REPORTING AND INFORMATION UNIT
The Saline Water Conversion Corporation

المؤسسة العامة لتحلية المياه المالحة
Saline Water Conversion Corporation (SWCC)

The Evolution of Water Reverse Osmosis Technology

"We Race the Future Where Life Is"

swcc_ksa

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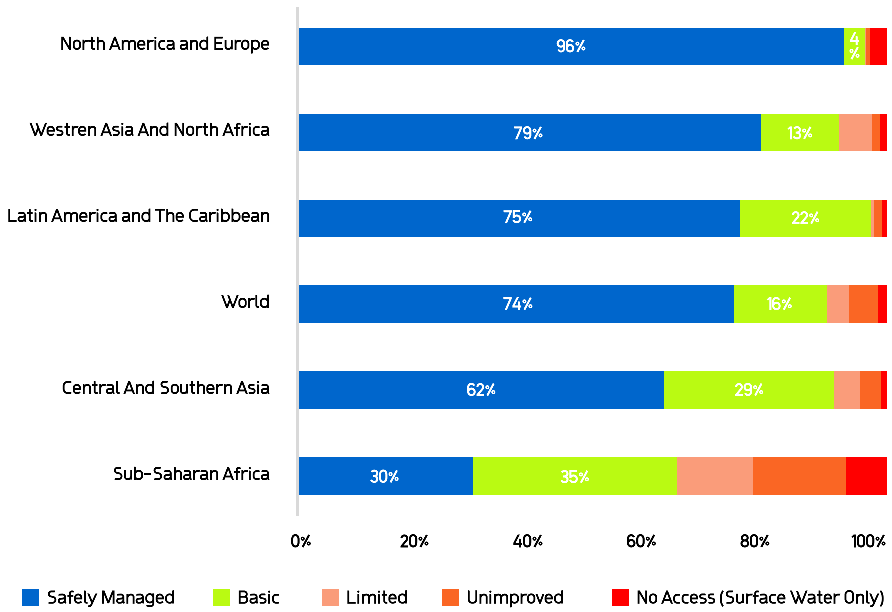
Introduction

Introduction

Increasing water demands and diminishing water supplies aggravate water scarcity in most world regions. Conventional approaches depending on natural resources like rainfall and river runoff in water-scarce areas must be revised to meet human needs. 97.5% of the water resources are in the sea. On the other hand, freshwater is 2.5% [1]. After realizing these facts, the world must look forward to a dependable and feasible solution that ensures the equilibrium state of the continuous growth of various sources of water demand and the availability of the security of water supply.
Desalination by reverse osmosis (RO) has developed as an important technology in facing global water challenges. RO desalination has transformed pure water production from saline sources by utilizing a semi-permeable membrane to separate water molecules from salt molecules.

One of the main challenges is water availability, In Figure 1 we can see the share of the population with access to pure water facilities in 2020, which indicates the overview of the status of the water sector infrastructure intentionally. This observed data concludes that almost three-quarters of the global population have access to a carefully managed water source.[2] In this paper, we will examine a comprehensive overview of the history of reverse osmosis desalination, discuss current advancements, and explore the prospects of this technology. As an important fundamental for providing a sustain production solution that will support the infrastructure globally.

Figure (I): Share of the population with access to drinking water



Source: Our World in data WHO/UNICEF (JMP),2020

Overview of Seawater Reverse Osmosis

Overview of Seawater Reverse Osmosis

The Early Discovery of Reverse Osmosis Technology (RO)

- The history of reverse osmosis (RO) can be traced back to the early 18th century when French physicist Jean Antoine Nollet observed the phenomenon of osmosis, which is the movement of water through a semipermeable membrane from an area of lower solute concentrations to a place of higher solute concentration.[3] The first practical application of osmosis occurred in 1748 when Swiss physician and naturalist Jean-Etienne Guettard used a pig bladder as a semipermeable membrane to purify water [4].

- The concept of reverse osmosis was first proposed in the 1950s when researchers began investigating synthetic membranes for water purification. The first successful application of reverse osmosis occurred in the late 1950s when University of California at Los Angeles (UCLA) researchers Sidney Loeb and Srinivasa Sourirajan developed a synthetic membrane capable of desalinating seawater.[5]

- The early RO membranes were made of cellulose acetate, a readily available and inexpensive material. However, these membranes were prone to fouling and degradation, which limited their effectiveness over time. In the 1960s, researchers began to investigate using thin-film composite (TFC) membranes, which were more durable and resistant to fouling.

- The development of TFC membranes in the 1970s led to a significant increase in reverse osmosis systems' efficiency and effectiveness. These membranes were made of multiple layers of synthetic materials, including polyamide and polysulfide, which could remove an extensive range of contaminants from water. TFC membranes also had a higher flux rate, allowing faster and more efficient water purification[6].

- The Kingdom of Saudi Arabia has known water desalination for many years since the beginning of the early assessment of the needs of this vital substance. The Kingdom has been working on continued research, developing new water creation methods, and ensuring the demand is always met.

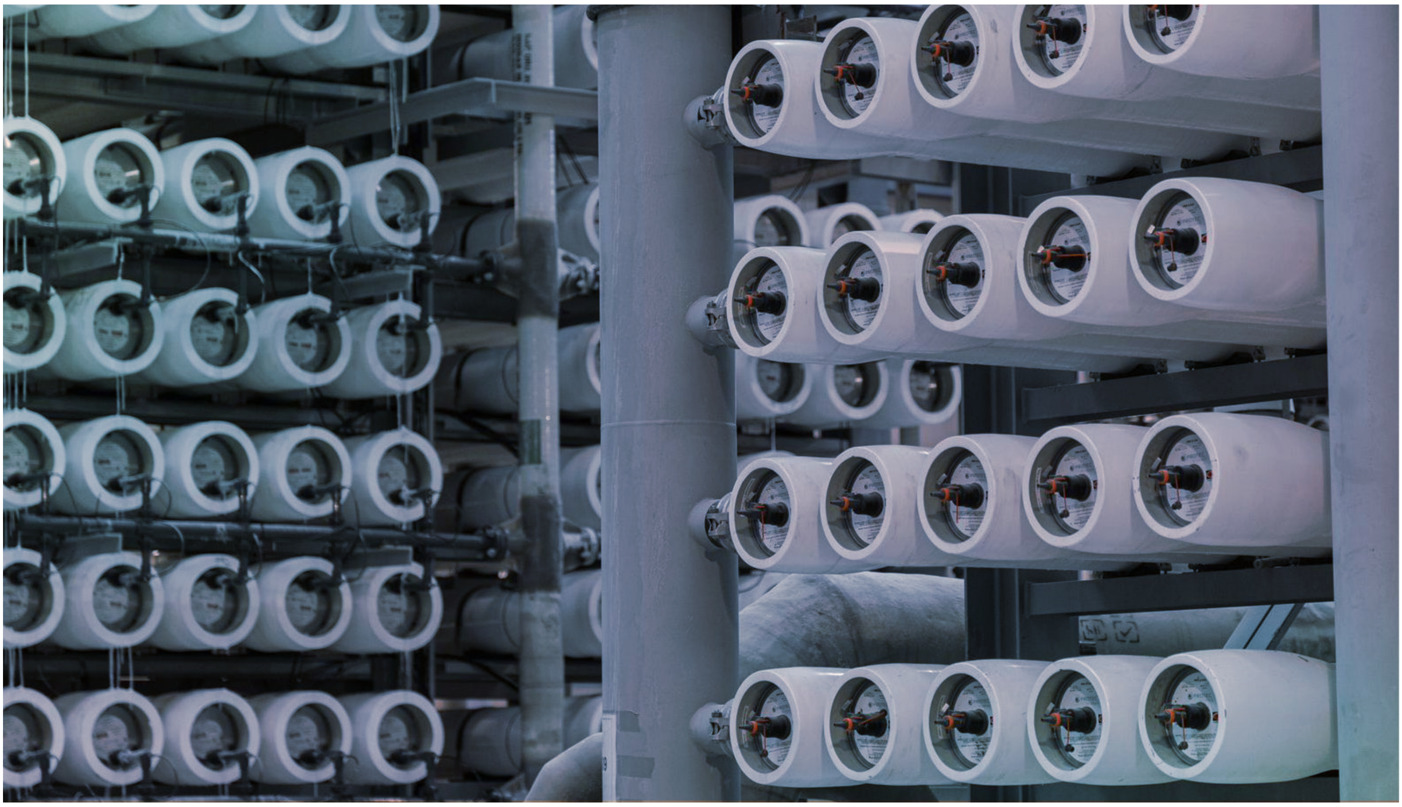
- In the mid-1900s, due to the challenges of pilgrims and Umrah performers from the lack of fresh water at their arrival in Jeddah, as the freshwater was barely sufficient for the inhabitants, ordered King Abdulaziz bin Abdulrahman Al Saud to import two large machines for distilling sea water to secure the water needs of pilgrims and Umrah performers, in addition to supplying the residents of the city Jeddah with water.

- The turning point was in 1974 when the royal decree was issued to establish The Saline Water Conversion Corporation (SWCC) so that the Corporation would undertake the construction and the operation of desalination and water transmissions.

- Starting from thermal technologies have five main stages: the intake via the source of water used for desalination; steam needed for evaporation of the source water; cooling water to condense the freshwater vapor generated from the source water's evaporation; low salinity distilled water (distillate); and concentrate (brine), which contains the salts and other impurities separated from the source water.

- In the 1978, the Kingdom adopted reverse osmosis desalination technology. A significant breakthrough in reverse osmosis desalination occurred in 1978 with the establishment of the world's most extensive seawater desalination system in Jeddah, Saudi Arabia. This momentous achievement served as a turning point in the field, highlighting the viability of reverse osmosis for large-scale freshwater production. The Jeddah plant deployed a newly developed membrane specifically engineered to withstand the high salinity of seawater. This pioneering accomplishment revolutionized the desalination landscape and paved the way for subsequent advancements in reverse osmosis technology.

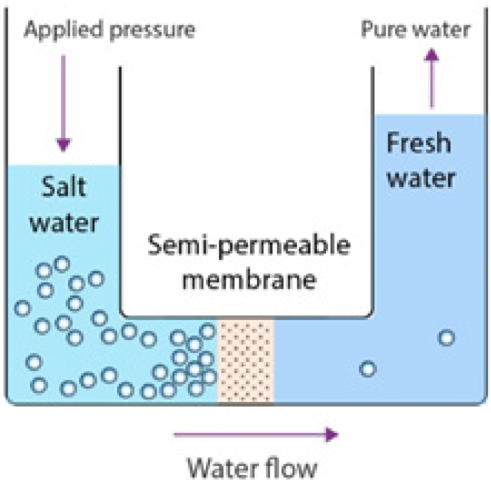
- Since then, reverse osmosis has become the most widely used desalination technology, providing drinking, industrial, and water for agricultural irrigation.



The Concept of Reverse Osmosis (RO)

Reverse osmosis (RO) is a water purification process that utilizes a semipermeable membrane to remove impurities and contaminants from water. This process is widely used in pharmaceuticals, food and beverage production, desalination plants, and households for water treatment.

The principle of reverse osmosis goes back to the natural process of osmosis process, which is the movement of water molecules from an area of low solute concentration to a place of high solute concentration across a semipermeable membrane.



In the case of reverse osmosis, however, the process is reversed. Water is moved from place of high solute concentration to an area of low solute concentration by applying pressure to the solution.

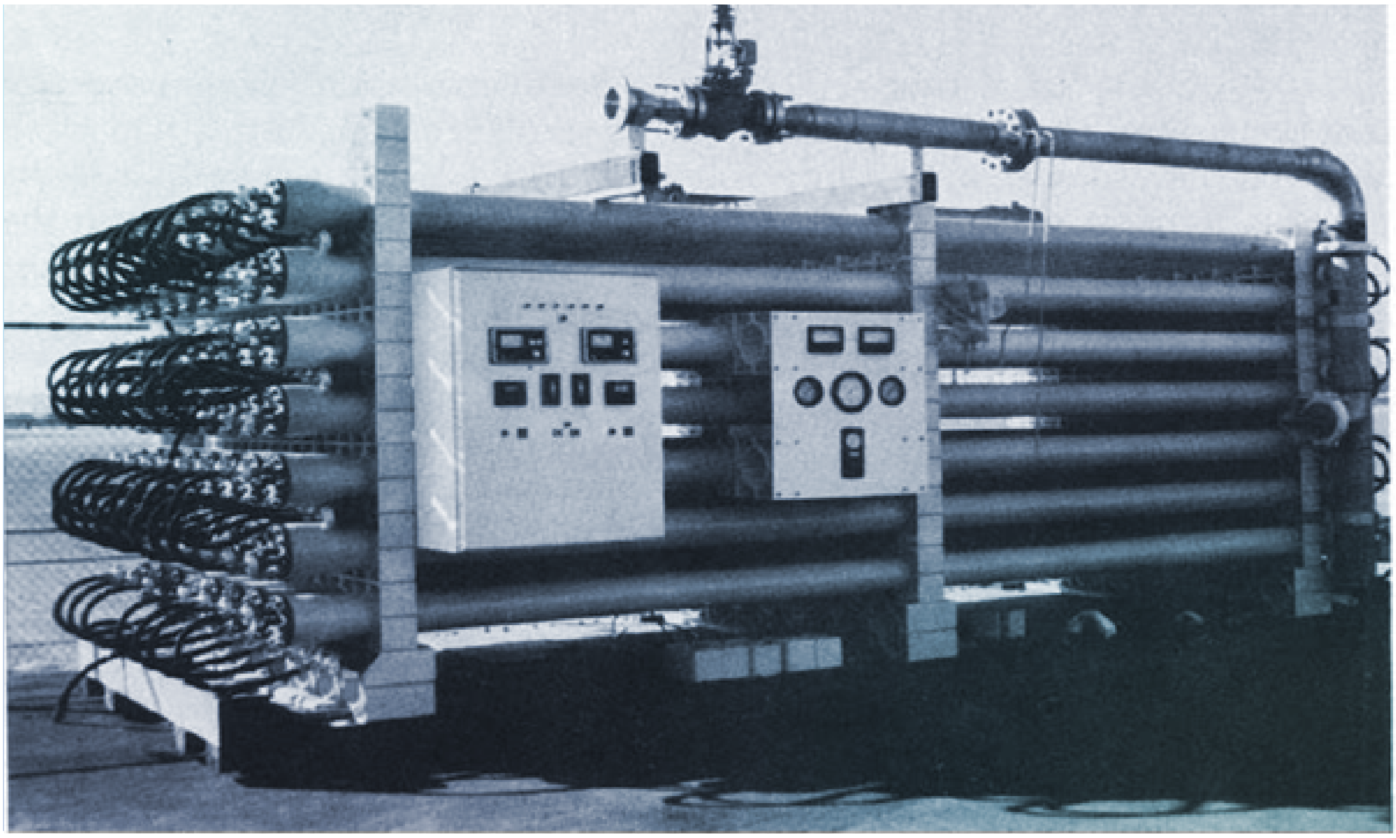
The RO unit consists of several components: a pre-filter, a semipermeable membrane, a post-filter, and a storage tank. The pre-filter removes large particles, such as sand and sediment, from the water. The semipermeable membrane is the heart of the RO system; There are two types of RO membrane material – Polyamide (PA) and Cellulose Acetate (CA). PA membranes are highly permeable but have zero chlorine tolerance; whereas CA membrane is low permeable but has a high tolerance to chlorine compared to PA. While both types of membranes have similar salt rejection. These membrane properties have immense effect on plant performance in production and fouling, particularly biological fouling. PA membrane is suitable for high production, while CA membrane is good for controlling biofouling. Nanofiltration is a low-pressure membrane with excellent rejection of divalent ions such as SO4, Ca, Mg, etc., as it selectively allows water molecules to pass through while blocking contaminants. The post-filter removes any remaining contamination from the water, such as odors and flavors. Finally, the purified water is stored in a tank until needed.

One of the main characteristics of reverse osmosis is that it produces high-quality water free from most contaminants and impurities. RO systems are highly effective at removing dissolved salts, such as sodium and chloride, from water, making them ideal for desalination plants. Additionally, RO systems are relatively easy to maintain and require minimal energy. [7]

The First World's Largest RO Plant in 1978

The Installation of a large reverse osmosis plant to desalt highly saline Red Sea water to supply municipal water needs at Jeddah, Saudi Arabia. The Saline Water Conversion Corporation (SWCC) of the Kingdom of Saudi Arabia awarded a competitively bid contract to the Fluid Systems Division of UOP Inc. for the design, fabrication, construction, and two years of operation and maintenance. The size of the first world's largest RO plant was (12,120) m3 /day.

The City of Jeddah, located on the Red Sea Coast, is the largest port and most important commercial center in the Western Region of the Kingdom of Saudi Arabia. It serves as the port of entry for the hundreds of thousands of pilgrims who annually visit Mecca from all over the world. The population was 1978 between 565,000-800,000.[8]



Source: SWCC Data, SWCC's paper published in the Elsevier Scientific Publishing Company,1978

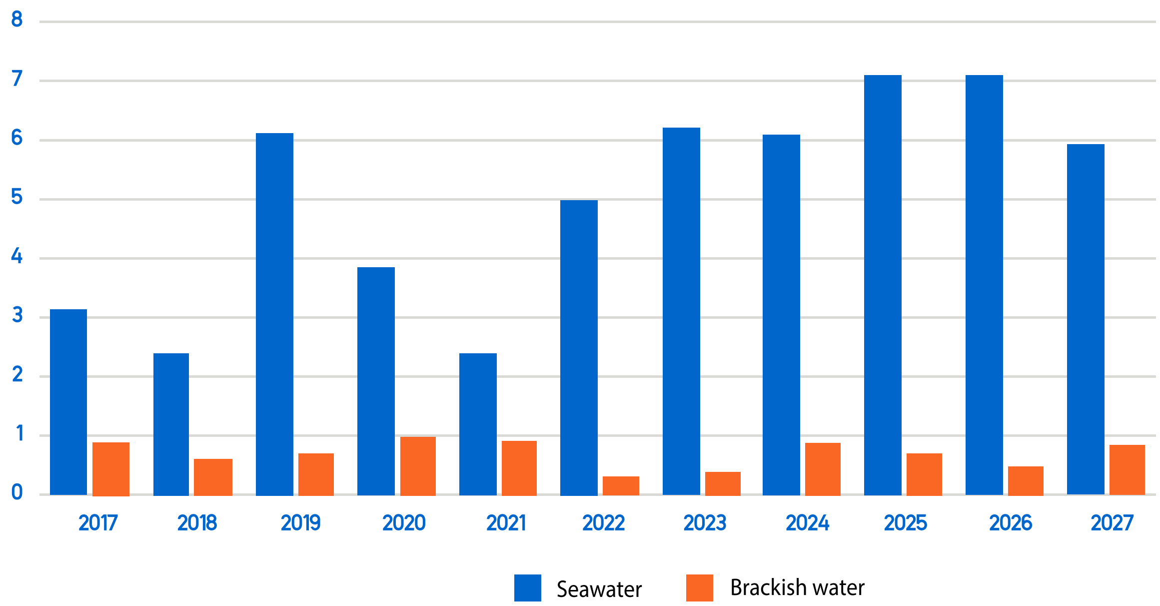
Desalination Industry Globally

Desalination Industry Globally

The Global Outlook of the Desalination

Desalination plants set up on the coasts produce fresh water from the sea for municipal or industrial uses. Desalination separates dissolved salts, creating fresh water from seawater or brackish water. (Water with a salt content of fewer than 10,000 milligrams per liter) or seawater (which generally has a salinity scope of 30,000 milligrams per liter to 50,000 milligrams per liter). Figure (2) shows the constructed seawater/brackish water desalination capacity 2017–2027.

Figure (2) shows the constructed seawater/brackish water desalination capacity (million m3/day) 2017–2027



Source: GWI DesalData

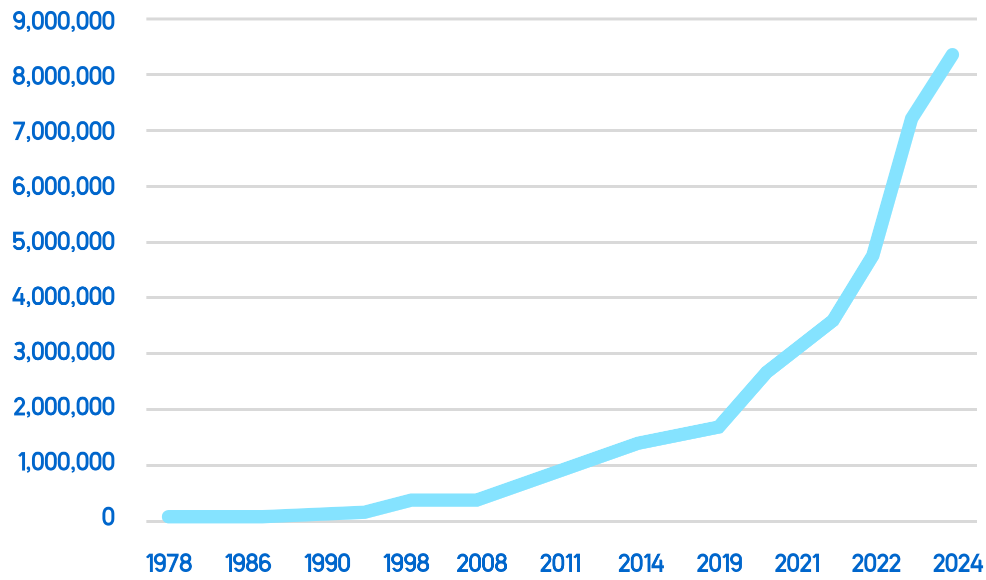
The Leading Role in the Field of Enabling RO Technologies

Desalination by reverse osmosis (RO) has emerged as a leading technology in addressing global water scarcity. RO desalination has revolutionized freshwater production from saline sources by utilizing a semi-permeable membrane to separate water molecules from salt molecules.

About 21,000 desalination plants operate worldwide, with over one hundred million cubic meters of production capacity daily. These plants are in 180 countries. Although brackish water and wastewater treatment methods offer immense potential for the future, seawater desalination is still the most widely used method.[9]

In the field of purification of Groundwater, the USA has initialized the development of groundwater management. On the other hand, Regarding the advancement in the desalination industry, KSA was the pioneer in this area. In terms of reverse osmosis, since 1978, KSA has been enabling reverse osmosis technologies by constructing large-scale desalination plants, dramatically impacting the desalination industry. Since the first RO plant was built by SWCC, it supported the fields of research and development by feeding them with the challenges and opportunities of this technology almost fifty years ago. Figure (3) illustrates the cumulative contracted capacity of reverse osmosis in KSA from 1978 to 2023.

Figure (3): cumulative contracted capacity of the reverse osmosis in KSA by the years 1978–2024



Source: SWCC Data

Table (1) shows SWCC's perseverance in enabling reverse osmosis since 1978 and endeavors to pioneer promising new mega plants under the making. This magnificent journey has numerous highlights. It started with the construction of the first largest reverse osmosis plant in 1978 and archived the world record in 2022 with a capacity of 630k m3/day. In addition to that, currently, the one million RO plant under construction due in 2024 will be the largest globally.

Table (1) The RO plants contracted in KSA, 1978–2024

Plant name	Owner	Year	Capacity (m3/day)	Remark
Jeddah	SWCC	1978	12,120	The first largest RO Plant in the world
Albirk	SWCC	1983	2,270	It has exceeded its lifespan. Due to its high level of maintenance. More than (30) years of operation.
Umluj 2	SWCC	1986	4,400	
Duba 3	SWCC	1989	4,400	
Jeddah RO1	SWCC	1989	56,800	The first large RO desalination plant feeds the distribution at a large scale to the users.
Haql 2	SWCC	1990	5,000	Exceeded its life span. Due to high-level maintenance. More than (30) years of operation
Jeddah RO2	SWCC	1994	56,800	Strengthening the production capacity in Jeddah.
Yanbu RO	SWCC	1998	127,800	The 1st Reverse osmosis plant uses the Hol- low-Fiber RO Membranes In the kingdom
Jubail RO1	SWCC	2000	90,909	The 1st Reverse osmosis plant in the eastern region of the Kingdom
Bwarj	SWCC	2008	50,000	Meeting the growing water demand, the flexibility of transporting desalinated water and the rapid response to emergencies
Shuqaiq 2	SWPC	2010	212,000	Supporting the entry of the private sector into the RO desalination plant industry
Shuaibah Expansion Project Co. (SEPCO)	SWPC	2011	150,000	
Jeddah RO3	SWCC	2013	240,000	The 1st RO plant that applies the energy recovery system

Plant name	Owner	Year	Capacity (m3/day)	Remark
Ras El Khair RO1	SWCC	2014	310,656	It is part of the largest desalination plant, which received a Guinness certificate as the largest desalination plant for water desalination and electricity production (dual purpose) worldwide. And the RO produces 30% of its production.
Haql Movable	SWCC	2018	5,000	The flexibility of transporting desalinated water and the rapid response to emergencies.
Duba Movable	SWCC	2018	5,000	
Alwajh Movable	SWCC	2018	5,000	
Yanbu Portable Unit	SWCC	2018	30,000	
Khafji 3	SWCC	2018	60,000	More than 50% if its production is from Renewable energy
Shuaibah II Water Development Project Co. (STPC)	SWPC	2019	250,000	Increasing the production of the desalination by private sector by almost 70%.
Duba Neom	Neom	2020	125,000	The important and supportive role in the strategic development expansion in NEOM, Saudi Arabia.
Khobar 4	SWCC	2020	210,000	It is the main input of water production and supply to the Aramco facility.
Haql 3	SWCC	2020	17,000	Reducing electricity consumption by (80%) and reaching it to less than (3) kilowatt-hours per cubic meter
Duba 4	SWCC	2020	17,000	
Alwajh 4	SWCC	2020	25,500	
Umluj 4	SWCC	2020	25,500	
Farasan 3	SWCC	2020	8,500	
Shuqaiq 4	SWCC	2020	42,500	Constructed in six months, it has (2.75) kWh/ m3
Shoaiba 4	SWCC	2020	400,000	The First desalination plant using nanotechnology. To produce magnesium in water to raise quality and promote health

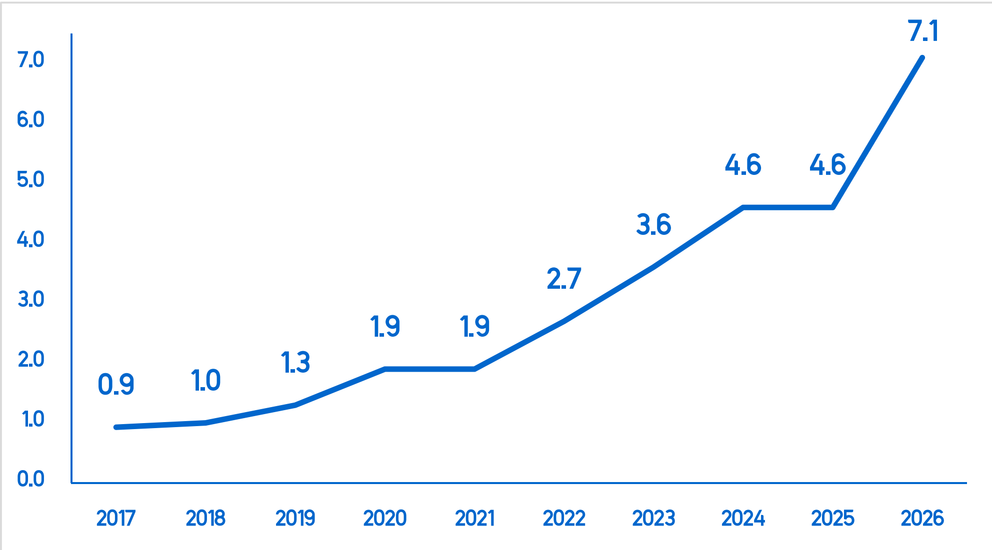
Plant name	Owner	Year	Capacity (m3/day)	Millstones achievements
Al-Gunfudha 2	SWCC	2021	51,000	Controlling the interaction with circuit breaker by racking- in and racking - out of medium voltage remotely 6.6kv
Allith 2	SWCC	2021	42,500	Reducing electricity consumption by (80%) and reaching it to less than (3) kilowatt-hours per cubic meter
Shuqaiq 3	SWPC	2021	450,000	Increasing the contribution of the private sector involvement by adding almost (1) M m3/day in 2021
Rabigh 3	SWPC	2021	600,000	
Jubail RO2	SWCC	2022	400,000	Replacing the MSF plant and reducing (2.22) M mt of CO2 emissions annually
Khobar RO2	SWCC	2022	630 ,000	New record of the largest RO plant in 2022
Bwarj Jazan	SWCC	2023	150,000	The floating desalination plants on the western coast of Saudi Arabia are the largest and aim to enhance water security in all regions of Saudi Arabia
Jubail 3A	SWPC	2023	600,000	Increasing the contribution of the private sector involvement by adding more than (1.6) M m3/day up to 2024
Jubail 3B	SWPC	UNDER CONSTRUCTION	570,000	
Rays 1 (Yanbu4)	SWPC	UNDER CONSTRUCTION	450,000	
Shoaiba 5	SWCC	UNDER CONSTRUCTION	600,000	Reducing the cost of producing a cubic meter of desalinated water to 1.27 riyals, and reducing electricity consumption to less than 2.75 kilowatt-hours per cubic meter
Shuqaiq 5	SWCC	UNDER CONSTRUCTION	400,000	Replacing the MSF plant and reducing (1.23) M mt of CO2 emissions annually
Jubail2 RO Replacement	SWCC	UNDER CONSTRUCTION	1,000,000	This plant will be the largest reverse osmosis technology, and the least energy consumption (2.7 kWh / m3), and by employing alternative energy the consumption rate will be (2.2 kWh / m3).

Source: SWCC Data , NOTE: SWPC Stands for Saudi Water Partnership Company

Globally, SWCC is considered the largest water producer facility in the world. Each day, it produces more than 11.5 million m3/day of desalinated and purified water. The Purification plants also relies on RO technologies; that have reduced power consumption due it is low level of salinity. The aim is to supply Saudi Arabia's cities and regions, especially during the high demand for fresh water in holy cities during pilgrimage and Umrah seasons, in Makkah and Al-Madinah. To sustain reliable production, SWCC has been able to lead innovative initiatives and adopt innovative operational practices.[10]

An immediate response to strategic change and the variety of domestic and international changes in the water sector pave the way for a new era in the water sector. SWCC has taken another step toward achieving the goals of Saudi Vision 2030, Water National Strategy, and National Transformation Program. SWCC aspires to make rapid progress toward technological development as a core value in planning and execution, and the Water Technologies Innovation Institute & Research Advancements (WTIIRA) plays a significant role in that.

Figure (4) SWCC's Seawater RO production capacity million (m3/day)



Source: SWCC Data

SWCC has been increasing the use of environmentally friendly technologies plants and infrastructure, thereby reducing environmental pollution and carbon emissions. Figure (4) shows the total seawater RO production capacity from 2017 to 2026.Also, SWCC is expanding opportunities for domestic economic growth through products such as seawater mineralization and reverse osmosis membranes recycling. Desalination plants, for instance, are being utilized to their full potential.

The Environmental Impact

Transitioning to Environmentally Friendly RO Technology

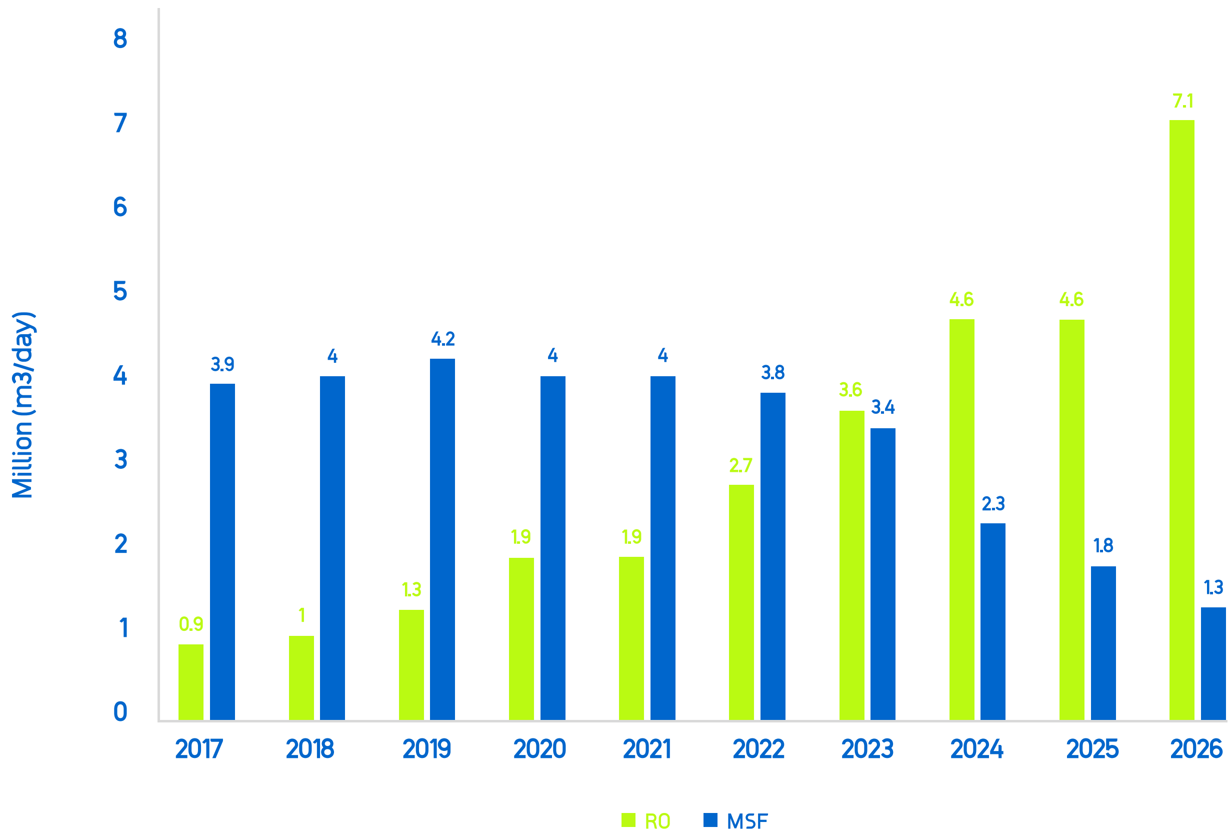
> With lower and more efficient energy-consuming RO technology, SWCC gradually replaces conventional, energy-intensive MSF and MED technologies. Further, the plants will be supplied with electricity from sources that reach almost 50% efficiency for the combined cycle power systems, and there are plans for capturing and reusing energy.

This switch reduces the energy consumption per cubic meter of potable water generated from 15 kWh/m3 to less than 3 kWh/m3—an 80% reduction.

SWCC is making swift progress in the replacement. To date, eight of the thirteen thermal desalination plants— which together produce 94% of the water from thermal desalination plants—are either already replaced with RO or currently under construction and scheduled to be completed by, at the latest, 2024. The largest plants include Jubail (one million m3/day), Khobar Phase 2 (630K m3/day), and Shuqaiq Phase 1 (600K m3/day). [11] In addition, there are plans to replace three further plants from MSF to RO and replace an old RO plant with a more efficient one by 2026, which will contribute to achieving more than 37 million metric tons of annual reduction of CO2 emissions.

Figure (5) shows the Transitioning quantities to clean desalination technologies from 2017 to 2026

Figure (5): Transitioning to clean desalination technologies (2017-2026)



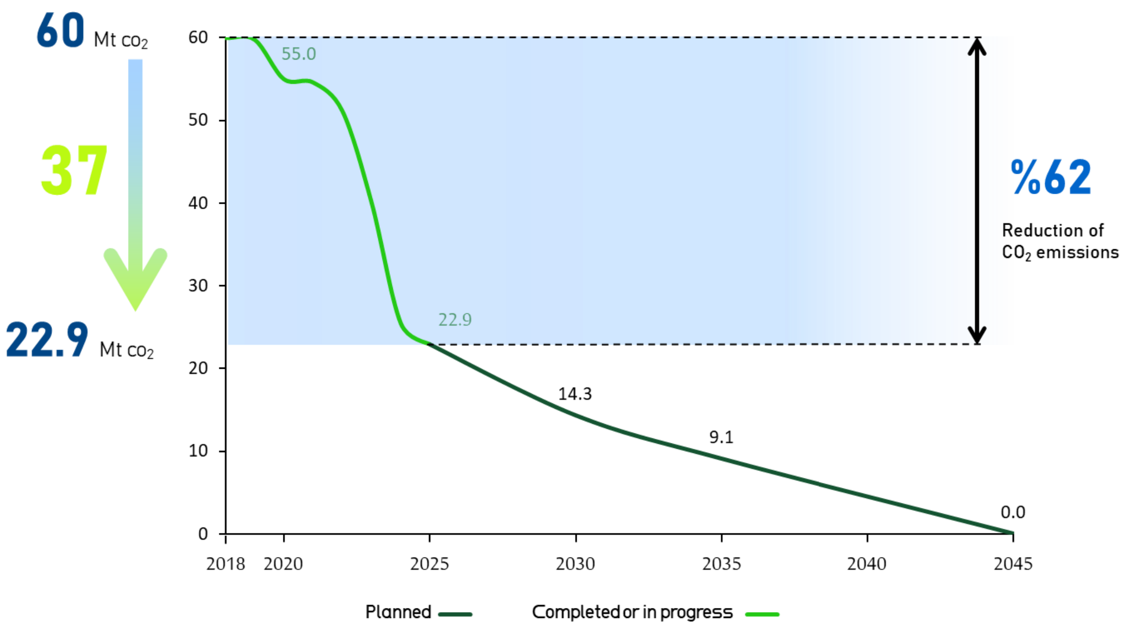
Source: SWCC Data

The Environmental Impact of the RO Desalination Industry

(SWCC) is committed to the Kingdom's ambitious objectives to reduce CO2 emissions to zero by 2060 and has developed an initiative to achieve net-zero carbon emissions. SWCC, responsible for desalination, has planned to be influential in achieving the Kingdom's climate change commitments within Vision 2030.

SWCC estimated that the starting point of total emissions from the production system is 60 MT CO2e annually. By 2025, around 62% of emissions will be reduced, while the remaining 38% is planned to be managed by 2045.

SWCC'S plan to reduce carbon emissions Million Metric Tons of CO2 (2018-2045)



Source: SWCC Data

The Future of Reverse Osmosis Desalination

The Future of Reverse Osmosis Desalination

Global Aspiration in the Fields of Research, Development and Innovation in RO

Reverse osmosis desalination is expected to grow and be essential in addressing global water challenges. The future of reverse osmosis desalination holds several promising developments.

In this section, we share the outlook of different partners in the research and development of RO desalination. Global Water Intelligence (GWI) and the International Desalination Association (IDA), in partnership with the Global Water Leaders Group, publish the IDA Desalination & Reuse Handbook.

> This non-profit organization facilitates communication and knowledge-sharing between utilities. One of the great quotes of the handbook calls the new way of desalination a "smart desalination,"

And according to the researchers, Reverse osmosis is heading to a world of digitalization and the process of developing, promoting and mandating standards-based and compatible technologies and procedures within the industry of RO.

In addition, Remote monitoring, predictive maintenance, and optimization of the production are the central core of the stakeholder's interests. This partnership leverages the expertise and extensive experience in desalination to supply clients with reliable, modern, and efficient plants.[12]

SWCCs Ambition in the RO Technology

Technological Innovations:

Continuous research and development efforts focus on improving membrane efficiency, exploring novel materials, and advancing energy recovery systems. These innovations aim to enhance system performance, reduce costs, and increase sustainability.

Seawater Reverse Osmosis (SWRO) Pretreatment Enhancement:

Ras Al Khair desalination plant is hybrid MSF and SWRO desalination plant. It consists of eight units of MSF evaporator units and two SWRO processes lines. In the SWRO process, a hollow fine fiber membrane was adopted. And it's required that the feed seawater pH is 6.4. To adjust feed seawater pH, sulfuric acid was dosed before the DAF system. Each MSF evaporator has a venting system to remove non-condensable gases, including CO2, air, and vapor. At present, part of non-condensable gases is used in the post-treatment system.

And the other is vented into the air. Vented non-condensable gases will be supplied to the DAF system. If CO2 is dissolved to feed water, feed water pH decreases. Then, sulfuric acid for pH adjustment can be eliminated. By eliminating sulfuric acid, we can save 1.1 M USD per annum. And by stopping the DAF air compressors and sulfuric acid dosing pumps, 0.3 M USD of energy cost can reduce (annually). DMF media depth increase in Ras Al Khair SWRO plant- another project developed to enhance the current pretreatment of SWRO.

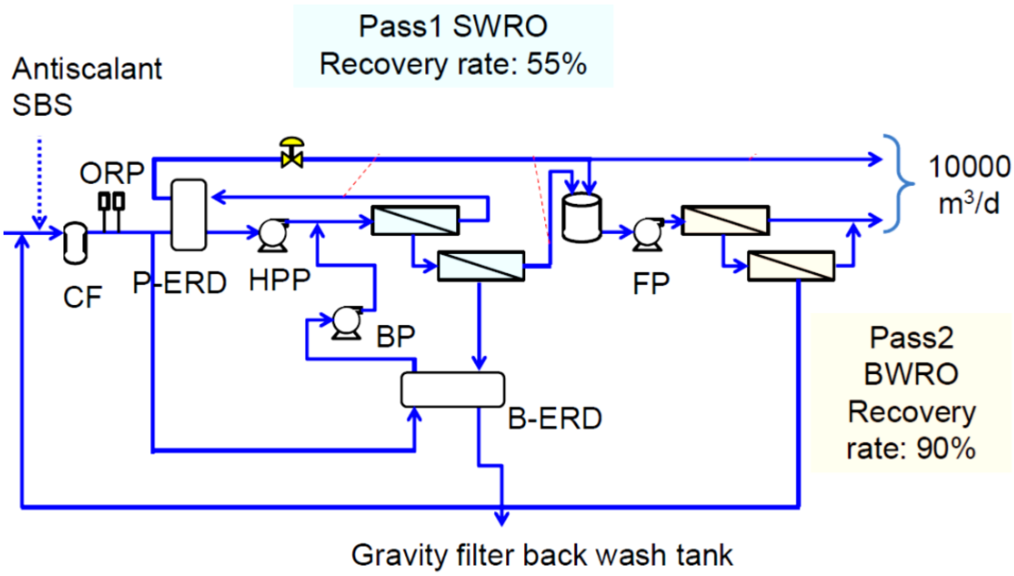
During the summer in the Arabian gulf sea, colloidal matter in raw seawater has increased. At the time, most pretreatment processes at the time suffered high Silt Density Index (SDI) values. It increases the differential pressures of the cartridge filter and RO membrane. Water demand in Ras Al Khair has been increasing, so, an extension project has been initiated for additional water production. Solid loading rate shows the relation between the TSS of seawater, TSS of coagulant, feed flow rate, filter run time, and media volume. Feed flow per filter or filter run time can be improved if media volume increases. SDI will decrease, and filter runtime will increase. If the feed flow rate increases, 20,000 m3/day of water production can be increased.

Megaton Project:

SWCC has constructed a plant with a unique technical approach reaching a 55% of recovery on the 1st pass and 90% recovery on the 2nd pass of a reverse osmosis system to develop an innovative design and membrane to reduce the operating cost and have an efficient system of the overall plant.

The system has been demonstrated to reach stable normalized DP for the proposed SWRO system with increased permeate flow, considering a continuous steady-state operation. At the same time, developing SWRO membranes for the piloted project is a crucial success factor in achieving the targeted water quality with an energy consumption of (2.48 kWh/ m3).

SWCC'S plan to reduce carbon emissions by Million Metric Tons of CO2 (2018-2045)

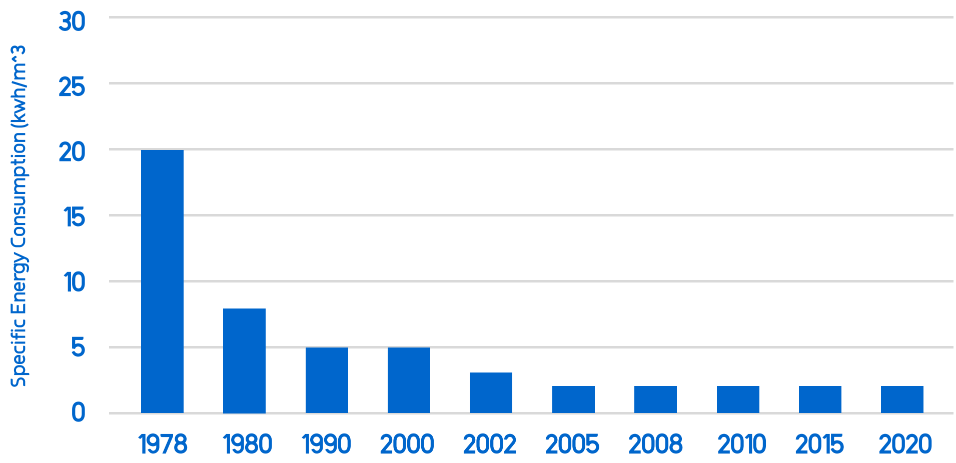


Source: SWCC Data

Energy Recovery System:

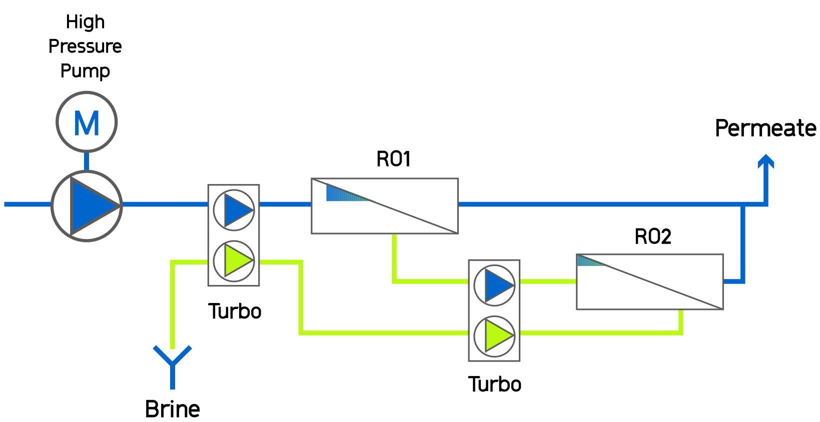
The Energy Recovery Device (ERD) system reuses the pressure energy of the RO concentrate to pressurize the feed water, significantly reducing the energy consumption of RO plants. Due to its importance in achieving carbon-neutral desalination, WTIIRA-SWCC has been actively involved in various ERD development projects, including pilot and commercial scale tests and evaluations. Recent international partners include the Megaton project team and a U.S. company, targeting a remarkably high recovery of 55~60% with new isobaric and turbocharger ERDs. The new isobaric brine-ERD demonstrated a world top-class efficiency of 98.9~99.5% in its 10,000 m3/day commercial plant in Duba, Saudi Arabia. The new turbocharger ERD configuration aims to maximize the recovery (60%) for later use of concentrate (~110,000 mg/L) in brine mining at a competitive SEC (2.6~3.1 kWh/ m3) in the RO island. The new turbo-based ERD is a Bi-turbo configurated into a single SWRO 1st pass, with lower flux that aims to prolong the membrane's age and further reduce the power consumption of the RO system to (~ 2.1 kWh/m3).

Falling SEC of SWRO



Source: Kumar et al

BiTurb



Source: SWCC data

Forward Osmosis (FO):

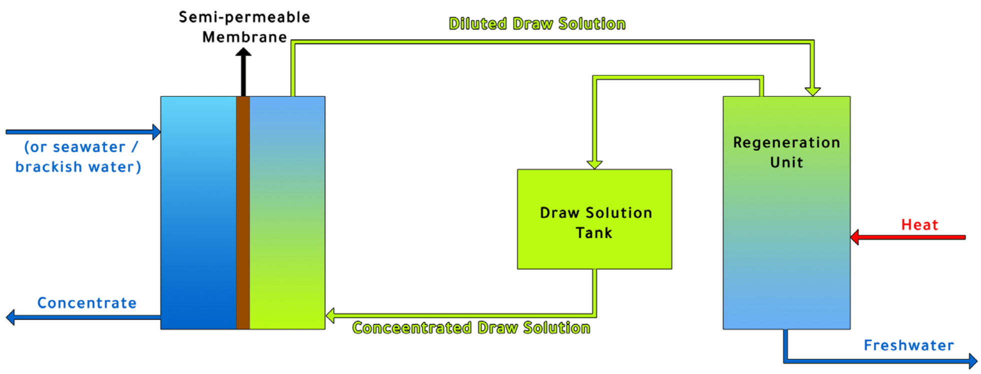
Forward osmosis is a promising water treatment technology with substantial potential in various industrial applications. While it faces specific challenges, ongoing research, and recent developments drive progress in membrane development, draw solution innovations, and system optimization.

With continued advancements and collaborative efforts, FO can play a significant role in addressing global water scarcity and environmental challenges. So, SWCC is currently conducting different research studies to explore the possibilities of using FO.

This project aims to couple different solar collector units with FO units in the Jubail pilot plant to find the best coupling way and testing FO process, which can lead to the best renewable desalination and evaluate solar system efficiency and reliability.

The validation of the integrated system will be measured as a comparison between actual reading and analysis compared with current desalination technology RO and the operation of the FO with solar energy with storage and without storage. . Another potential area could be considered for FO applications to be used after crystallization unit for mineral recovery and freshwater production.

FO Conceptual Design



Source: Waterwhelm

Decentralized Desalination:

The advent of smaller, modular reverse osmosis systems allows for decentralized desalination, catering to specific regional or local water needs. This approach enables more efficient water supply systems and reduces reliance on extensive infrastructure.

Renewable energy-driven reverse osmosis:

Desalination offers a promising solution to mitigate the carbon footprint associated with fossil fuel- based energy sources. Utilizing renewable energy, such as solar, wind, or geothermal power, to drive RO desalination plants reduces greenhouse gas emissions and promotes sustainable water production. Integrating renewable energy sources with RO technology enables clean freshwater production while minimizing environmental impact, contributing to a more sustainable and resilient water supply. SWCC is currently studying the feasibility of exploring high-capacity factor (CF) wind power for areas with moderate wind power density. This project aims to produce fresh water and green hydrogen from wind systems. The economics of a green hydrogen system driven by a 100 MW wind park will be highlighted. Hybrid Photovoltaic (PV) and wind power is another project to synchronize PV and Wind to produce higher capacity factor renewable energy (500 kW PV + 1000 kW Wind). Engage Renewable energy to operate the HP pump motor (1050 kW) of the SWRO plant. And to establish a renewable electricity feeding configuration to increase renewable penetration rate (Renewable electricity+ Supplemented by existing electricity feeder).

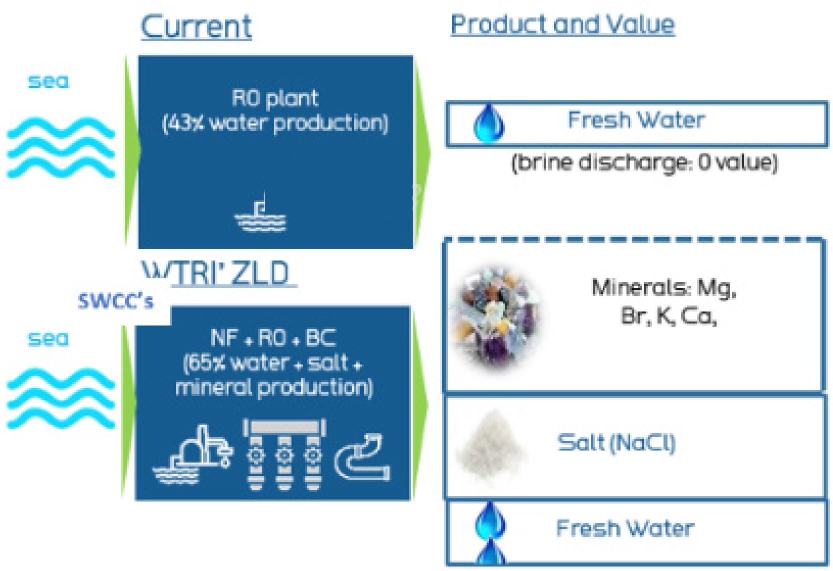
Source: SWCC data

Graphene oxide (GO):

shows promise for desalination with exceptional properties like high strength, stability, and water permeability. Its unique structure rejects salt ions, allowing rapid water transport and enhancing desalination performance. The tunable surface chemistry enables selective ion transport, further improving capabilities. These results highlight GO's potential to revolutionize desalination for a sustainable and efficient solution to global water scarcity.

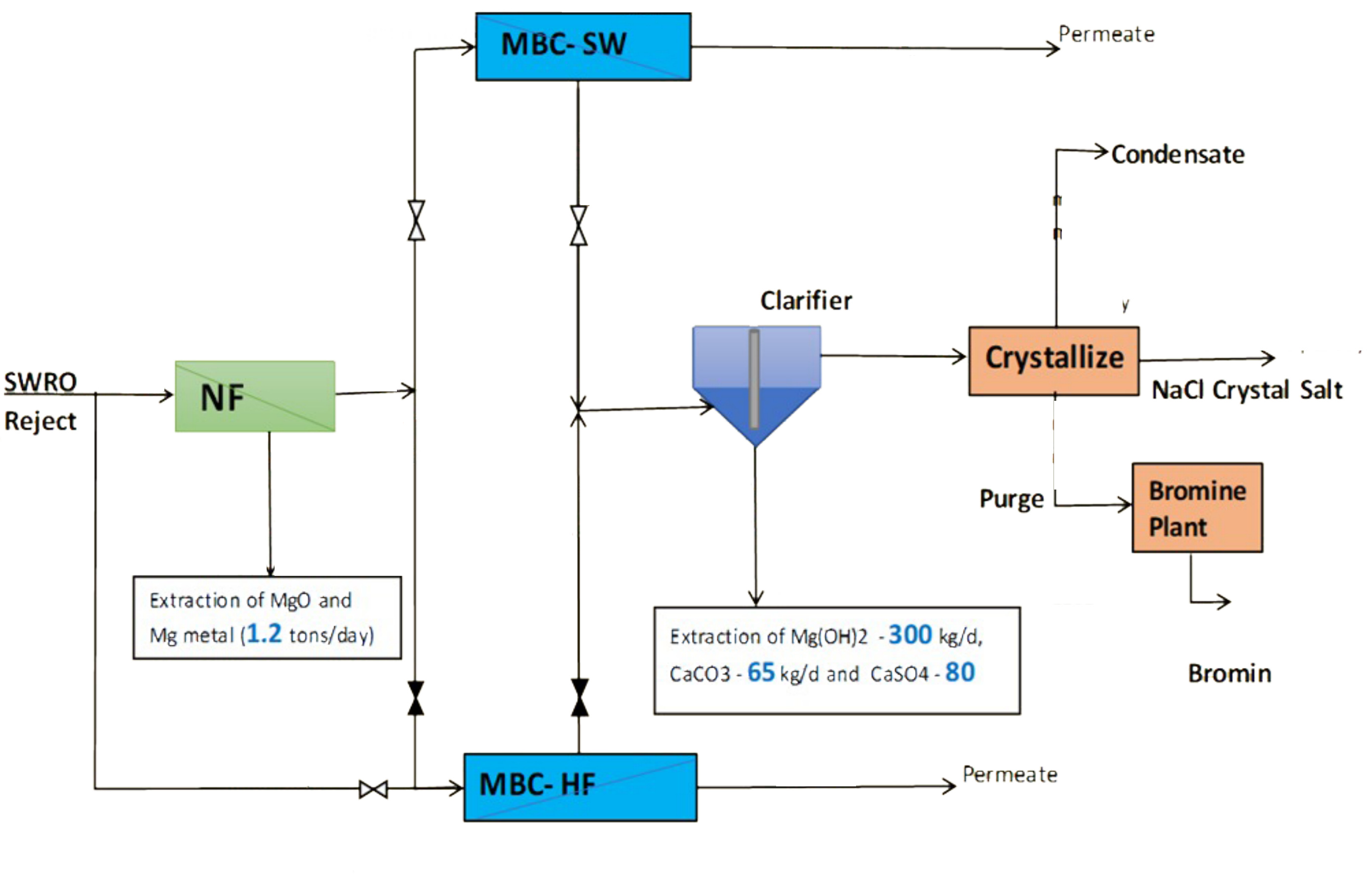
Brine mining:

SWCC is heading toward investing in brine from desalination processes in all its plants.[13] Given the high concentrations of salts and minerals, brine mining is considered a valuable investment opportunity. Brine mining shows promise in desalination, addressing environmental concerns and providing economic benefits. It reduces concentrated brine volume, mitigating its environmental impact as a by-product of desalination. Additionally, recovering valuable minerals offers resource conservation and economic value. Brine mining's potential as a sustainable and efficient desalination solution highlights its contribution to freshwater preservation and a circular economy. SWCC is demonstrating the Zero Liquid Discharge (ZLD) plant which aims to extract valuable salts and minerals from brine and increase freshwater recovery by up to 65%. This technology is distinguished for being environment-friendly and contributing to developing local content and industry following the kingdom's 2030 vision. SWCC is demonstrating the Zero Liquid Discharge (ZLD) plant. A portion of the brine stream (about <1%) from one of SWRO desalination plant will be directed to the ZLD Plant equipped with a nanofiltration (NF) system, membrane brine concentration, crystallizer and a bro-mine extraction process. The NF system can be operated at a recovery of 70% producing permeate with low content of calcium and sulfate. The permeate will be fed to MBC system for further concentration. The brine generated from the NF system will be treated with NaOH or lime in a small clarifier and the sludge from clarifier will be centrifuged to produce CaSO4 and Mg(OH)2 solid for further processing to produce metallic magnesium solid. ZLD plant is aimed to produce sodium chloride, magnesium metal and bromine.



Source: SWCC data

SWCC successfully built a pilot plant crystallization unit. Various operational modes of the pilot Crystallizer were conducted to study the quality of NaCl crystal salt. The performances of NF ion rejection, OARO concentration, and clarifier were carefully studied in connection to the final NaCl salt quality.[14] Magnesium is one of the most abundant minerals dissolved in seawater. In 2019, SWCC-DTRI developed a patented technology that uses a multiple-stage Nano-Filtration (NF) membrane system. With this technology, Magnesium, and calcium (healthy minerals) can be efficiently extracted from seawater while minimizing unnecessary sodium and chloride. The concept was demonstrated in the SWCC-DTRI pilot plant in Jubail. Shoaibah plant was selected to construct the world's first multi-stage NF system with inter-stage dilution (NF-Mg plant). After awarding the project in May 2021 and starting site works in July 2021, the first Mg- enriched brine was produced in Mar. 2022, and the Shoiabah NF-Mg plant has been in total production of Mg-rich brine from seawater since May 2022. The produced Mg-rich brine is mixed with 400,000 m3/day of product water in Shoaibah Phase 4 to make its Mg ≥ 15ppm, serving about 1.3 million people (about the population of New Hampshire) people with healthy Mg-enriched water.



Source: SWCC data

Subsea Desalination Technology:

WTIIRA-SWCC is making significant strides in developing a ground-breaking subsea desalination plant. It all begins with a prototype system that will demonstrate the effectiveness of subsea desalination and pave the way for constructing several complete independent plants, each with a capacity of 50,000 m3/day. The primary objective of this ambitious project is to harness the hydrostatic head at depth, thereby enhancing the overall energy efficiency of the SWRO process.

Beyond its energy efficiency goals, this project serves another crucial purpose: highlighting the strategic production of water at specific depths. This approach provides a diversified water production source during emergencies and conflicts, ensuring water availability even in the most challenging situations.

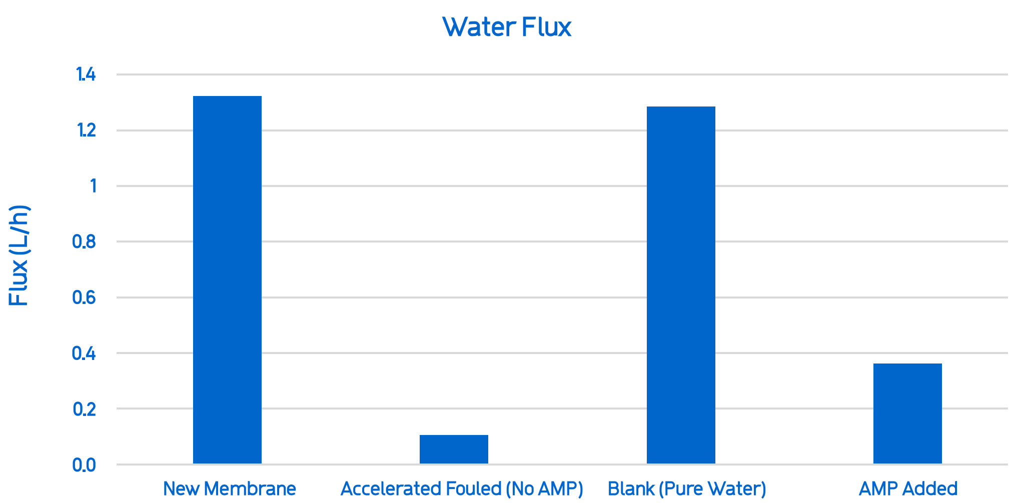
The subsea desalination unit is designed with a strong emphasis on cost-effectiveness and environmental responsibility. It comprises simple feed and permeate pumps and pressure vessels containing SWRO membranes and cartridge filters. Notably, this unit stands apart from terrestrial SWRO plants as it eliminates the need for chemicals and conventional pretreatment, owing to the improved seawater quality found at subsea depths ranging from 300 to 500 meters.

Source: SWCC data

Anti-fouling reverse osmosis (AF-RO), membranes:
show promising results in desalination by combating fouling challenges. These membranes incorporate surface modifications to minimize foulant accumulation, ensuring sustained performance, reducing cleaning needs, and extending lifespan. AF-RO membranes enhance operational efficiency, productivity, and cost-effectiveness in desalination. They offer a viable solution for sustainable production of clean water. The membrane surface can be treated with anti-fouling materials, such as hydrophilic substances, either through coating or grafting techniques (e.g., zwitterions).

Closed circuit reverse osmosis (CC-RO) and flow reversal reverse osmosis (FR-RO) are innovative approaches that show promising results in desalination. CC-RO involves recirculating the reject stream back to the feed side of the membrane, maximizing water recovery, and reducing waste. However, FR-RO periodically changes the flow direction during the filtration process, minimizing fouling and enhancing membrane performance. These techniques offer potential advancements in desalination efficiency, water recovery, and cost-effectiveness, contributing to sustainable freshwater production.

Anti-Microbial Peptide (AMP) For Membrane Biofouling Control:
Membrane biofouling is one of the main challenges of the seawater RO desalination process, which can cause up to 24% of the SWRO OPEX. To limit biofouling Chemical biocides are intensively used for biofouling prevention and membrane cleaning to limit biofouling. However, the usage of chemical biocides is expensive and not environmentally friendly. Considering the green initiative of Saudi Arabia, it is necessary to develop an alternative membrane biofouling control strategy. Natural anti-microbial peptide (AMP) is an excellent potential membrane biofouling control substance that is naturally released from the inner immune system of microorganisms during their growth. These peptides can physically penetrate the bacteria cells, thus destroying them and limiting the consequent biofilm formation on SWRO membranes. By harvesting the AMP from bacteria, it has been shown that AMP could reduce 80% membrane biofouling in wastewater treatment using FO membranes. This project is to evaluate the effectiveness of AMP on SWRO membrane biofouling control. And the preliminary evaluation on seawater treatment has shown that the AMP could also reduce up to 50% flux decline caused by the biofilm formation of spiked marine yeast.



Source: SWCC data

Clean-In-Place System for The Cartridge Filters In SWRO:

The cartridge filters (CF) system, a critical part of the pretreatment system for the SWRO desalination plants, is usually replaced every three months due to contamination of the suspended solids and other contaminants from the seawater. In addition, ferric chloride, which is used in the DMF to coagulate the contaminants, is usually accumulated in the CF. As a result, the flow rate decreases, and the pressure differential increases, drastically decreasing performance. This practice is costly and leaves a tremendous amount of waste; for instance, one of the plants of the SWCC on the Eastern coast of Saudi Arabia is replacing 52,204 filters annually with a total cost of 802,636 SAR. Therefore, WTIIRA-SWCC initiated a chemical cleaning system to increase the lifetime of the CF and minimize the replacement cost. A chemical cleaning system was installed on one of the SWCC plants. HCl acid was added to the design and mixed with service water for a pH range of 2.5 to 3.5. Then, the solution was pumped to wash the existing cartridge filter vessel in the SWRO and returned to the system a few times. The answer will be soaked in the CF vessel for one day at the final stage before flushing and returning to the service. After implementing the CIP system in a large-scale desalination plant, the following outcomes were achieved: The lifetime of the CF elements increased by 51% & the amount of filtered water increased by 42%.

Alternative Approaches to Membrane-Based Seawater Desalination:

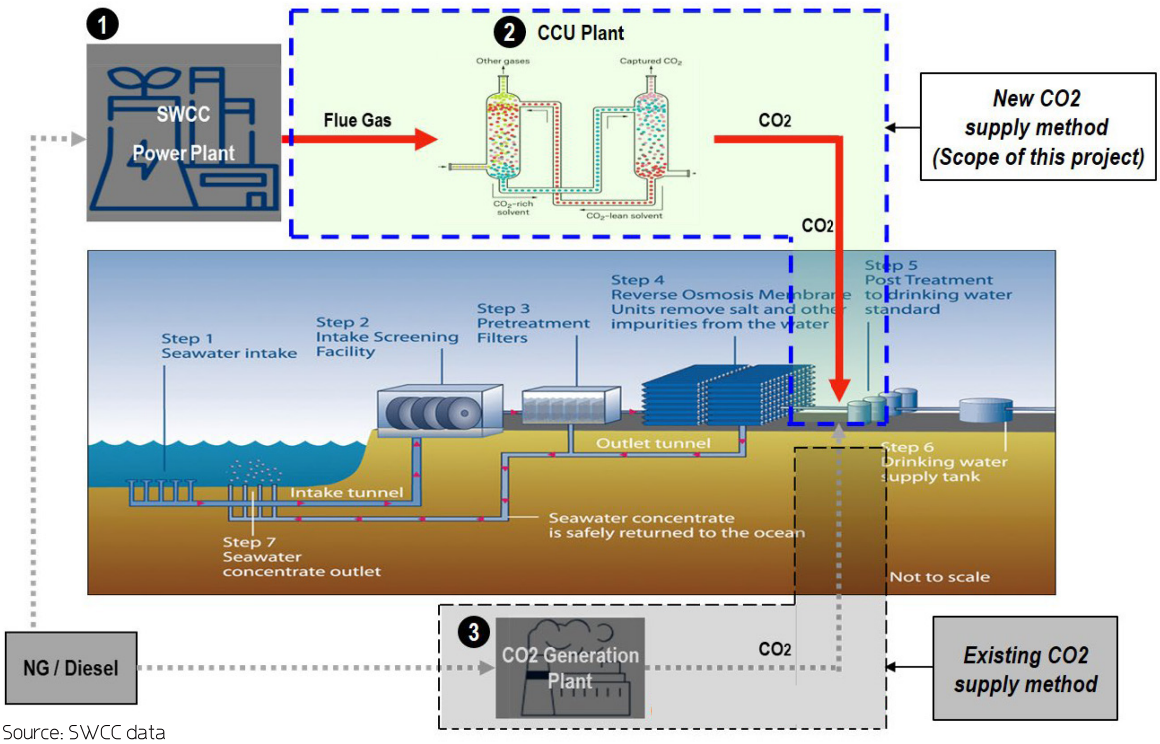
Electrodialysis (ED) desalination, membrane distillation (MD) desalination, and forward osmosis (FO) desalination are emerging techniques that hold promising results in the field of desalination. ED desalination utilizes an electric field to separate salt ions from water, offering high efficiency and low energy consumption. MD desalination employs a hydrophobic membrane to separate freshwater from saltwater using the Vapor pressure difference, enabling effective salt rejection and resilience to foul. FO desalination leverages the osmotic gradient across a semi-permeable membrane to draw freshwater through while leaving behind salts. These techniques demonstrate the potential to improve desalination efficiency, reduce energy requirements, and expand access to clean water resources.

Carbon Capture Storage and Reuse Using Algae (CCS-R):

Carbon dioxide, with the longest atmospheric residency time, accounts for almost 76% of all greenhouse gas emissions, which is the cause of global warming. Although SWRO is not directly involved in greenhouse gas emissions (through fossil fuel combustion processes), using electricity to run the technology ascribes an energy consumption carbon footprint. Therefore, SWCC has strategically considered this reality and is exploring innovative carbon capture and sequester technologies. Algae is the most efficient, least energy-intensive carbon capture and storage green solution to Carbon Capture and Sequester (CCS) challenges.

In addition, the oils, proteins, and sugars potentially produced from algae have economic value for the biofuel, food, pharmaceutical, cosmetic, dye, animal and fish feed, fuel, and probiotic industries. Microalgae are cultivated photosynthetically, consuming sunlight, CO2, and nutrients and producing oxygen, oils, proteins, sugars, etc. In addition to CO2 sequestering, the generated organic waste from desalination plants could be biodegraded and converted to biomethane under anaerobic conditions. Microalgae cultivation could absorb the cogenerated CO2 from bio-methane production without CO2 emission. Literature reviews of related research and studies have been finished, and a novel CO2 sequestering concept utilizing anaerobic digestion and microalgae cultivation aiming at CO2 sequestering and waste disposal within desalination plants have been developed.

Demonstration of carbon capture system with high-efficiency amine solvent and development of 'carbon to x' conversion process. In desalination processes, carbon dioxide is used in the post-treatment system to remineralize product water by dissolving calcium carbonate. The carbon dioxide was captured from the venting in the vacuum system of thermal desalination units. However, as thermal processes are phasing out, it is now generated by firing fossil fuels. The carbon footprint to generate carbon dioxide can be offset when the same amount of carbon dioxide is captured from the flue gas of the thermal power plant and sequestered in the SWRO process. The idea is to capture carbon dioxide in one of the thermal power plants using high-efficiency amine solvent and distribute captured carbon dioxide to the SWRO plant to avoid burning fossil fuels to generate carbon dioxide. • It is estimated that CO2 consumption in SWRO would reach 200 ~ 400 tons per day. If this amount of CO2 is captured in the thermal power plant and utilized in SWRO plants, it is equivalent to substituting 75 ~ 150 liter (about 39.63 gal) of diesel consumption every day, 27,375



Source: SWCC data

Conclusion

Reverse osmosis (RO) desalination has transformed freshwater production, combating global water scarcity as the leading technology. With over 21,000 plants operating worldwide, RO desalination is the most widely used method, providing water for drinking, industry, and irrigation in 180 countries. This report comprehensively overviews its history, advancements, and prospects.

Despite alternatives, seawater desalination via RO remains dominant and forward-looking. Innovations in membranes, energy recovery, hybrids, and materials like graphene oxide enhance performance, water recovery, energy efficiency, and sustainability.

Though challenges persist, ongoing research optimizes RO desalination, with prospects in decentralized systems, renewable energy integration, closed circuits, anti-fouling membranes, and alternative techniques. RO desalination has transformed freshwater production and will continue to address water scarcity through research, technological advancements, and sustainable practices.

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