Santander X Innovation Xperts

Innovations and challenges to provide clean and sustainable water through desalination

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By Santander

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01

Introduction

This paper presents **desalination as a technical solution for alleviating global and local water scarcity.** By 2050, due to population growth, urbanization, and climate change, about 40% of the world's population is projected to live under severe water stress, including almost the entire population of the Middle East and South Asia, plus significant parts of China and North Africa[1]. Utilizing unconventional water resources is an emerging opportunity to narrow the water demand-supply gap[2]. Seawater is considered to be a drought-proof water source, as it does not depend on river flows, rain fall, reservoir levels, or climate change. **Desalination may be an option to alleviate scarcity in industry and coastal cities.**

In **section 1,** the dominating and **emerging technologies for desalination** of seawater, brackish water and freshwater will be presented on their contexts, along with supporting data establishing its current potential. The current global desalination capacity per technology, water type by region, per customer and the expected growth and emerging markets will be presented. The subsequent section will discuss the **ever-present challenges and costs involved in the process:** environmental and operational concerns will be described with instances of successful approaches that are readily available. In the final section, we will take a step further into the future and describe upcoming advances in desalination indicating medium-term opportunities for development in relation to challenges such as brine management, deteriorating source water quality, energy supply, and climate change.

02

The case for desalination

Water use has been growing at more than twice the rate of population increase in the last century[3]. The combination of economic and demographic growth in particular has led to over-abstraction of conventional freshwater resources in various parts of the world. With this, we have seen an increase in water scarcity, defined as a total annual runoff available for human use of less than 1,000 m^3 per capita each year.

At the same time, still many people are waiting to be connected to safe water supply. Despite recent progress in providing access through the MDG and SDG programs, 2.2 billion people around the world are still expecting access to safely managed drinking water, including 785 million without access to basic safe drinking water[4]. Simultaneously, the world's population is expected to reach 9.7 billion by 2050[5]. Combined with a more erratic and uncertain supply, this will aggravate the situation in particular in regions that are already water-stressed (North Africa and the Middle East), and generate water stress in regions currently featuring abundant water resources.

There are several technical solutions that can help to solve water scarcity around the world, chiefly five categories:

- **i) reduce water demand,** by increasing efficiency in agriculture and industry, reducing leakage in public water supply, or by actively stimulating consumption reduction through awareness campaigns or progressive tariffs, for example;
- **ii) transporting water,** although this generally requires transport over long distances, potentially with high energy costs;
- **iii) storing river water** in aquifers during periods of high flow;
- **iv) reusing water** mainly in industry and agriculture;
- **v) or desalting**
    - a. brackish water (i.e., water in estuaries, mangroves and other areas with mixed fresh and saline water),
    - b. wastewater effluent, and
    - c. **seawater** as a non-conventional water resource.

Among these solutions, desalination is usually only implemented as a last resort when conventional freshwater resources have been stretched to the limit. Desalination has also recently gained recognition as a way of solving water scarcity. In the "UN World Water Development report 2021: Valuing water"[6] desalination is presented as "one of the technological options that can provide an additional source of freshwater for irrigation, especially in water-stressed coastal areas, underlying how thanks to decreasing costs, the supply of desalinated water for agriculture is most likely to be cost-effective in a tightly controlled environment, using agricultural practices with the most efficient water use, crops with high productivity, and renewable energies".

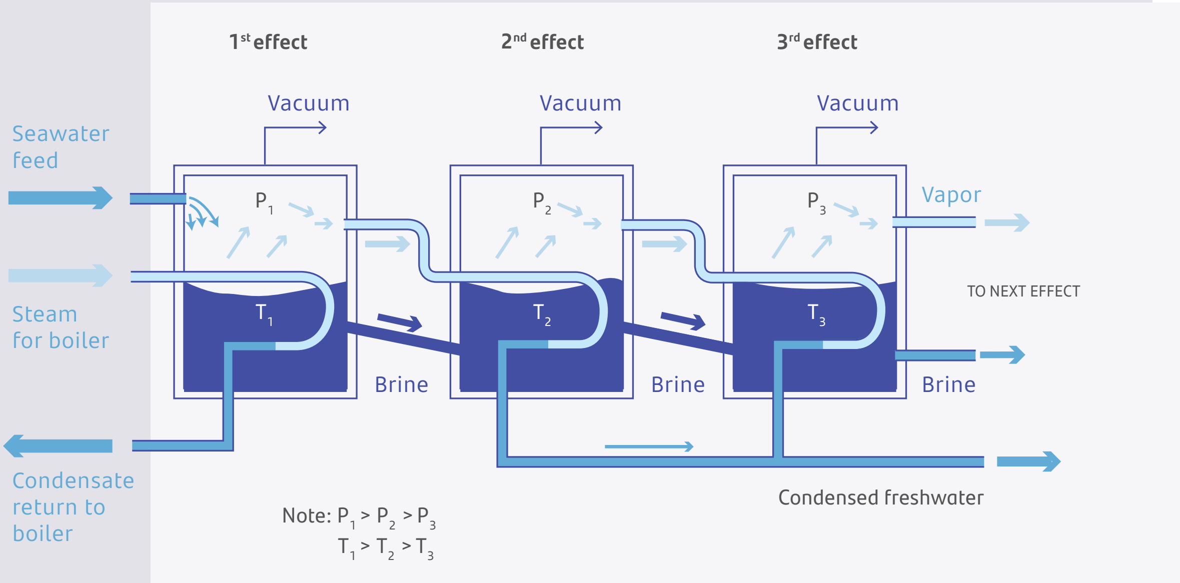
In focus

Desalination: basic facts and technologies

There are several desalination technologies (thermal-based and membrane-based processes) currently employed that have been developed over the years. Six different membrane technologies are applied to produce drinking and industrial water, namely: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), electro-dialysis (ED), electro-deionization (EDI).

Distillation is the oldest known process for producing freshwater from seawater. When salt water is boiled, the salt ions remain behind as freshwater vapor is boiled away. In the distillation process water is first boiled and then the steam (water vapor) is cooled in a clean vessel. This cooling condenses the steam (water vapor) to water again. For water vapor to condense to a liquid, it is necessary that the heat of condensation is removed, preferably recovered. There are three major distillation processes being used in the industry today: multi-effect evaporation / distillation (MED), multi-stage flash (MSF), and vapor compression (VC).

Figure 1. Example of a multi effect distillation unit with three effects. (With permission from 7)



Reverse osmosis (henceforth RO) has main applications in seawater and brackish water desalination. Electrodialysis is applied in desalination of brackish water. Nanofiltration is mainly applied for the removal of sulphate, hardness and natural organic matter. Ultra- and micro-filtration are applied to remove suspended and colloidal matter and for disinfection of drinking water.

Figure 2. Schematic of a RO system including pre-treatment and post-treatment. (With permission from 7)

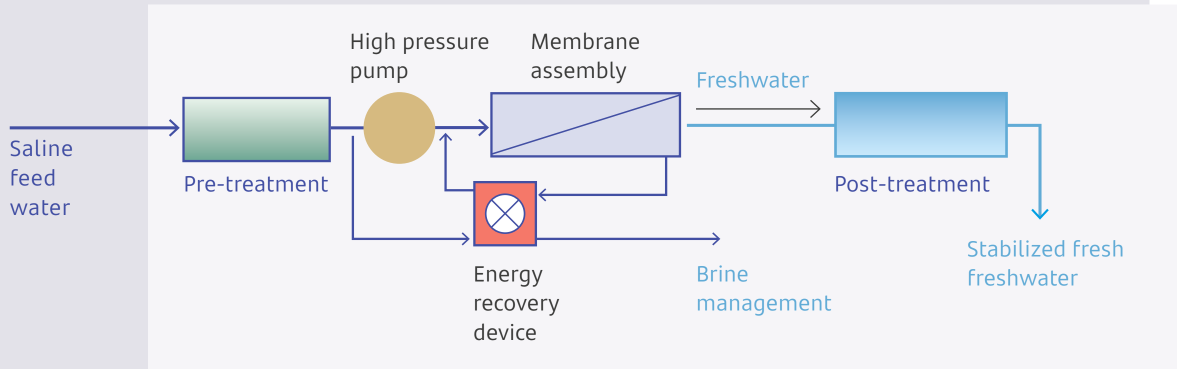
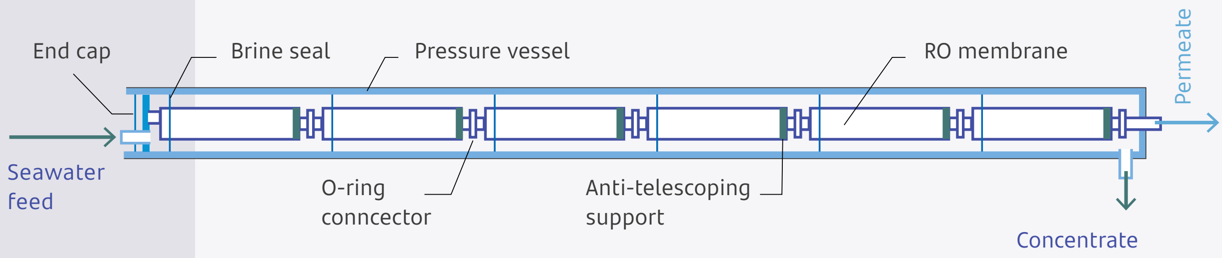


Figure 2 illustrates the various components of a RO desalination plant, including pre-treatment, high-pressure pump units, the assembly of RO elements in pressure vessels, and the post-treatment required to re-mineralize the RO permeate water. With the help of energy recovering devices, the pressure of the RO concentrate after leaving the pressure vessel is transferred hydraulically to the feed water. Pre-treatment needs to guarantee that the RO feedwater has a silt density index value (SDI) of less than 5 but preferably less than 3. Post-treatment will introduce minerals back in the RO permeate and will make sure the final water is fit for purpose.

Figure 3: Schematic of a RO pressure vessel containing 6 RO membrane elements and illustrating the RO feed, RO permeate and RO concentrate streams.
(With permission from 7)



The ranges of energy consumption and pressure, including a reference production cost for various technologies are presented in Table 1. The treatment of freshwater by conventional water treatment is the less energy demanding in comparison with the other technologies. In membrane-based sea water desalination, the energy consumption is in average 3-4 kWh/m3 with pressure range between 50 and 90 bar. The evolution of the energy demand is presented in Figure 5.

Table 1. Energy consumption and pressure for various treatment technologies 7

Technology	Pressure, bar	Energy consumption, kWh/m^3	Heat	Cost, euro or $ per m^3
Conventional drinking water	0.1 - 0.2	-		
Electro-dialysis				0.25 - 0.50
Ultra- and micro- filtration	0.5 - 2	0.1 - 0.2	-	0.05 - 0.10
Brackish RO	5 - 10	0.3 - 0.5	-	0.15 - 0.25
Seawater RO	50 - 90	3 - 4	-	0.50 - 1.00
Distillation	-	1 - 4	160 MJ/m^3	
Cost of energy		0.05-0.1 $/kWh	5-15 $/GJ	

The production cost in sea water reverse osmosis plants can be divided in the following categories (see Figure 4): energy consumption represents about 40% of the total production cost, amortization also amounts for about 40%, staff costs amounts 4-11%, consumption of chemicals during treatment 2-6.5%, costs of RO membranes 2-5%, plant maintenance 3.5-4.5%, and cleaning of the RO membranes about 0.2-0.3%. Any optimization in energy consumption will decrease the production cost. It is expected that by using renewables energies (off-set from electricity grid), the energy costs will decrease while at the same time minimizing effects on environment. Renewable energy also has potential for direct application in small or remote plants.

Figure 4: Production costs in seawater reverse osmosis plants[8]

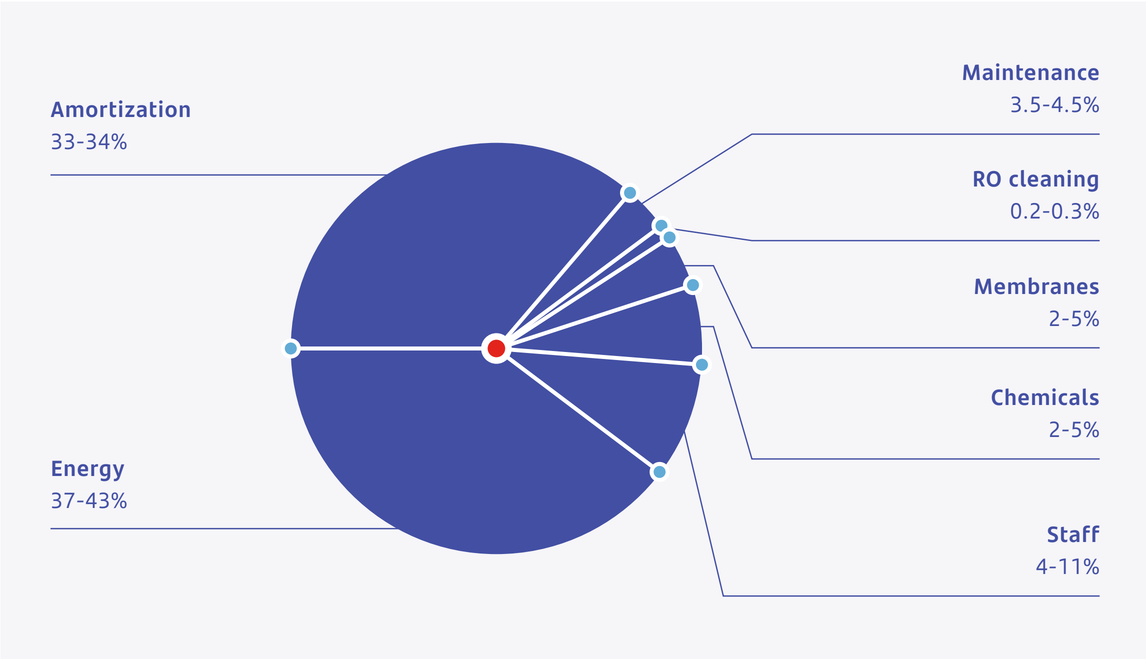
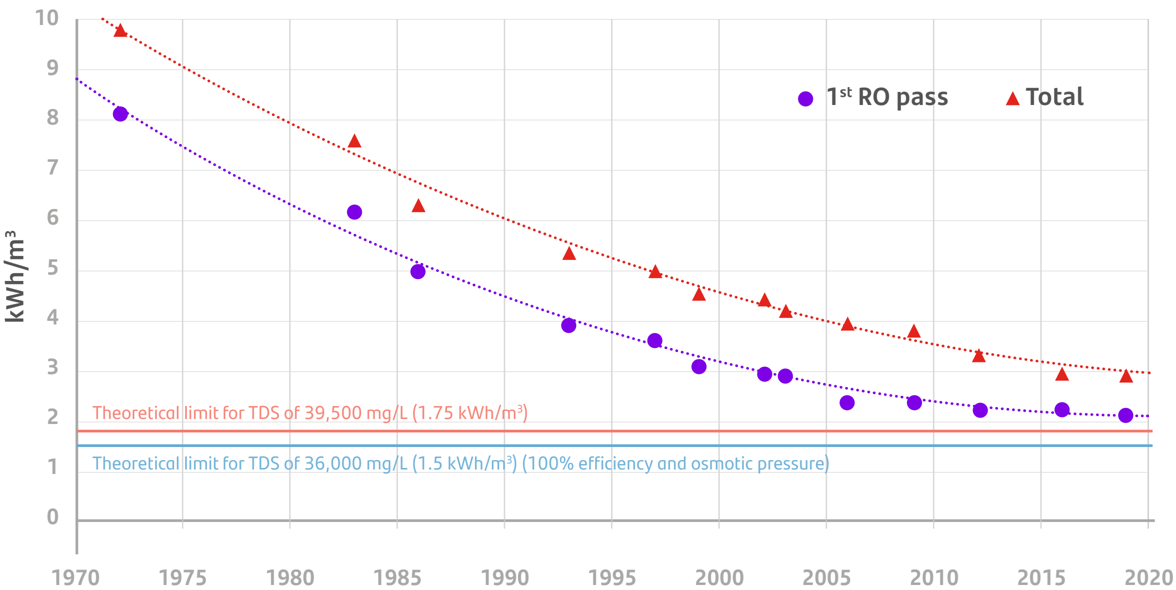


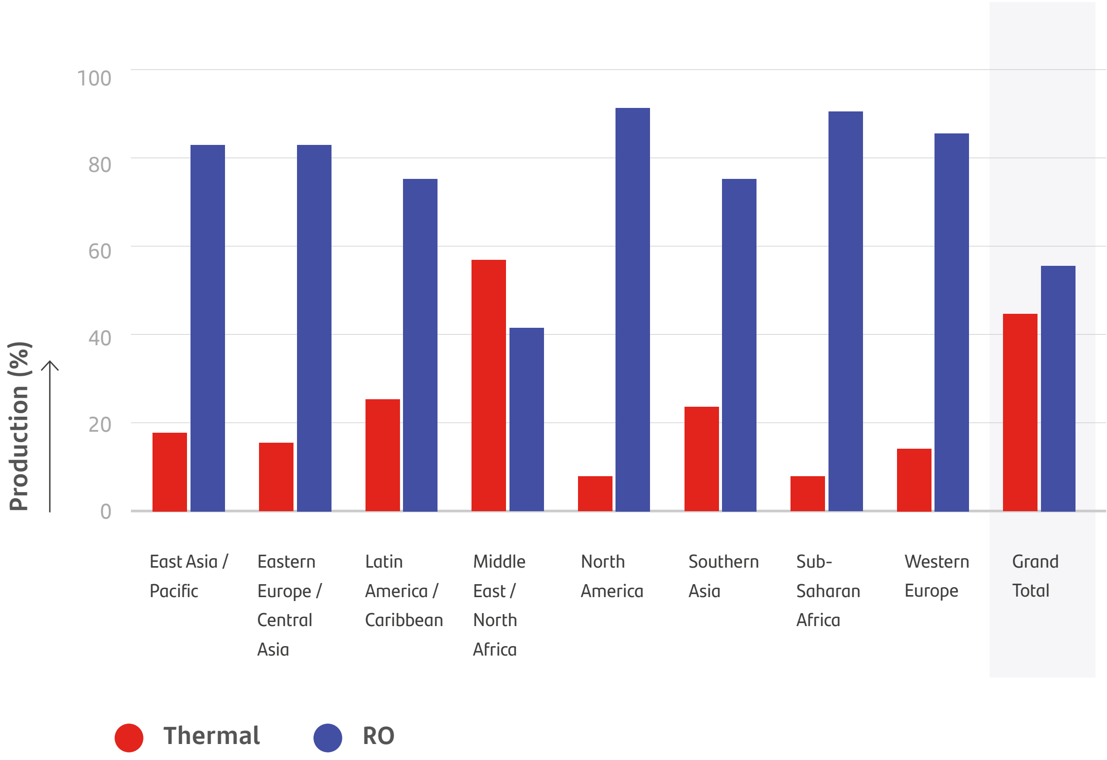
Figure 5: Historical evolution of energy consumption in SWRO. Adapted from 8



Yet, **there are strong reasons to begin considering desalination as a first-resort option. Desalination is set to provide** (more so than currently) **an option to alleviate scarcity, especially in industry and coastal cities, through at least three mechanisms:**

- → **Gained efficiency.** Continuous lowering of production prices and energy consumption has allowed desalination to obtain a more prominent position in water treatment options. Membrane-based desalination with reverse osmosis (RO) dominates the market (~70%). Its investment cost and energy requirements today are lower than for thermal processes (MSF and MED, 24%). Distillation is only of relevance for seawater. When comparing membrane-based desalination and thermal-based desalination per region (see Figure 6), it is only in the Middle East and North Africa where thermal desalination has more capacity than reverse osmosis plants (57% vs. 43%). In the rest of the world reverse osmosis is (83% vs. 17%) the dominant technology. Altogether, the world average production capacity is 45% for thermal processes vs. 55% for reverse osmosis.

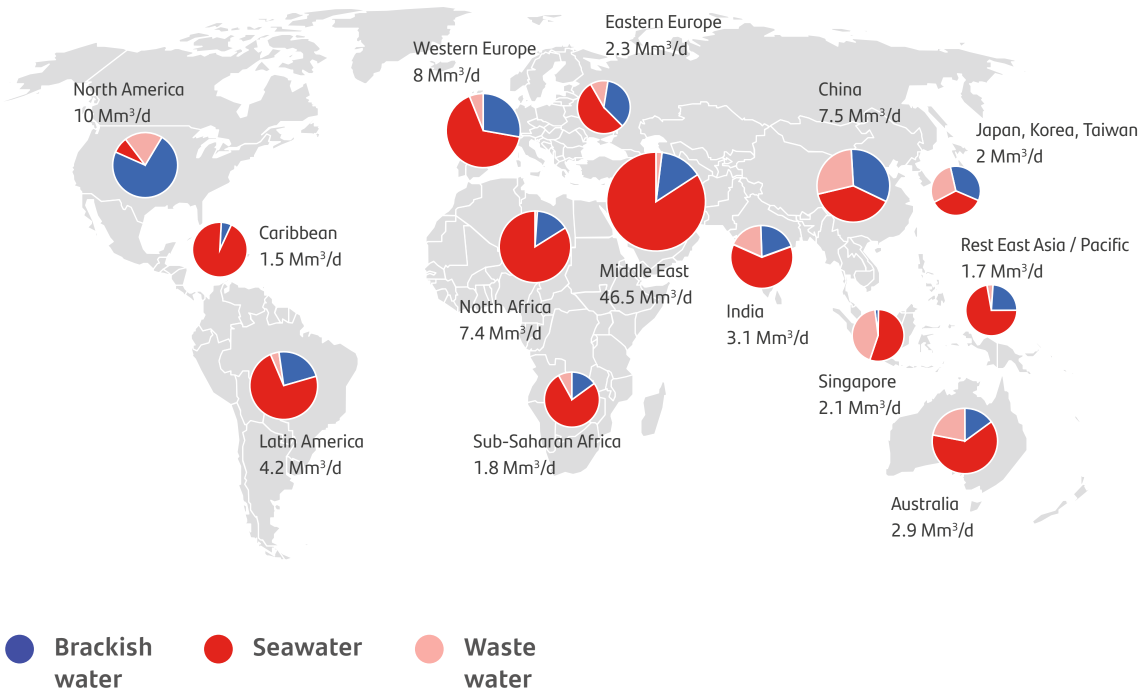
Figure 6: Thermal vs. Membrane-based seawater desalination in 2020[7]



→ **Resilience.** Desalination is considered as a drought-proof water source, which does not depend on river flows, reservoir levels or climate change.

→ **Geographical convenience.** Megacities where water demand is typically high are very often situated at the coast, where desalination fits perfectly [9,10] in particular. Around 680 million people currently live in low-lying coastal zones. This is expected to increase to a billion by 2050[11]. Also, nearly 2.4 billion people live within 100 km of the coast[12], and 65 million live in small island developing States[13]. Consequently, cities along or close to the coast may consider the use of seawater as an alternative source for drinking water production, for agriculture, or for industry. The global desalination capacity per region and per type of water is illustrated in Figure 7.

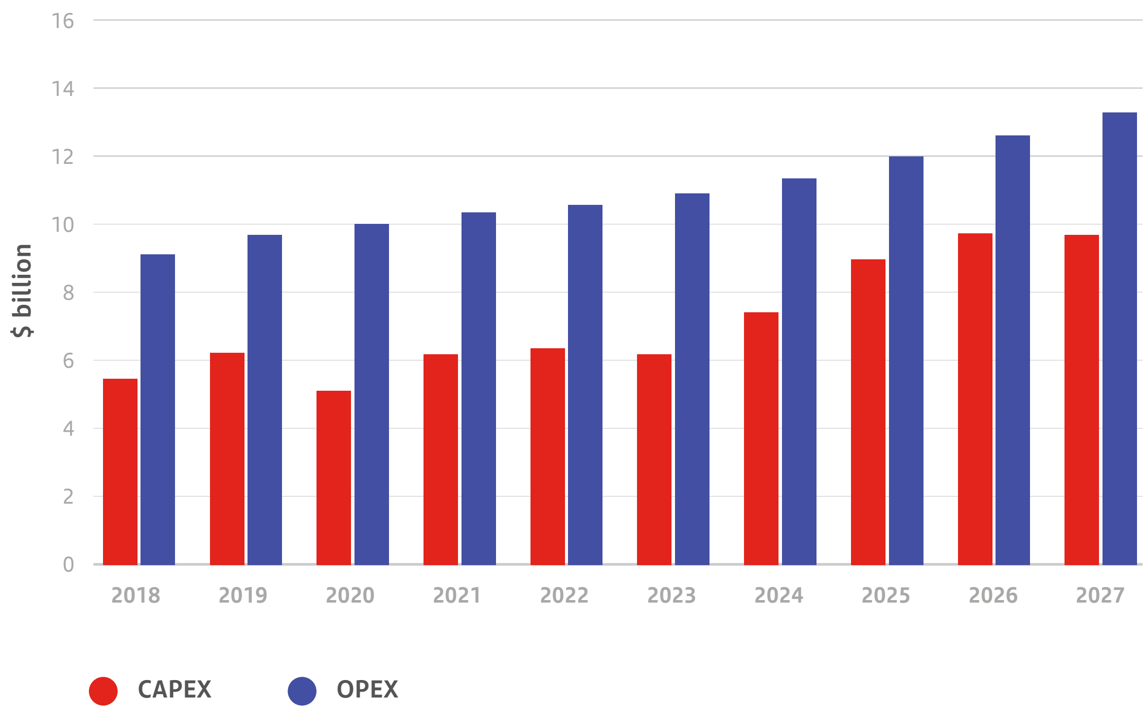
Figure 7: Desalination capacity in different regions of the world per percentage capacity production of various water sources (seawater, brackish water, wastewater effluent) (Information from 14, with permission from 7). For example: North America desalinates water with a total capacity of 10 Mm³/d of which 73% is produced from brackish water, 19% from waste water treated effluent and 8% from seawater.



Perhaps the strongest proof for the promising future of desalination is on its recent past and present uses, particularly in countries with pressing water demands situated in the Middle East. The installed capacity for desalination of seawater and brackish water has grown rapidly over the last thirty years (See Figure 9). Global contracted capacity is now more than 100 million cubic metres per year, helping satisfy the growing municipal, agricultural and industrial water demand. Currently, about 330 million people in the world receive drinking water from desalination plants (at 120 litres per capita per day).

Despite significant delays in 2021-22, the seawater and brackish water desalination market is continuing to grow, from current 6.1 billion USD in capex and 10.5 billion USD in opex (see Figure 8), with strong indications of new capacity in both historically leading and more minor markets. Seawater desalination market had in 2020 a compound annual growth rate of 7.9% and the contracted capacity is expected to increase by 39 Mm^3 by 2027 [15].

Figure 8: Desalination sector expenditure 15

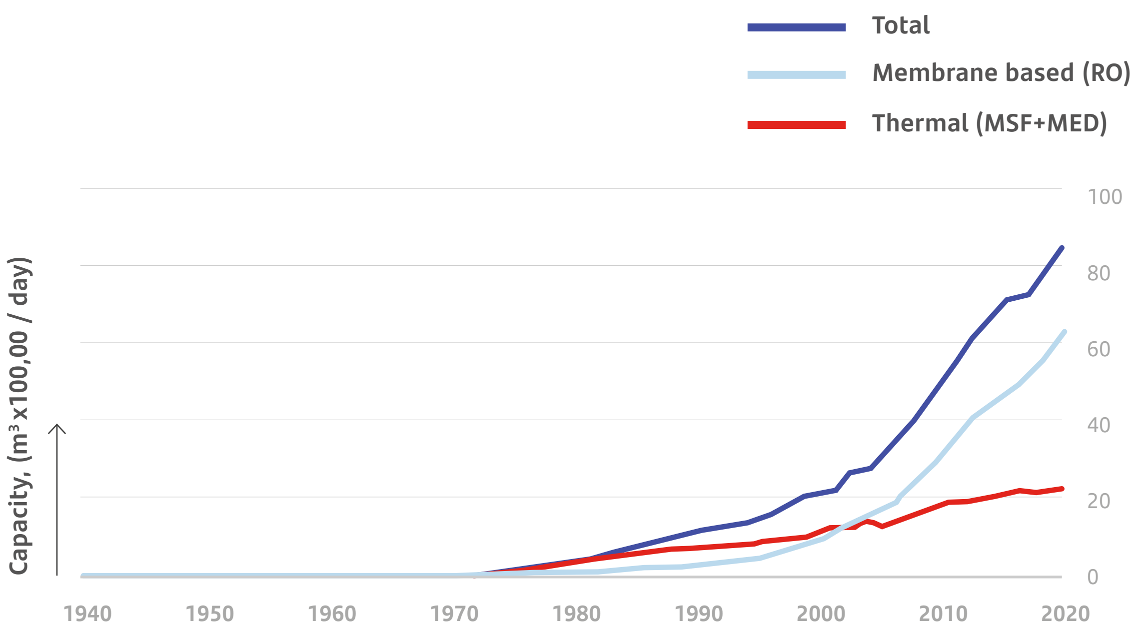


Seawater is the main water source for desalination in all regions, with the exception of North America, where the regional capacity is based on brackish water desalination (73% / 7.3 Mm^3/d) followed by wastewater effluent (19% / 1.9 Mm^3/d). Japan, South Korea, Taiwan, and China desalinate seawater, brackish water, and wastewater effluent in almost equal parts.

Therefore, desalinated water is already proving its efficacy in the areas of drinking water provision, water for industry and water for irrigation. Most of the Middle East countries rely on desalination for municipal use, while countries such as China, India, South Korea, Brazil, Taiwan, Chile, Indonesia use desalination to satisfy industrial demand.

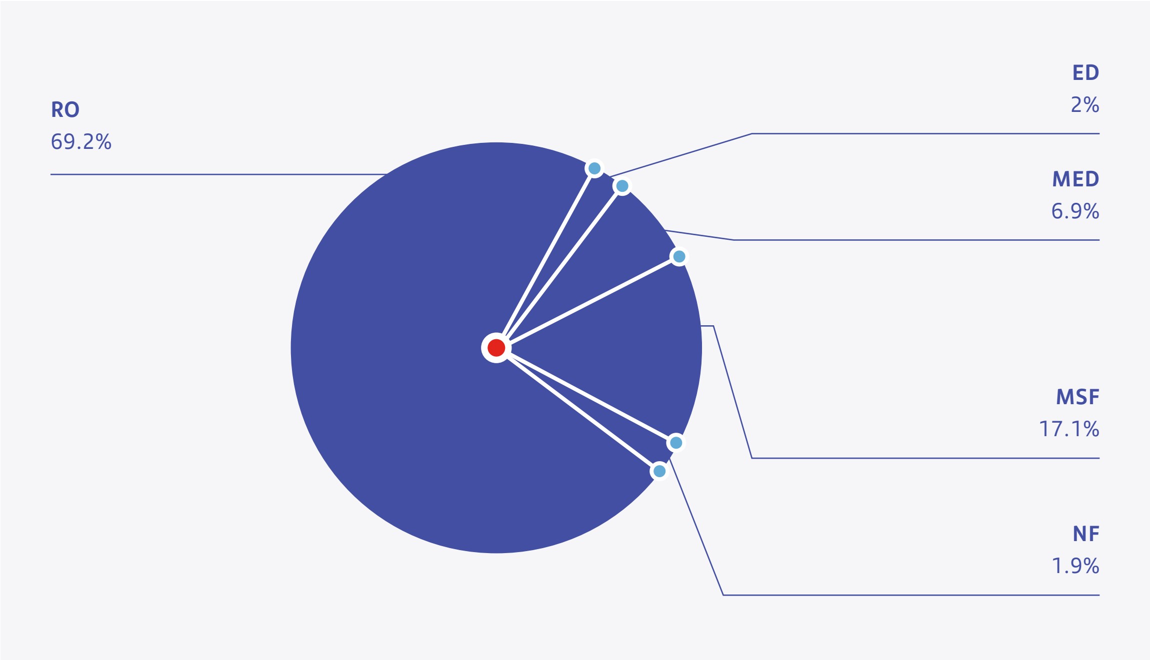
Figure 9 presents the global historical cumulative production capacity of desalination plants for all raw water sources, including: seawater, brackish water, fresh water, treated wastewater, pure water. Over two-thirds of the current total capacity is produced by membrane-based desalination technology (reverse osmosis) and less than one-third is produced by thermal processes (multi-stage flash distillation, and multi-effect distillation). One of the reasons why sea water reverse osmosis production capacity grows faster than thermal processes is the lower investment costs and the lower energy consumption (3-4 kWh/m^3). In the last thirty years, the online production capacity has increased from 13.7 Mm^3/d to the current 101.6 Mm^3/d, which is about 7.5x more capacity. In the last 10 years, the growth in desalination capacity has been about 41% and mostly related to the new plants making use of reverse osmosis as main desalination technology. The implementation of desalination plants has increased in many parts of the world. Much of the growth of the desalination capacity takes place in the sea water desalination industry, although wastewater desalination and brackish water desalination is becoming more relevant.

Figure 9: Total desalination capacity in the world (seawater, brackish, wastewater, and fresh water) (Information from 14, with permission from 7)



For all source water types reverse osmosis (RO) is the preferred desalination technology. It accounts for 69.2% (67 Mm^3/d) of the global capacity (Figure 10); 24% or 23.2 Mm^3/d of the global capacity is produced by distillation plants, either multi-stage flash (MSF) or multi-effect distillation (MED) plants, with relative market shares of 17% (16.6 Mm^3/d) and 7% (6.6 Mm^3/d), respectively. Electrodialysis (ED) process with about 2% market share (1.97 Mm^3/d), and other processes, such as electro-de-ionization (EDI) account for 0.3% (0.3 Mm^3/d), nano-filtration (NF) accounts for another ~2% (1.8 Mm^3/d) of the world desalination capacity.

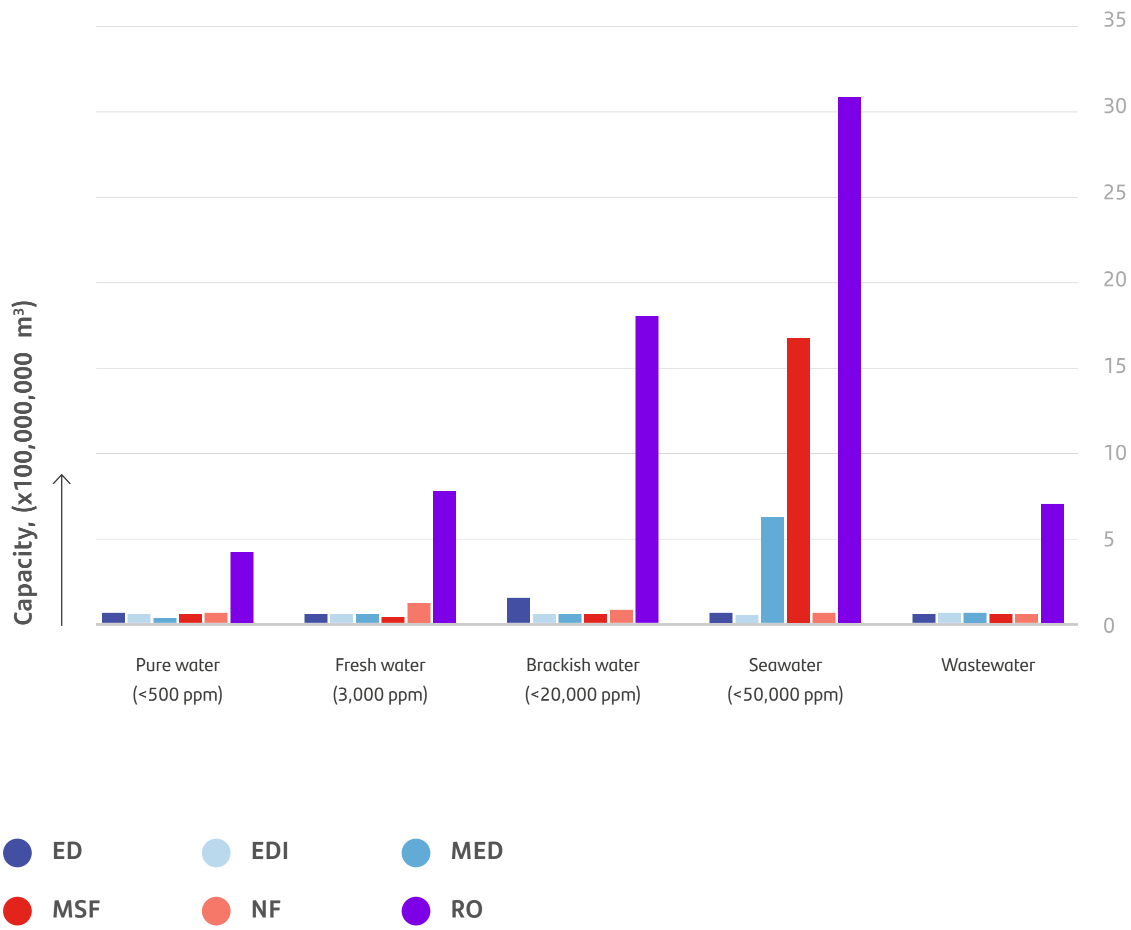
Figure 10: Desalination capacity by type of technology
(RO = reverse osmosis, NF = nano-filtration, MSF = multi-stage flash distillation, MED = multi-effect distillation, ED = electro-dialysis).
(Information from 14, with permission from 7)



At present, ~60% of the total desalination capacity is produced from seawater, 20% is produced from brackish water sources, mainly brackish groundwater, 8% is produced from waste water effluent, 8% from fresh water, and 4% from pure water. Seawater is hence the predominant source water for desalination and accounts for a worldwide water production of ~60 Mm^3/d.

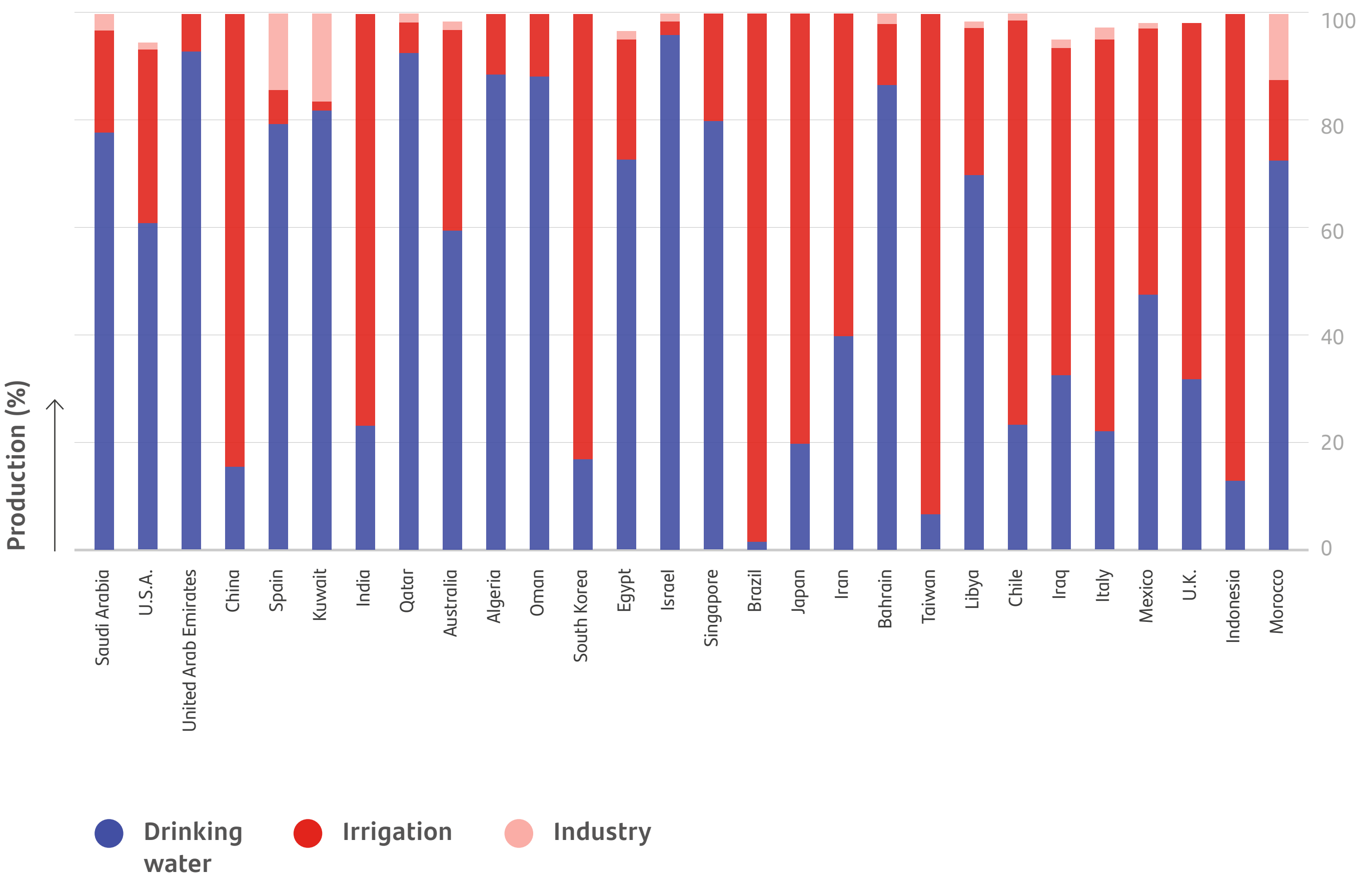
Figure 11 distinguishes between the different source-water types and the technologies that are applied. For seawater, RO and thermal processes dominate the global sea water desalination production (34.4 Mm^3/d and 25.7 Mm^3/d). MSF is the main thermal process, accounting for 31% of the global seawater desalination production. RO is the dominant process for brackish water (90%, 17.8 Mm^3/d) and for waste water (91%, 6.9 Mm^3/d) desalination.

Figure 11: Desalination production capacity per raw water source and per technology for plants online and presumed online. (Information from 14, with permission from 7)



The countries with desalination capacities larger than 650,000 m³/d are presented in Figure 12. The use of desalination for irrigation is relevant in three countries, namely, Spain, Kuwait, and Morocco. China, India, South Korea, Brazil, Japan, Taiwan, Indonesia rely on desalination for industry applications. Saudi Arabia, USA, UAE, Spain, Kuwait, Algeria, Oman, Israel, Singapore, Bahrain, Libya, Morocco rely on desalination for municipal use. In conclusion, about 68% or 68.5 Mm³/d of the worldwide desalination capacity was produced from seawater sources in 2020. The global desalination capacity increased by 41% compared to the year 2010 (59.2 Mm³/d). Of the desalinated seawater, 57% is produced by reverse osmosis. The MSF distillation process is reserved almost exclusively for the desalination of seawater, mainly in the Gulf countries.

Figure 12: Highest capacity desalination countries and main use of desalination (drinking water, industry, irrigation) in 2020. (Information from 14, with permission from 7)



03 Ever-present challenges and how to address them

Desalination is often considered too technical, too costly, too energy intensive, and limited by technical and environmental challenges. As with all drinking water technologies, desalination has its challenges and also has solutions to those challenges. The price per cubic metre of water has reduced significantly over the years due to more efficient membrane production, implementation of energy recovery devices, cost engineering, etc, and a larger market. Energy demand per cubic meter has already reduced (see Figure 5), and costs related could be brought down (0.02 to 0.08 $/kWh[8]), further by switching to renewable energy sources or direct coupling in small or remote plants. Yet, **membrane fouling** is still the main "Achilles heel" for an overall application of reverse osmosis. **Environmental concerns** constitute a separate, equally significant, challenge to be overcome in the coming years.

MEMBRANE FOULING: THE MAIN CHALLENGE

Membrane fouling tends to result in a variety of problems, such as the need for (frequent) membrane cleaning, reduction of production capacity, higher energy consumption, decrease in produced water quality. Extensive fouling makes RO production facilities less reliable, and evolves in the need for more frequent membrane replacement.

There are five types of membrane fouling to be tackled:

i) **particulate** fouling due to suspended and particulate matter,

ii) **inorganic** fouling due to iron and manganese,

iii) **organic** fouling due to organic compounds,

iv) **biofouling** due to growth of bacteria, and

v) **scaling** due to deposition of sparingly soluble compounds.

Fouling and scaling may manifest in three ways:

i) increased differential pressure across the spacer in spiral wound elements due to clogging, resulting in potential **membrane damage;**

ii) **decreased membrane permeability** due to deposition and/or adsorption of materials on the membrane surface, resulting in higher required water feed pressure to maintain capacity; and

iii) **increased salt passage** due to concentration polarization[i] in the fouling layer, resulting in higher salinity in the product water.

Readily available solutions that would benefit from further development. Particulate and colloidal fouling are mostly well controlled by the pre-treatment systems (see below), but the occurrence of organic fouling and biofouling is still a major issue, being the main reason for the need for frequent cleaning of the reverse osmosis membranes.

To prevent the occurrence of membrane fouling, **pre-treatment** in RO plants is essential. Pre-treatment can take place in the form of filtration units (single or dual media such as anthracite and sand), membrane filtration such as ultrafiltration membranes; and the use of dissolved air flotation[ii] in combination with the previously mentioned two options. **Methods and tools monitoring the performance** of the pre-treatment with regards to fouling control and process optimization are also of great help.

ENVIRONMENTAL CONCERNS

Like all human activities, desalination plants have also environmental impact. Despite many efforts, there are still some environmental concerns[16], mainly:

- Disposal of material use
- Land use
- Energy use to desalinate water and greenhouse gas (GHGs) emission from providing that energy
- Discharge of concentrate
- High volume of chemical use
- Loss of aquatic organism from marine pollution and open seawater intake

i. Concentration polarization is the accumulation of salts (ions) on the membrane surface. As a result, the concentration of the ions at the membrane surface is higher than in the feed water. This phenomenon results from the water flow through a membrane, from the rejection of ions by the membrane and overtime accumulation of the retained salts on the membrane surface.

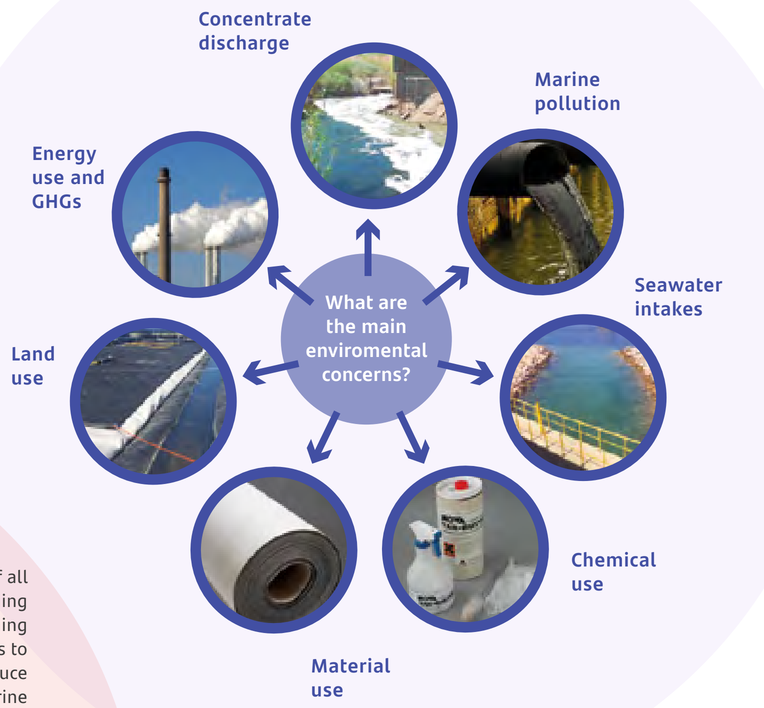
ii. In dissolved air flotation, air bubbles are produced by the reduction in pressure of a water stream saturated with air. Flotation is employed mainly for the treatment of nutrient-rich reservoir waters that may have heavy algal blooms and for low-turbidity, low-alkalinity coloured waters.

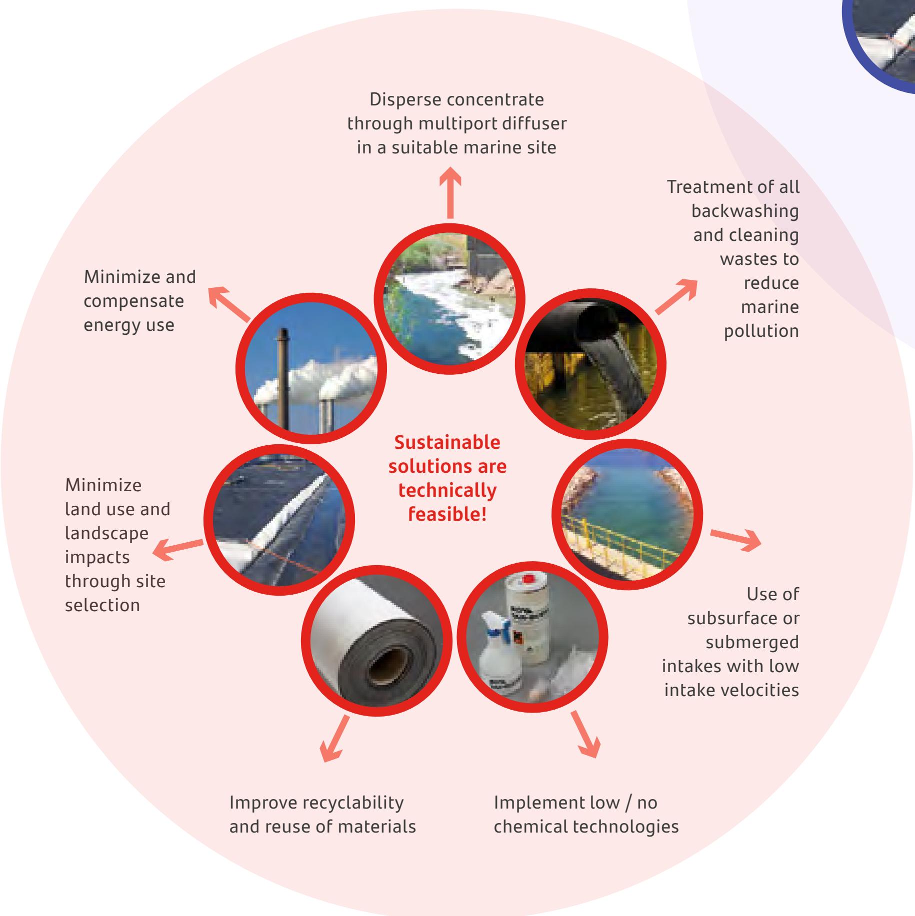
The recent technological advances (such as the use of energy recovery devices) helped to decrease GHG emissions[17]. The use of high volumes of chemicals during pre- and post-treatment of seawater is another environmental concern. The main concern is the discharge of chemicals into natural water, which affects the ecological imbalance[16]. Furthermore, the design of open seawater intake has a potential role in the loss of aquatic organism, as these organisms colloid with the intake screen or are sometimes drawn into the plant[17].

Figure 13:

Environmental concerns (up) and sustainable and technical solutions (down) in membrane-based desalination plants.

Source: Adapted from 18





Readily available solutions to ameliorate environmental impact. Among the alternatives for sustainable solutions to prevent/minimize the issue listed above[18] the following have shown results and should be included on any new development, and might be used as a "safe environmental checklist" with viable alternatives that should be considered by any current or upcoming desalination project:

- On surface and ground water pollution (concentrate and residual chemicals):
  - → minimize chemical use by using best available techniques,
  - → treatment of all backwashing and cleaning solutions,
  - → use and design diffusers to disperse the concentrate in order to meet mixing regulations.

- On sediments and soil impacts (pollution of sediments, changed erosion, and the deposition processes):
  - → place intake and outfall pipelines below ground to minimize the disturbance of coastal and marine sediment.

- On land use & landscape impacts:
  - → identify suitable sites through environmental impact assessment (EIA) process,
  - → aesthetic design of facilities, green building and landscaping,
  - → noise reduction and shielding measures,
  - → minimize land use and compensate habitat loss if necessary.

- Air quality and climate (greenhouse gas and other air pollutant emissions):
  - → compensate the remaining energy demand if necessary, e.g., by renewable energy or reforestation projects.

- Resource consumption (energy, water, materials, chemicals, land):
  - → minimize energy use by using best available techniques such as pressure exchangers,
  - → conduct life cycle assessment and multi-criteria analysis to identify processes and modes of operation that reduce resource consumption,
  - → improve recyclability or identify options for beneficial reuse.

In focus

Foreseeable mechanisms coming from the public sector

Given the potential (and actual) environmental impact related to desalination, regulatory intervention beyond the initiative of desalinization facilities should be considered, especially on two areas: evaluation and policy.

Need for evaluation. Ecosystem impacts (brine discharge management, desal plant construction impacts, habitat loss, intake effects due to high inflow velocities on marine flora and fauna or design) should be closely evaluated through EIA studies including: field monitoring, whole brine toxicity, hydrodynamic modelling of the intakes and brine discharge for ensuring a fast and efficient mixing and minimizing marine life being affected;

Policy actions. At least on three fronts: mixing zone regulations for brine discharge; the growing use tunnelling for intake and outfall pipelines to minimize disturbance of sensitive benthic ecosystems; use subsurface or offshore submerged intakes to lower chemical use in pre-treatment to minimize impingement and entrainment (with low intake velocity) of marine life in intake structures.

04

The paths forward

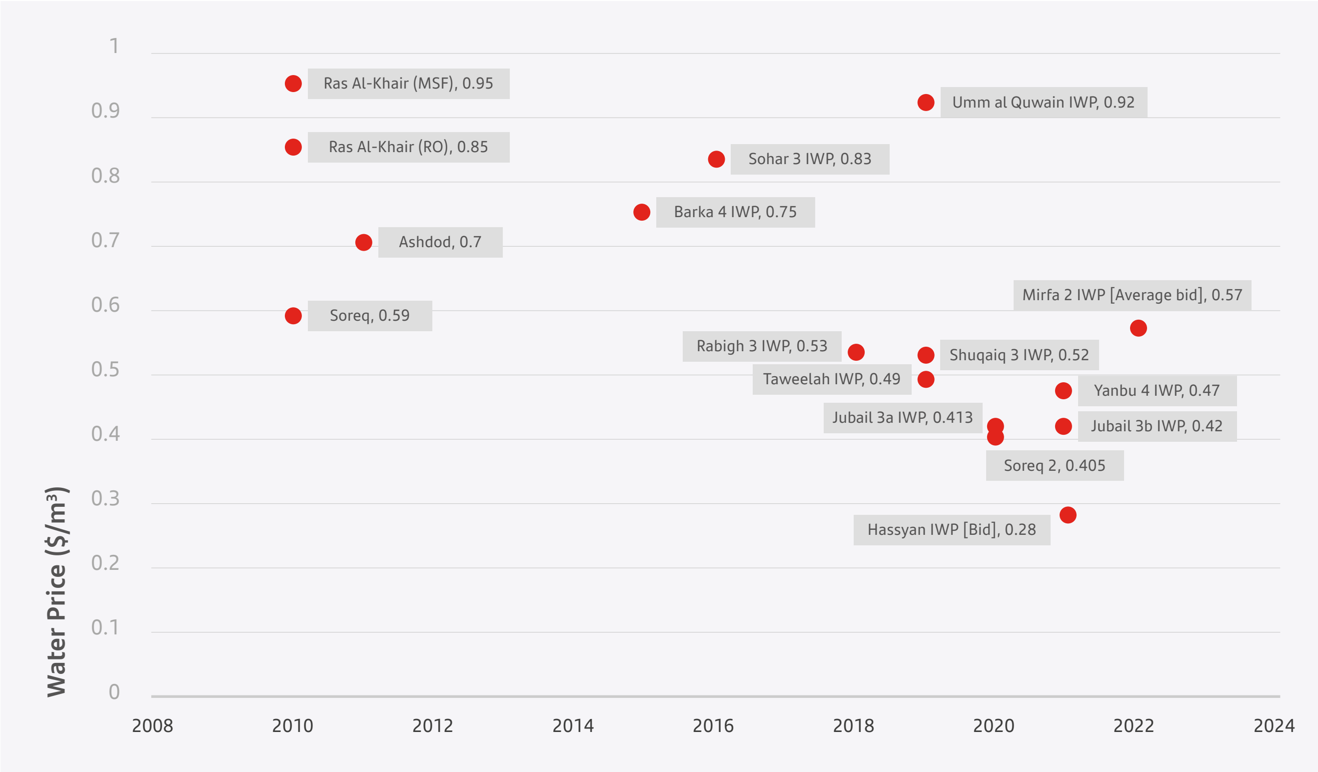
The choice for new seawater desalination facilities clearly points to seawater reverse osmosis (SWRO), with 92% of new plants in 2018 being SWRO facilities. This dominance is highlighted by at least two sets of indicators:

- → **Performance.** The SWRO technology is dynamically evolving through advances in desalination performance. Since the goal of desalination is to take salt out of the water to make it available for human use, the capacity of salinity rejection is a fundamental way to measure performance. SWRO is proving itself the most competitive alternative in this regard, as well as on the removal on certain problematical elements for human consumption, especially boro[iii]. As a result, key performance indicators are on track of improvement, prominently: unit cost (€/m^3), specific energy consumption (kWh/m^3), permeability, and fouling resistance[19]. This final indicator is of particular importance given that it addresses what was previously identified as the most immediate challenge to proliferation of desalination.
- → **Efficiency.** As a result of the above, the SWRO energy footprint has decreased to levels approaching a specific energy consumption of 2.5 and 3.5 kWh/m^3 of processed water, respectively, for the RO step alone and the overall system.

However, there is a theoretical limit to the energy required for desalinating seawater with a value of about 1 kWh/m^3, which is well below present practice. Present system unit costs are in the general vicinity of 0.5-1.00 €/m^3 [20,21], depending on size and financing, roughly double that for drinking water from freshwater sources (notably, intakes and outfalls can account for up to 20% of capital costs). These latter figures indicate that there is quite a bit of room for improvement. An example of the evolution of prices in desalination projects in the middle east and north Africa is presented in Figure 14. These projects are both larger and less costly than ever: the \$0.53/m^3 record set at Ashkelon (Israel) in 2003 was broken several times in 2019-20, with the new record currently held by IDE Technologies at Soreq 2 (Israel), which was awarded at a tariff of \$0.405/m^3 . Higher recovery rates, economies of scale, and securing cheap energy have been key to these reductions.

iii. While boron is a necessary element for organic consumption, there is a limit to that: the WHO set it at 2.4 mg per liter in 2009, and certain countries demand even lower concentrations, some following previous WHO guidelines at 0.5 mg per liter. Excess boron is especially problematic for plants, thus being a concern on water used towards irrigation. Traditionally, RO membrane technology has not been effective enough at removing it. Hence why improvements on boron removal are particularly valuable for the industry.

Figure 14: Recent MENA desal mega projects by water price ($/m³)[22]



Along with these figures and the witnessed increase in the number of desalination plants (reaching a cumulative total of about 21,000 plants in 2020), the capacity of the plants has increased significantly over time. We have seen a growing preference for extra-large plants (those with capacity above 50,000 m^3 per day). More extra-large plants are expected in the future. This means that the aforementioned reliable pre-treatment systems and monitoring tools will be essential for these plants, as cleaning in place of membrane modules more than once per year is difficult. But these will not suffice, and further, efforts are needed precisely in specific, potentially fruitful fronts that will allow us to improve reverse osmosis (RO). Below we explore the most promising avenues on five different areas: material science, operational and process setups, energy supply for operation, pre- and post-treatment innovations.

MATERIAL IMPROVEMENTS

There is already considerable ongoing material-science work on improving SWRO performance through development of high-permeability membranes, permitting less membrane area for a given operating pressure, and anti-fouling membranes, enabling longer operational cycles between cleaning-in-place events with less chemical wastes coming from cleaning solutions.

Anti-fouling membranes. Tackling what we have characterized as the ever-standing challenge for desalination, a general approach to fabrication of membranes has been surface modification of conventional membranes by physical and chemical methods[23,24], including creation of surface patterns, as well as development of organic/inorganic composite membranes with good fouling resistance.

On their most recent and promising iterations, materials with antifouling properties are being coated or grafted onto the membrane surface, including materials that are attracted to water by its own properties (i.e., hydrophilic). This makes deterioration less likely. Another recent approach worth considering is the use of polymeric membranes that are impregnated with silver[25,26] or iron nanoparticles[27], aimed at preventing the deterioration provoked by biological material (i.e., biofouling). Last but not least, the internal structure of membranes can be modified: on this approach its geometrical configuration is rearranged to promote conditions that minimize fouling.

High permeability membranes. The fabrication of membranes with improved permeability can provide a lower energy consumption[28] and added operational flexibility since they would achieve higher flux at typical SWRO operating pressures, or comparable flux rates at lower pressures.

Material science innovations have opened up this area through fabrication of mixed-matrix inorganic-organic membranes made with nano-composites[iv], membranes designed through bio-mimesis (i.e., engineering approaches imitating or inspired upon the observation of natural process[v]) and graphene oxide membranes[26,29].

However, there are two challenges to be considered regarding permeability: first, there is a limit to lowering the SWRO membrane pressure because of the inherent osmotic pressure of about 25 bar for seawater. Second, it is very difficult to manufacture membranes of high permeability while maintaining high salt rejection (NB. the nominal salt rejection of RO membranes is >99.7%) since there is an inherent trade-off between the amount of water the membrane lets pass and its capacity to retain saline materials.

iv. Some of the key nano-based approaches to be taken into consideration are: impregnation of zeolites, metal oxide frameworks, or biocides like silver nanoparticles.

v. Here, aquaporins, synthetic water and ion channels are of particular interest.

NOVEL PROCESS CONFIGURATIONS

In addition to changes in membrane materials, novel process configurations such as closed-circuit and flow reversal RO are being developed, using standard SWRO spiral wound elements, to promote higher water recovery with lower scaling[19].

Configuration design of membrane systems. There are at least two configurations of reverse osmosis systems alternative to standard RO that should catch our attention based on its recent and prospective results.

- → **Closed-circuit reverse osmosis** is a semi-batch mode of operation: rather than working at a steady inflow of water, as conventional RO does, closed-circuit approaches stays on hold for a period of time, then goes through a flush cycle, and then resumes operation. Cross-flow filtration is provided by a circulation pump to limit fouling and deposition of particles and scaling[vi]. Closed-circuit systems are projected to attain a 15-20% reduction in specific energy consumption, suggesting that it could approach the efficiency horizon of 2.0 kWh per m^3 in seawater desalination. On brackish water, model simulations showed up to 37% energy savings for desalination at a high-water recovery[30] compared to standard RO. This would, however, come at a cost in form of complexity and additional setup investment. It should also be kept in mind that, thus far, closed-circuit systems have only been deployed at smaller scale for seawater desalination.

- → **Operational mode of flow reversal reverse osmosis**. This approach consists of periodically reversing the direction of the water feed right before a solution with non-dissolved particulate precipitate from the concentrate onto the membrane. The timing is determined by knowledge of the inflow water composition and operating conditions. Scaling is prevented by controlling the solubility of a specific compound before precipitation occurs as determined by its induction time[vii]. Besides the benefit of minimizing or eliminating the need for anti-scalant chemical addition to control scaling, an overall increase in water recovery and decrease in residual brine is also realized, as well as less-frequent cleaning in place. However, as with closed-circuit approaches, so far this alternative has only been deployed at smaller scale, albeit for brackish water desalination.

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vi. Scaling is the precipitation of sparingly soluble inorganic compounds (e.g., calcium carbonate) on the membrane surface due to exceeding solubility limits. Scale forms a dense layer having a high hydraulic resistance, resulting in dramatic reduction in permeability of the membrane.

vii. The time between the start of the super saturated state and the first observed change in concentration of one of the parameters e.g., calcium or pH.

RENEWABLE ENERGY DRIVEN DESALINATION

When energy for seawater desalination is provided by fossil fuels, there is also a significant carbon footprint of desalting seawater, e.g., up to about 1 kg CO2-equivalent for each kWh spent, depending on the fossil-fuel mix. This has promoted an interest in renewable energy[31,33], especially solar, to drive SWRO as well as other desalinization methods. Options tend to focus on solar heat collectors and solar electric (photovoltaic), as well as wind and geothermal. For solar, however, there is a trade-off between capital costs (panel or solar-thermal collector investments) and operational (energy) costs. Furthermore, a key constraint for solar is its intermittency, necessitating storage or augmentation by the electrical grid. As a way to overcome this challenge, an innovative hybrid approach being considered is combining solar and geothermal energy using an alternating 12-hour cycle[Viii].

Case in point

Success cases on desalinization plants powered by renewable energy

Ras Al-Khafji Desalination Solar Facility, the world's largest solar-electric SWRO (desalinizing around 60,000 m^3 per day) is located in Al Khafji, Saudi Arabia, next to a neighbouring solar power plant with a capacity of 20 MW, but is also connected to the electrical grid.

The Perth Australia SWRO facility, capacity of 306,000 m^3 per day, with its energy demand topping at 3.6 kWh per processed m^3. It is indirectly driven by wind and solar energy. The plant's total energy consumption is offset by energy production from Mumbida[ix] wind farm with 34 turbines producing 85 MW and the Greenough Solar Farm (yielding total 40 MW), versus 85 MW needed by plant. The Perth desal plant approach is one of energy use compensation with grid connections.

Viii. A related opportunity would be to integrate waste heat recovery and utilization to substitute for solar-thermal to drive alternative forms of desalination: MD and thermolytic-forward osmosis, both needing only low-grade waste heat (60-80 °C) or solar-thermal.

ix. mumbidawindfarm.com.au

INNOVATIONS IN PRE-TREATMENT

Conventional seawater pre-treatment typically consists of dual-media filtration using anthracite and sand followed by cartridge filtration. However, and aside from helping on membrane fouling in general as stated in the previous section, more robust pre-treatment schemes are now being implemented in response to challenging water quality conditions. For instance, due to harmful algal blooms, which are increasingly contaminating water bodies across the globe.

→ **Ultra-filtration membranes,** has shown resilience towards harmful algal bloom events through adaptation in operating conditions, for instance, by inline coagulation, lowering the flux rate for controlling the fouling development, and by more frequent backwashing.

→ **Dissolved air flotation** has also shown an ability to remove oil and grease associated with shipping-channel impacts on seawater quality. It works through the introduction of pressured air in the water and then its release at atmospheric pressure. If working properly, undesirable particles should float along with released air to then be definitely removed through either membrane or other types of filter.

→ There is increasing interest in **subsurface impacts,** such as those at the seabed level, given their ability to provide pre-treatment for SWRO through the mere biodegradation of organic substances.

→ There is a growing consensus that **biopolymers** and **transparent exo-polymeric particles** (TEP) are principal SWRO organic foulants, with TEP serving as a precursor to SWRO membrane biofouling[33,34] promoted by assimilable organic carbon[35]. Removal of these components by pre-treatment minimizes the need for pre-chlorination[x] (for controlling growth of marine life inside pipeline from the intake to the desalination plant) and de-chlorination before the reverse osmosis step, a costly and risky treatment in and on itself. **Calcium carbonate** remains as a principal scalant; nevertheless, recent studies have demonstrated that acid dosing or anti-scalant addition can be stopped or dose significantly reduced, as the SWRO concentrate is either undersaturated with respect to calcium carbonate or has very slow precipitation kinetics[36,37]. Emerging strategies for scaling control include:

- managing the recovery of the first RO stage to permit acid addition only;
- when necessary, use a biodegradable anti-scalant (e.g., carboxymethyl inulin[38]);
- consider nanofiltration pre-treatment for removal of divalent ions;
- consider new process configurations like those described above.

x. RO membranes when in contact with free chlorine lose their salt rejection, and thus sodium meta-bisulfite needs to be added to neutralize free-chlorine added at the intake side.

MONITORING TOOLS

- The **modified fouling index with ultrafiltration membranes** (MFI-UF) at constant flux operation incorporates the effects of *i)* particle deposition on RO membranes, *ii)* filtration flux rate effect on fouling development, and allows predicting the particulate fouling rate in RO membrane systems. The MFI-UF overcomes the deficiencies and limitations of the silt density index (SDI) used in the desalination sector as indicator for RO feedwater quality[39,40,41].
- Simple, reliable and accurate methods to assess the extent to which **biological fouling potential** is reduced during pre-treatment are not yet available for seawater. Recently, a new adenosine-tri-phosphate-based laboratory method was developed to measure bacterial growth potential (BGP) using the native bacterial consortium in seawater and new reagents capable of working at high ionic strength conditions. A good correlation was observed between BGP measured in SWRO feed water and the pressure-drop increase in the SWRO systems, suggesting the suitability of using the ATP-based BGP method as a biofouling indicator in SWRO. A safe level of BGP (<70 µg/L) was preliminarily proposed for SWRO feed water to ensure a chemical cleaning frequency of once/year or lower .

These *new* monitoring tools can enable engineers, plant operators and scientists not only to design better plants, but also to improve operation and monitoring of biological and particulate fouling in SWRO systems.

05

Concluding remarks

The global demand for water has increased over the past decades due to population growth, increase in per capita water demand, expanded irrigation schemes, and economic development. Furthermore, uneven rainfall distribution, pollution of water resources, uneven population distribution, and unequal water use distribution have further increased regional water scarcity. Although desalination is widely used to produce freshwater from seawater, it can also be used to treat slightly salty (brackish) water, polluted surface and groundwater as well as wastewater.

The largest desalination capacity in the world is located in the Middle East and North Africa, but due to water scarcity, drought, growing demand, etc, many countries in Asia and Latin America, are implementing the use of desalination to alleviate their water demand needs either for industry, domestic use or irrigation. Desalination technologies can not only produce sufficient quantity of water but can also produce water with a very solid quality due to the ability of removal of salts and emerging contaminants.

From thermal and membrane-based desalination, reverse osmosis dominates the market due to lower investment costs and lower energy consumption than for thermal processes. Energy demand is a significant aspect of the total cost of desalination and thus new innovations that can lower the energy demand will have a significant impact in the sector. Currently, renewable energy sources, are applied to off-set the energy consumption from the electricity grid. Solar farms and wind parks contribute to a more sustainable desalination sector.

Another important aspect is the stable operation of desalination plants, as this is challenged by fouling development on the membrane surface and clogging of the feed spacers inside the membrane elements. Pre-treatment, either conventional or advanced, plays an important role in controlling the water quality fed to RO membranes. Sensitive water quality sensors can contribute to the monitoring of the performance and control of pre-treatment.

Overcoming technical challenges are not the only limitation for the full implementation of desalination. Also, softer issues as capacity development of staff in the desalination sector plays an important role for the sustainable and long-term successful operation of the desalination plants.

A final challenge remains the adequate disposal of the brine or concentrate water produced by reverse osmosis during the removal of the salts in the water. There are several initiatives aiming at the valorisation of the brines for the recovery of minerals such as lithium, magnesium, scandium, etc.

Taking all of the above into account, desalination will play a key role in the water cycle of the future and even of the near future. Making use of multidisciplinary research lines, technical challenges may be solved at a foreseeable time, still they remain important as the non-technical issues.

Desalination has moved away from early development stages and is a now full-grown drinking water technology and will continue to expand its contribution to meeting the global demand for safe and clean water.

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