Desalination in the Arab region: Status, Challenges, and Prospects

Table of Contents

1. Introduction

1.1 Water scarcity in the Arab region

Aridity, limited water resources, and long coastlines make the Arab region particularly vulnerable to climate change. The Arab region is the most water-scarce area in the world, with sustainable water resources per capita of only 1,000 m^3/year. This is far below the minimum renewable water resources threshold of 1,700 m^3/year per capita [1]. That problem is then compounded by a changing climate in which global temperatures are rising, and precipitation levels will fall, which may result in diminishing resources. In the Arab region, water availability per capita might decrease by half by 2050, resulting in a 50 percent increase in deficit between supply and demand [2]. However, this could be coupled with a halving demand for fresh water. Many factors contribute to the scarcity of freshwater, such as dependence on shared water resources, pollution, the effects of climate change, droughts and extreme weather events, unrenewable losses of water, inefficient use of water, and high population growth rates. The increasing scarcity of water requires that alternative water sources be managed, such as the desalination of seawater to produce clean water [3].

1.2 Overview of desalination Technologies

Desalination removes salts and minerals from saltwater to produce clean drinking water, and it is a potential solution to shortages, particularly in warmer and drier climates. Although desalination plants may be found or are under construction in practically every part of the world, the Arab region has the greatest concentration of such facilities, accounting for 46.7 % of global production capacity(GWI) as shows in Figure 1 Saudi Arabia (35 million population) currently uses about 60 % of the water from seawater desalination for domestic use. In the early twentieth-century commercial desalination facilities started operating and were quickly developed in the Arab region. It is said that a Dutch company built the first desalination plant in the Gulf region in 1907 in Jeddah, Kingdom of Saudi Arabia (KSA). Large-scale desalination plants were created worldwide during the middle of the twentieth century, although the Middle East was the first area to use them. In the Arab region, the desalination industry has grown dramatically, with a total installed capacity of 57 million m^3/d from 6782 desalination units operating on seawater, brackish water, wastewater, river water, and brine by 2022 (GWI). The capacity of these projects is between 100 to 1,000,000 m^3/day [4, 5].

Desalination technology has three main categories: Evaporation and Condensation, Filtration, and Crystallization. Evaporation and condensation were the earliest desalination processes to be introduced and applied for domestic freshwater production. These processes use thermal or mechanical energy to seawater, produce a vapor, and then condense it. The most popular technologies in the first example are multi-effect desalination (MED), multi-stage flash distillation (MSF), and vapor compression (VC). Other alternatives are now being investigated including solar still distillation (SSD), solar chimneys (SC), and humidification-dehumidification (HDH). In the case of the filtration method, Reverse Osmosis (RO) is the most utilized desalination technology. Electrodialysis (ED) and Ion Exchange Resin (IXR) are also used to create water with an extremely low salt concentration. Other approaches, such as Forward Osmosis (FO), Nanofiltration (NF), membrane distillation (MD), and Capacitive Deionization (CDI), are in the early stages of development [6].

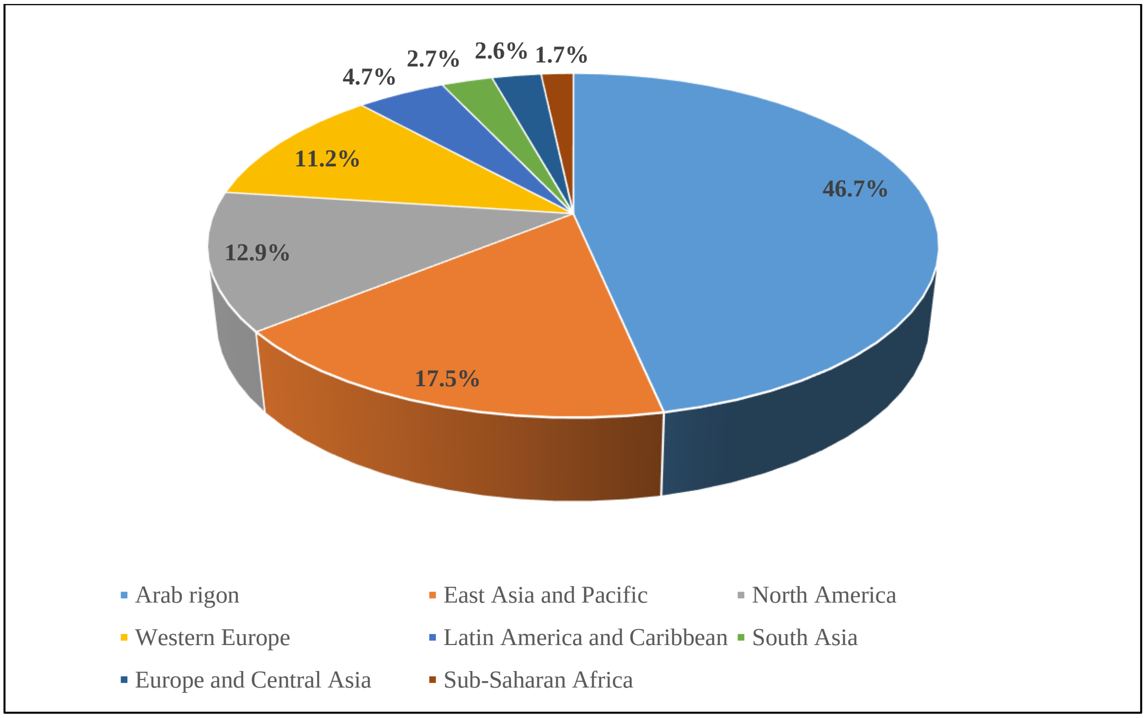

Figure1. Share of global desalination capacity (GWI)

1.2.1 Thermal Desalination

Thermal desalination remained the most popular and reliable technique for many decades, but, due to enormous energy requirements, it is now being largely supplanted by membrane-based systems. Producing 1000 m^3/d of fresh water by thermal technologies requires around 10,000 tons of fossil fuels per year, attributable entirely to the thermal energy requirements (60-80 kWh/m^3) of electrical energy. Even so, thermal processes are ideal for Middle Eastern countries because of the low cost of fossil fuels and energy supply. This is why, led by the UAE and KSA, Arab Gulf governments account for nearly 90% of the thermal energy globally utilized for desalination applications. The principal methods used in the thermal technology category are multi-stage flash (MSF), multi-effect distillation (MED), and mechanical vapor compression (MVC) or thermal vapor compression (TVC) [7].

The MSF method is used by all GCC council countries, and it is used in conjunction with the power plants that are linked to it. A brine heater raises the seawater that enters the system to a high temperature throughout this operation. The heated water is then poured into vacuum-sealed chambers, with the first chamber being hotter than the one preceding it, and so on. As the water enters the chambers, it is flashed to stem and evaporates. Because the pressure in the next chamber is lower, water at a lower temperature flashes. The distillate is the accumulated freshwater in the coldest or final stage, and as the seawater concentration increases from one step to the next, brine accumulates and is eliminated in the final stage. MSF plants usually have 18-25 stages but can have up to 40 stages[5].

MED, like MSF, occurs in phases and uses the same principles of evaporation and condensation at progressively lower pressures in each stage, but without the addition of added heat. The essential difference between MSF and MED is the process of evaporation and heat transfer, which occurs at a lower temperature (70°C for MED and 90-110°C for MSF)[4]. Moreover, MED is the earliest of the principal thermal processes, where feed water is blasted through heated tubes to evaporate through nozzles. However, if the water is extremely turbid, these nozzles can be clogged with scaling and fouling. Because of these concerns, MSF distillation began to dominate the global desalination business after 1960. As a result of further technological improvements, however, MED now competes with MSF both technically and economically, but MSF distillation remains a trusted and proven technique that is regarded a cost-effective method in areas where fuel prices are low.

Along with MED and MSF, MVC is an important thermal-based desalination technology in which feedwater is transformed to vapor via a heat exchanger and then compressed mechanically or thermally. Regardless of the method used to make the vapor, the vapor is condensed into the distillate by passing through a heat exchanger. However, the significant feature of MVC is that about 100% of the latent heat created by the water vapor is transferred to the brine; and , according to the recovery , only a little external heat is required [4].

1.2.2 Membrane Desalination

Membrane-based desalination technology uses membranes for seawater desalination and has grown in popularity since the year 2000 (nearly 70% of desalination processes are now membrane-based). MD is a thermally driven separation technology in which only vapour molecules pass through a microporous hydrophobic membrane. The vapour pressure differential caused by the temperature difference across the hydrophobic membrane drives the MD process. It is therefore a highly promising technology for desalting highly saline waters. Moreover, MD offers numerous appealing properties, including operating temperatures that are lower than in conventional processes; the solution (mostly water) is not always heated to the boiling point. Furthermore, the hydrostatic pressure employed in MD is lower than that encountered in pressure-driven membrane processes such as reverse osmosis (RO)[8]. In the Arab region there is no data for the number of desalination plants using MD that are to be constructed between 2020 and 2030 based on GWI/desaldata.

Reverse osmosis (RO) is a membrane-based desalination technology that is widely used around the world and is regarded as one of the most efficient methods of desalination. RO is a pressure-driven process in which separation happens via the solution-diffusion mechanism via a semi-permeable membrane. RO has the benefit of requiring neither phase separation nor heating. Electrical energy is required exclusively to power the high-pressure centrifugal pumps. The amount of pressure required is determined by the salinity of the input water. The concentrated solution left behind, known as brine, is simply returned to the ocean. Commercially, the RO process includes pre-treatment, in which incoming feed water is often treated with chemicals to make it more appropriate for RO membranes by reducing turbidity, bacteria, pollutants, TSS, and the silt density index. Some of the notable membrane based desalination plants, such as Shuqaiq-3, which is one of the largest desalination plants in Saudi Arabia, also uses SWRO technology to produce 450 thousand m^3/day, enough to meet the needs of 2 million people [4].

Reverse osmosis desalination is regarded as the world's fastest growing desalination technology, with a market value of $9.227 billion predicted by 2022. For seawater RO (SWRO), the typical working pressure ranges between 55 and 70 bars, while for brackish water RO, the pressure ranges between 15 and 30 bars. As many as 78 plants are operated or expected to be constructed between 2020-2030 using RO technology, with capacity between 100 and 1000000 m^3/day. All of the planed RO plants are in land-based locations except for three in Saudi Arabia which are mobile. These have the project names SWCC barge-mounted desal 1,2,3. The chart in Figure 2 shows the distribution of these plants in Arab region. Saudi Arabia own the highest number of these plants, following by Tunisia and UAE. However, Qatar, Libya, Yemen and Iraq is expected to have only 1 new RO desalination plant.

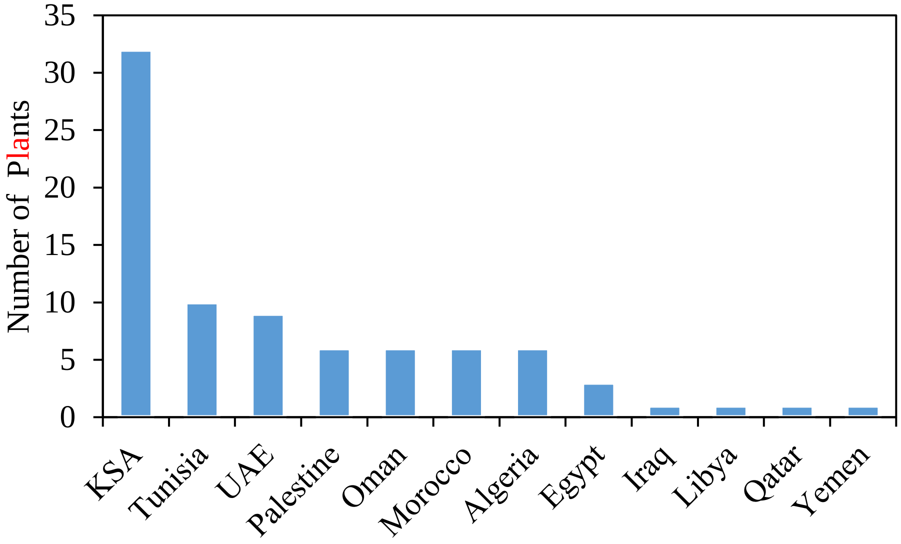

Figure 2: Distribution of RO-based desalination plants (2020-2030), Source: GWI DesalData / IDA

Electricity is used to drive membrane-based desalination technologies. Most of the capacity in Oman, and approximately half in Saudi Arabia, can be attributed to "reverse osmosis (RO) technologies" in membrane-based processes. As part of a project being developed by the Saudi State Electricity Company, the Rabigh 3 project was inaugurated in 2022, with the potential to become one of the largest membrane-based seawater desalination plants in the world, and a major player in the Kingdom’s water supply.

Another type of membrane is Electro-dialysis (ED) is similar to ion exchange, by which the ions present in water are attracted to electrodes with an opposite charge. However, ED is different in using selective membranes that allow either anions or cations (but not both) to pass when placed between a pair of electrodes. ED units are typically used to desalinate brackish (low salinity) water. To reduce scaling and membrane fouling, electro-dialysis reversal (EDR) reverses the direction of the ion flow (with the reversal of electrical polarity) after a specified time period. Like RO, ED requires a pump to push water through membranes but is generally less expensive [9]. However, since ED is more resistant to membrane fouling, costs associated with their replacement, and cleaning, can reduce the overall cost [7]. Because ED is usually used on brackish water with low levels of total dissolved solid (TDS), the cost is inexpensive (around 0.6 $/m3). ED has a high recovery rate of 85-94% and a TDS concentration of 140-600 mg/L.

On the other hand, Forward Osmosis (FO) is a new process that has attracted the interest of the desalination industry due to several different features. The fundamental process provides high permeate recoveries, up to 90%, and does not require the use of pressure. FO desalination, like RO desalination, uses a selectively permeable membrane to separate the desalinating water from its feedwater, with the difference in solute concentration levels on both sides of the membrane driving the separation. A new ammonia-carbon dioxide FO method was devised with added benefits such as increased carbon dioxide and ammonia gas solubility in water and a high osmotic pressure of produced ammonium bicarbonate solution. The technique requires as little as 0.25 kWh/m3 of energy to pump fluid around a unit. As a result, the overall operating and maintenance costs have been greatly reduced. Because of these benefits, many countries are increasingly adopting this method. In 2009, a forward osmosis facility was established in Oman's Khaluf area. This plant has a capacity of 100 m^3 per day, and when compared to nearby seawater RO, it performs at the same capacity with no chemical cleaning [5].

Nanofiltration (NF) is a membrane filtration method used to remove dissolved ions or organic matter from water to generate water with a limited concentration of the ions that cause scaling (Ca^{2+}, Mg^{2+}...). RO is generally similar to this approach. The main distinction is the action required to extract the ions from the saltwater. NF uses a semipermeable membrane, and its thrust force is hydraulic pressure[6]. The word "Nano" refers to the pore diameters, which range from 1 to 10 nanometers, making them smaller than those of other filtration techniques (microfiltration and ultrafiltration) but larger than those of RO. As a result, with 90% to 98% efficiency, this method eliminates primarily divalent ions (e.g., Ca^{2+} and Mg^{2+}). Monovalent ion elimination is restricted between 60% and 85%.

There are two NF desalination plants operated in 2020 in the Arab region, one in Saudi Arabia called Sulfate Removal Facilities Project (SRF) - Nanofiltration (NF) Package plant which have a capacity of 69,266 m^3/d and a smaller one in Oman under a project named Oman with a capacity of 329 m^3/d. Only 1 plant is still under construction between 2020-2030 using NF technology. This is in Saudi Arabia, under a project named the Tabouk Water Treatment Plant (Nano Filtration) using brackish water or inland water where the total dissolved solid (TDS) is 3000ppm - <20000ppm. It targeted to produce drinking water with a TDS level of 10ppm - <1000ppm for Saudi municipalities and will have a capacity of 150000 m^3/day (GWI/desaldata).

1.2.3 Emerging Technologies

Membrane Distillation for hypersaline water

'Emerging' technologies are those that are still in the research and development stage (Forward Osmosis, Membrane Distillation and Capacitive Deionization). Membrane Distillation (MD) is a new separation technique that combines thermally driven and membrane-based desalination technology with the ability to use low-grade heat. As is briefly explained in the working principles in MD section above, ions and other nonvolatile solutes are retained in the saline feed stream. Most of the high-salinity MD desalination studies have been conducted on bench-scale setups and laboratory prototypes. A recent article described a 2 m^3/d (528 gal/d) MD setup in Qatar that desalinated discharge concentrate from a seawater distillation facility with 70,000 ppm TDS to a 34% water recovery yield. Full-scale MD desalination plants, hypersaline or otherwise, have yet to be reported. Because salts are nonvolatile, MD product water has an extremely low TDS, usually less than 20 ppm regardless of input salinity. As a result, MD offers the advantages of both hypersalinity performance resilience and high-purity product water. Because MD can be powered by moderate temperatures, another frequently highlighted advantage is the ability to use low-grade thermal energy instead of high-quality energy inputs[10].

- **Forward Osmosis for highly contaminated water**

Forward osmosis is a two-step process for desalination. In the first step, a highly concentrated designed solution osmotically sucks water from the saline feed stream across a semipermeable barrier. Freshwater is separated from the diluted draw stream in the second stage, most typically by applying heat, yielding product water, and regenerating the draw agent so that it can be recycled back to the first step. The membranes used for this technology are RO membranes. However, experts are working on producing specialized high productivity FO membranes The potential FO for high-salinity, low salinity and highly contaminated water desalination has been addressed in numerous review publications and investigated in several experimental studies. Unlike RO membranes, which experience pressures that scale with feed salinity, FO membranes encounter pressures that are extremely near to ambient, independent of feed concentration. This lower working pressure has been demonstrated to reduce dramatically the negative effects of fouling on FO membranes. Fouling is mostly reversible, and foulants can be eliminated using comparatively simple cleaning processes. Accordingly, FO shows promise in addressing one of the main issues confronting membrane-based methods for highly contaminated water desalination and for potentially achieving large water recoveries [10].

Solar Desalination

- **Direct solar desalination**

Solar stills are among the earliest and most basic types of solar desalination. Saline water is evaporated directly by sun energy in a solar still and then condenses as distilled water. However, the productivity of simple evaporation and condensation desalting falls short of the needed levels of desalted fresh water (with an efficiency of 30-45% and freshwater productivity of 5 L/m^2/day). As a result, during the last few decades, solar stills have been merged with other processes and technology including as heaters, reflectors, and condensers to improve desalination efficiency[11, 12].

There are two sorts of solar stills based on their effect: single-effect (single-slope solar still) and multi-effect solar stills. The single-slope solar stills have an efficiency rate of 30–40%. On the other hand, the multi-effect solar stills are more efficient than single-effect variety. In the case of multi-effect solar stills, the latent heat of condensation is essential[12].

- **Indirect solar desalination**

Thermal and non-thermal techniques are commonly used in indirect solar desalination. The most widely used indirect solar desalination process is reverse osmosis (RO). An understanding of the energy usage in RO plants is vital in influencing how solar energy is used to power RO. Although a RO plant's specific energy consumption (SEC) includes contributions from the feed intake facility, pre- and post-treatment, and brine disposal, the membrane desalination portion accounts for 60-80% of the SEC[11].

According to Bhambare et al, almost all regions of Oman receive an average daily sum of global horizontal irradiation between 6 and 6.75 kWh/m^2 with a higher sky clearness index. As a result, Oman is regarded as one of the best destinations for solar applications. However, the whole potential of solar energy in Oman has yet to be fully realized. At present, the Sultanate has almost no solar thermal installations[13]. Nevertheless, on 27 July 2022, TotalEnergies and Veolia announced the agreement to construct the largest solar photovoltaic (PV) to provide power to an RO desalination system in Sur City, Oman. The 17-megawatt peak system will be the first to be installed in the region. It will produce more than a third of the desalination plant's daily consumption, using more than 30,000 MWh of electricity annually [14, 15].

- **Capacitive Deionization Desalination for brackish water Desalination**

Given that there is more brackish water than freshwater in the planet, it is evident that utilizing the vast brackish water resources for human consumption and for residential use, agriculture, and industry is particularly appealing. Over the years, capacitive deionization (CDI) has emerged as a reliable, energy-efficient, and cost-effective technology for desalinating water with low to moderate salt concentration. The energy efficiency of CDI for water with a salt concentration of less than 10 g/L [16]. The technology is based on the recognition that high-surface-area electrodes, when electrically charged, can quantitatively adsorb ionic components from water, resulting in desalination [17].

1.3 Main desalination technologies: best features and weakest points

Despite the high suitability of thermal processes for seawater desalination in countries with low fossil fuel prices (e.g., the Middle East), membrane-based processes are highly recommended for desalination in countries where high energy prices are a major concern [18]. In addition, membrane-based separation technology, which incorporates a variety of distinct separation processes, provides a more comprehensive solution and allows for treatments that address both the salinity effect and the specificity of individual pollutant features. The cost of membrane technologies has decreased in recent years, while their applicability in diverse treatment procedures has expanded. When compared to most conventional technologies, membrane processes have the advantage of being adaptable, with various auxiliary processes, in wastewater treatment and resource recovery without significantly affecting product water quality or space requirements [19]. For hypersaline water MD has a reduced fouling tendency when compared with RO, owing to the lack of applied hydraulic pressures [10].

The main industrially used desalination systems are RO, MSF, and MED. A recent sustainability study conducted for seawater desalination plants in UAE showed the superiority of RO desalination compared to MSF and MED. The researchers developed a sustainability score and compared it with a UNESCO-developed sustainability score. Both scores showed higher RO sustainability. The study concluded that even though MED and MSF have higher sustainability than RO in social and techno-economic factors, they performed lower in environmental factors [20]. The investigated factors were:

- Environmental factors include seawater extraction, the impact of discharged brine, CO2, other environmental impacts, and land use.
- Techno-economic factors include techno-economic technology reliability and robustness, quality of water produced, scaling and fouling, levelized cost of water production, the sensitivity of levelized cost of water production, and internal rate of return.
- Social factors include social level of aesthetic acceptability, level of noise, provision of employment, technology safety, intergenerational Equity (consumption of fossil fuel)

Amongst the three leading desalination technologies, RO is the most used. RO's main advantages are:

- Easily adapts to changing conditions.
- Flexible production capacity
- Significant cost savings in brackish groundwater desalination
- Modular and occupies less land space.

However, RO requires extensive pre-treatment. It also suffers from membrane fouling, its configuration is complicated, and operation and maintenance require competent professionals.

2. Desalination in the Arab region

2.1 Water demand trends in the Arab world

In areas with arid and semi-arid climates, available water resources are forecast to diminish, causing water scarcity problems worldwide in the near future. As water scarcity intensifies and food demand increases, there is a rising demand for irrigation in many regions, and it has become necessary to explore alternative water supply options. Growing demand for domestic and industrial water use competes with the expansion of irrigated agriculture in water-scarce regions, which can result in conflicts between users, allocating water to high-priority sectors at the expense of agriculture.

Several strategies can be implemented to enhance water resource availability for irrigation, including infrastructure modernization, smart irrigation systems, and regional water transfers. However, none of these strategies is likely to increase conventional water resources; in most cases, they may only be able to improve water use or location. The only way to increase water supply beyond what is available from the hydrological cycle is to use non-conventional water resources (desalination and recycling). The recycling of freshwater and the desalination of brackish groundwater may be limited by domestic wastewater production and aquifer exhaustion, but seawater desalination is a necessary means of addressing the problem of global water scarcity, providing a reliable source of water for sustainable agricultural production [21].

Compared with conventional water resources, desalinated seawater presents an abundant and steady water source without adversely affecting continental aquatic ecosystems. In arid coastal regions without apparent alternatives to water, desalinated seawater has generated a high return for agriculture because of these intrinsic characteristics. Recent years have seen a dramatic increase in brackish water desalination for agriculture since its cost is typically lower than half of the seawater desalination cost. Historically, desalinated seawater had been too costly to be considered a crop irrigation method, but now it is a viable option for some regions. Several countries including USA, (Florida and California) and Spain are currently assessing or planning to apply desalinated seawater in agriculture[21, 22].

Although desalinated seawater is mainly used to augment other conventional sources for crop irrigation, direct irrigation is also practiced. In the near future, desalinated seawater is expected to become an even more crucial alternative water source for agriculture. Desalinated seawater was initially only a solution for domestic and industrial needs. Still, as desalination technology improves and the costs for desalinated seawater decrease, its application might well be extended to the agriculture sector [21]. Two decades ago, Egypt tested the applicability of seawater desalination for irrigation using desalination plants that produced around a billion m^3 [23]. he economic analysis concluded that irrigating extensive crops such as wheat, corn, and rice with desalinated water is not economically efficient. Table 1 shows the tested desalination plants and their installation and production costs. It is clear from the table that seawater desalination was not cost-effective for growing field crops. However, it may be cost-effective to cultivate high-value vegetables and fruits. Also, this practice did not include the use of reverse osmosis technology, which later became more feasible than the tested thermal technologies.

Table 1: Types of desalination plants and their installation and production costs.

Desalination Plant	Installation Cost (US $/m^3)	Water Production Cost (US $/m^3)
MSF	1200-1500	1.10-1.25
MED	900-1000	0.75-0.85

Experts concluded in a recent study that desalination with high-return crops has become economically feasible, although its cost remains prohibitive for most irrigated agriculture. There are, of course, several factors to consider when planning to use desalinated seawater for crop irrigation. The agronomic quality of the water is a critical issue for desalinated seawater irrigation. RO membranes typically produce water with a TDS content of less than 250 mg/liter, an acidic pH, a very low hardness, and a very low buffering capacity. Water with these properties is unsuitable for domestic, industrial, or agricultural purposes. It may also damage the water distribution system. It is, therefore, necessary to post-treat RO permeate to remineralize and ionically balance it before distribution. As a result, the chemical composition of desalinated seawater depends heavily on the type of post-treatment it has received. The quality of desalinated seawater that can be released into a distribution system is not defined by any formal worldwide regulations. Generally, desalinated seawater must comply with the national potable water regulations, which differ significantly from the characteristics required for irrigation. Since most seawater desalination plants are destined for domestic use, they rely heavily on potable water regulations. No specific water quality criteria have been developed for desalinated seawater destined for agricultural use, unlike urban wastewater reclamation for irrigation, which is subject to specific regulations in most developed countries[21, 24].

An extensive set of regulations covers the quality standard for irrigation water. There are ten quality parameters involved in the set of criteria for combining agricultural and municipal use of desalinated seawater. The criteria are: pH, electrical conductivity, levels of chlorine, sodium, boron, calcium, magnesium, and sulfur (SO_4^{2+}), and calcium carbonate precipitation potential It is therefore necessary to identify some similar irrigation quality standards in order to determine the desalinated seawater chemical composition that will best meet crop irrigation requirements.

There is considerable variation in the agronomic effects of the use of desalinated seawater in agriculture due to the quality of the irrigation water that is replaced with desalinated seawater, as well as the cost of the desalinated seawater itself. By replacing low quality irrigation waters with desalinated seawater that has a low electrical conductivity (0.5 dS m^{-1}) and that reduces salinity stress, crop yields can be increased and their quality improved. As a result, irrigation requirements can be dramatically reduced since salt leaching can be prevented using supplemental irrigation water [21].

Surface water and groundwater are used for irrigation in the Arab region. Eighty percent of water demand is from the agricultural sector. Irrigation water requirements and withdrawals must be assessed to determine the stress irrigation has on available water resources. Industrial, domestic, and agricultural water consumption will increase significantly in the next two decades. Agriculture will continue to be the largest sector in demand as illustrated in Figure 3. However, non-agricultural demand will grow faster than agricultural demand over the next few years.

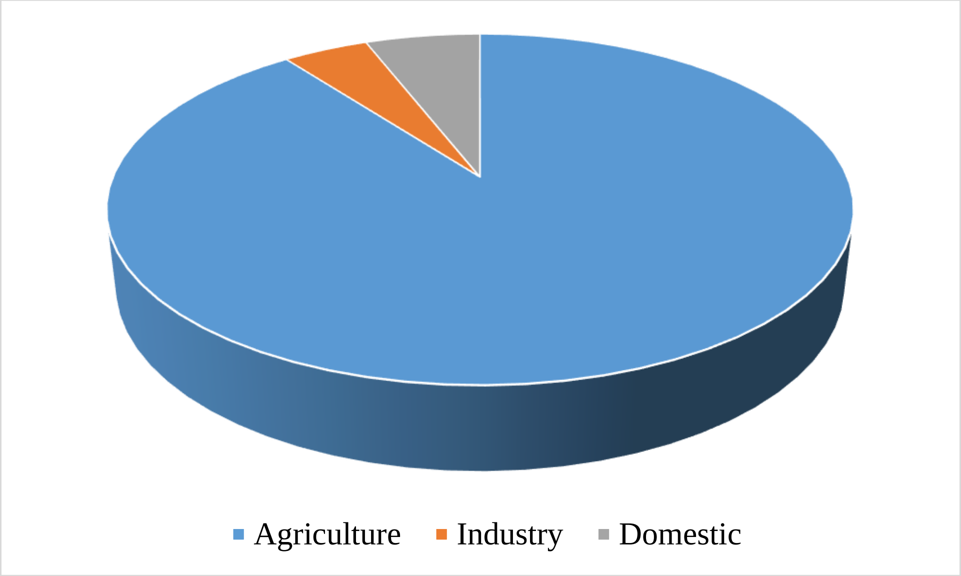

Figure 3. Water consumption per sector in the Arab world

2.2 Non-conventional water resources

According to numerous International organizations such as The International Desalination Association (IDA) and The Global Clean Water Desalination Alliance (GCWDA) , non-conventional water sources can supply high-quality drinking water for domestic, industrial, and agricultural uses, thus preventing water scarcity and promoting economic growth. The most popular sources of non-conventional water resources are desalinated seawater or brackish water, greywater and treated domestic and industrial waste water [25]. As a non-conventional water resource, brackish groundwater offers the potential for economic desalination.

2.3 Dependency on desalination in the Arab region

There is no doubt that the Arab region, one of the world's most water-scarce regions, has one of the lowest levels of water availability per capita. Consequently, the Arab region is highly dependent on desalination, especially for domestic use. It currently accounts for ninety percent of the thermal energy used in desalination worldwide, with UAE and KSA being the prominent consumers [26]. Desalination in the Arab region is predicted to grow at a rate of 7-9 % annually. Currently, the Arab region has 78 desalination projects operating or planned for construction between 2020 and 2030, as shown in Figure 4 (Source: GWI DesalData / IDA).

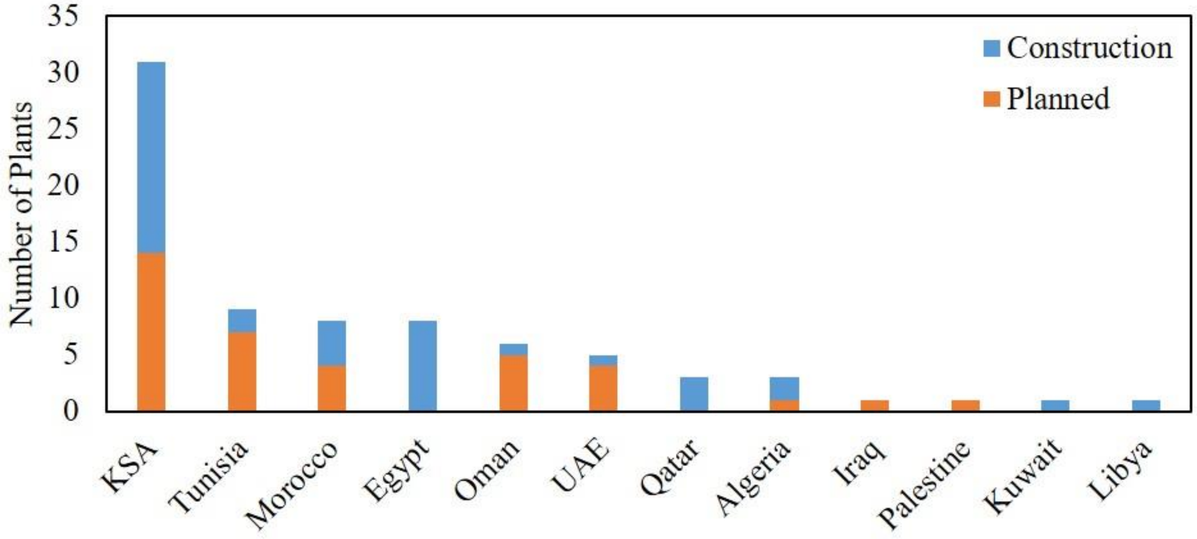

Figure 4: Arab desalination projects distribution (2020-2030), Source: GWI DesalData / IDA

Due to the ongoing Gulf procurement boom, new seawater desalination capacity is concentrated in a few large-scale projects as indicated by GWI Worldwide Desalting Inventory. Five projects that account for more than 40% of the total daily capacity in the Arab region are located in Saudi Arabia:- Jubail 2 Replacement SWRO and Shoaiba 3 conversion project (constructed in 2022), Jubail 3b IWP (constructed in 2021) and Jubail 3a IWP and Shoaiba 5 (SWCC) (constructed in 2020). Rabigh 4 IWP is intended to add 600,000 m^3/d in 2022. In addition to Hassyan IWP, Mirfa 2 IWP, Neom, Rabigh 4 IWP, Jubail 3b, Al Ghubrah 3, Massirah IWA, and Jafurah planned for construction in 2022. High-capacity desalination plants were awarded in Morocco, Egypt, Algeria and Tunisia in the 2020-2022 period. A record expansion of new capacity was awarded in 2022 in the rest of the Arab world, totaling 1.16 million m^3/d. The Arab Gulf is experiencing a new era of cheap desalinated water at a rate of below \$0.50 per m^3 because of this new record. Low prices of desalinated water have been driven by high recovery rates, economies of scale, and cheap energy, especially renewable energy. However, as margins shrink, further reductions in costs become harder to achieve [27].

2.4 Sectorial desalinated water use in the Arab region

Twenty-one desalination plants in the Arab region are being constructed or are planned to be constructed in 2020-2030 to meet the region's industrial requirements. Using RO technology, these plants will be utilized in different industries, such as food and beverages, metals, mining, oil and gas, power, pulp and paper, textiles, and power stations. Most of these plants are in the KSA and the UAE, where the feed water is either brackish water or seawater. The capacity of these plants ranges between 50 and 500,000 m^3/day. The Neom desalination plant has the highest capacity among these plants. It is an RO desalination plant powered by renewable energy from the Neom grid, which generates an estimated 500,000 m^3/day of fresh water. The BWRO Water Factory (BW-0126 project) has the lowest capacity. Both plants are in Saudi Arabia (GWI/desaldata).

Fifty-Five desalination plants in the Arab region are also planned (2020-2030) for municipal purposes. These plants are in Palestine, Tunisia, UAE, Oman, Morocco, KSA, UAE, Algeria, Egypt, Qatar, and Libya. The capacity of these plants ranges between 200- 1,000,000 m^3/d, most of which are in KSA. The Basra water supply project (Iraq) and Jubail 2 replacement (Saudi Arabia) have the highest production capacity. All desalination projects will have the potential to be used to provide municipalities with drinking water where TDS is between 10ppm - <1000ppm. In contrast, only one project is planned for irrigation purposes. The Mirfa 2 IWP project in the United Arab Emirates was established in 2021, with projected operation in 2024. It is an RO desalination plant and has a capacity of 363,680 m^3/d (GWI/desaldata).

Moreover, the Agadir desalination plant was constructed 2018 in Chtouka in Morocco with the contract being signed under Private Public Partnerships (PPP) and the work on this facility is 98.5% complete in 2022. It aims to produce drinking water and farm water with a total production capacity of 275,000 m^3/day. The local city and its surrounding territory will receive at least 150,000 m^3 of water per day. Moreover, there is the possibility of expanding the capacity to

450,000 m3/d. In addition to meeting domestic water needs in the Agadir area, this large-scale project is ecologically friendly, and it can be powered by wind power.

3. Desalination dimensions in the Arab region

Desalination plants are being designed in various ways, paying attention to the environment, and considering sustainability and energy use. In the years to come, it is estimated that there will be a 15% increase in demand for desalinated water each year [28]. This has increased their types, configurations, settings, power sources, and environmental considerations.

3.1 Legal and political dimensions

There are two main trends in regulating desalination plants in the Arab region. The first encourages government participation in designing and running desalination plants. The second trend is to support lower energy-intensive desalination projects and causes a lower environmental impact. Governments can support these projects by granting concessionary management contracts to supply residents with water. National water agencies may support desalination projects by analyzing their impact on sustainability at each stage of the desalination process. The law protects private water rights, but the public and private sectors do not have equal legal rights regarding developing and utilizing water. There are three ways to achieve sustainability: economically, socially, and environmentally. Water, air quality, ocean space, water reservoirs, and other factors may all be adversely affected by desalination facilities. The environmental consequences of these facilities are typically considered at the national level, and their acceptability and mitigation requirements vary depending on the context [29]. World Health Organization (WHO) recommends implementing post-installation monitoring programs to monitor desalination plants' impact on sustainability.

3.2 Economical Dimensions

Globally, RO is becoming more popular than thermal desalination. RO's popularity is due to many factors, including energy consumption, environmental effects, and the costs associated with total capital expenditure (Capex) and total operational expenditure (Opex). The total Capex of desalination plants in the Arab region in 2021 was approx. $6,818 million, while Opex was $11,002 million. By August 2022, the Capex had increased to $8,162 million, while the Opex was 11,434 (GWI/desaldata), as shown in Figures 5 and 6. In 2020, despite the pandemic, the desalination market held steady, as 44% of new capacity was awarded under the COVID-19 pandemic. Even though the total number of new contracted capacity fell from 6.7 million m3/d in 2019 to 4.7 million m3/d in 2020, it was still the fourth highest yearly volume in history. Though the pipeline has experienced sequential delays, 2022 is expected to see a breakthrough in the market.

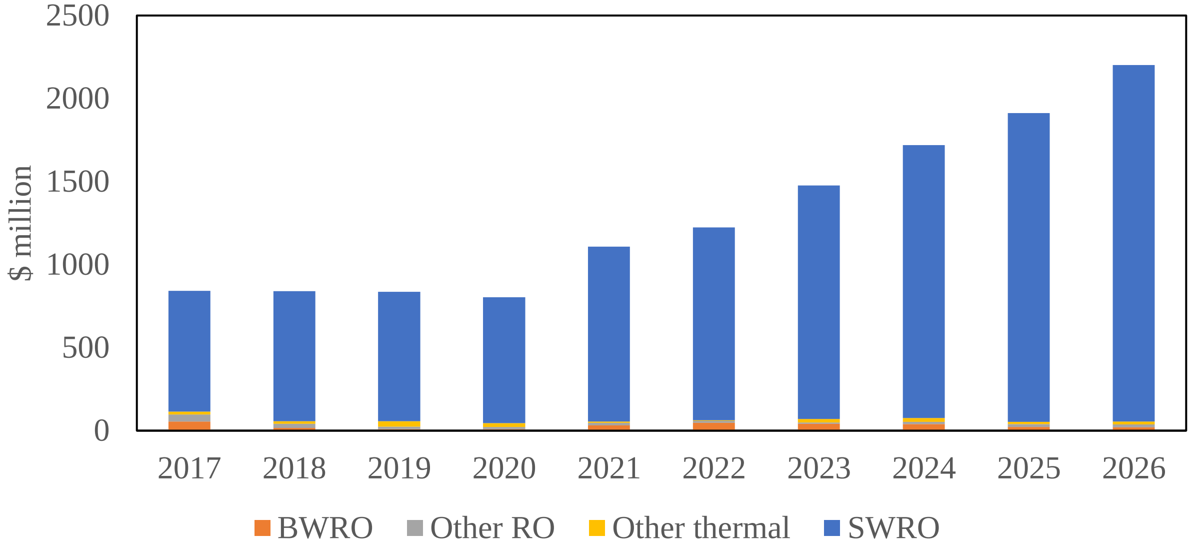

Figure 5. CAPEX breakdown of desalination plants in Arab region (2017-2026)

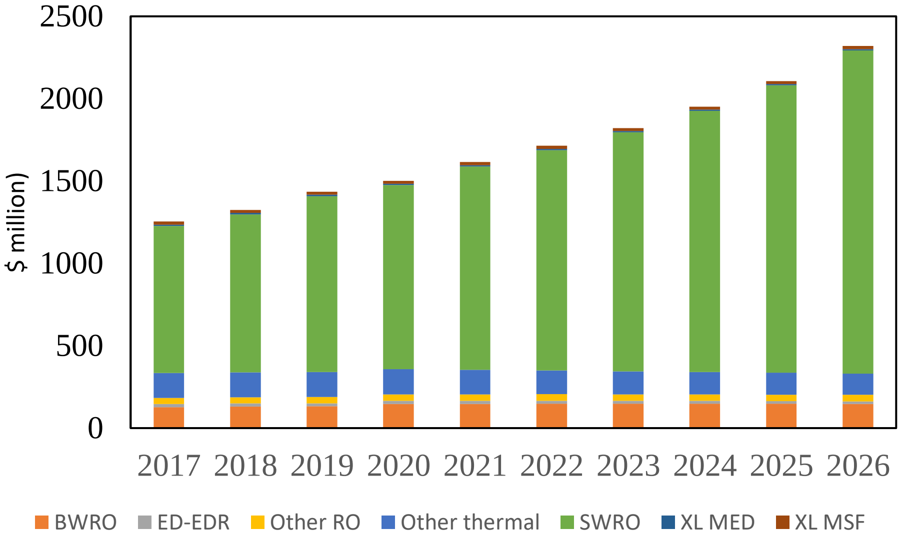

Figure 6. OPEX breakdown of desalination plants in Arab region (2017-2026)

There are two main categories of CAPEX: direct and indirect. Typically, 50 percent to 85 percent of the total CAPEX is devoted to direct costs, which include equipment, buildings, pipelines, and site development. Indirect costs include finance interest and fees, engineering, legal, administrative expenses, and contingencies. For most desalination plants, the CAPEX costs and components are divided into nine parts: the intake and conveyance of raw water; pretreatment; desalination; post-treatment; pumping and storing of the product water, the electrical and instrumentation system, the buildings, the site and the civil works of the plant, brine discharge and the handling of solids, as well as miscellaneous engineering and development costs. Several other factors must also be considered, such as the type of intake and its location from the plant, the type of intake screens and intake structures, and the type of intake pipelines (buried or above ground). Global Water Intelligence (GWI) has a "cost estimator" tool. Based on that estimator, the total CAPEX breakdown is $169,684,851 for an SWRO desalination plant and $344,796,409 for an MSF desalination plant. Figures 7 and 8 provide a complete CAPEX breakdown. At the same time, the OPEX breakdown is $24,794,600 for an SWRO desalination plant and $37,431,545 for an MSF desalination plant. The pretreatment costs $14,423,212 for SWRO (GWI/desaldata).

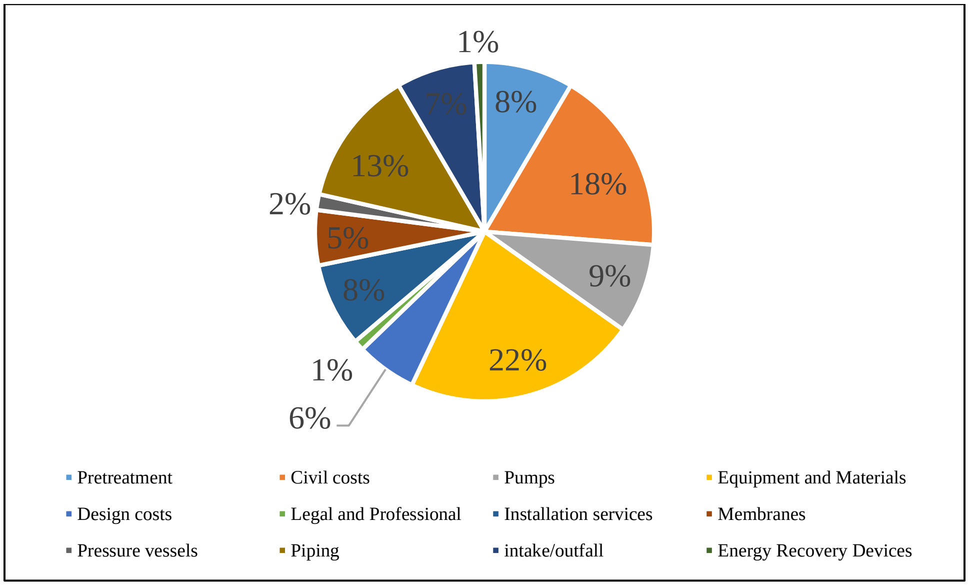

Figure 7. Desalination cost in conventional RO: CAPEX breakdown

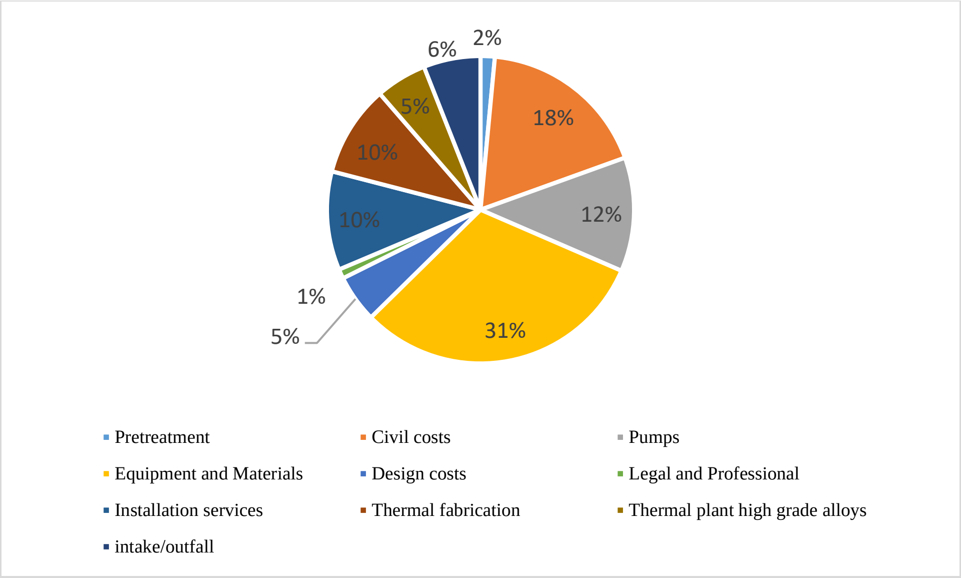

Figure 8. Desalination cost in MSF distillation: CAPEX breakdown

The intake, pretreatment, outfall, and high-pressure pumps commonly used in RO use large amounts of energy, making it expensive. Energy costs contribute the highest to operational costs for thermal and membrane desalination processes, with almost 40-60%, as shown in Figure 9. MSF is not economically competitive for desalination due to the high capital costs. Desalination technology innovations will continue to reduce the cost of RO desalination. There are ongoing research efforts for brackish water and seawater RO desalination, which will increase the diversity and availability of potable water sources and reduce water costs.

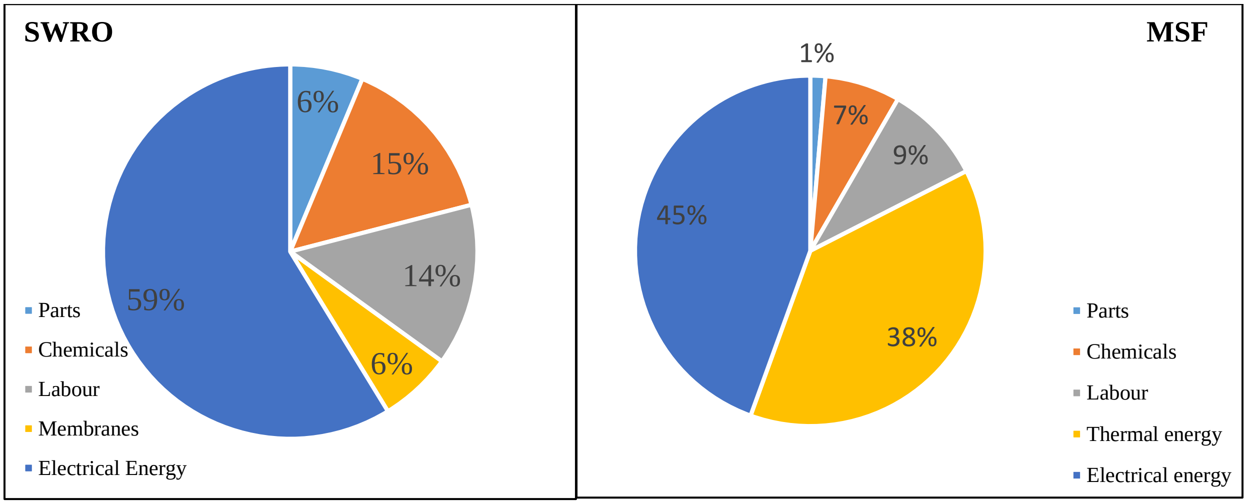

Figure 9. Seawater RO and MSF desalination cost: OPEX breakdown

A key consideration when commissioning new or upgrading old plants is energy efficiency. KSA which has 35 percent of the Arab region's dewatering capacity, uses 25 percent of its petroleum and gas production to generate electricity and water [32]. Seawater desalination is highly energy intensive compared to other water resources treatment. Figure 10 presents the energy use of different water supply options and an overview of typical SWRO desalination plants' energy use. SWRO desalination plants' energy consumption is 2.5–4.0 kWh/m^3. The RO system dominates the plant's energy consumption. As a result, it directly influences the plant's specific energy consumption (SEC). The plant's SEC is around 1 kWh/m^3, greater than the RO system. The pre- and post-treatment processes consume 0.2 to 0.4 kWh/m^3 regardless of the feed conditions and other factors. In addition, seawater intake consumes around 0.19 kWh/m^3, and other facilities consume approximately 0.27 kWh/m3. The quality and quantity of target water affect SEC [30, 31].

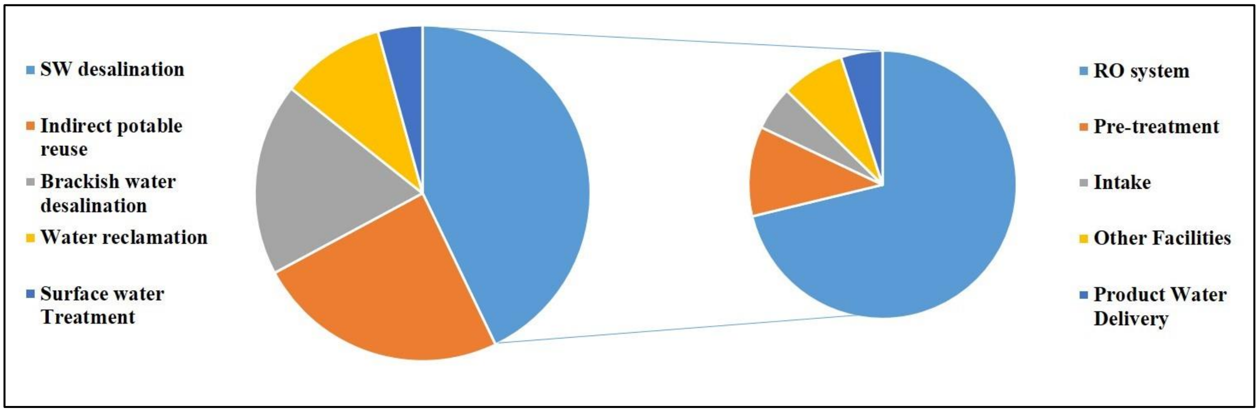

Figure 10. Energy consumption of water supply options and an energy breakdown of a SWRO desalination plant.

3.2.1 Tariff structure

The Arab region is one of the world's most water-stressed regions; two-thirds of the water produced from seawater desalination is produced through thermal desalination based on fossil fuels, and the remainder is produced by membrane-based desalination, which relies heavily on electricity generated using natural gas. More than 90% of all daily water requirements in the Arab region are met using seawater desalination. The governments in the region have significantly increased their investment in desalination plants, producing 46.7% of the world's desalinated water. Kuwait, KSA, and UAE have some of the world's largest water desalination plants [34]. Accordingly, the Arab region has invested US$ 20.3 bn in the top 10 water desalination plants. In 2020, the Arab region awarded contracts worth US$ 7.8 bn in desalination projects. GWI estimated that the desalination market in the Arab region is expected to reach $4.3 billion by 2022. The assumed basic OPEX is 95% utilization, $0.08/kWh tariff, 3.5kWh/m^3 for SWRO, 1.5kWh/m^3, and 4kWh/m^3 for MED and MSF, respectively.

During the past two years, the cost of producing desalinated water in the Arab region has dropped by nearly half. Decreasing desalinated water costs enabled impoverished countries to undertake desalination as a conventional water source. Several key factors contributed to this, including enhancing energy efficiency, low-interest rates - making desalination project financing appealing. The tariff is between USD 0.5 and USD 0.9 per m^3 of desalinated water. However, cost of desalinating water can rise to $1.50 per delivered cubic meter depending on the country [33]. From 2023, Dubai Electricity & Water will charge $0.306 per m^3 of water, the world's lowest water Levelized tariff to date. However, low-cost desalination primarily struggles with energy costs, and changes in $/kWh have a more significant impact than other factors, such as capital costs.

3.3 Institutional and regulatory frameworks for private investment

Non-conventional water resources can be mainstreamed if the regulation of related sector services is revisited. Depending on the institution's needs, a private company may be able to assist with desalination development and operational activities. In KSA, the government has established a single buyer responsible for collecting all the water from the desalination facilities and selling it to the wholesaler (SWCC) or directly to distribution companies. There should be a thorough assessment of the risks inherent to the desalination and reuse initiative before assigning responsibilities to one or another and whether these services should be managed internally or delegated to a private partner. In addition to examining historical roles, legal mandates, technical and managerial abilities, financing, and contractual power of the various stakeholders in the sector, the different stakeholders should also consider their financial and contracting power [35]. This includes:

- Establish a stakeholder forum that facilitates knowledge exchange and capacity-building activities and prioritizes them
- Assisting key decision makers in the planning of desalination projects
- Evaluate desalination potential taking into account economic, environmental, and social costs
- Assist and offer expertise as needed and promote the best practices
- Participate in the development of national and regional desalination policies

As a result of public-private partnerships (PPP), the delivery of water services in Arab countries has improved, but the public sector remains the dominant mode of delivery. Many countries have entered into PPPs to manage their water supply networks and construct new infrastructure to provide water and sanitation services, including Algeria, Egypt, Qatar, Saudi Arabia, and the United Arab Emirates. PPP has been applied for the Agadir desalination plant, which was built in 2018. Moreover, utilities in Amman and Casablanca will be operated by the private sector under management contracts. As a result of privatization and changes to its foreign capital investment law, Oman has made significant efforts to improve the foreign investment climate and broaden private sector participation.

3.4 Market and off-taker

Arab investments in the water desalination market increased significantly, accounting for 48% of global desalination projects, according to Ventures Onsite's Arab Desalination Market report, which tracks construction projects in the region. Further investments are expected to boost the market to $4.3 billion by 2022 [36]. One-fifth of global production is accounted for by KSA, which leads the world in desalinated water production, producing 4,000,000 m^3/day. Over the next ten years, an estimated $80bn is expected to be invested in additional projects. Growing investment in new water desalination capacities has led KSA and the UAE to remain leaders in 2022 [36]. The Arab and GCC governments have been expediting their water desalination investments using different technologies. As a result of their high energy requirements, MSF and MED have declined significantly in the Arab world and GCC. RO, however, has gained popularity.

On the other hand, governmental and private entities may be off-takers (water purchasers) of desalination plants. An off-taker might be a local government agency or an industrial process company that needs water to supply its operations. Price setting and fluctuation under the offtake/water purchase agreement are critical. In some jurisdictions, water rates are set by public utility commissions or governmental agencies. In addition, the offtake/water purchase agreement must address which party will accept any future rate reductions after the agreement is signed. A reverse-osmosis sponsor should determine whether they prefer to contract directly with the membrane supplier or have their plant's operator contract directly with the supplier. There are two types of contracts: direct contracts and allocating responsibility to an operator. A direct contract is where Sponsors/owners may prefer direct contracts over indirect contracts, as they are more transparent and allow them to have direct control over membrane quality and price. However, sponsors/owners may not want to deal with this contract independently. Suppose an operator is assigned responsibility for membrane supply under an operation and maintenance agreement with the plant's operator. In that case, the consequences vary depending on whether the agreement is structured on a fixed-price basis or a pass-through cost basis. If the O&M agreement is a fixed price, the operator must be constrained from compromising membrane quality or delaying replacement to reduce costs. As a result of cost pass-through, the sponsor/owner must control costs through the budgeting process, keeping the operators incentivized to maintain the membranes. However, since the off-takers are usually governments or governments with sovereign guarantees, the off-taker risk is low [37].

3.5 Construction, technical and operational risks

Ten desalination plants using seawater as feed are currently in the construction stage in the Arab region with TDS of (20000ppm - 50000ppm), as shown in detail in Table 2. These plants use Reverse Osmosis (RO) technology designed to provide municipalities with drinking water (TDS 10ppm - <1000ppm).

Table2: Desalination plants in construction stage 2022

Country	*Location*	*State/Region*	*Project name*	*Capacity (m^3/d)*
Oman	Barka	Al Bāţinah	Barka 5 IWP	100000

Saudi Arabia	Al Jubail		Jubail2 replacement	1000000
Algeria	Corso Reghaia	Boumerdès	Corso SWRO	80000
Saudi Arabia	Shoaiba		Shoaiba 3 Conversion Project	600000
Saudi Arabia			Temporary Desal Plant	21000
Saudi Arabia			Ma'aden	6000
Saudi Arabia			Ma'aden	6000
Saudi Arabia			Submerged Sea Water Reverse Osmosis- Subsea Plant	50
Saudi Arabia			Crystallization Plant for Saline Water Conversion Corporation	58
Saudi Arabia			Provide Reverse Osmosis (R.O.) Unit at SSPP with Installation	2000

In construction, there is the possibility that costs increase during the implementation period because of unusual subsurface conditions on the site, delays in equipment delivery and installation, construction costs overrun, errors and omissions by designers and contractors, as well as reliability and performance risks associated with plant startup, commissioning, and acceptance.

Regarding the operational and technical risks in desalination plants, operation and maintenance (O&M) can pose several risks over the facility's lifespan or the length of the lender's investment. Maintaining and operating the plant consistently and reliably is essential to meet financial obligations, so revenue streams remain steady. In the absence of experience in operating desalination plants of similar size, the project owner may benefit from contracting out the operation and management of the desalination plant to a well-established, well-specialized private contractor with proven experience. Over time, the O&M challenges and risks associated with a lack of skilled local labor diminish in importance as the desalination market matures. Additionally, an intake pretreatment system for seawater desalination plants can be overwhelmed by sudden and variable seawater conditions, especially harmful algal blooms. The installation of DAF systems can be considered as a standby solution in such cases, but it would be a significant capital expense for a system. Moreover, achieving the highest membrane production at the lowest operating pressure is ideal. SWRO typically operates between 50-70 bar; reducing the pressure generally results in lower water production. In addition, membrane permeability is reduced by slowly accumulating biological matter, organic material, biofilms, and inorganic solutes during operation. A membrane cleaning procedure takes the plant offline and creates liquid waste, adding to energy consumption and water costs over the plant's life.

3.6 Financing structure

Financial costs heavily influence desalination costs because such projects are expensive. Developers usually provide private capital, while financial institutions provide loans. The return on investment varies depending on the project risks, and sometimes debt is less expensive than private equity injection. Depending on the country's risk, the project's risk, and the client's flexibility, the leverage between one and the other ranges typically between 30/70 and 15/85 equity/debt.

Different variables affect the production costs of desalinated water, making direct comparisons between projects difficult. In recent years, desalination has become more competitive because of increased liquidity and the maturity of financial markets. A wide range of prices is available for producing 1 m^3 of RO desalinated water, starting at US\$0.60/m^3 for large desalination plants with an approximate capacity of (325,000 m^3/day) to around US\$ 1.25/m^3 for small plants (10,000 m^3/day).

4. Challenges

4.1 Environmental impact

Understanding that concentrate (brine) is a product of the concentration of solutes released from the RO system is essential. RO concentrate contains almost all source water constituents with the same load but at a higher concentration. It also contains the chemicals used during the pretreatment process. Thus RO concentrate is approximately 5-7 times as concentrated as the source water. The impact of seawater intake is not just limited to the intake itself. Impingement, entrainment, and the choking of large organisms also occur, and smaller and unicellular organisms can pass through the initial screening into the water supply affecting the desalination system and the content of the discharged brine. Chemical discharge is also a significant concern. Source water undergoes various chemical treatments for controlling biofouling, removing suspended solids, removing antiscalants, controlling foam, and cleaning. The type and quantity of the chemicals used for preconditioning and the configuration and design of intakes and outlets determine the desalination's impact on intakes and outfalls [38]. Varying formulation compositions of commercial treatment products and plant-specific process controls cause the chemical contamination of discharges to vary between desalination plants. Chemical contamination of discharges, moreover, can be caused by the corrosion of metal parts within the system [39].

4.2 Construction

In addition to experimental, field, and modeling studies, there is evidence that desalination has specific biological and ecological impacts affected by locations, the individual desalination plants themselves, and species-specific criteria. Certain factors should be considered in desalination plant construction, including the coastal zone and seafloor ecology, bird and mammal habitats, erosion, and non-point source pollution. Plant construction can impact environmentally sensitive areas due to the construction of water intake infrastructure and the pipe network transporting water to the plant. In addition, an open coastline can cause the brine to concentrate and build up if discharge plumes are released into confined water bodies or areas with bathymetric topography that reduces dispersal [39].

4.3 Air Quality and Carbon footprint

Although attention is now being paid to atmospheric pollution caused by brine pollution and chemicals in the reject streams, little attention has been paid to the indirect effects of desalination. The massive production of desalination plants in the Gulf region contributes to the area's poor air quality. Nitrogen oxide emissions, among other pollutants, may well contribute to forming a photochemical smog over some of the larger cities [39].

All the emission scenarios considered by scientists suggest that it will be impossible to lower global temperatures by even 2°C this century without dramatically reducing carbon dioxide emissions. One general construction and decommissioning impact associated with coastal development is the release of atmospheric CO_2 emissions that result from project energy requirements [40].

As well as the plant's efficiency, the source of energy that drives a desalination plant determines its direct carbon footprint. RO has lower CO2 emissions than thermal desalination technologies. SWRO desalination plants estimated carbon footprint is 0.4 – 6.7 kg CO_2 eq/m^3. However, this is generally higher than brackish water RO desalination's estimated carbon footprint of 0.4 – 2.5 kg CO_2 eq/m^3. Such values vary in different parts of the world. The variation is attributed to the location, the technologies, the life cycle stages, the parameters used, and the estimation tools, all of which have been identified as significant obstacles to provide accurate comparisons. It is also common for desalination plants to emit indirect greenhouse gases (GHGs).

4.4 Marine environment

Seawater desalination plants, whether they are built, operated, or decommissioned in the long run, cause several negative impacts on the marine environment, and these should not be overlooked. As stated earlier (Section 4.1) an open coastline can cause a concentration of brines if discharge plumes are released into confined water bodies or areas with bathymetric topography that reduce dispersal. A desalination plant's impact on intakes and outfalls is determined by both the type and amount of water preconditioning chemicals that are used, as well as on the configuration and design of intakes and outlets.

The impact of desalination on the environment is another critical aspect of the overall process. Protecting marine life is one of the most important considerations when dealing with seawater plants. One first step, in this regard, is to minimize the risk of impingement or entraining of marine species. New designs in seawater intakes provide a wide range of options such as submerged offshore intakes, subsea bed intakes, co-located intakes, beach and coastal wells, and passive intakes.

Hypersaline brine discharge from desalination plants causes problems for the marine ecosystem, especially in the closed Arabian Gulf region. It has been demonstrated in recent studies that the areas of the space where brine discharge points are located within modern seawater facilities are often a lively habitat for marine life. Various methods are utilized to reduce the impact of brine discharge, including multi-port diffusers; co-located, blended discharges of cooling water and wastewater effluent; deep well injection, evaporation, and the recovery of salt and minerals. Other mitigation methods are available to address potential negative impacts. These mitigation methods include:

- Reducing the number and concentration of chemicals permitted in the outfall and ensuring that discharge limits are met
- Reducing the chemical load of reverse osmosis desalination plants with low-pressure membrane pretreatment. In addition, new methods have also been developed for dealing with and disposing of solids recovered from backwash during the desalination process.
- One essential aspect of the overall operation of a desalination plant is monitoring the environment adjacent to the site. Improved monitoring techniques and practices allow for more accurate observations of any potential impact. It allows the facility operators to alter operating conditions in accordance with environmental demands, should that be necessary.

The disposal of brine by brackish water plants must also be considered. The brine can sometimes be discharged from the plant without affecting the existing water body. In other cases, it may be injected into a deep well or an evaporation pond. In either case, safe disposal of brine must be considered in the original design of the plants with the expected increase in capital cost. Operating cost projections can then be adjusted accordingly.

5. Best practices

More than 200 million people are currently living in scarcity conditions and 160 million are living in conditions of absolute water scarcity [41]. Arab countries must therefore adopt innovative ways to address competing water demands and implement integrated water resources management (IWRM) to cope with their rapidly growing populations, economic development, environmental considerations and climate change. A key part of the Arab Strategy for Water Security (ASWS) is advancing the IWRM principles to meet the challenges and requirements for sustainable development. It is also necessary to create active policies, legislative frameworks and institutional frameworks for managing IWRMs. As part of their national development plans, most Arab countries have developed strategies for Sustainable Development Goals (SDGs), specifically target 6.5, which further commits to IWRM for sustainable development and efficient water management.

5.1 Data and information availability and accessibility

Data and information sharing is limited in some countries, being mainly done on an ad-hoc or on a project basis. Establishing national water information systems and a national consolidation will facilitate effective collaboration among key stakeholders, including ministerial departments and water institutions. As part of its water laws and protocols or decrees, Lebanon is integrating the need for the establishment of a national water information system, including mandatory sharing of information across different institutions and authorities. It might also be possible to make use of artificial intelligence, in cases of desalination, as an alternative approach to analyzing desalination data.

In some countries, multi-stakeholder workshops have been held and these provided valuable insight into the efforts to implement integrated water resources management (IWRM). Several organizations have participated in the identification and training of national focal points, including the United Nations Environment Programme (UNEP), the UNEP-DHI Centre on Water and Environment, Cap-Net UNDP, the World Health Organization, and UN-Water.

To achieve further progress, national water monitoring must be enhanced and modernized, data and information sharing between countries must be prioritized, and transboundary data and information sharing must be strengthened.

5.2 Expanding and modernizing national monitoring of water availability

In addition to building an enabling environment (consultations, training, etc.) and establishing a governance structure to manage and implement the national water information system, Lebanon has undertaken the investments necessary to ensure data production, storage, processing, and access for stakeholders. Many countries, including Jordan, Lebanon, Morocco, Oman, and Somalia, have suggested developing, modernizing, and expanding monitoring networks.

5.3 Transboundary data and information sharing.

The significance of transboundary water in the region requires the formalization and strengthening of arrangements to exchange data and information. Some suggestions have included the creation of a public online portal shared by all countries. Data and information exchange could then be extended to other sectors.

A regional observatory is recommended to increase cooperation and knowledge between Arab countries regarding desalination technology to support their expanding water demand by adopting the most efficient and sustainable desalination technologies. This will promote the development of innovations and knowledge transfer between Arab countries.

6. The role of the private sector

Private finance is now a significant factor in the development of water projects worldwide. 38% of the capacity of desalination plants built between 2000-2020 came from private financing. Different delivery models are used to procure desalination projects. The delivery model chosen depends on whether the project financing is from a public or private source. A desalination project can be classified under any of the following terms and models of contract:

- Private Public Partnership (PPP)
- Concessions or utility outsourcing transactions
- Independent Water and Power Project (IWPP)
- Build Own Operate (BOO) schemes
- Build Own Operate schemes with a transfer component attached (BOOT)

Conflicts will inevitably arise due to the multiple objectives of integrating desalination plants' design, construction, operation, and maintenance with ownership and financing. In order to achieve the lowest borrowing cost, a company must minimize the risks. On the other hand, technological innovations are associated with higher levels of risk. Any successful private sector entity has to select the most appropriate technical solution based on the asset's whole life cost, to optimize capital and operating costs and achieve a competitive tariff (price/m^3 of water).

In today's construction industry, three primary contract models are used: EPC (engineering, procurement, and construction Contract), DBO (design-build-operate), and BOT (build-operate-transfer). Build, own, operate, and transfer (BOOT) water desalination projects are becoming increasingly prevalent worldwide since they allow municipalities and public utilities to shift the risk associated with desalinated water costs to the private sector.

There are infrastructure constraints on the application of PPPs. For example, desalination usually requires long-distance transportation of desalinated water to the desired location. PPPs must be complemented by institutional constraints, including establishing water pricing policies, R&D investments, and managing integrated water resources. The public's perception of private sector involvement in PPPs is also a constraint. Concerns include the possibility of price increases, inappropriate business practices, and less-than-ideal dissemination of information. Human resources and related organizations are still nascent, and water quality has not been quantified for socio-economic growth.

6.1 Plant purchase

The choice of a procurement model for a desalination project is influenced by different factors, such as the project's location, the size of the plant, the project's risk profile, funding sources, bonds, and the owner's experience. Moreover, different delivery models are used to procure desalination projects, depending on whether the project is financed by a public agency or by a private entity. These delivery models are used when the client wants to keep ownership of the plant. These categories include engineering, procurement, and construction (EPC), design-build (DB), or design-bid-build (DBB). The client commission any of these models to prepare drawings and detailed specifications. The drawings and specifications are then brought to a contractor by the client so that construction can commence [42].

6.2 Design-build-operate (DBO)

During the bidding process, the clients needing the desalination plant award contracts for construction, operation, and maintenance (O&M) as a single package. In some cases, different consortium members making the bid carry different responsibilities in the contract for construction and operation. The model requires fewer legal frameworks than other models (such as BOT) and incentivizes long-term reliability as a key development goal since the operational component of the contract requires more stringent legal frameworks than those of models based on BOT [42]. This model was used for the Basra water supply projects.

6.3 Build-operate-transfer (BOT)

In this delivery model, a private development company owns the assets, and the clients receive their assets at the end of the contract period. In 2020, the involvement of private finance enabled a high level of investment in new desalination projects. The projects made significant use of the Independent Water Producer (IWP) contract model, which involved a long-term BOT contract. Most of the capacity awarded through this model occurred in the GCC. Many BOT projects now produce desalinated water at below \$0.50/m^3. These projects include Jubail 3a (\$0.41/m^3), Jubail 3b (\$0.42/m^3), and Yanbu 4 (\$0.47/m^3). However, low prices may be unobtainable outside of the Middle East due to higher environmental, regulatory, and labor costs [42]. In North Africa, Moroccan PPPs are also gaining traction. The planned 800,000 m3/d Casablanca plant is expected to use a BOT contract, while a new law will, when enacted, expand the list of public bodies that can participate in PPPs. Similarly, Egypt's massive desalination program for 2050 is expected to require private financing. Tunisia's Gabès desalination plant will also follow a BOT model.

6.4 Build-own-operate (BOO)

Unlike BOT, this model does not involve asset transfer. Municipalities and public utilities are increasingly opting for the build own operate transfer (BOOT) project delivery method to transfer the risks of desalinating water to the private sector. It is important to note that certain risks are associated with the operation of extensive seawater desalination plants. These include predicting plant performance because of challenges in obtaining permits, water quality, startup and commissioning costs, and the public sector's limited experience concerning membrane technology and equipment [42].

6.5 Constraints related to the public perception of private-sector involvement in PPPs

By partnering with the private sector, governments can reduce costs and improve the out-of-sale services offered by the private sector. Private Public Partnerships (PPPs) have been extensively discussed in the Arab region in the last decade. Particular attention has been paid to their relations with institutional and regulatory frameworks, market risks, off-taker risks, tariff structures, desalinated water charges, construction, technical and operational risks, financing mechanisms, credit enhancements, and environmental risks. The application of PPPs, however, is affected by infrastructure constraints. Furthermore, established institutions need to be consulted in conjunction with PPPs, such as establishing water storage systems. Water resources management is often intertwined with establishing a water pricing policy and an incentive program, and these are other factors that need to be addressed in conjunction with PPPs. As a result of their perceptions regarding the involvement of the private sector in PPPs, the public is frequently concerned about price increases, inappropriate business practices, and a general lack of easily understood information. In fact, to date, there has been no full quantification to explain why water quality negatively affects socio-economic development, and the human resources and related organizations required to establish this nexus are still in their infancy [42].

Another constraint is the public's perception of private sector participation in PPPs. Concerns include the potential exploitation of an essential resource in the interests of profit. Moreover, investment and produced water costs are self-evidently key factors in influencing decision makers to select appropriate technologies, which can be combined with local incentives and contract delivery models. Costs per m^3 of desalinated water may vary significantly depending on several factors, including water production capacity and quality, feed water source (Seawater or brackish water), location, and the type of energy used.

7. Capacity development

In the Arab region, mainly in the Arab Gulf countries, desalination has developed into one of the biggest markets in the world. In addition to being world leaders in desalination technology, the

Arab Gulf area can contribute years of training to their neighboring countries. According to industry experts, the urgent need for training and capacity-building in desalination is indisputable. Nowadays, large-scale desalination plants are built faster than the people who can operate them are trained. There is a continuous need for the development and training of human resources to run the existing and future desalination plants in the Arab region.

The Arab region lacks the appropriate workforce in the desalination field - consultants, designers, expert researchers, skilled technicians, and operators - to adequately meet its needs now and in the future. Several estimates indicate that the existing and future operations of the desalination industry in this region will require a significant number of personnel at all technical levels. Furthermore, most contractors and consultants are not locals. This factor can be attributed to the fact that most of the desalination activities in the region began in oil-producing countries that could afford expatriate labor or had no local skills on hand. Conversely, most non-oil-producing countries have just begun desalination and do not have the human resources needed in this field.
Currently, regional education about desalination is dominated by private sector initiatives and the specialized courses offered by regional universities. Despite these initiatives, it is unlikely they will be able to meet the estimated industry growth needs alone. An approach that involves the participation of several institutes and organizations is necessary to provide the most effective education and training.

Research and development play a vital role in all the areas that lead to the advancement of technology. Unfortunately, most companies that supply desalination technologies do not invest much in research and development, possibly due to a lack of funds. Significant investment must be devoted to developing economically viable technologies to gain a competitive edge in the market.

Similarly, despite the high level of competition in the desalination market, most technology users do not actively engage in improvements to their plants to increase their operational performance. Again, this may be due to the lack of funding or trained human resources to supervise and conduct research. It should be noted that some countries in the Arab region already have well-established desalination programs, including the GCC and, to some extent, Libya.

However, the main problem with these developments is the lack of qualified staff in many of these countries, as many do not have training facilities or tailored staff training programs. Plant suppliers are attempting to solve this problem by establishing training facilities and programs within the host country or abroad. As part of this initiative, in Oman, the Middle East Desalination Research Center (MEDRC) offers short training courses that are conducted in the region by internationally recognized experts in the field. It enhances research capabilities by including local researchers in the research teams of each project sponsored by the center and sponsors students to pursue postgraduate qualifications in desalination and its related fields.

7.1 Academic degrees and roles

Universities and research centers in the Arab region have limited resources, facilities, or staffing available to develop new technologies. They do, however, research to improve existing processes. Most of the research work in Arab universities focuses on assessment studies, process simulations for evaluating existing plants, small desalination systems, and renewable energy applications in desalination. Very few universities worldwide offer water purification courses in their engineering programs. However, exceptions, such as King Abdulaziz University in Jeddah, Kuwait University, and L'Ecole Nationale d'Ingénieur de Tunis do exist. To further address this need, Oman’s Middle East Desalination Research Center helped to launch MSc and Ph.D. scholarships and introduced postgraduate courses in Arab universities. Arab countries offered scholarship programs to study outside the region [43].

7.2 Research and development

Research and information access improvement supported the region's desalination research and development growth. In most institutions, research and development focus primarily on improving the efficiency of their local desalination plants and on improving available technologies. In addition, research in desalination-related phenomena like scaling, membrane fouling, cleaning, disinfection, and corrosion is also conducted. However, few desalination-focused centers exist in the Arab region, namely Salt Water Conversion Corporation (SWCC) in KSA, the Kuwait Institute of Scientific Research (KISR) in Kuwait, and the Middle East Research Center (MEDRC) in Oman.

It is essential to have qualified and experienced personnel to establish a well-established desalination industry. Several estimates indicate a need for more support staff at all technical levels. Training and education centers must be established, and academic institutions should train personnel working in the sector. Water desalination technologies and related topics must be studied to create a feasible education program, particularly on specific technologies that differ from country to country. The education process should be flexible and dynamic, capable of addressing changes and improvements as technologies develop [43].

Awareness of water issues and programs should begin at primary and secondary school levels. Recently, many Arab countries have been developing capacity-building programs in dewatering at local, regional, and international levels. The programs provide practical, hands-on training on instrument handling, laboratory work, chemical and physical analysis, and the testing and understanding of plant components. Privatization of the desalination industry is expected to increase the investment in capacity-building programs offering:

1. Utilization of new science, experience, materials, and applications to revive previously unsuccessful technologies
2. Innovating entirely new processes
3. Continuously improving existing technologies

7.3 Vocational and technical training

International desalination companies and institutions conduct training courses regularly, such as DH Paul and Masar Technologies DME Desalination Institute, Haward Technology Middle East, Bushnak Academy, and Apex. In addition, international associations like the InternationalInternational Desalination Association (IDA), the International Water Association (IWA), and the European Desalination Society (EDS) assist in conducting training courses and workshops during their annual conferences.

Every water development project can be successful and seamless if residents are involved in all the stages preceding completion (the planning and implementation phases). Communities will do their best to ensure the successful management of these projects since they are the ultimate beneficiaries. More support should be provided for desalination technical and vocational education programs (including e-learning). Conducting vocational and technical training and involving the locals help reduce the cost of desalination directly or indirectly.

8. Recommendations and perspectives

8.1 New visions for innovative technologies

International research centers and institutions are developing new desalination technologies for non-conventional wastewater, most importantly oil-field produced water. Old oil-field wells produce a large amount of water during oil production. In Oman, 9 barrels of saline wastewater is produced for every 1 barrel of oil. It is essential to consider this water as another water source rather than a highly contaminated wastewater destined for disposal. When desalinated, this water offers an excellent usable water source, especially for irrigation.

Environmentally friendly zero-liquid discharge processes promote the development of new desalination technologies such as membrane distillation and crystalization. Other technologies are also developed for specialized non-seawater desalination. In addition, advanced research is ongoing to develop desalination technologies for agriculture applications, including NF, CDI, EDR, and hybrid desalination processes. The application of these technologies is expected to increase, leading to segregation between seawater desalination technologies and groundwater desalination technologies.

8.2 Financial sustainability

Several factors contribute to the high cost of desalination, including the dominance of the public sector in the industry and the enormous investment costs associated with new desalination plants, especially for heavily subsidies projects. Due to these factors, it will be difficult for the global water industry to meet the rapidly increasing demand for water. It will also put a heavy burden on national budgets. To achieve economic sustainability, governments can design incentives for local businesses and encourage local investment in the manufacturing of key desalination plant components. Localizing technologies and manufacturing will increase the GDP, increase job opportunities, enhance local skills, reduce the cost of desalination and strengthen the private sector's role in desalination. Governments should promote innovation in technology and operations by valuing energy at world market prices, as practiced by the private sector. In addition, governments should take measures to minimize the life-cycle cost of water, especially for large desalination plants. Governments should utilize locally produced products and local human resources to minimize water costs

8.3 Environmental sustainability

Using renewable energy to reduce greenhouse gas emissions and climate-related impacts and adopting stricter environmental regulations ensures environmental sustainability. Another key recommendation is to minimize environmental impact by using low-quality water or seawater instead of fresh or desalinated water in the industries, especially for cooling.

The Arab region may consider the USA's Environmental Protection Agency (EPA) regulations regarding direct and indirect discharges of residues from drinking water production. Zero-liquid discharge (ZLD) has recently gained traction to minimize brine's environmental impact on sea life and coral reefs. ZLD produces higher water recovery and provides the option of salts recovery producing minimal water and solid wastes.

The Arab region relies heavily on agriculture contributing 80% of total water use. Encouraging farmers to use non-conventional water for irrigation through public awareness sessions, legislation, and empowerment by providing them with training and modern tools and equipment is essential. The Arab world can invest in new desalination technologies better suited for agriculture, such as nanofiltration, CDI, and EDR processes. These processes are highly suited for groundwater (low-medium salinity) desalination and can control the desalinated water's salinity. Research is necessary to investigate the applicability of mixing different quantities and qualities of groundwater, treated wastewater, desalinated water, and surface water for agriculture purposes. In addition, more research is crucial in saline agriculture, aquaponics, and hydroponics.

8.4 Pursuit to modernize legislations and laws

Increasing capacity, knowledge, and value added to the local economy requires a review of policies and practices. Much of the Arab community's expertise and capacity is currently devoted to operations and maintenance, while little attention is paid to plant design, manufacturing, and construction. Some Arab States are yet to achieve balance in water policies by implementing the necessary legal and legislative frameworks. If they do exist, these frameworks are not ideally practiced for their assigned purposes. Laws and legislation do not adequately address all the issues, or the implementing instruments fail to guarantee that proper application occurs, which leads to a lack of enforcement.

Robust legal and legislative frameworks are paramount to ensure the proper implementation of policies and achieve balanced development. A comprehensive regulatory framework for desalination should be developed in addition to incentive programs aimed at reduction of the carbon footprint and the environmental impact associated with the desalination process. Furthermore, legislators should cooperate with Arab and international peers while developing appropriate water legislation. Collaboration enables legislators to develop comprehensive and wide-ranged legislation suitable for the whole region and future generations.

8.5 Water demand in the fourth industrial revolution and the effect of disruptive technologies

- Nanotechnology has a wide range of potential applications in the water industry because it can pioneer new materials, systems, and technologies at lower costs and with increased efficiency. Through nanotechnology, new water sources can be unleashed at scale, bringing benefits to multiple industries, including water decontamination, infrastructure development, and monitoring. In recognition of the potential impact of this technology, the global economy is already investing in nanotechnology. The sector is expected to exceed $125 billion by 2024.
- Renewable energy for direct or indirect desalination is gaining interest in sun-rich countries. Recent developments proved the capability of renewable energy to replace energy-intensive pretreatment processes and harmful chemicals used in desalination.

Renewable energy-powered desalination plants are desalination's future. It reduces energy costs, offsets energy demand during peak hours, and is highly environmentally friendly.

- The recent shift to net zero emissions stressed the need for green hydrogen production rather than other hydrogen colors. Green hydrogen is produced using electricity to split water molecules into hydrogen and oxygen. Current technologies demand high water purity for green hydrogen production. Approx. 9 liters of water are needed to produce 1 kg hydrogen and 8 kg oxygen. The total amount of hydrogen production today, about 70 million tons of hydrogen, requires 617 million cubic meters of water if it were all produced by electrolysis [44].

  Hydrogen projects within regions experiencing above medium water stress could lead to a fivefold increase in desalination demand by 2040 [45]. As a result, Arab countries planning to produce green hydrogen must rely on seawater desalination to source the water necessary for the process.

  Given this significant growth in demand, Saline Water Conversion Corporation, KSA, signed a memorandum of understanding with Cummins Arabia to explore ways to develop green hydrogen technologies jointly. As one of the kingdom's major megaprojects to diversify its economy, the $500 billion Neom development on the Red Sea coast will develop one of the first large-scale green hydrogen projects in the Middle East. Additionally, an ambitious new project to produce green hydrogen from desalinated water is underway in Abu Dhabi, which is making a major move into the new energy market. Abu Dhabi Ports and Taqa, which control all the emirate's water infrastructure, are discussing the possibility of creating a green hydrogen-ammonia plant in the Khalifa Industrial Zone. A 2 GW photovoltaic solar power plant will power the electrolysis process.

References:

[1] G. Baggio, M. Qadir, V. Smakhtin, Freshwater availability status across countries for human and ecosystem needs, Science of The Total Environment, 792 (2021) 148230.
[2] H. Adun, H.P. Ishaku, A.T. Ogungbemi, Towards Renewable energy targets for the Middle East and North African region: A decarbonization assessment of energy-water nexus, Journal of Cleaner Production, 374 (2022) 133944.
[3] D. Dimkić, M. Dimkić, S. Vujasinović, Drought and alluvial groundwater resources, (2021).

[4] M. Ayaz, M. Namazi, M.A. ud Din, M.M. Ershath, A. Mansour, Sustainable seawater desalination: Current status, environmental implications and future expectations, Desalination, 540 (2022) 116022.
[5] B. Moossa, P. Trivedi, H. Saleem, S.J. Zaidi, Desalination in the GCC countries-a review, Journal of Cleaner Production, (2022) 131717.
[6] D. Curto, V. Franzitta, A. Guercio, A review of the water desalination technologies, Applied Sciences, 11 (2021) 670.
[7] Y. Shatilla, Nuclear desalination, Nuclear Reactor Technology Development and Utilization, Elsevier2020, pp. 247-270.
[8] A. Alkhudhiri, N. Darwish, N. Hilal, Membrane distillation: A comprehensive review, Desalination, 287 (2012) 2-18.
[9] T. Mezher, H. Fath, Z. Abbas, A. Khaled, Techno-economic assessment and environmental impacts of desalination technologies, Desalination, 266 (2011) 263-273.
[10] K.M. Shah, I.H. Billinge, X. Chen, H. Fan, Y. Huang, R.K. Winton, N.Y. Yip, Drivers, challenges, and emerging technologies for desalination of high-salinity brines: A critical review, Desalination, 538 (2022) 115827.
[11] F.E. Ahmed, R. Hashaikeh, N. Hilal, Solar powered desalination–Technology, energy and future outlook, Desalination, 453 (2019) 54-76.
[12] M. Rahman, Foreword I, Green Energy and Technology, Springer, Singapore. https://doi. org/10.1007/978-981-13-6887-5, 2019.
[13] P.S. Bhambare, M. Majumder, C. Sudhir, Solar thermal desalination: a sustainable alternative for Sultanate of Oman, International Journal of Renewable Energy Resources, 8 (2018) 733-751.
[14] Veolia and TotalEnergies partner to build largest solar system for desalination plant in Oman, Times of Oman, 2022.
[15] Solar energy to power sur desalination plant Oman Observer Oman, 2022.
[16] P.S.Z.R. Van Der, Wal A. Presser V. Biesheuvel P, Prog. Mater. Sci, 58 (2013) 1388.
[17] Y. Oren, Capacitive deionization (CDI) for desalination and water treatment—past, present and future (a review), Desalination, 228 (2008) 10-29.
[18] N.J. Vickers, Animal communication: when i'm calling you, will you answer too?, Current biology, 27 (2017) R713-R715.
[19] P. Goh, K. Wong, A. Ismail, Membrane technology: A versatile tool for saline wastewater treatment and resource recovery, Desalination, 521 (2022) 115377.
[20] Y. Ibrahim, H.A. Arafat, T. Mezher, F. AlMarzooqi, An integrated framework for sustainability assessment of seawater desalination, Desalination, 447 (2018) 1-17.
[21] H.A. Awaad, E. Mansour, M. Akrami, H.E. Fath, A.A. Javadi, A. Negm, Availability and feasibility of water desalination as a non-conventional resource for agricultural irrigation in the mena region: A review, Sustainability, 12 (2020) 7592.
[22] J.A. Aznar-Sanchez, L.J. Belmonte-Urena, J.F. Velasco-Munoz, D.L. Valera, Farmers' profiles and behaviours toward desalinated seawater for irrigation: Insights from South-east Spain, Journal of Cleaner Production, 296 (2021) 126568.
[23] A. Hafez, S. El-Manharawy, Economics of seawater RO desalination in the Red Sea region, Egypt. Part 1. A case study, Desalination, 153 (2003) 335-347.
[24] J.M. Beltrán, S. Koo-Oshima, Water desalination for agricultural applications, FAO Land and water discussion paper, 5 (2006) 48.
[25] C.-Y. Chen, S.-W. Wang, H. Kim, S.-Y. Pan, C. Fan, Y.J. Lin, Non-conventional water reuse in agriculture: A circular water economy, Water Research, 199 (2021) 117193.
[26] T. Kober, H.-W. Schiffer, M. Densing, E. Panos, Global energy perspectives to 2060–WEC's World Energy Scenarios 2019, Energy Strategy Reviews, 31 (2020) 100523.

[27] N. Ghaffour, T.M. Missimer, G.L. Amy, Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability, Desalination, 309 (2013) 197-207.
[28] H. Sewilam, P. Nasr, Desalinated water for food production in the Arab region, The water, energy, and food security nexus in the Arab region, Springer2017, pp. 59-81.
[29] J. Eke, A. Yusuf, A. Giwa, A. Sodiq, The global status of desalination: An assessment of current desalination technologies, plants and capacity, Desalination, 495 (2020) 114633.
[30] J. Kim, K. Park, D.R. Yang, S. Hong, A comprehensive review of energy consumption of seawater reverse osmosis desalination plants, Applied Energy, 254 (2019) 113652.
[31] N. Voutchkov, Energy use for membrane seawater desalination–current status and trends, Desalination, 431 (2018) 2-14.
[32] U. Caldera, D. Bogdanov, S. Afanasyeva, C. Breyer, Role of seawater desalination in the management of an integrated water and 100% renewable energy based power sector in Saudi Arabia, Water, 10 (2017) 3.
[33] M. Fawzi, M.I. Al Ajlouni, Water Safety Plan Resources In Jordan Quantity and Quality, (2021).
[34] E. ALEISA, A. ALJUWAISSERI, K. ALSHAYJI, A. AL-MUTIRI, ENVIRONMENTAL IMPACTS OF REVERSE OSMOSIS IN WASTEWATER TREATMENT VERSUS DESALINATION TO MEND THE WATER CYCLE: A LIFE CYCLE ASSESSMENT, WIT Transactions on Ecology and the Environment, 257 (2022) 27-37.
[35] R.A. Al-Masri, J. Chenoweth, R.J. Murphy, Exploring the Status Quo of Water-Energy Nexus Policies and Governance in Jordan, Environmental Science & Policy, 100 (2019) 192-204.
[36] S.M. East, N. Africa, A.R. Egypt, ROAD AHEAD.
[37] D.M. Warsinger, Desalination Innovations Needed to Ensure Clean Water for the Next 50 Years, The Bridge, (2020).
[38] E.J. Campos, F. Vieira, G. Cavalcante, B. Kjerfve, M. Abouleish, S. Shahriar, R. Mohamed, A.L. Gordon, Impacts of brine disposal from water desalination plants on the physical environment in the Persian/Arabian Gulf, Environmental Research Communications, 2 (2020) 125003.
[39] M.A. Dawoud, S.O. Alaswad, H.A. Ewea, R.M. Dawoud, Towards sustainable desalination industry in Arab region: challenges and opportunities, 4th international water desalination conference: future of water desalination in Egypt and the Middle East, 2020.
[40] M.A. Dawoud, Environmental impacts of seawater desalination: Arabian Gulf case study, International Journal of Environment and Sustainability, 1 (2012).
[41] J. Daher, Water scarcity, mismanagement and pollution in Syria, European University Institute, 2022.
[42] R.A. Greer, K. Lee, A. Fencl, G. Sneegas, Public–Private Partnerships in the Water Sector: The Case of Desalination, Water Resources Management, 35 (2021) 3497-3511.
[43] N. Ghaffour, The challenge of capacity-building strategies and perspectives for desalination for sustainable water use in MENA, Desalination and Water Treatment, 5 (2009) 48-53.
[44] F. Birol, The future of hydrogen: seizing today’s opportunities, IEA Report prepared for the G, 20 (2019).
[45] A. Boretti, L. Rosa, Reassessing the projections of the world water development report, NPJ Clean Water, 2 (2019) 1-6.