–344.
[23] GCC, (Gulf Cooperation Council Secretariat), Desalination in the GCC: The History, The Present, The Future, Desalination Experts group, Water resources Committee, GCC Secretariat, Riyadh, KSA, 2014, pp. 1–54.
[24] AGEDI, Final Technical: Regional Desalination and Climate Change, Abu Dhabi Global Environmental Data Initiative, LNRCCP, CCRG/IO, Abu Dhabi, UAE, 2016, pp. 1–105.
[25] H. Marsh, S. Sobtzick, Dugong Dugon, The IUCN Red List of Threatened Species 2015, e.T6909A43792211, 2015. Available at: http://dx.doi.org/10.2305/IUCN.UK.2015-4.RLTS.T6909A43792211.en
[26] M.A. Dawoud, Economic feasibility of small scale solar powered RO desalination for brackish/saline groundwater in arid regions, Int. J. Water Resour. Arid Environ., 6 (2017) 103–114.