
DEDICATION

"Let us give to Caesar what belongs to Caesar"

I dedicate this work to all the people who have touched my life. To the heroine of my life, the one who gave me life and raised me. I am deeply grateful to my mother, whose unconditional love, unwavering support, and unwavering faith in me have guided and inspired me throughout this journey. She is the embodiment of my life, my source of inspiration, and the source of my pride. My father suffered and sacrificed so much so that I could be happy. To all my brothers and sisters, thank you for your support; you are my joy in life. I am deeply grateful to my grandmother for their boundless love and the priceless memories they have bestowed upon me. You are the roots of my strength and the wings of my inspiration. To my aunt Yasmina and my uncle Hamoudi, whose love and support have been bright beacons in the darkest moments. Thank you for always believing in me and accompanying me with such tenderness and generosity. Thank you for being there for me and helping me through my depression despite the distance. Your presence and support were lights in the darkness. I will always be thankful to my childhood friends Maissa and Nada for the memories we've made and will make. Thanks for being by my side throughout our adolescence and for continuing to enrich my life with your precious friendship. I look forward to creating new memories with you in the future. I am deeply grateful to Nada and Amira for the unforgettable moments and precious memories we shared at school and on the university campus. Thanks for your friendship and the laughter that lit up our journey. You made this adventure even more beautiful. To myself, because it is not often heard.

Malak

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I would also like to thank the members of the jury for their time, remarks, and evaluation.

Malak

ملخص

الهدف من هذا العمل هو دراسة تحسين بناء محطة تحلية المياه على أساس الاستثمار (النفقات الرأسمالية) والتمويل التشغيلي (النفقات التشغيلية) كدالة للطاقة الإنتاجية لتحلية المياه. يركز تطبيق الدراسة على مشروع محطة تحلية مياه البحر في كوديت دراوشة بولاية الطارف، ويقترح عملية تحلية غشائية وحرارية هجينة من نوع (RO/ MED). نتيج هذه العملية ضمان الأمن المائي وزيادة مرونة النظام وتقليل تكاليف الإنتاج بشكل كبير. ولتحقيق ذلك، تم تطوير كود حسابي يتيح تحديد الحجم بناءً على التكاليف الكامنة في التمويل. يوفر الحل الهجين الموصى به (التناضح العكسي/التعقيم المتبادل) مزايا من حيث الأمن المائي ومرونة أكبر في تشغيل المحطة، مع تقليل نفقات التشغيلية لكل متر مكعب

الكلمات المفتاحية الاستثمار، التمويل، التشغيل، تحلية المياه، العمليات، الهجين، الطاقة المتجددة

Résumé

Ce travail vise à étudier l'optimisation de la réalisation d'une usine de dessalement à partir des financements d'investissement (CAPEX) et opérationnel (OPEX) en fonction des capacités de production de dessalement. L'application de l'étude s'intéresse au projet de la station de dessalement de Koudiet Draouche pour la proposition d'un procédé de dessalement hybride membranaire et thermique de type (RO/MED).

Ce procédé permet de garantir une sécurité hydrique, d'augmenter la résilience du système et de réduire considérablement les coûts de production. Pour ce faire, un code de calcul a été élaboré, permettant le dimensionnement sur la base des coûts inhérents aux financements. La solution hybride recommandée (RO/MED) offre des avantages en termes de sécurité de l'eau et une plus ample flexibilité dans le fonctionnement de l'usine, tout en minimisant les dépenses OPEX par mètre cube.

Mots clés : Investissement, financement, opérationnel, dessalement, procédés, Hybride, renouvelable.

Abstract

The aim of this work is to study the optimization of the construction of a desalination plant on the basis of investment (CAPEX) and operational (OPEX) financing as a function of desalination production capacity. The application of the study focuses on the Koudiet Draouche desalination plant project, proposing a hybrid membrane and thermal desalination process of the RO/MED type. This process makes it possible to guarantee water security, increase the resilience of the system and considerably reduce production costs. To achieve this, a calculation code has been developed, enabling sizing based on the costs inherent in the financing. The recommended hybrid solution (RO/MED) offers advantages in terms of water security and greater flexibility in plant operation, while also minimizing OPEX expenditure per cubic meter.

Key words: investment, financing, operational, desalination, processes, hybrid, energy.

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List of acronyms and symbols

CAPEX:	Capital Expenditure
OPEX:	Operating Expenditure
RO:	Reverse Osmosis
MED:	Multi-Effect Distillation
MSF:	Multi-Stage Flash
VCD:	Vapor Compression Distillation
ED:	Electrodialysis
MEE:	Multiple Effect Evaporation
TVC:	Thermal Vapor Compression
MVC:	Mechanical Vapor Compression
ADV:	Adsorption Desalination and Vacuum
ABV :	Absorption-Based Vacuum
CVC:	Chemical Vapor Compression
SEE:	Specific Energy Expenditure
HDH:	Humidification-Dehumidification
UF:	Ultrafiltration
MF:	Microfiltration
SWDP:	Seawater Desalination Plant
ER:	Energy Recovery
MENA:	Middle East and North Africa
USD:	United States Dollar
UPC:	Unit Production Cost
PND:	Preliminary and Detailed Design
PPP:	Public-Private Partnership
DBOO:	Design-Build-Own-Operate
DBO:	Design-Build-Operate
NMSO:	National Maritime Signaling Organization
TSS:	Total Suspended Solids
TDS:	Total Dissolved Solids
TOC:	Total Organic Carbon
MES:	Membrane Electro-Separation
PLC:	Programmable Logic Controller

PPM:	Parts Per Million
FDI:	Foreign Direct Investment
VOC:	Volatile Organic Compounds
CNRS:	Centre National de la Recherche Scientifique
FRP:	Fiber Reinforced Plastic
EDTA:	Ethylenediaminetetraacetic Acid
DAF:	Dissolved Air Flotation
CaCO₃:	Calcium Carbonate
SO₂:	Sulfur Dioxide
CO₂:	Carbon Dioxide
NO_x:	Nitrogen Oxides
MgO :	Magnesium Oxide
NTU :	Nephelometric Turbidity Units
μS:	Microsiemens (unit of electrical conductivity)

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General Introduction

Many countries around the world, particularly in arid and semi-arid regions such as Algeria, are suffering from a growing shortage of water as an energy pillar on which to base human life, economic and industrial growth threatened by climatic and demographic factors and the current challenges faced by the desalination industry as a single alternative to deal with the context of water stress and increasing demand for drinking water. There is a need not only to reduce production costs but also to guarantee security for the supply of drinking water. Admittedly, the reverse osmosis process remains the most advantageous in view of the initial costs of high and operational investment costs; the latter is mainly influenced by energy consumption.

For this reason, countries are working hard to reuse unconventional water in two major ways: either by reusing wastewater or by developing and using seawater desalination technologies in coastal areas as a second alternative solution to obtain this fresh and usable source, which is almost extinct. On a global scale, the amount of water generated by desalination currently stands more than 115 million cubic meters daily. Numerous desalination plants are being built worldwide, notably in Libya, Australia, and the UK. They are mainly located in countries facing water shortages, such as Algeria and Libya, as well as in the Gulf States. They are also found in southern Europe, such as Spain, Italy, Greece and the United States.

After the drought experienced during the 2000 and 2001 seasons, when Algeria was on the verge of importing water, the public authorities took major steps to overcome the water shortage that hit the capital Algiers and other coastal wilayas.

In 2002, an emergency program was launched to build 21 monobloc desalination plants with a total output of 5750 m³/d to serve fewer than 400 000 inhabitants. In 2003, the national desalination plan was launched with the construction of 11 desalination plants with a total production of 2.11 million m³/d to secure the drinking water supply for more than 7 million inhabitants of coastal towns, where the rate of desalinated water production was close to 17% of national production.

After the more or less wet hydrological years of 2013 and 2017, Algeria was faced with water stress from 2020 onwards, accentuated during 2021 when almost 18 wilayas were seriously affected by the drop in water reserves in the dams used to supply drinking water to several communes.

To secure the public drinking water service, the government, in the Council of Ministers of 30 May 2021 and 25 July 2021, decided to replace renewable water with desalinated water and to increase desalinated water production capacity by 3.0 million cubic meters/day in two phases: before 2025, the construction and commissioning of 5 desalination plants, each with a capacity of 300 000 m³/d; then the construction of 5 or more, by 2030, to achieve a production of more than 2 billion cubic meters, serving almost 60% of the population spread over 14 coastal towns and supplying other towns on a backbone stretching 150 km.

In 2025, two new facilities will be added, each with a capacity of 300 000 m³/day, a major investment by the public authorities in terms of capital expenditure (CAPEX) and operating expenditure (OPEX) to guarantee drinking water for several communes in the wilayas of El-Taref, Annaba, Guelma, and Skikda. After commissioning on 26/02/2025, the new desalination plant at Koudiet Eddraouche is currently undergoing a trial period. The desalination process deployed is reverse osmosis (RO), a technique that remains the most advantageous compared with other thermal processes (MED or MSF) or even membrane processes (electrodialysis). However, reverse osmosis (RO) encounters several difficulties when the water is loaded with suspended solids, particularly during periods when the seawater is agitated by swell storms. This makes the process sensitive to variations in the quality of the input water (raw water), necessitating a temporary shutdown, sometimes lasting several days, which can lead to supply disruptions and affect the quality of the public service. Not to mention the risk of irreversible damage caused by certain abrasive particles (sand) that can physically damage the membranes. Other negative effects can be observed, such as...

- ***Clogging and fouling of membranes,***
- ***Increased energy consumption***
- ***Reduced productivity***
- ***Increased operating and maintenance costs***

It was with this goal in mind that we undertook this study, seeking to stem this operating problem by proposing an alternative aimed at developing greater resilience and guaranteeing water security in the supply of drinking water.

The aim is to carry out an optimisation study based on the investment financing (CAPEX) and operational expenses generated by the operation (OPEX), and to propose, on the basis of a feasibility study, a hybrid-type process plant comprising a membrane process represented by reverse osmosis (RO) and a thermal process chosen from among multi-effect

distillation (MED), multi-stage flash (MSF) and mechanical vapor compressor (MVC). This solution should guarantee greater autonomy, improved operating margins and better drinking water quality than the conventional reverse osmosis (RO) process.

The final choice of the hybrid variant will be dictated by economic considerations that take into account the financing projects made up of investment capital (CAPEX) and operating capital (OPEX). To this end, this study is structured as follows:

- ✓ After a general introduction describing the problem and the objectives of the study, this work is divided into five chapters:
- ✓ The first chapter focuses on the technologies used in the seawater desalination process, detailing their advantages, disadvantages, production limits and environmental considerations.
- ✓ The second chapter analyses the capital expenditure (CAPEX) and operating expenditure (OPEX) associated with a desalination plant project.
- ✓ The third chapter presents the calculation code used to size and optimise the operating parameters of a hybrid desalination plant.
- ✓ The fourth chapter examines the case study: the Koudiet Draouche desalination plant project.
- ✓ The final chapter discusses strategies for preserving the environment at the plant site, including waste dilution and dispersion techniques, brine recycling and the use of renewable energies.

Finally, a general conclusion is punctuated and supported by technical recommendations.

CHAPTER I

DESALINATION OF SEA WATER PROCESS

Introduction

Desalination technology has advanced and developed as a result of the massive efforts sponsored and funded by the US Department of Interior's Office of Saline Water that had a significant influence on the development of currently available desalination processes and almost all of the technologies that are currently used in commercial settings were developed and tested under the program. The process of extracting salt and other minerals from seawater or other salty water sources including brackish water in order to create fresh water, fit for human consumption or other use is called desalination or desalinization (Siddiqui et al., 2022). The primary purpose of desalination in Algeria is to provide water for industrial and residential consumption. Algeria now operates plants with a combined daily capacity of 2 170 000 cubic meters, according to a study published by the International Desalination Association.

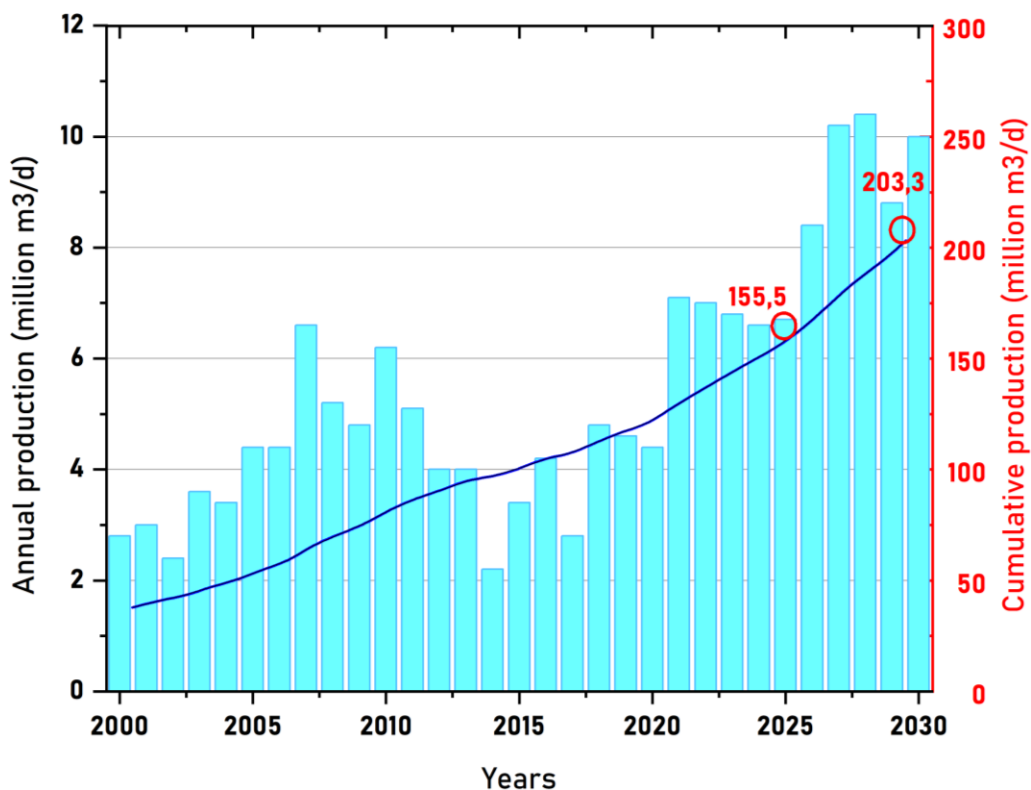


Fig I.1: Alternatively, evolution of desalination worldwide (WBG,2025)

This graph shows how desalination production has changed over time on a global scale. The blue curve illustrates the general upward trend in the total amount of desalinated water produced. Labels and Red Circles emphasize noteworthy milestones in total production: 155.5 million m³/day about 2025 than 203.3 million m³/day around 2030.

Despite occasional variations, the yearly production of desalination has risen throughout time. There is an increasing exponential tendency in the total production. By 2030, it is anticipated that total output would have surpassed 200 million cubic meters per day with different size of desalination plants that exist around the world.

Tab I.1: Classification of desalination plant (Voutchkov, 2013)

Plant size (m ³ /d)	Design (Months)	Construction (Months)	Start-Up and commissioning (Months)	Total (Months)
Less than 1000	1-2	2-3	1-2	4-7
5000	2-3	4-6	1-2	7-11
10 000	2-4	6-8	1-2	9-14
20 000	3-5	8-10	2-3	13-18
40 000	3-6	14-16	2-3	19-25
100 000	5-8	18-20	3-4	26-32
200 000	6-10	20-24	3-4	29-38

The figure I.2 shows the quantity of desalination facilities with a capacity greater than 10 000 m³/d is also highlighted. With 47 sizable plants and the largest installed capacity (11.3 million m³/d), Saudi Arabia is a major force in the water desalination industry. There is also substantial desalination infrastructure in Algeria and the United Arab Emirates. The desalination capacity of North African nations (Algeria, Morocco and Tunisia) is moderate but increasing.

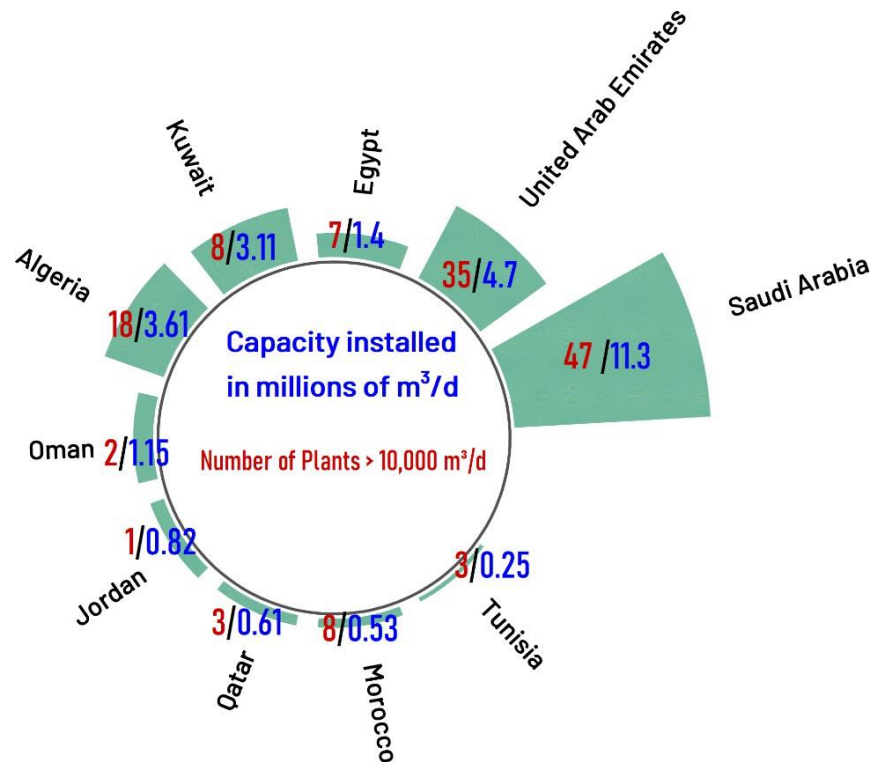


Fig I.2: Installed desalination capacity and plants for the MENA area by 2025 (WBG, 2025)

I.1. DIFFERENT DESALINATION PROCESSES

There are more over 15 000 desalination units worldwide producing around 56 million m³/year across 120 countries. Water from the sea makes up 60.6% of the water treated at these plants. The Moyen-Orient countries, mainly those in the Persian Gulf, account for 12 million m³/year: Al-Saoudite accounts for 22.7% of the global total, followed by the Emirates Arabes United (16.3%) and Kuwait (6.4%). Regarding the quantity of installations, the United States ranks first (small installations are included) and Saudi Arabia comes in second. Spain ranks fifth in terms of installations, fourth in terms of seawater desalination, and second in terms of inverse osmose. The production capacity is distributed according to the processes used as outlined below: 42.9% using a multiple stage flash evaporator and 38.9% using RO. The remaining percentage applies to other technologies. MSF is used by 57.5% of plants larger than 400 m³/j, whereas RO is used by 27.6%. The Mediterranean makes up almost a quarter of the world's desalination, and scientists predict that by 2030, the region may approach 30 to 40 million m³/year.

Thermal or membrane separation techniques may serve as a basis for the desalination procedures. The two primary types of thermal procedures are evaporation, which is followed

by condensation of the water vapor and freezing, which is followed by melting of the water ice crystals. The former method is the most often used in desalination and it is almost always combined with power production units which can be based on gas turbine or steam systems. Evaporation can occur inside the liquid bulk and is known as blinking or it can occur across a heat transfer region and is known as boiling.

RO and ED are the main methods used in membrane desalination, which uses selective permeability to extract salts from water. These approaches are selected according to operational necessities, feedwater salinity and energy consumption (El-Dessouky et al., 2002).

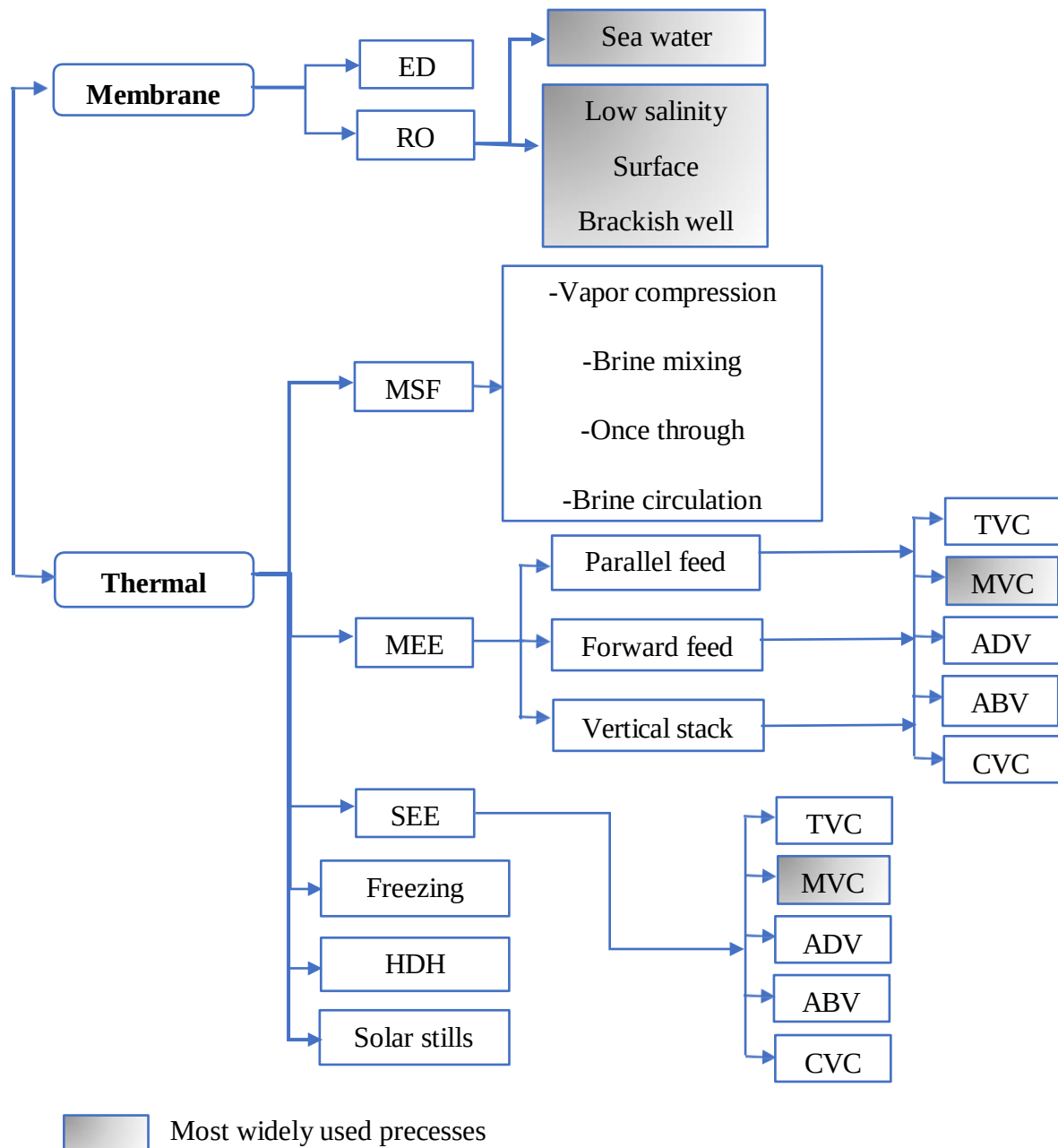


Fig I.3: Thermal and membrane desalination processes (El-Dessouky et al., 2002).

Mechanical power for desalination is the category that the RO and MVC systems fall under. Water is forced across the membrane in the RO process by mechanical energy, also known as the pressure differential across the membrane, which also keeps the salt in the brine stream. Regarding the MVC process, the feed seawater is heated by the distillate vapor's increased temperature and pressure due to the vapor compressor's mechanical energy. Water and salt are separated using electrical energy is the process of electrodialysis, in which electrically charged ions are propelled across selective membranes by electric energy.

Tab I.2: The various desalination processes (Wetterau, 2011)

Techniques		Process	Strength	Drawback	Production capacity
Membrane	RO	An external high pressure is applied to force the solvent to migrate through a semipermeable membrane, leaving the solutions in the concentrate.	Achieve up to 50% recovery rate; compact size relatively small footprint; reduction in equipment and membrane costs.	High capital cost; susceptible to membrane fouling; brine discharge; significant energy consumption.	Highly scalable; access to modern thin-film membranes
	ED	Uses a series of alternating anion and cation exchange membranes, which separate it into two streams. The electric field drives the cations across the cation membrane, as does the anions. The ions are then removed from the water, producing two	Suitable for brackish water; low energy consumption.	Residual turbidity is not affected by this process and remains in the water; this requiring additional treatment to meet drinking water standards.	When the salinity is higher, its efficacy decreases.

		streams: one depleted of ions (the desalinated water) and the other concentrated in ions (the brine).			
Thermal distillation	MSF	Seawater is heated to produce steam then condensed to produce fresh water. The process involves multiple heating and cooling steps.	High quality of permeate; can use waste heat to reduce energy rate; More energy efficiency.	Requires large footprint; large complexity of the plant.	The range of recovery for conventional processes is restricted from 10% to 30% for seawater desalination.
	MED	Similar in concept to MSF, this method uses several evaporation and condensation steps to increase efficiency.		Expensive to design and operate compared to single stage flash distillation; despite improvements.	Suitable for medium to large scale [8-16] containers to reduce energy consumption; the recovery rate 20% to 35% of the feed flow.
	VCD	Compressing the water vapor in a tube enables the condensation heat to be transferred to the other side of the surface, which		More complex; may require more maintenance; can be more sensitive to fouling.	For a range of plant size.

		causes vaporization. In order to lower its ebullition temperature, the compressor increases the pressure on the side of the vapor and decreases the pressure on the side of the alimentation.			
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Alabi., 2025 and Odunlami et al., 2023 affirmed that Cellules of Desalination Microbials (CDM) are an invention that combines simultaneous wastewater treatment, electricity generation and desalination without the need for an external energy source. They are similar to heaps of combustible Microbials (PCM). They rely on the activity of microorganisms to produce electricity while removing salts through ion-exchange membranes. Various configurations have been developed, including the simple and cost-effective CDM. Furthermore, the cathodic for air out which is limited by a redox slow kinetic; the biocathodes, which are more durable and self-regenerating and require ideal conditions; the structures stacked, which increase the efficiency of desalination by transferring the charge accrued; and the CDM by recycling (rMDC) in the solutions are recycled to stabilize the pH and improve overall performance.

I.2. ENERGY RECOVERY PLANT

Urrea et al., 2019 presented a comprehensive review of the choice to adapt the ER is therefore a sensitive and challenging one for managers of existing SWRO installations. It makes it possible to extend the plant's usable life and get the most energy savings throughout the desalination process. Making the most of the existing equipment might be another way to try to boost the plant's output capacity. There are more than 130 seawater desalination plants with a total installed capacity of more than 400 000 m³/d in the Canary Archipelago alone, which is a European reference in the area of desalination plants and has one of the greatest densities of SWROs in the world (22.73 km²/plant).

The ceramic ER device uses the principle of positive displacement and isolated chambers to provide a very efficient energy transfer. The seawater, which is supplied by the alimentation pump, circulates at low pressure in a return channel on the left side, where it expels the salt that is present on the right side. When the rotor passes over a sculled zone, the high-pressure shock travels through the right conduit, so compromising the water of the sea. This latter, which is now under high pressure, is then sent toward the suppression pump. The circulating water creates a horizontal concentration gradient throughout the membrane's length. When one of the following circumstances is noticed, membrane cleaning becomes necessary:

- The normalized permeate debit decreased by 10%.
- Compared to the original charge loss, the charge loss between the alimentation circuit and the concentrate has increased by 15%.

The energy intensities reported for various desalination technologies are shown in the figure below, expressed as an equivalent electrical total. It distinguishes between thermal, membrane and hybrid processes as well as the distribution of their energy consumption between thermal and electrical.

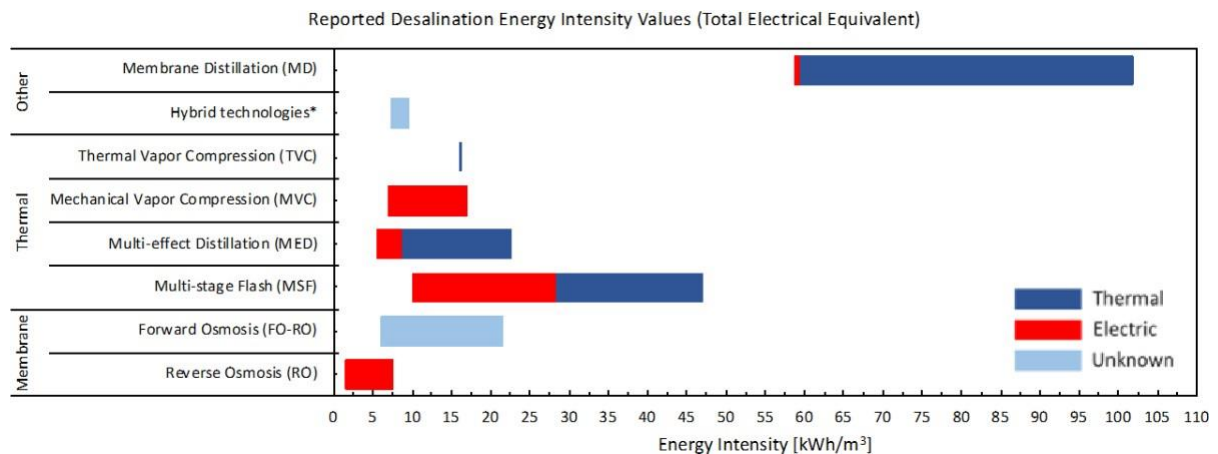


Fig I.4: Energy intensities (in kWhT,equiv/m³) of various seawater desalination technologies as reported in the available literature (Rao, 2018)

I.3. DESALINATION STRATEGY IN ALGERIA

Algeria has historically struggled with water shortages, which has been made worse by extended droughts and climatic unpredictability. The country experienced a serious water

crisis during 2001 and 2002 as a result of a three-decade reduction in rainfall. In order to guarantee an adequate source of water for the expanding population and economic growth, this dilemma brought to light the pressing need for alternate water sources. Algeria thus decided to use desalination as a tactical approach to lessen water scarcity and improve water security. The Algerian government integrated seawater desalination facilities under the national water delivery strategy and launched a massive desalination program to alleviate the water issue.

In line with the National Desalination Plan (PNE), this endeavour sought to diversify water sources in order to lessen reliance on traditional freshwater resources, like groundwater and surface water, which were growing more and more unreliable as a result of over-extraction and climate change (Hamiche et al., 2019). Since the early 2000s, Algeria has developed several large-scale desalination projects, solidifying its position as a leader in the region.

Among the significant turning points are:

Public-private partnerships (PPP) enabled the quick growth of desalination capacity by facilitating technological transfer and international investment. RO technology adoption, which uses less energy than conventional thermal desalination techniques (Ghaffour et al., 2013).

I.3.1 National Desalination Plan (PNE)

Before giving an overview of the national water desalination strategy, it is interesting and appropriate to talk about the initial considerations made by Algerian scientists and researchers on the feasibility of using seawater desalination. In this context, an initial study day on seawater desalination (JESEM, 98) was held on 25 and 26 October 1998 by the Higher National School for Hydraulics (ENSH, Cf. Annex I.1).

The recommendations at the time converged on the superposition of energy and water needs in order to use desalination water as a backup to cope with water shortages in certain regions of the capital and the west of the country.

Implementation of the PNE following the inter-ministerial council meeting of 12 October 2003. It aims to launch an emergency programme of 21 single-block plants with a capacity of less than 10 000 m³/d, followed by a structural programme to build 13 large desalination plants.

Site identification studies have been entrusted to the French consultancy SAFEG, with the aim of:

- Identify all potential sites for the construction of desalination plants close to existing drinking water storage and distribution infrastructures.
- Define a short- medium- and long-term strategy for the development of seawater desalination for the production of drinking water.

In 2005, the results of the study revealed a set of forty-three sites deemed to be priorities for preliminary design studies. Conceptually, two processes were identified: reverse osmosis and distillation.

Tab I.3: Status of monobloc desalination plants (MRE, 2020)

Plants	Wilaya	Capacity (m ³ /d)	Commissioning Date
Ghazaouet	Tlemcen	5000	2004
Tigzirt	TiziOuzou	2500	
Beni haoua	Chlef	5000	2016
Mainis			2007
Bouzedjar	Ain Temouchent		2006
Bousfer 1,2,3 and 4	Oran	5500	2005
Dunes 1&2		5000	2006
Skikda 1&2	Skikda	7000	2002
Zeralda 1&2	Algeria	5000	2003
Ain Benian 1&2		2500	2005
Palm Beach			
Bou Ismail	Tipaza	5000	2004
Total Capacity (m ³ /d)	57000		

The national desalination plan (PND) has led to the construction of 11 seawater desalination plants, with an installed production capacity of 2 110 000 m³/d (i.e. an annual production of 770 million m³/year) for a population impact of 7 189 904 inhabitants (see the table below).

Tab I.4: Status of desalination plants under the national plan, by locality (MRE, 2020).

Plants	Wilaya	Capacity (m³/d)	Commissioning Date
Kahrama	Oran	90 000	2005
Hamma	Algeria	200 000	2008
Skikda	Skikda	100 000	2009
Chatt el Hillal	Ain Temouchent	200 000	
Sonagter	Mostaganem		2011
Fouka	Tipaza	120 000	
Souk Tleta	Tlemcen	200 000	
Honaine			
Cap djinet	Boumerdes	100 000	2012
Tenes	Chlef	200 000	2015
Magtaa	Oran	500 000	2016
Total Capacity (m3/d)	2 110 000		

Production of desalination has steadily grown in the nation especially after 2005. Magtaa with a capacity of 500 000 m³/d accounting for 23.7% of the total is an important desalination center. Then, we can see in the following figure that all the first six stations have a long delay of implementation and exceed the limit that can be directly linked by the functionality of the workforce on the national territory, because the commissioning period is 48 months according to the standards and normal conditions.

Since the drought that Algeria experienced between 2000 and 2001, the public authorities have set up a programme to anticipate future demand in order to guarantee access to drinking water and thus address the water deficit caused by the country's economic development and population growth.

The national desalination programme was launched in 2005 and completed in 2016, which consisted, in addition to the monobloc station programme, of building 11 desalination plants spread across the coastal wilayas with a total installed capacity of 2.11 million m³/day. The distribution of desalination plants by region is:

- Western Region: 6 desalination plants account for 73% of total installed production.
- Central Region: 3 desalination plants account for 22% of total installed production.
- Eastern Region: 2 desalination plants account for 5% of total installed production.

The 11 desalination plants built are managed by project companies as part of a public-private partnership financial arrangement with turnkey contracts (EPC: Engineering, procurement, construction). This RO desalination plants, except for the Kahrama desalination plant (Oran) where the process is MSF, Algeria has become one of the desalination nations in the MENA region.

Figure 5 provides an overview of the completion times for the 11 stations commissioned with a delay for multiple reasons, except the El Hamma (Algiers) plant, commissioned in February 2008 for US\$258 million by Ionix, 75% of which was financed by an American bank loan (OPIC).

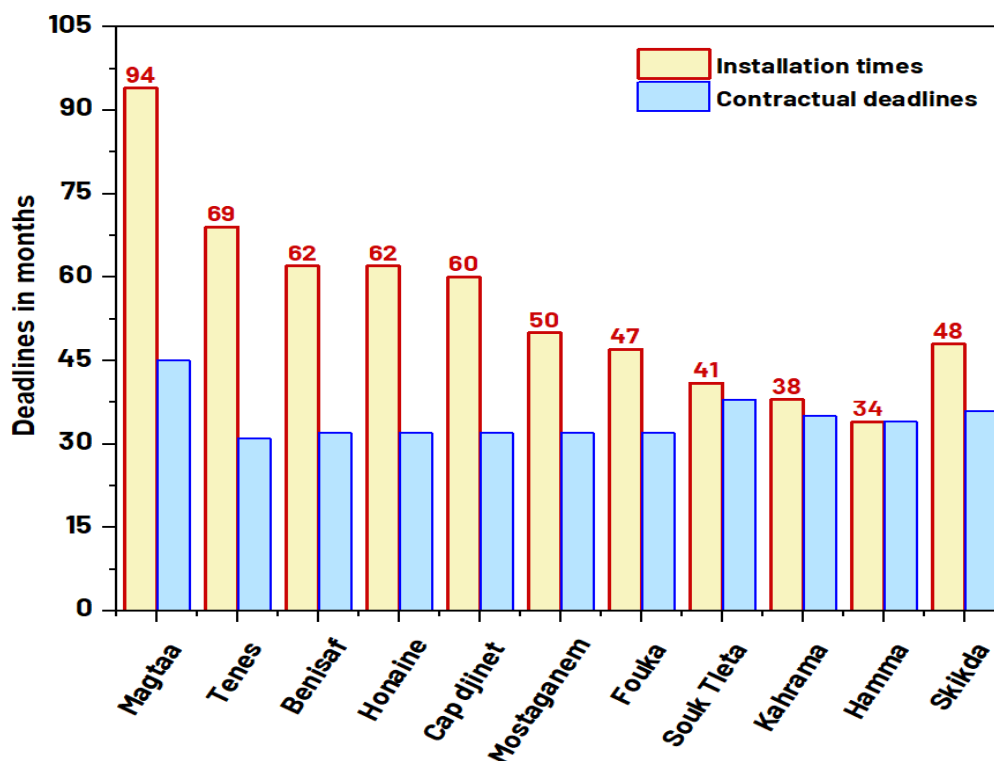


Fig I.5: The months of construction of desalination plants (MRE, 2020)

It should be remembered that the deadlines for the construction of desalination plants depend not only on the type of desalination process, but also on other influencing factors, such as:

1. **Complexity of the project:** servicing of the land, seawater intake, brine discharge.
2. **Supply of equipment:** delays by suppliers in importing membranes, high-pressure pumps, automation systems, etc.
3. **Regulatory authorizations:** delays in removing restrictions and obtaining permits.
4. **Labor:** the limited number of technical managers and engineers qualified for the testing phases.

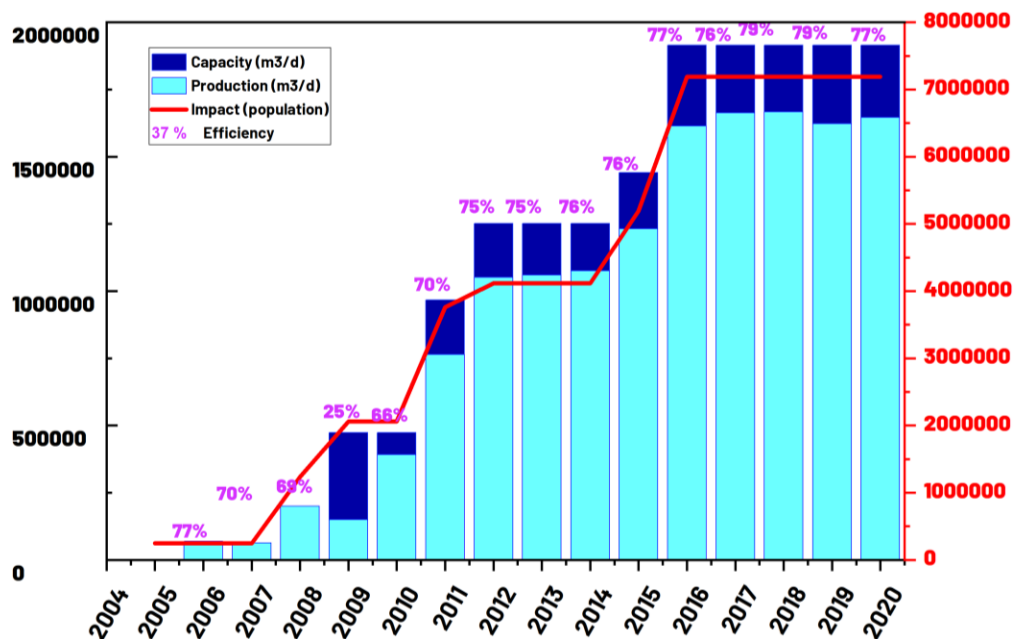


Fig I.6: Desalination plant production trends from 2005 to 2020 (MRE, 2020)

As the consumption of drinking water is approximately 3.4 billion m³/year, which is equivalent to 55 m³/inhabitant/year. this has a direct relation by the way of the selection of water according to different sources presented in the figure below.

The distribution of Algeria's water resources can be divided into three main sources: surface water (such as rivers and dams), subsurface water (such as groundwater), and desalination water that it is necessary to measure a good diversification strategy because desalinated water rise to 39% in 2025 and become majorities with 52% in 2030.

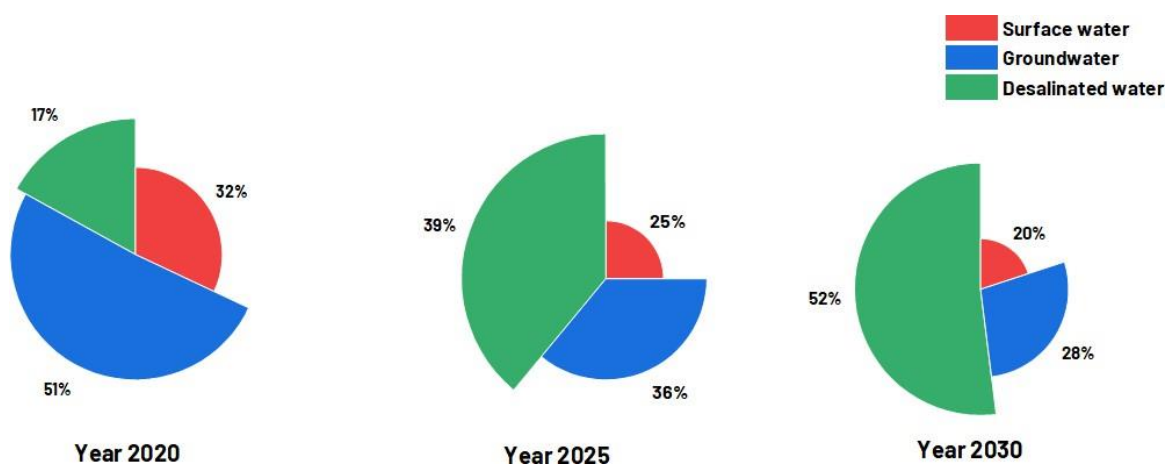


Fig I.7: Drinking water production rate by conventional and non-conventional resource type

I.3.2. Technical constraints on Projects

We know that the cost of desalinated water is estimated from the sum of three items: financial charges, the cost of energy, the cost of downstream investments, and operating and maintenance costs.

The construction of all the SWDP involved investments of 2,879 million \$ US. The total amount of the loan is 1907 million \$ US, with a national contribution of around 1,726 million \$ US (i.e. almost 70% of the investment). The ratio per cubic meter produced from the SDEMs reflects the costs borne by the stations and the profit that pays for the capital investment (CAPEX), which changes each year according to the ratio of the following cost segments (MRE, 2020):

- Cost of debt servicing: 34.4%
- Cost of electrical energy: 22.6%
- Cost of remuneration (repayment) of investment: 21.1%
- Cost of consumables: chemical reagents, membranes and filters: 9.5%

The terms and conditions of Sonatrach's financial reimbursement have been defined by a framework agreement between Sonatrach and the State represented by the Ministry of Finance and the Ministry of Energy.

The price of desalinated water has risen sharply since the contracts were signed. This increase is mainly due to inflation and the devaluation of the dinar in recent years (dinar/dollar parity) as in the case of the El Hamma plant, where the average price per cubic meter of desalinated water has risen from 114.15 DA in 2018 to 191.23 DA in 2019.

It should be remembered that Sonatrach and the project companies enter into ‘purchase-sale’ contracts for water, the remuneration for which is calculated on the basis of three separate operations:

- Remuneration for water production.
- Remuneration for production capacity, calculated on the basis of availability performance premiums (PRD).
- Remuneration for excess capacity in the event that the plant is able to produce excess capacity during the operating period.

It is important to note that, despite the scale effect on the investment cost, the operating cost of the SDEMs built is relatively high due to the complex contractual management model of the desalination plants, which has required the assistance of foreign firms, where the financing model is that of project finance with a DBOO (Design-Build-Own-Operate) contractual arrangement, which has been adopted for all 11 desalination plants built (MRE, 2020).

This type of contract is governed by the ‘Take or Pay’ clause, which requires the purchaser to pay availability performance premiums (PRD) on the quantities of water not delivered. The private operator is responsible for financing the construction and retains ownership of the infrastructure, which means that it generates revenue by operating the water sales service.

Tab I.5: Comparative overview between DBO, DBOO and BOOT financing methods (Lyonnet du Mortier, 2003) (*Public-Private Partnership Resource Center | Public Private Partnership* [no date]).

Criteria	DBO Design-Build-Operate	DBOO Design-Build-Own-Operate	BOOT Build-Own-Operate-Transfer
Financing	Public (State, community, public organization)	Private (investors, compagnies, funds)	Temporary private with return to public
Ownership of infrastructure	Public (returns to the state after operation)	Private	The private contractor builds, owns and temporarily operates
Financial risk	Supported mainly by the State	Supported by the private operator	Supported by the private operator
Operating	By private operator for a limited period	By the private operator on an ongoing basis.	By private operator for a limited period
Contract duration	Average duration of 10 to 20 years.	Long-term ranging from 20 to 30 years or more.	Private ownership during the concession period (usually 15-30 years)
Initial investment	Financed by public funds	Generated directly by private operators.	Private financing with guaranteed return on investment
Operating revenue	Part of which is paid back to the State	Generated directly by private operators	The private sector recovers its investments through operating income.
Scope of the contracts	Wastewater treatment plant project, temporary public infrastructure... etc.	Desalination plants, private power stations and major infrastructure projects	Desalination plants, private power stations and major infrastructure projects

Although the choice of this model is justified for public-private partnership (PPP) financing, it does not encourage the integration of local labor or local engineering know-how, nor the integration of national production in the construction of desalination plants or consumables during operation.

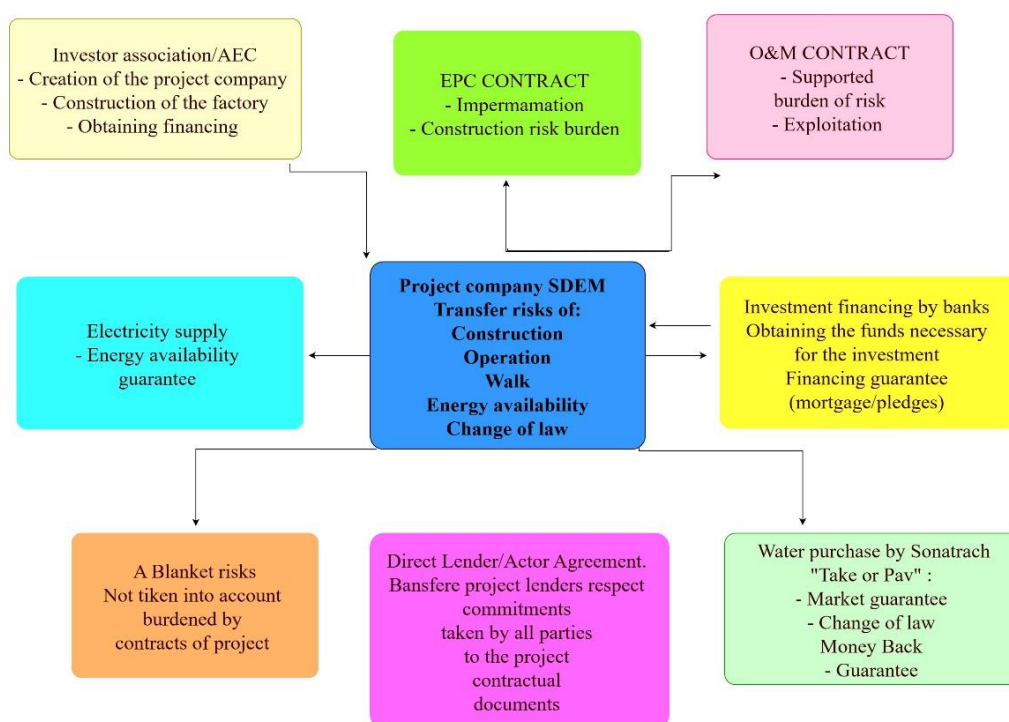


Fig I.8: Explanatory diagram of the DBOO type contractual arrangement for desalination plant projects Water Purchase and Sale Contract (CVAE) on behalf of Sonatrach to ADE

In this context, no training program for the staff in charge of the public water service has been undertaken, and no transfer of know-how to the desalination plants has taken place. It should be emphasized that the concession contracts concluded do not provide for the renegotiation of contractual clauses concerning the revision of prices in favor of the purchaser.

I.3.3. Technical solutions for the protection of water intakes

To ensure operational effectiveness, reduce environmental impacts and abide to regulatory standards, water intakes in desalination plants using RO processes must be protected. Also, it must be emphasized the importance of designing infrastructure taking into account the position of the intake, in particular by placing it at a sufficient distance from the coast more than 1100 feet to reduce impacts.

Tab I.6: Water intake protection solutions (Suez. 2025, ACCIONA, Team 2019).

	Description	Advantages	Limitations	Estimated Costs
1.Coarse Bar Screens	Large screens with openings between 20 mm and 150 mm to trap large debris and marine organisms.	Simple, economical, and easy-to-maintain design.	Ineffective for smaller particles and organisms.	Equipment: \$10 000 to \$50 000 Installation: \$5000 to \$20 000
2.Fine Screens	Screens with finer mesh (1 mm to 10 mm) to capture finer debris and organisms.	Effective for smaller particles, available in fixed or rotating versions.	Higher maintenance than coarse screens.	Equipment: \$20 000 to \$100 000 Installation: \$10 000 to \$30 000
3.Passive Wire Screens	Screens with very low flow velocities and small slots to minimize impacts and entrainment (I&E).	Highly effective in reducing, suitable for open-ocean water intakes.	Higher initial costs and complex installation.	Equipment: \$50 000 to \$200 000 Installation: \$20 000 to \$50 000.
4.Subsurface Water Intakes	Systems such as beach wells or infiltration galleries that use the natural filtration of the seabed to pre-filter seawater.	Significant reduction of I&E-related impacts, natural filtration	High initial costs and complex installation.	Equipment: \$100 000 to \$500 000 Installation: \$50 000 to \$200 000

		improves water quality.		
5.Filter Barriers	Full-depth porous filter fabric placed at the intake inlet to reduce I&E.	Economical and easy to install.	Limited lifespan and risk of clogging.	Equipment: \$30 000 to \$150 000 Installation: \$15 000 to \$40 000
6.Movable Screens	That clean themselves periodically to prevent clogging.	Effective for heavy debris loads, reduce maintenance downtime.	Higher initial and maintenance	Equipment: \$50 000 to \$250 000 Installation: \$25 000 to \$75 000

Groundwater intakes, such seabed filtering systems, infiltration galleries, or beach wells, are becoming more and more acknowledged as a sustainable way to provide feedwater to desalination facilities. Higher-quality feedwater from natural filtration prolongs membrane life and uses fewer chemicals in desalination facilities (Voutchkov, 2012). Not possible everywhere; appropriate geological conditions (low clay concentration and permeable sand) are necessary.

- Coarse bar screens and fine screens are unquestionably the greatest options for small farms or enterprises with a tight budget.
- Despite their high initial cost, subsurface intakes are great for large-scale, ecologically sensitive projects.
- Should budgetary constraints and environmental preservation be a consideration, passive wedge wire could be a suitable compromise.

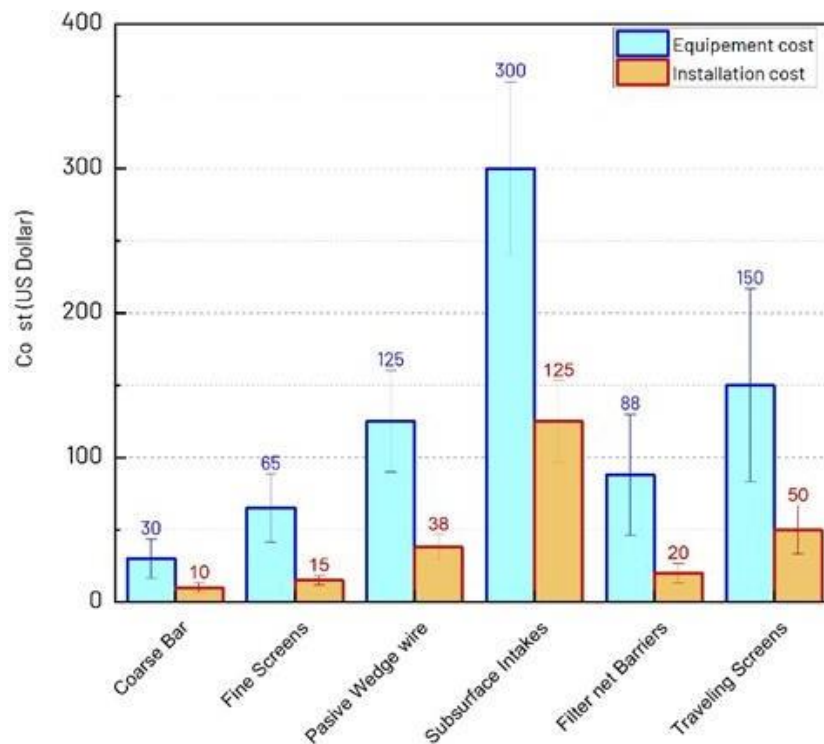


Fig I.9: Cost comparison of water intake protection solutions (Voutchkov., 2011).

The quality of the drinking water is improved by the advanced filtering systems and good water immersions that reduce turbidity. Furthermore, despite their comparatively high installation and maintenance costs, breakwaters are distinguished by their exceptional ability to withstand strong winds as shown figure below.

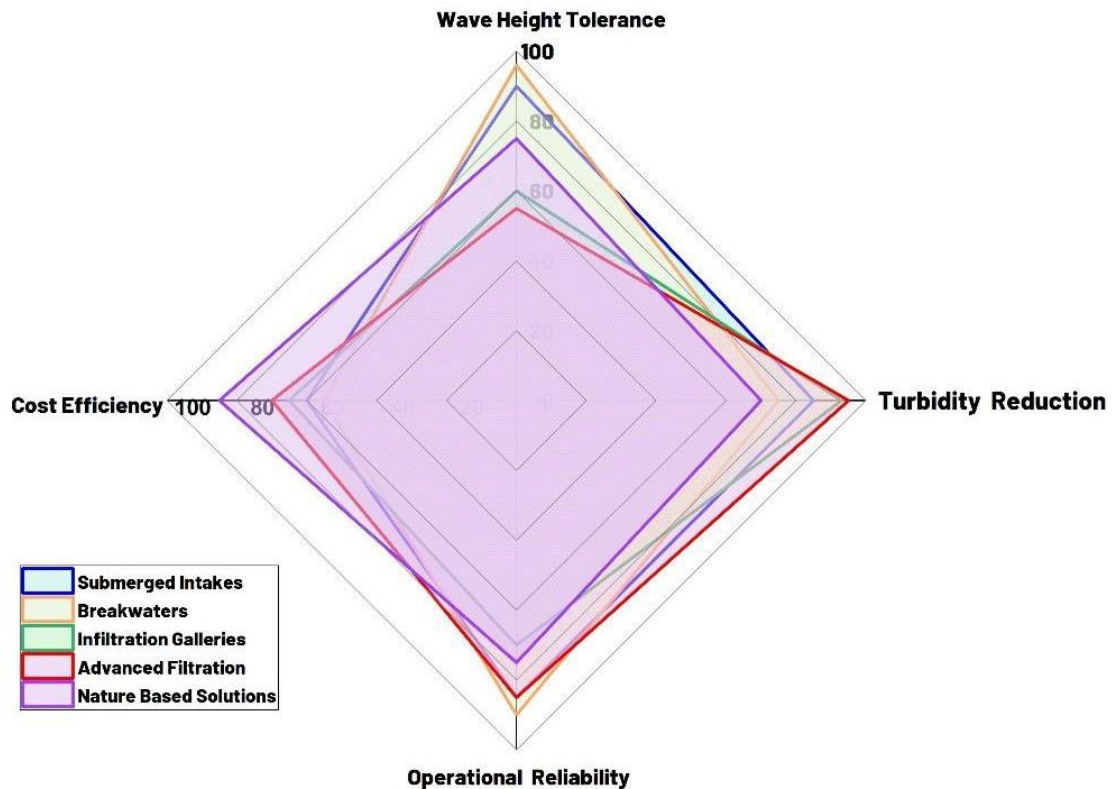


Fig I.10: Cost comparison of water intake methods (Suez 2025, Team 2019).

The decision matrix for choosing a desalination solution is based on a number of important evaluation criteria in order to choose the best technology. Among these criteria, protecting marine life is crucial since it helps to lessen the ecological impact on marine ecosystems. Effective debris management is also necessary to prevent entanglement and blockages in systems, ensuring smooth and long-lasting operation. The ease of maintenance is an important factor as it affects the frequency and cost of repairs required to keep the system in good condition. Another crucial element that ensures the solution's long-term economic viability is rentability, which includes installation, exploitation, and maintenance costs.

Among the best performances, passive metal grilles and water ground filters stand out for their ability to effectively manage debris and safeguard marine life while providing a long-lasting and affordable solution.

In the following table, the original investment and maintenance costs of several water protection methods are compared. Although, the initial cost of subterranean water extraction is high, there are long-term environmental benefits and the smaller exploitations can hire the larger tamis and fins.

Tab I.7: Cost comparison of water intake protection solutions for RO desalination plants (ACCIONA).

Various segments	Cost (Thousands USD)	
	Min	Max
Infiltration Galleries	200	500
Beach Wells	100	300
Fine Mesh Screens	100	200
Fish-Friendly Pumps	50	150
Havioral Deterrents	50	100
Coarse Bar Screens	50	100
Physical Barriers/Nets	25	50

I.3.4. Desalinated water production failures

The national program has advantages and a positive impact on improving the public water service, a number of technical problems have been identified due to technologies that are not adapted to the specific characteristics of the Mediterranean Sea. The quality of the seawater is often poor due to the high turbidity of suspended matter, which has often led to unscheduled shutdowns. This observation also applies to the nine plants, where the number of shutdowns reached the equivalent of 70 days during 2020 (i.e. almost 1680 hours), resulting in a shortfall in production to be delivered to the buyer of almost 14 631 651 million m³/day compared with installed capacity (figure I.11 below).

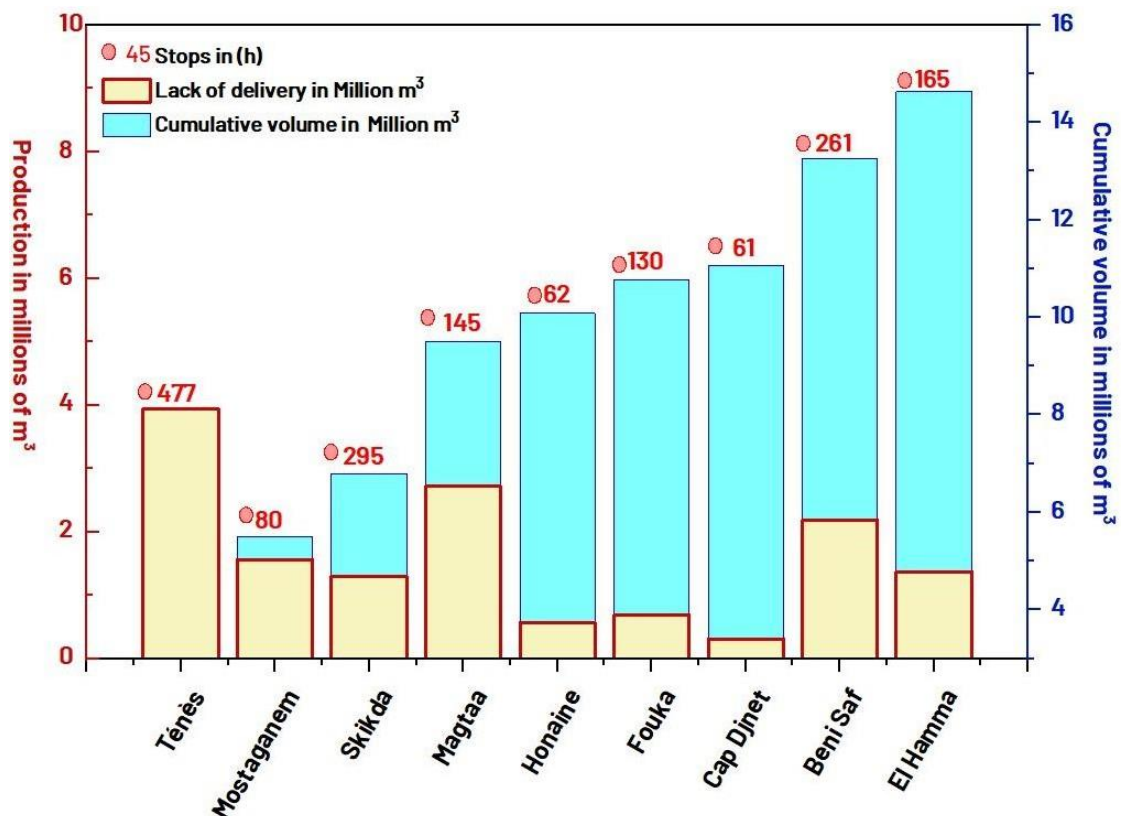


Fig I.11: Status of the SWDPs in operation during the year 2020 at the request of the project company (MRE, 2021)

The choice of sea intakes for some plants has been poorly chosen or badly designed (length of pipe and depth), as in the case of the Mostaganem, Tenes (Chlef), Souk Telta (Tlemcen) and Cap Djinet (Boumèrdes) desalination plants. Several faults in the design of UF pre-treatment basins, as in the case of the Souk Telta (Tlemcen) and Magtaa (Oran) plants.

Poor choice of sites closes to wadi outlets, which leads to an increase in raw water turbidity, causing the plant and drinking water production to grind to a halt. This is the case at the Souk Telta Souk Telta Souk Telta (Tlemcen), Tenes (Chlef), Hamma (Algiers) and Skikda plants. Pollution of the sea due to maritime traffic, as in the case of the Hamma (Algiers), Kahrama (Arzew-Oran) and Tenes (Chlef).

These inconsistencies have often led to problems and failures in O&M (Operate and maintenance) management, as in the case of the:

Magtaa (Oran) plant: since the plant was commissioned, it has been unable to guarantee production of 500 000 m³/d due to:

- Technical problems (breakdowns, unavailability of spare parts, failure of the Ultrafiltration system, etc.)
- Poor O&M management by the operator.
- Absence of a clearly defined curative or preventive maintenance strategy
- Lack of computer-assisted management at the maintenance unit of the operating company owned by Hyflux Operation & Maintenance Algeria (Homa Eurl).

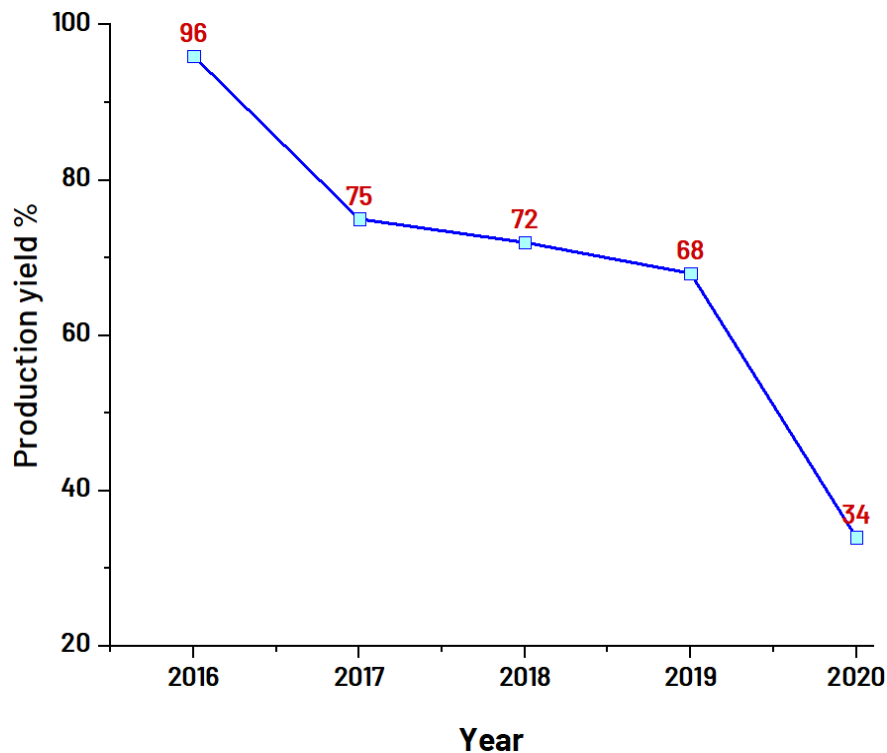


Fig I.12: Evolution of the decline in production yield of the El Magtaa desalination plant (MRE, 2020)

These recurring unscheduled stoppages have forced the water utility operator SEOR to resort to using surface water from the MAO system to ensure continuity of the drinking water service for Oran and Mascara. The second problem has been seen at the Souk Tleta desalination plant (Tlemcen), where, during commissioning from April 2011, it has seen a drop in production of between 68% and 80%. Recurrent stoppages have occurred since the desalination plant was commissioned on 13 April 2011.

The contractual clauses of the CVAE (purchase-sale agreement) in favor of Sonatrach have not been respected, and the partner companies in the project, Malakoff (Malaysia) and Hyflux (Singapore), both incorporated under French law as Tidic, have failed to operate and maintain the plant. On 22 October 2019, the desalination plant was irrevocably shut down as shown (Fig I.11).

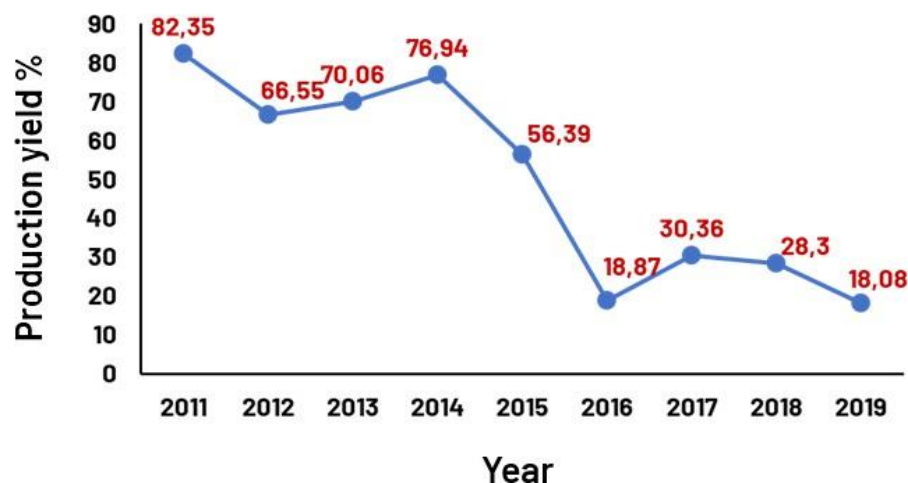


Fig I.13: Evolution of the decline in production yield of the Souk Tleta desalination plant (MRE, 2020).

The nature of the shut-downs at the Souk Tleta desalination plant is as follows:

- 740 hours due to poor seawater quality (high TSS) according to the Project Company.
- 459 hours due to plant maintenance operations scheduled by the project company (membrane cleaning and replacement).
- 68 hours due to power cuts (SONELGAZ).

The two figures below, follow a challenge who causes arrets at the plant, respectively show the number of days with agitation of swell each month for the years 1999 and 2002 at Kala region, a coastal station and the height significative maximum of waves (H_s). These data are essential for the ongoing and secure use of a desalination plant.

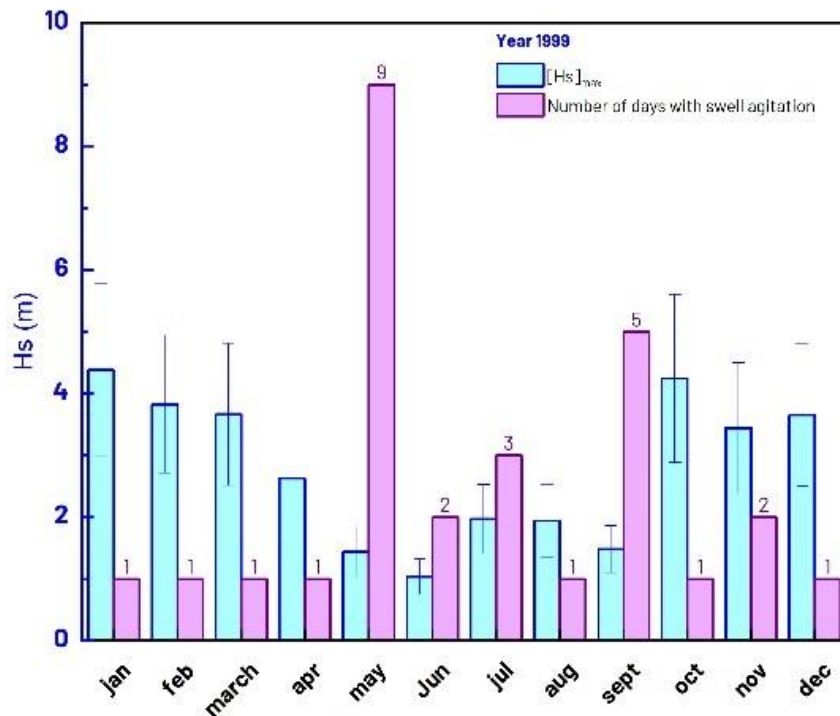


Fig I.14: Assessment influence on the continued exploitation of desalination plants, compile and complete the swell of Kala agitation data (NMSO).

The heights of swell are still generally moderate (between 1.5 and 4.5 m), with pic taken at 4.5 m in January and October. The exception of a few days in May (9 days), the number of days with a disruptive swell is low throughout the year (between 1 and 3 days). This implies that the use of a desalination plants would be steady for the most part of the year, with a mostly May risk of termination or malfunction.

The number of days disturbed is significantly higher in 2002 as shown next figure, with 12 days in February, 13 days in September, and many months with more than five days of disturbance (April, May, July, August, and November). This level of agitation would make plant stops more frequent and prolonged, particularly in the winter and fall, endangering the ongoing production of drinkable water.

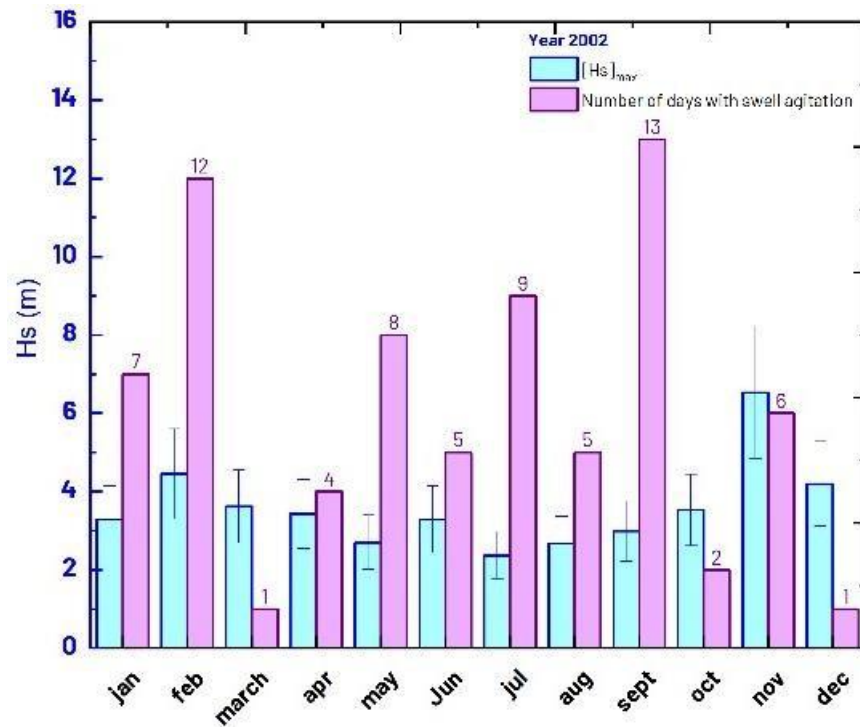


Fig I.15: Assessment influence on the continued exploitation of desalination plants, compile and complete the swell of Kala agitation data (NMSO).

Sporadic and localized disruptions. This demonstrates how crucial it is to consider interannual ocean conditions when estimating and using a coastal station.

Conclusion

According to local weekly daily development, the \$3 billion desalination expansion program in Algeria is a component of a \$5.4 billion project to strengthen the nation's capacity to supply drinking water as it deals with growing climate-related concerns.

The country's capacity to generate drinking water from the Mediterranean will raise from 2.2 million cubic meters per day to 3.7 million m³/day thanks to the new facilities. Algeria's desalination capacity will have grown to 5.8 million m³/day, with SWRO plants each of which can produce up to 300 000 m³/day of drinking water supplying 60% of the nation's drinking water.

The state-owned water distribution firm water Algerian will pay energy firm between 52 and 100 Algerian dinars/m³ (\$0.39 and \$0.76/m³) for the plant's operation (Muhsen, Projects [no date]). Moreover, all of these projects that provide a measurable return to cover needs are directly dependent on the wisdom of water based on in-depth research on the investment and exploitation costs of these projects' programmers.

CHAPTER II

ANALYSIS OF THE COSTS OF A DESALINATION PLANT PROJECT

Introduction

The difficulty is to provide sufficiently accurate costs without a case-by-case study that takes into account local technical and economic variables. The cost of energy is high in the MENA zone and extremely high for isolated areas. There may be no relationship between the cost price and the price paid by the customer after government subsidies in some cases (such as the French West Indies or Saudi Arabia) or the cost of chemicals after they have been manufactured locally or have had to undergo transport of varying lengths.

The fluctuations of currencies, in particular for the RO modules which come almost exclusively from the United States, and the variations in the value of the dollar currency make it impossible to communicate precise prices, and inflation varies according to the countries and the periods. Thus, the financing conditions and the cost of the primary operation, even in concrete cases, can be difficult to estimate and vary according to the distribution of costs between electricity and water (Benahmed et al., 2025).

II.1. Definition of Capital expenditure (CAPEX) and Operational expenditure (OPEX) costs

II.1.1. CAPEX

The relative reduction in unit costs increases with scale. As a desalination plant expands in size (water production capacity), the unit cost per cubic meter of generated water diminishes. Economies of scale result in the distribution of certain fixed expenses, like engineering studies, buildings, and electromechanical equipment, across a greater output. For instance, acquiring essential components like membranes or pumps in bulk can result in a lower price. Complexity increases with larger installations: Nevertheless, on a large scale, infrastructure expenses (water conveyance, connections, energy management) can escalate swiftly. The necessity for redundancy and resilience to prevent disruptions may incur additional expenses.

This document outlines the expenses related to the acquisition and setup of the infrastructure equipment and other capital assets needed for the plant's construction.

Usually, upfront payment for these expenses can result in a substantial financial burden (Fig II.1).

The facility's owner or operator must make a commitment. Include pumps, membranes, tanks, and piping as well as the cost of constructing the plant itself (Ghaffour et al., 2013).

- Installation costs: (30-40) %: site preparations, civil workers, piping and conduits.
- Equipment costs: (20-30) %: purchase of high-pressure pumps, energy recovery devices, membranes.
- Electrical and control system: (10-15) %.
- Infrastructure costs: (15-20) %: include the construction of a desalination plant's building, site security and fencing, and power supply line.
- Design costs: (10–15) %: development of layouts and equipment specifications, detailed engineering drawings and construction plans.

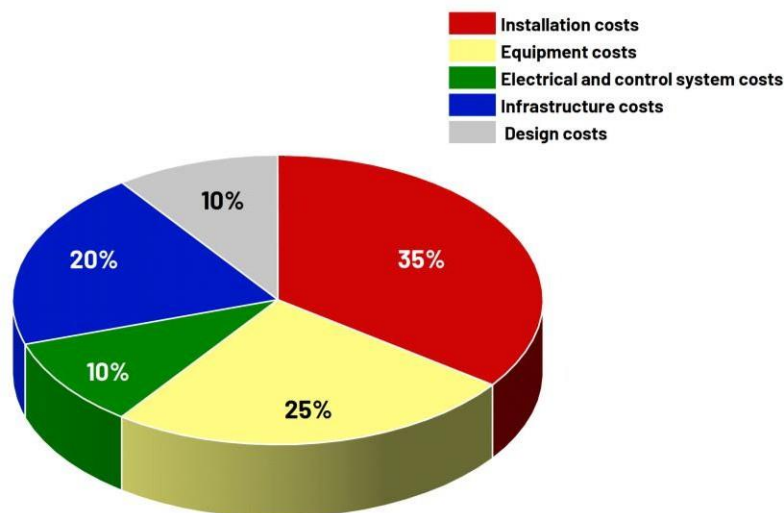


Fig II.1: Average ratios of the different CAPEX segments (Ghaffour et al., 2013).

II.1.2. OPEX

Larger installations frequently have reduced unit operating costs due to enhanced energy efficiency, streamlined procedures and centralized maintenance. Energy recovery technologies such as pressure exchangers in RO exhibit greater efficiency at bigger scales.

Variable costs that are proportional include energy expenses, which constitute a substantial component. These costs escalate with scale. However, the energy efficiency of larger facilities can mitigate this. Maintenance and management for larger stations need specialized

staff and more intricate logistics, potentially elevating fixed operational expenses. Nonetheless, these expenses are mitigated by heightened productivity.

Refers to the ongoing costs associated with the plant's daily upkeep and operation (Cf. Annex II.1). In order to maintain the plant's smooth operation and optimal performance, these expenses are necessary to keep it operating, providing fresh water, and maintaining its operations as chemicals, labor, energy consumption and consumables like filters (Fig II.2).

- Energy costs 35-45%: electric diesel or other fuels (pumps, compressors...)
- Labor costs 15-25%: wages and salaries for plants operators, technicians, maintenance staff, development programs with up to technicians.
- Chemicals 5-15%: anti-scalents, coagulant.
- Maintenance 5-15%: include replacement, worn or damaged equipment/piping or valves, regular inspections, cleaning membranes and filters.
- Membrane replacement: 5-10%

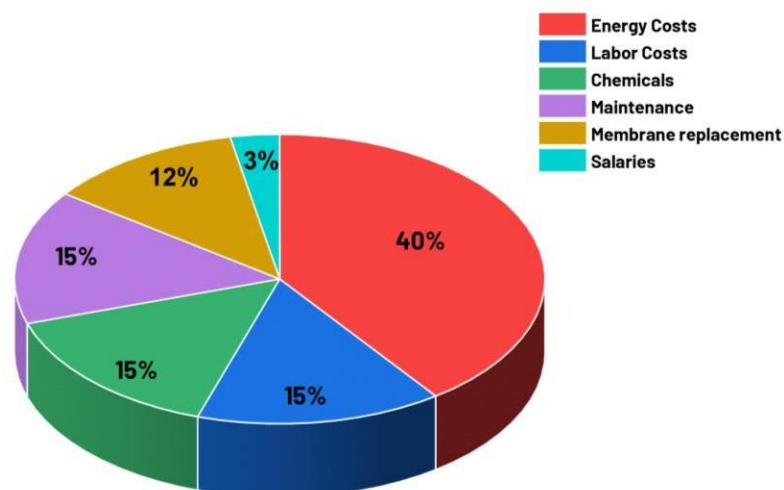


Fig II.2: Average ratios of the different OPEX segments (Ghaffour et al., 2013).

Unless there are no other options, small desalination plants are less appropriate for large scale water delivery due to their much higher cost with a minimum cost of about 0.6 \$/m³ and a maximum cost of 0.8 \$/m³. Very big units have the lowest cost per cubic meter has increased moderately with average units ranging from 1.0 to 1.5 \$/m³. Compared to saltwater desalination, big units that treat brackish water are substantially less expensive with prices ranging from 0.2 to 0.5 \$/m³ (Maurel, 2006).

Tab II.1: The cost of desalinated water on MENA area (*Astee* [no date]).

	Average CAPEX (\$ Billion)	Average OPEX unit (\$/m³)	Average Total water cost unit (\$/m³)
Thermal distillation (type MSF)	1.4	0.22	1.19
Reverse Osmosis (Mediterranean Basin)	1.02	0.30	0.83
Reverse Osmosis (Middle East)	1.27	0.54	1.15

Significant differences in investment, and overall water production costs are shown by the cost analysis of desalination methods. The capital-intensive character of MSF is demonstrated by its maximum investment cost of 1.4 \$Billion. In the Mediterranean Basin on the other hand RO turns out to be the most economical choice. Its moderate operating cost of 0.30 \$/m³ results in a total desalination cost of 0.83 \$/m³ as overall cost. However, is 1.15 \$/m³ in the Middle East due to a larger investment and noticeably higher operating expenses of 0.54 \$/m³. These variations imply that although RO is often less expensive, its total cost-effectiveness is impacted by geographical variables like infrastructure and energy prices.

Tab II.2: Water production costs of different size SWRO desalination Plants (Voutchkov., 2018).

Classification	Cost of Water (USD/m³)
Low-end plant	0.5–0.8
Medium range	0.9–1.5
High-end bracket	1.6–3.0
Average	1.1

The cost for each cubic meter of water treated can fluctuate between 0.60 and 3.00 \$. The cost per liter of water is about 0.0005 to 0.001 USD is relatively low, but it remains a table that cannot be ignored in mass production, so OPEX remains a constant concern throughout the

life of a desalination plant. This statistic highlights the need for long-term cost planning in the study of reverse osmosis seawater compared to hybrid systems.

According to (*accueil* [no date]), the economic costs of desalination are continuously rising; from 2018 to 2045, the average annual rise in CAPEX and OPEX expenses was 6.3% and 3.75%, respectively. With an average yearly rise of 18.66% for CAPEX and 7.96% for OPEX during the same time, the observation is even more noteworthy in the Mediterranean, which includes nine riparian nations (Spain, Cyprus, Turkey, Egypt, Israel, Morocco, Algeria, Tunisia, and Palestine).

II.2. Investment and operating costs

The variation in CAPEX and OPEX as a function of the size of a desalination plant generally follows characteristic trends influenced by economies of scale and operational complexity as shown table below.

Tab II.3: Comparative Table for three desalination technologies (Wilf and Awerbuch., 2007) and (Voutchkov, 2013).

	Processes		
	RO	MED	MSF
CAPEX	Generally lower than for MED and MSF, as the process relies mainly on equipment such as membranes, high-pressure pumps, and energy recovery systems. Installation costs are reduced and economies of scale are significant for large capacities.	Higher than for RO, as it requires a more complex infrastructure: several condensation/evaporation stages, heat exchangers and piping. Economies of scale are important for large installations, but initial fixed costs are significant.	Generally, the highest of the three processes, as it requires a massive and robust infrastructure to withstand the high pressure and high temperature conditions. Economies of scale are significant, but the unit cost remains higher than for MED and RO.

OPEX	Dominated by energy costs, as reverse osmosis uses high-pressure pumps to push water through semi permeable membranes. Modern systems incorporate energy recovery devices, which reduce OPEX. Maintenance costs (membrane replacement, cleaning) increase with the size of the installation but remain relatively low.	Lower than for MSF and comparable to RO in certain configurations. Energy consumption is mainly thermal, and energy efficiency is better than for MSF thanks to optimized use of heat (steam used in several cycles). Maintenance costs are linked to salt deposits on the thermal equipment, but these are manageable.	The highest of the three processes, because it consumes a lot of thermal energy (steam) and electricity (pumps for the large quantities of water to be heated and cooled). Maintenance is complex and costly, as MSF systems are subject to high thermal and mechanical stress.
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Depending on the necessary equipment and energy consumption, the choice of desalination technology has a significant impact on costs. Two of the most often used technologies are RO and MED.

The MED technology uses thermal energy to evaporate seawater, requiring equipment like boilers, heat exchangers, and pipelines. This results in higher investment costs but also better fouling resistance and greater component durability (Al-Karaghoul et Kazmerski., 2013).

Conversely, RO uses semi-permeable membranes and high-pressure pumps which lowers energy consumption but necessitates periodic membrane replacement, which affects operating costs (Gude., 2016). The following table provides a detailed comparison of the costs in terms of original investment, maintenance, and energy use.

Tab II.4: Comparative table of daily CAPEX and OPEX: MED vs RO.

Segment	MED	RO
Daily CAPEX (\$/m³/day)	1200-2000 \$/m ³ /day	800-1000 \$/m ³ /day
Main Equipment	55-60% (Boilers, heat exchangers, pipelines)	60-70% (Pumps, membranes, filtration systems)
Construction & Civil Engineering	25-30%	20-25%
Design & Engineering	10-15%	10-15%
Other Costs (Contingencies)	5-10%	5-10%
Total CAPEX (example)	1500 \$/m ³ /day 75 M\$ (50 000 m ³ /d)	900 \$/m ² /day 45 M\$ (50 000 m ³ /day)
OPEX (\$/m³)	2.0-2.5 \$/m ³	0.5-1.0 \$/m ³
Energy	75-85% (~1.85 \$/m ³ : thermal + electric)	50-60% (~0.3 \$/m ² : electric only)
Maintenance	10-15% (0.15-0.25 \$/m ³)	20-30% (0.15-0.25 \$/m ³ : membranes)
Consumables	5-10% (-0.10 \$/m ² : Anti-Scalants, chemicals)	10-15% (-0.10 \$/m ³ : Antifouling, cleaning)
Labor and management	0.1-0.2 \$/m ³ (~5%)	0.05-0.1 \$/m ² (~5%)
Total OPEX (example)	2.1 \$/m ³ (50 000 m ³ /d)	0.8 \$/m ³ (50 000 m ³ /d)

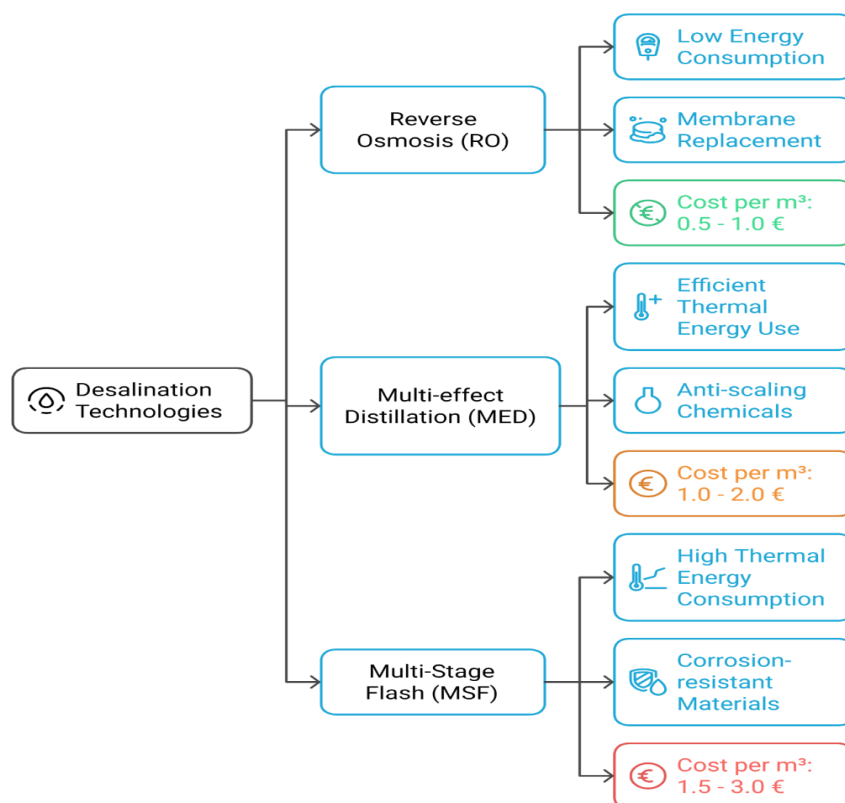


Fig II.3: Comparative synthesis of desalination processes: RO, MED and MSF.

While MED maximizes the use of thermal energy but requires the use of anti-incrusting products which cost between 1.0 and 2.0 \$/m³, RO stands out for its low energy consumption but requires periodic membrane replacement. MSF uses corrosion-resistant materials, although they have a high thermal consumption.

Tab II.5: Comparative summary of the different desalination processes.

Property	RO	MED	MSF	FO	MD	TVC	MVC
CAPEX	Low to Moderate	Moderate to High	Very High	Low to Moderate	Moderate to High	High	
OPEX	Moderate (Elect)	Moderate (Heat)	High (Heat +Elect)	Low to Moderate (Elect)	Moderate (Heat+ Elect)	High (Heat)	High (Elect)
Economie of Scale	Significant			Moderate	Low	Moderate	

Maintenance	Membrane Replacement	Thermal Deposits	Heavy	Membrane Fouling	Scaling and Fouling	Thermal Deposits	Compressor Maintenance
Comparative summary of OPEX							
Electrical Energy kWh/m³	3-5	1.5-2 elect + steam	3-5 elect + steam	1-3	2-5 elect + heat	2-4 elect + steam	7-12
Consumables	Membrane	Anti-scalants		Draw solutions, Membrane	Anti-scalants, Hydrophobic membrane	Anti-scalants	
Maintenance	Moderate (membrane replacement)	High	Very high	Moderate (membrane fouling)	Scaling and Fouling	Thermal Deposits	Compressor Maintenance
Service Life	7-10 years (membranes)	20-25 years (equipment)	20-30 years (equipment)	7-10 years (membranes)	10-15 years (membranes)	20-30 years	15-25 years

Two parties may cancel the specific investment (in USD per square meter/year of installed capacity):

- cost of the factory itself, this is equivalent to the cost of the desalination plant built on a site where electricity and vapor are available, with the exception of the small distillation units where a vapor generator is included.
- costs incurred by the owner.

This portion of the investments includes preliminary studies and consulting fees, potential land purchase and site development (civil engineering, access route, fences, etc.) and the extraction of seawater (pumping, gross filtering, chlorination...). In order to produce 1 m³ of soft water, 10 m³ of seawater must be pumped, the saltwater rejects must be located sufficiently far

from the seawater intake. These include piping and the storage of soft water; stores for out-of-town and detached parts as well as a game of exchangeable parts on the beginning of the business and staff training. It may be extremely low for a factory that is built on an existing industrial site and high on an infrastructure building site.

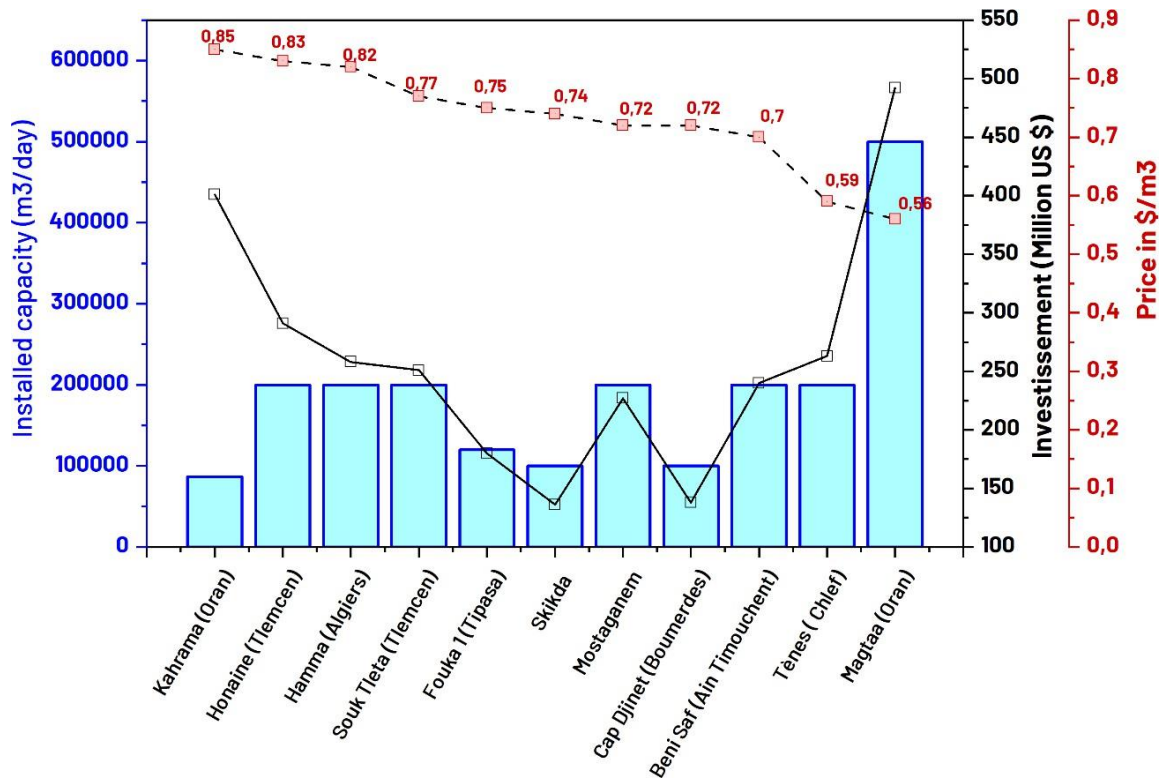


Fig II.4: Investment expenditures and water costs according to the capacity of Algeria stations (MRE, 2020)

The decreasing trend is well observed: the more installed capacity increases, the more the unit cost (\$/m³) decreases, thus confirming the scale effect. By looking at the stations of 200 000 m³/d around 227M\$-250M\$ and 500 000 m³/d (459M\$) with cost of: For 200 000 m³/d (0.5885\$-0.8299\$) and 500 000 m³/d is approximated 0.5577\$.

II.3. Modeling costs based on production

Depending on the plant's size, mechanism, and operating regime, the power, raw fluid, and reagent consumption, among other statistics, varied. The plant was automated, using an industrial computer and many programmable logic controllers (PLCs) for effective management.

Huehmer., 2011 affirmed that the costs of investing in seawater desalination facilities, along with related experimental cost models, it examines several cost estimating techniques, such as empirical and parametric models. The authors look at a number of commercially available computerized cost models, including WTCost II, GWI SWRO Cost Estimator and CH2M HILL CPES. Among the most often used cost models created with support from the US Bureau of Land Reclamation. The model was presented in the "Desalination Guide for Planners" and includes historical data, salt water reverse osmosis systems, nanoscale filtering, and sea water desalination using reverse osmosis (Fig II.5)

The model also includes experimental curves for thermal processes. There have been several other experimental cost models released in the literature. We frequently examine these models - a semi-logarithmic model, a logarithmic-logarithmic approach, or a multi-boundary formula.

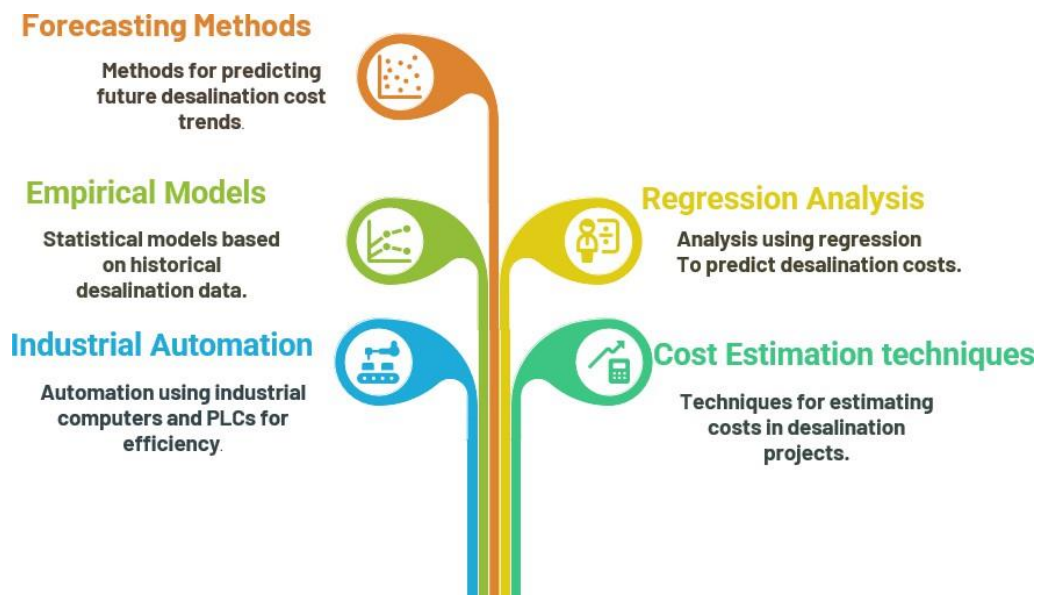


Fig II.5: Schema explaining the cost estimating models in seawater desalination.

Desalination Handbook for Managers discusses cost estimation techniques used in seawater desalination. Empirical cost models, which are based on statistical evaluation and curve fitting of past data usually use capacity as the primary variable.

- Zhou and Tol, 2005 used regression analysis to construct a total water cost model from 2514 data points. The model derived was in general form: Equation log-log and semi-log forms were analyzed. The regression analysis accomplished a fit with a R^2 of 0.72.
- Dore, 2005 used an auto-aggressive integrated moving average model to forecast the change in desalination unit costs over time. The model was applied to historical desalination unit cost data. Total water cost for desalinated water is between \$0.25/m³ and \$0.71/m³.
- Analyzed desalination cost data collected from a wide variety of sources including surveys, reports, and published journals spanning a period of 35 years. Using 90 sets of BWRO data and 112 sets of SWRO data, linear regression using least squares was completed to fit data to power (Fig II.6).

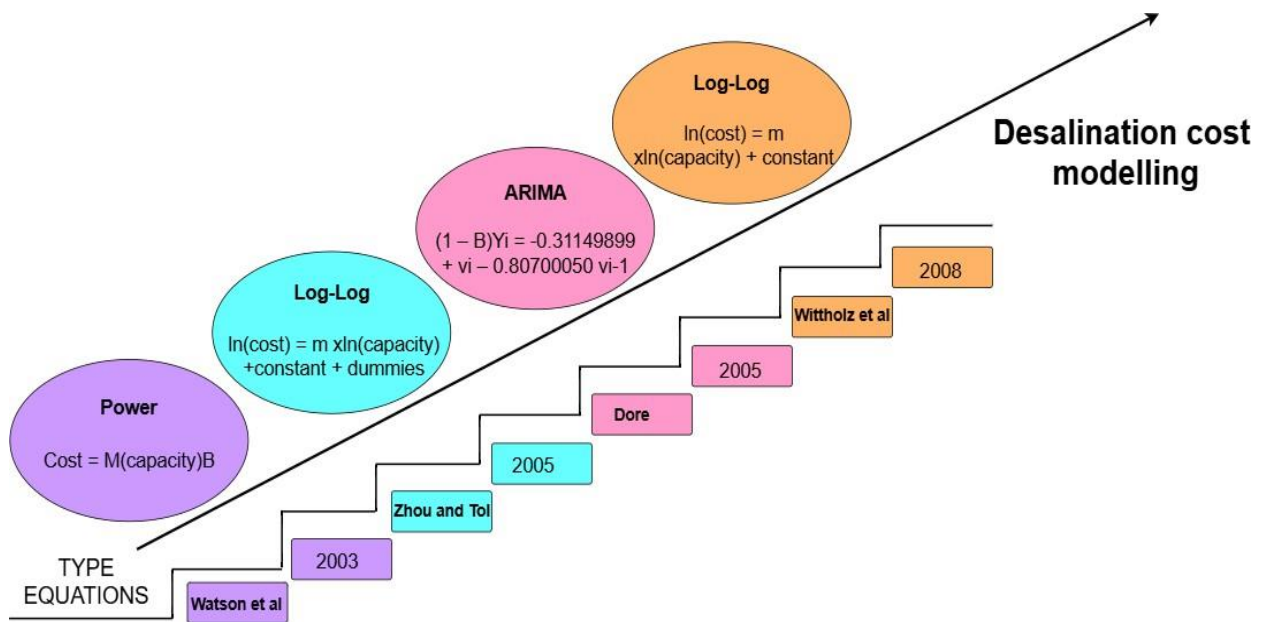


Fig II.6: Illustrative diagram of empirical models of CAPEX calculation for the reverse osmosis process.

Wittholz et al., 2008 examined data on desalination costs gathered from a variety of sources including published reports, studies and reviews during 35 years. The data was normalized to 2006 with the use of cost indices. Using 90 BWRO data sets and 112 SWRO data sets, a linear regression using least squares was performed to adjust the data to the law of power.

The subsequent formula illustrates what was found empirical correlation based on the examples of precedent 11 stations:

$$\ln (\text{Capital cost}) = m \ln (\text{Capacity}) + \text{constant} \quad (\text{II.1})$$

II.4. Basic formula for calculating daily CAPEX

c- Daily CAPEX (\$/m³/day)

Is obtained by dividing total CAPEX by an estimate of the plant's lifetime and taking into account the interest rate, if applicable. A simplified formula is as follows:

$$\text{Daily CAPEX} = \frac{\text{CAPEX Total}}{\text{Production (m}^3/\text{ days)}} \quad (\text{II.2})$$

In more precise calculations, a discount rate (or interest rate) is also included to reflect the time value of money:

$$\text{Daily CAPEX} = \frac{\text{CAPEX Total. Annuity factor(A)}}{\text{Production (m}^3/\text{ days)}} \quad (\text{II.3})$$

Where:

Annuity Factor: The annuity factor (or annual depreciation factor) is a financial coefficient used to convert an initial investment (CAPEX) into equivalent annual payments over the life of a project. It is used to estimate how much the capital investment (CAPEX) represents per year, taking into account the interest rate (or discount rate) and the life of the equipment.

Calculated from the interest rate and lifetime according to:

$$A = \frac{i(1+i)^n}{(1+i)^n - 1} = \frac{0.05(1+0.05)^{25}}{(1+0.05)^{25} - 1} \quad (\text{II.4})$$

Where,

i = interest rate (e.g., 5% or 0.05).

n=25 years = plant life time.

d- Unit amortised CAPEX (\$/m³)

$$\text{Unit CAPEX} = \frac{\text{Daily CAPEX}}{\text{Total life time (in days)}} = \frac{\text{Daily CAPEX}}{365 * 25} = \frac{\text{Daily CAPEX}}{9125} \quad (\text{II.5})$$

Where unit CAPEX is the unit amortised CAPEX.

II.5. Basic formula for calculating OPEX

II.5.1 OPEX Annual

The OPEX depends on the inputs of the type of desalination process.

Because of the ongoing advancements made to cut the cost of producing water and minimize energy usage, RO performs better techno-economically than these technologies. Although the majority of publications claim that RO is the least costly method of recovering fresh water, most studies fail to account for the impending increases in energy costs. In contrast to thermal procedures which may more easily use waste heat or solar thermal energy since RO is exclusively dependent on electricity to function.

$$\text{Annual OPEX}(\$) = 365 * (C_E + C_M + C_S + C_R + C_O) \quad (\text{II.6})$$

With,

C_E : Energy costs , $C_E = (0,40) * A.OPEX$;

C_M : Maintenance costs , $C_M = (0,15) * A.OPEX$

C_S : Staff costs , $C_S = (0,15) * A.OPEX$;

C_C : Chemicals costs , $C_C = (0,15) * A.OPEX$

C_R : Membrane/ Distiller replacement costs, $C_R = (0,10) * A.OPEX$;

C_O : Other costs, $C_O = (0,05) * A.OPEX$

II.5.2 OPEX Daily

$$\text{Daily OPEX } (\$/j) = \text{Annual OPEX}(\$) / 365$$

II.5.3 OPEX Unit

$$\text{Unit OPEX } (\$/m^3) = \text{Daily OPEX}(\$ / m^3) / \text{Daily Production}$$

II.5.1.1. Energy costs

Energy type, local rates and system efficiency all affect desalination energy costs, which differ greatly throughout technologies. The high reliance on electrical power in (RO). Operating expenses are greatly decreased in Algeria by the cheap energy rates brought on by the country's plentiful natural gas (around 0.03\$/kWh as opposed to 0.10\$/kWh in Europe). On the other hand, important elements such excessive salinity (>35 g/L) can elevate pretreatment costs by 10% to 20% and energy consumption also (Sassi et al., 2010). Raw water of high turbidity quality leads to additional costs for reagents in the pre-treatment phase. Therefore, the total cost-effectiveness of a desalination plant is greatly influenced by energy costs and technological efficiency depending on the number of effects.

The cost of (MED) is determined using thermal energy needs that range from 30 to 70 kWh_{th}/m³. The method consumes 1.5 to 3 kWh/m³ of power for pumping, while heat from residual sources can cost as little as 0.02 to 0.05 \$/kWh_{th} with an energy cost, MSF demands considerably more thermal input because of its flash mechanism. Due to steam recycling by mechanical or thermal compression, energy consumption in VCD is relatively reduced. Energy expenses include both thermal and electrical components.

➤ For Reverse Osmosis (RO)

With estimates ranging from 3.8 to 12.6 trillion USD, the method that uses a membrane to filter the sediments and impurities from seawater under pressure and is thought to be effective for desalination is seen as crucial for the next decades (Eyl-Mazzega et al., 2022).

$$\frac{\text{Electricity consumption(kWh/m}^3\text{)} * \text{Electricity prices(\$/kwh)}}{\text{System efficiency(\%)}} \quad (\text{II.7})$$

➤ For Multi-Effect Distillation (MED)

Thermal Energy Requirement:

$$\frac{\text{Thermic consumption(kWh}_{th}\text{/m}^3\text{)} * \text{Heat Prices (\$/kWh)}}{\text{Thermic Efficiency(\%)}} \quad (\text{II.8})$$

- Thermal requirement (30–70) kWh/m³, depending on the number of effects.
- Heat price (0.02–0.05\$/kWh if residual heat).
- Thermal efficiency (60 – 85%).
- Electricity for pumps (1.5 –3 kWh/m³)

➤ **For Multi stages flash (MSF)**

The MSF process requires more heat energy due to the sudden flash because it is heat-intensive with more pumps (3–5 kWh/m³) to maintain the pressure stages.

➤ **For Vapor Compression Distillation (VCD)**

As the VCD process uses mechanical or thermal compression to recycle the steam it reduces energy consumption compared to the MSF process. The OPEX of energy consumption is composed of two energies: electrical (Equation II.7) and thermal (Equation II.8).

In terms of cost, the dominant energy consumed in MSF is thermal heat representing (3-5)% of the total CAPEX. On the other hand, in the VCD process the dominant energy is electrical, representing (5-7) % of the total CAPEX (El-Dessouky et al., 2002)

II.5.1.2. Maintenance

$$Maintenance = Pourcent\ of\ CAPEX_{annual} \times \frac{CAPEX_{Total}}{Annual\ Capacity\ (m^3)} \quad (II.9)$$

II.5.1.3. The Staff

$$Staff = \frac{Staff\ number \times Average\ annual\ salary}{Annual\ capacity\ (m^3)} \quad (II.10)$$

II.5.1.4. Chemical products (Pre-treatment/cleaning)

$$Chemicals = \sum [Products] / Kg \quad (II.11)$$

- VCD For chemical products such as the MSF process, but reduced requirements (less scaling)

II.5.1.5. Replacement of the membranes / Distiller

$$Membranes = \frac{Membrane\ numbers \times Unit\ price(\$)}{Lifetime(year) \times yearly\ production(m^3)} \quad (II.12)$$

Cost of RO membranes: ~100–150 USD/m² (replacement every 5–7 years) and for distiller's replacement every 25 years.

II.6. Total Water Cost (TWC)

For an accurate estimate of total unit cost, it is more accurate to write the following relationship:

$$TWC \left(\frac{\$}{m^3} \right) = Unit\ amortised\ CAPEX \left(\frac{\$}{m^3} \right) + Unit.OPEX \left(\frac{\$}{m^3} \right) \quad (II.13)$$

II.7. Adaptation with renewable energies

The integration of renewable energies (solar thermal, photovoltaic, wind) in a desalination plant allows significant gains on CAPEX and OPEX, although these gains vary depending on the technologies and the local context. Regarding CAPEX, additional initial costs include solar photovoltaic panels (500-800\$/kW to power the RO), solar thermal collectors for the MED (200-400\$/m²) and storage systems like batteries or thermal storage approximate to 15-25% additional cost (Miklyayev et al., 2022).

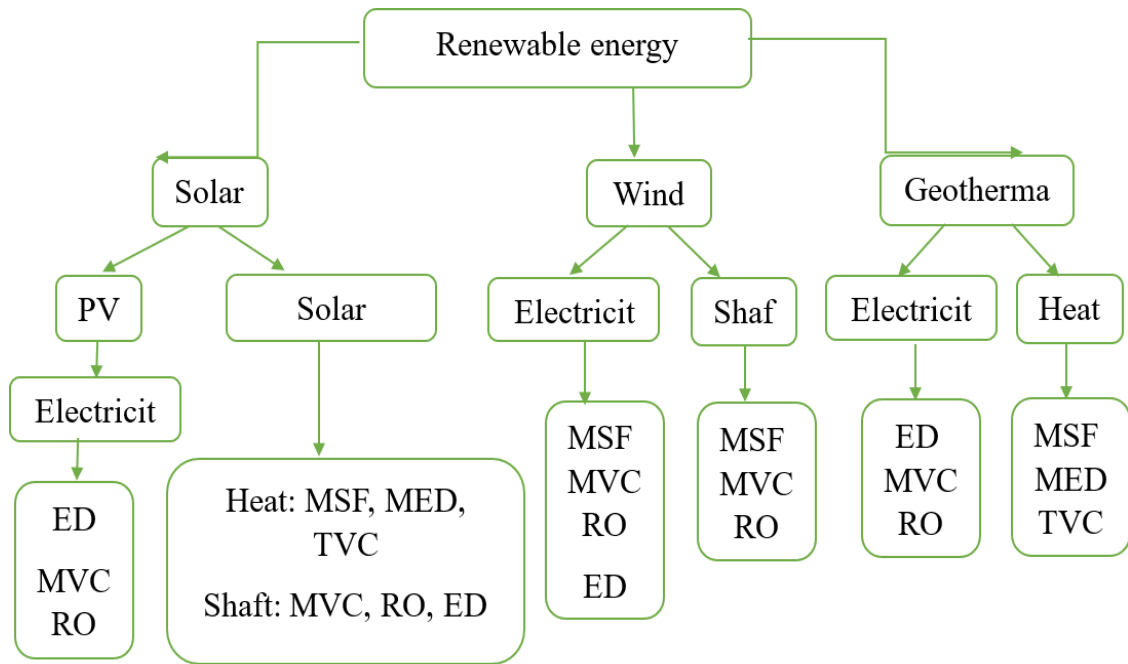


Fig II.7: Integration of renewable energies of RES with desalination technologies (Eltawil et al., 2009)

For example, the NEOM project in Saudi Arabia enabled a 20% reduction in CAPEX thanks to local synergies (*Home* [no date]). Regarding OPEX, renewable energies allow for a significant reduction in energy costs: electricity for RO can be reduced to 0.02–0.05\$/kWh while the cost of heat for MED can drop to 0.01–0.03\$/kWh (compared to 0.03–0.06\$ with gas). For a 300 000 m³/d plant, this translates into a 25–40% reduction in OPEX, with annual savings on the electricity and heat bill of up to 30–60%. Although, maintenance costs for solar systems (cleaning, batteries) are slightly higher, they remain stable in the long term, without fluctuations in gas prices (Riera et al., 2022). In Algeria, with 2500 kWh/m²/year of sunshine, the payback period can vary from 5 to 10 years with an estimated return on investment of 7 years. Additional benefits include energy independence, reduced geopolitical risks related to gas prices, and environmental sustainability with a carbon footprint reduction of up to 70%, projects can access international financing to support the energy transition such as the Green Climate Fund (Ahmed et al., 2019; Bundschuh et al., 2021).

Desalination stations that use the distillation by VC technology are often smaller than those that use processes like RO or MED. The main applications for VCD installations are in industrial or offshore settings where their energy efficiency and compatibility are very beneficial. In general, VCD stations are smaller than large MED or RO facilities we can find station of AI Zawrah in Ajman, Emirates Arabs unis with 6 000 m³/day. For instance, the Arabie

Saoudite station Rabigh, which uses RO technology, has a 600 000 m³/day. Additionally, the Shuaiba station in Saoudite Arabia uses MED technology to reach a capacity of 92 000 m³/day.

The largest known VCD units reach about 76 m³/h equivalent to 1800 m³/day is example of the company MECO offers industrial VCD systems.

CAPEX VCD is overhead compared to MED and OPEX by adding a higher factor that might reflect inefficiencies on a large scale, such as for small capacities, VC remains competitive and for large capacities and becomes more expensive than MED when Plan bleu affirmed that the average annual increase in CAPEX was 18.66%, which is significant and shows a growing trend in the need for investments in desalination infrastructures. CAPEX approximated 3060/m³ for MED technology in Chypre, while OPEX grew more moderately, increasing by 79.96% annually. This can be explained by rising energy costs and maintenance requirements. OPEX can vary widely, ranging from 134 /m³ in Algeria RO to 930/m³ à Chypre for MED.

II.7.1. Comparative scenarios

Al-Hotmani et al., 2020 present the novel idea of an integrated desalination system that combines (MED) with (TVC) and (RO). The goal of integrating two or more processes is to overcome the shortcomings of individual processes and create high-performance systems. Thermal processes like the MED-TVC are energy-intensive and generate a lot of sulfur. Membrane processes such as RO suffer from low productivity, entrapment, and encrassment issues. The goal of integration is to resolve these inconveniences, the studies foundation is a straightforward integrated system called MED-TVC and Reverse Osmosis at Reprocessing of Permeate (RORP), which was previously created and verified by the same authors. This basic system has shown low salinity of the produced soft water and low specific energy consumption, but it has also shown low productivity and a significant loss in retention in two cases:

1. The initial idea combines two RO processes of the Permeate Reprocessing type (PRRO+MED - TVC+PRRO) with MED-TVC.
2. The second idea combines the MED-TVC with two RO processes: one of the types Retentate Reprocessing and another of the type Permeate Reprocessing (PRRO+MED-TVC+RRRO).

Tab II.6: Comparison of performance of hybrid configurations (Al-Hotmani et al., 2020)

Hybrid configurations	PRRO+MED-TVC+PRRO	PRRO+MED-TVC+RRRO
Productivity	Increased productivity by approximately 8.96%	Approximately 9.65%
Freshwater salinity	It went from 10.882 ppm for the base case to 38.474 ppm	278.667 ppm
Discharge flow (brine)	Reduction in the total discharge flow of 5.07%	Reduction in the total discharge flow of 5.46%
Total water recovery rate	Improvements to 9.15%	9.8%
Total specific energy consumption	Consumed 14.250 kWh/m ³ , representing a negligible energy saving of 0.29% compared to the base case (14.295 kWh/m ³)	Showed a 9.85% increase in specific energy consumption (15.704 kWh/m ³), which is a disadvantage for this design.

According to Feria-Díaz et al., 2021 depending on the energy requirements and the availability of renewable resources, the hybrid RO configuration with MED or MSF can reduce the specific energy consumption to approximately 14.51 kWh/m³ of produced water and a high recovery rate, for instance up to 36.03%. Some hybrid configurations achieve a recovery rate of 92% for pure water production and a thermal efficiency of 79.2% with optimized treatment ratios between 1 and 10.

As shown Figure 8, over a long service life of 05 to 25 years, the two given graphs provide important insights into the (OPEX) patterns of three desalination system configurations. The curves show that the RO is less expensive but varies due to replacements (all 5 years). The MED is more steady but more expensive were hybrid system offers a better technical-economic compromise and fits an intermediate.

In the near term, RO is cost-effective since it has the lowest OPEX is 0.75 USD/m³. However, rises dramatically as the system matures because to membrane fouling, increasing energy use and increased maintenance requirements by year 25, it has risen to nearly 7.5 USD/m³. MED, on the other hand, benefits from constant thermal performance and system endurance, maintaining a stable OPEX (2 USD/m³). In the long term, the hybrid design is more

economically viable since it includes the benefits of both technologies and exhibits a more gradual cost increase over time, starting with an intermediate OPEX (1.1 USD/m³).

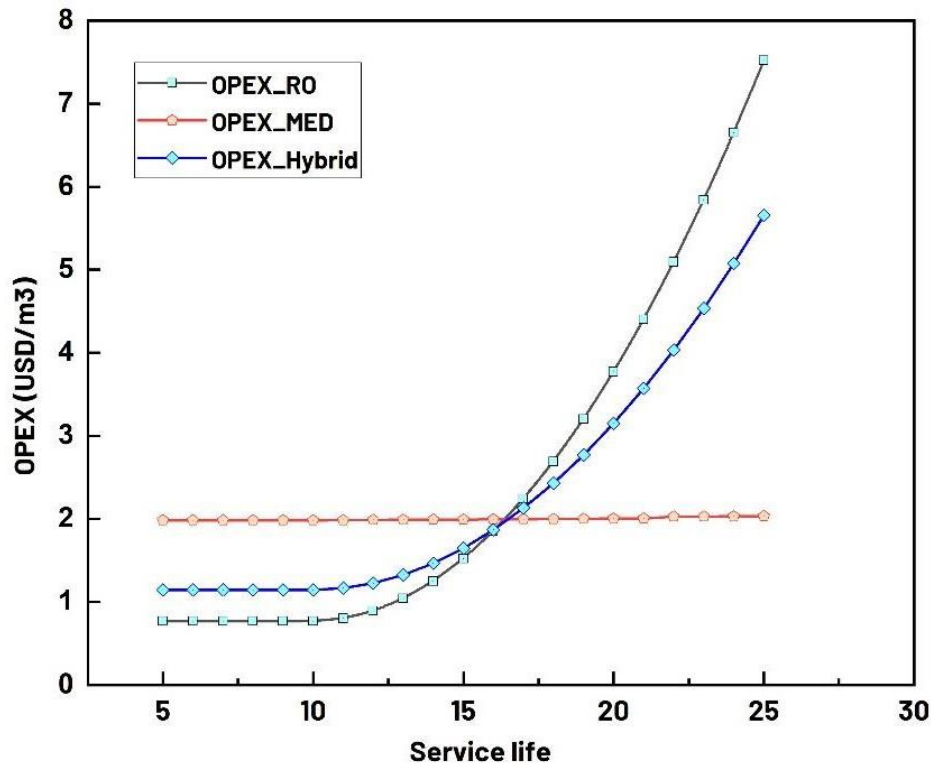


Fig II.8: Changes in OPEX for desalination systems with service life

The next graph, which compares the OPEX of the hybrid system with RO, confirms that although RO is less expensive in the beginning, the cost advantage ends at year 15. The cost-effectiveness of hybrid systems increases after this, and by year 25, savings are close to \$2 USD/m³. This change highlights how crucial it is to take the entire lifetime into account when choosing a desalination system. hybrid systems offer a mix of cost, dependability, and operational sustainability, particularly in long-term infrastructure planning where stability and resilience are critical, whereas RO is best suited for short-term or budget-constrained projects.

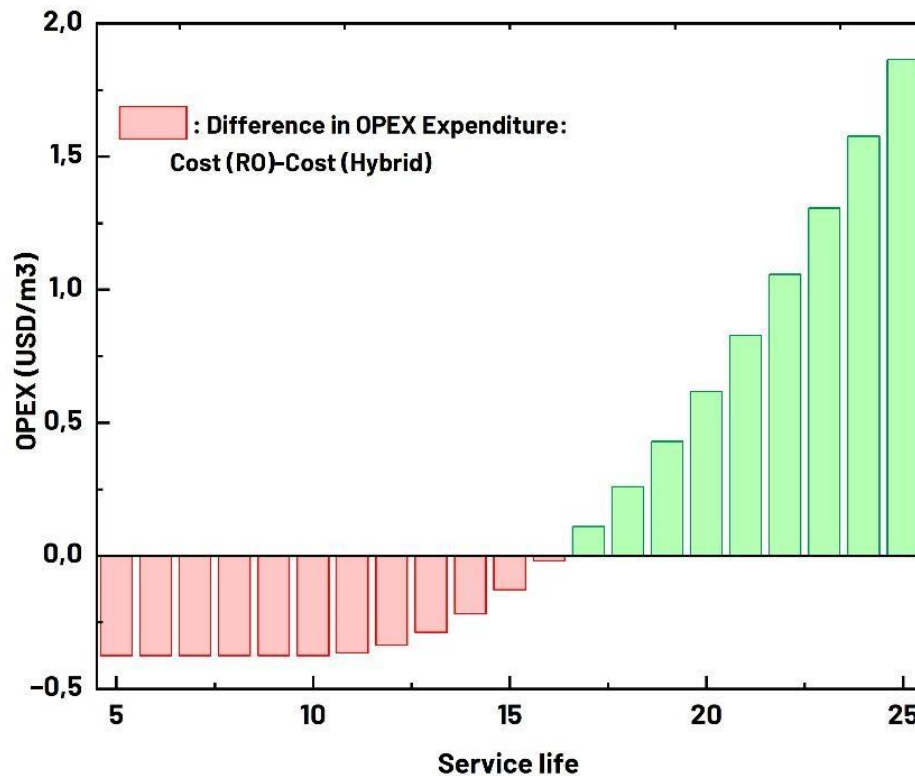


Fig II.9: Over time, the OPEX cost difference between hybrid and RO desalination systems.

Then, photovoltaic uses solar panels (silicon cells) to directly convert solar light into electricity. For example, a solar updraft tower uses solar heat to heat air in a giant serre that rises into a high path, creating a current of air that turns a turbine to generate mechanical electricity.

Tab II.7: Photovoltaic vs solar chimney uses as renewable energy

(What is build-operate-transfer (BOT) | Learn how build-operate-transfer models work | Build-operate-transfer examples and benefits 2025)

Aspect	Photovoltaic	Solar chimney
Energy type	Direct electricity	Thermal energy → mechanical
Efficiency	15–22%	1–3%
Space requirement	Moderate	Very large (chimney + greenhouse)
Complexity	Low (PV installations)	Medium to high
Maturity	Very mature	Not widespread, few actual projects

A RO/MED hybrid plant that uses renewable energy sources enables: A 25–40% decrease in OPEX, 5–20 years for amortization due to Algerian sunlight assure sustainable energy and water security.

As shown table below an RO desalination with capacity of 2016 l/d for brackish water was installed at the solar energy development unit (SEDU) in Tipaza, Algeria. Two scenarios are compared: one that is powered by the electrical grid (On-Grid) and the other that is powered by an autonomous photovoltaic system (Off-Grid) that consists of solar panels, batteries and an inverter. According to the results, the Off-Grid system's cost leveled of water (LWC) is 0.33 \$/m³, which is 14% less than that of the On-Grid system 0.38 \$/m³. It also has a higher financial rentability.

Tab II.8: Comparison of simulation results (Adda et al., 2024)

Project	Technologies	CAPEX (USD/m ³ /day)	Unit OPEX (USD/m ³)	Energy Gains
Algeria – Tipaza (SEDU)	RO + PV (Off-Grid)	13,610	0.33	Diminution of OPEX by 14% vs On-Grid system
	RO + Grid (On-Grid)	11,220	0.38	

The abundant solar potential (up to 485 W/m²) makes this solar solution economically advantageous and especially suited to desert and isolated areas. According to the study's findings, integrating solar into RO units not only lowers production costs but also provides long-term energy independence, which is crucial in a nation heavily affected by hydrological stress.

Comparison of the costs between two hybrid desalination plants as shown table below (RO 2/3 and MED 1/3) and the second plant (RO 1/2 and MED 1/2) in terms of CAPEX and OPEX with and without the contribution of renewable energies for the case of Algeria for an installed capacity of 300 000 m³/d, according to the data provided from the projects carried out and those of the costs of fossil energy and electricity.

Bourouni et al., 2011 asserted that significant efforts have been undertaken to incorporate renewable energy sources (RES) into diverse desalination systems. Despite existing technological and economic constraints, (*Documents & Reports - All Documents | The World Bank* [no date]) regards the use of RES for desalination as exceptionally ecologically sustainable due to little waste production. In hybrid processes, the

integrated approach is commonly employed to mitigate the constraints of intermittent renewable energy sources, such as wind velocity and solar irradiance. Effective integrated designs have synergistic effects between desalination and RES. More specifically, figure 8 the likely combinations of RES with different desalination technologies, and includes membrane methods such as (RO) and thermal methods such as (MED).

In addition, a performance analysis of a hybrid (MED) and (RO) system for seawater desalination was carried out by modelling and simulation and it is also noted are the most appropriate desalination technologies to be exploited by concentrated solar energy (Lotfy et al., 2022). Therefore, the integration of renewable energies with a hybrid RO/MED process is not only conceivable, but also an area of active research and application for more sustainable and economical desalination.

Tab II.9: Hybrid (RO/MED) system for seawater desalination proposition.

Without renewable energy							
With RE (solar PV + thermal)							
Configuration	Part RO	Part MED	Total CAPEX (M\$)	Daily CAPEX (\$/m ³ /d)	Unit CAPEX (\$/m ³)	Unit OPEX (\$/m ³)	TWC (\$/m ³)
Plant A (RO 2/3 + MED 1/3)	200 000 m ³ /d	100 000 m ³ /d	700–900	3500–4500	0.384–0.493	0.70–1.10	1.084–1.593
			850–1100	8500–11000	0.932–1.205	0.50–0.90	1.432–2.105
Plant B (RO 1/2 + MED 1/2)	150 000 m ³ /d	150 000 m ³ /d	800–1100	5334–7334	0.585–0.804	0.80–1.30	1.385–2.104
			950–1300	6334–8666	0.694–0.950	0.60–1.00	1.294–1.950

The RO is less expensive to install than the MED (exchangers, anti-corrosion systems). Although labor expenses in Algeria are reasonable, desalination equipment is frequently imported in foreign currency. (*DesalData* [no date]) affirmed that energy OPEX is lowered by 30–50% using solar PV. OPEX for membrane replacement is reduced by 25–40% when power generated by PV renewable energy is used.

Tab II.10: OPEX of the hybrid (RO/MED) system without and with RE.

Configuration	OPEX (\$/m ³)	Details/ Economies
Plant A	0.70–1.10	The RO dominates moderate electricity cost.
	0.50–0.90	30%
Plant B	0.80–1.30	MED higher thermal cost (complex maintenance).
	0.60–1.00	20–30%

MED thermal costs between 0.01 and 0.03 \$/kWh while gas costs arrive at 0.06 \$. Even with solar power, maintaining the MED is more costly. The perfect mix is plant A that has lower MED for CAPEX and OPEX it is more beneficial (*GW* [no date]). Solar PV is a better fit for RO (mature technology, lower prices).

The VCD process was historically developed for small to medium-sized installations (anything from a few thousand to tens of thousands of m³/day). However, with a hybrid RO+VCD, the 4/5 RO + 1/5 VCD approach is different, meaning that only 20% of the water is produced by VCD and 80% of the water is produced by the more scalable process of RO. Therefore, even if VCD isn't designed for big volumes alone, it only manages a small portion here.

Conclusion

The large size of a desalination plant has a considerable impact on CAPEX and OPEX, but the cost per cubic meter of treated water is amortized thanks to economies of scale. Although they require a larger initial investment, larger installations are usually more profitable in the long term due to the reduction in unit operating expenses.

Limiting factors and geographical complexities can hinder this trend. It is also important to point out that the combination of membranes and thermal processes for a hybrid desalination plant can be a favorable factor in reducing maintenance costs, leading to a reduction in operating expenses.

This chapter will show a calculation code that helps figure out investment and operating costs by looking at different ratios for CAPEX and OPEX related to the four desalination methods: RO, MED, MSF, and VCD, as well as how to optimise by combining the RO and MED processes or the RO and VCD processes.

CHAPITRE III

CALCULATION CODE FOR SIZING AND OPTIMIZATION OF THE OPERATING PARAMETERS OF A HYBRID DESALINATION PLANT

Introduction

Seawater desalination has become an essential way to meet the growing demand for water particularly in arid and semi-arid areas, as the world's freshwater supply becomes scarcer of the most widely used technologies. RO systems are frequently preferred because to their reduced operational and capital expenses, which typically range from 0.45\$ to 1.00\$ per m³ of water produced and 900\$ to 2000\$ per m³/day of capacity (Ghaffour et al., 2013 and (*Statistiques de Capacité Renouvelable 2022*)). Thermal desalination techniques on the other hand, use more energy but may be useful in cogeneration environments where waste heat from power plants is accessible.

Hybrid desalination systems, which combine RO and MED have drawn interest as a way to close the gap between these technologies. These systems provide more adaptability to changing demand enhanced energy efficiency and operational flexibility. Because hybrid systems fall somewhere between standalone RO and MED, their capital costs typically vary from 1100\$ to 2300\$ per m³/day of capacity (Plimmer 2024). Their OPEX is often lower than thermal-only alternatives, even though it is higher than RO-only systems, especially when optimal energy integration is used (Shahzad et al., 2017). computation code for different technologies of desalination plants to make evident a hybrid desalination system's sizing and optimization. Energy consumption, water recovery, cost factors, and site-specific elements are all considered when simulating plant performance under various design and operational scenarios.

Fundamentally, “humans and computers are the two most fundamentally opposed entities in existence. The man is loaned, very intuitive and not very rigorous. The computer is incredibly fast, extremely rigorous, and fully functional” (Gérard Berry, an information specialist, 2014 CNRS Medal winner, and professor at the College of France).

It seeks to assist in the development of desalination facilities that are economical, environmentally friendly and suited to regional circumstances. To achieve this goal, a calculation code was created in Python, a language widely used in engineering for multi-objective optimization and digital modeling. Key criteria, including start-up daily production capacity, are highlighted in the following table that compares the largest desalination facilities worldwide to see how different desalination technology and project delivery strategies relate to

different sizes and financial structures. The table below shown how large-scale desalination projects throughout the world vary in terms of pricing, contract forms and capabilities.

Tab III.1: SWRO/MED water costs for large-scale projects (Ghaffour., 2013)

Site	Start-up	Capacity (m ³ /d)	Contract type	Capital cost
Fujairah 2 MED/SWRO (United Arab Emirates)	2011	460 000/136 000	Independent Water and Power Project	616M\$/190M\$
Adelaide SWRO 2-pass (South Australia)		273 000	Design Build Operate and Maintain	1.79 B\$
Sydney SWRO 2-pass (South Australia)	2010	250 000	Design Build Operate	933 M\$

III.1. CHOICE OF LIBRARIES

Numerous domains, including web development, data science, artificial intelligence, automation, and software engineering, make extensive use of Python, which was developed by Guido van Rossum and was made available in 1991. Its strength and versatility are enhanced by its large standard library and vibrant community, which enable developers to create reliable applications fast.

Python is being utilized more and more in open-source or commercial research contexts, as well as in scientific applications that have historically been dominated by other languages. The quality of documentation, availability, and the maturity and stability of the core numerical libraries ([NumPy], [SciPy], and others) have greatly contributed to making Python comfortable and accessible for a wide range of users. Furthermore, an interactive research and development environment with data visualization appropriate for the majority of users is offered by [matplotlib] connected with [Python]. In contrast to other computer science domains, Python's uptake for applied statistical modeling has been rather sluggish. The absence of libraries that implement standard models and a unified framework for model specification has historically been a significant problem for aspiring statistical Python programmers.

The absence of libraries that implement standard models and a unified framework for model specification has historically been a significant problem for aspiring statistical Python programmers. Nonetheless, there have been notable advancements in econometrics recently (McKinney., 2010).

To achieve the objectives of the code: Calculation of total and daily CAPEX and OPEX based on production capacity (economies of scale) make an application of a model with annuity factor (interest rate, life). The choice of libraries should be in line with the main analytical tasks needed for creating a Python-based application for modeling CAPEX and OPEX in desalination plants: data management, statistical modeling, visualization, and numerical computing. For effective numerical computations and fitting cost models to actual data, including scaling laws for CAPEX depending on plant capacity, NumPy is more crucial (Virtanen et al., 2020).

Matplotlib.pyplot package It is used for illustrating graphs (bar visualizations, line plots, etc.) and is ideal for displaying comparisons, trends, and NumPy data related to CAPEX and OPEX formula calculations. Arrays, mathematical operations, and numerical models are all handled by this essential Python numerical library. Analytical computing and data analysis frequently use both databases in conjunction.

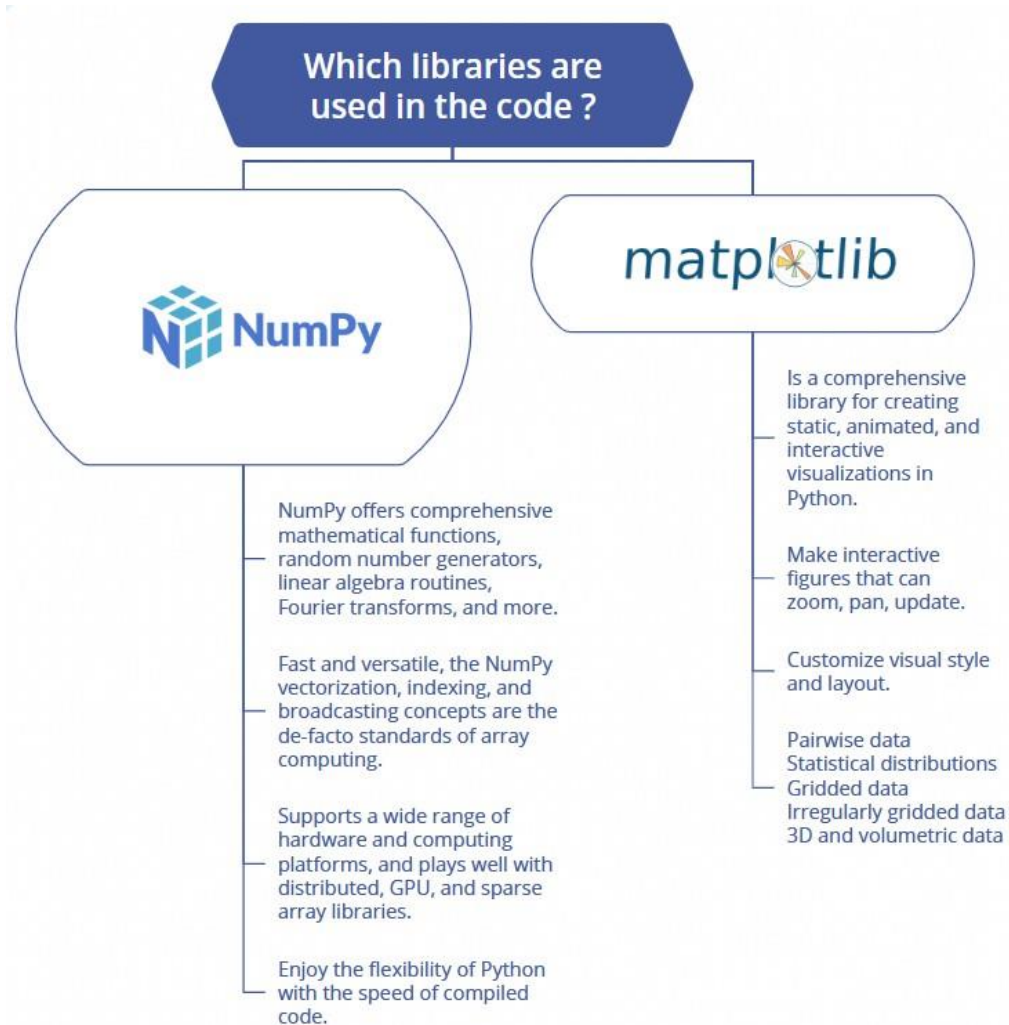


Fig III.1: Conceptual overview of the libraries used.

The cost per m³ of capacity falls as plant size increases, and TWC reduction is steepest in MSF, suggesting that despite its high cost, it benefits more from scale than SWRO or MED. The capital cost increases for all technologies as capacity increases, but not linearly when economies of scale are evident. The most economical technology at all sizes is SWRO, which is particularly appealing for large-scale projects. MED provides a compromise and is frequently selected for industrial applications or situations where energy integration (such as with waste heat) is feasible. Although sturdy and dependable, MSF is less cost-effective, especially for lesser capacities, but it could still be used in areas where operational dependability under challenging circumstances is crucial.

Tab III.2: Summary of costs for different technologies for three capacities (Wittholz et al., 2008)

Tech	Capacity (m ³ /d)	Capital cost CAPEX(M\$)	TWC (M\$)
------	------------------------------	----------------------------	-----------

SWRO	50 000	74	0.7
	275 000	293	0.5
	500 000	476.7	0.45
MSF	50 000	149.5	1.23
	275 000	498.1	0.74
	500 000	759.6	0.62
MED	50 000	108.4	0.89
	275 000	446.7	0.67
	500 000	734	0.6

III.2. STRUCTURE AND VALIDATION OF THE MODEL

III.2.1. Comparative analysis of desalination technologies based on CAPEX, OPEX and energy costs across varying production capacities

The total CAPEX is based on reference data for the RO technology, table below according to linear regression which includes values in millions of dollars for daily production capacities (200 000 to 800 000 m³/day). A multiplicative factor is applied to estimate the CAPEX of other technologies (Najafi et al., 2016). The most critical element, accounting for 40% of OPEX, is the estimate of daily energy costs based on technology energy yields with Algerian electricity and heating prices: RO using only electricity, MED/MSF: heat and electricity, VC: electricity through a compressor.

Tab III.3: Status of desalination plants.

Capacity (m³/day)	Total CAPEX (M. \$)	Daily CAPEX (\$/m³/d)	Unit OPEX (\$/m³)
200 000	202	1010	0.65225
300 000	212	967	0.594385
400 000	282	962,5	0.554109
500 000	412	860	0.522869
600 000	602	840	0.497344
700 000	852	828.5	0.475763
800 000	1 162	812.5	0.457069

According to Papapetro et al. (2017), maintenance costs are expressed as a percentage of CAPEX based on annual production; the results are shown in the following table.

Tab III.4: Unit maintenance cost evaluation by capacity and process (\$/m³).

Capacity (m³/d)	RO	MED	MSF	VCD
200 000	0.0830	0.1438	0.2352	0.1826
300 000	0.0580	0.1006	0.1645	0.1277
400 000	0.0579	0.1004	0.1641	0.1274
500 000	0.0677	0.1173	0.1918	0.1489
600 000	0.0824	0.1429	0.2336	0.1814
700 000	0.1000	0.1734	0.2834	0.2200
800 000	0.1193	0.2069	0.3382	0.2626

Each technology has a different staff composition, which affects its price. Details are printed for each case based on capacity and the cost of chemical products for each technology is then calculated based on the consumption of two products:

-Antiscalant: between [0.003 and 5 \$/kg]

-Chlore: [1.2 \$/kg to 0.001 kg/m³]

These values are adjusted based on the technology (for example: VCD and MED consume less) with condition logic allows to execute as the following figure.

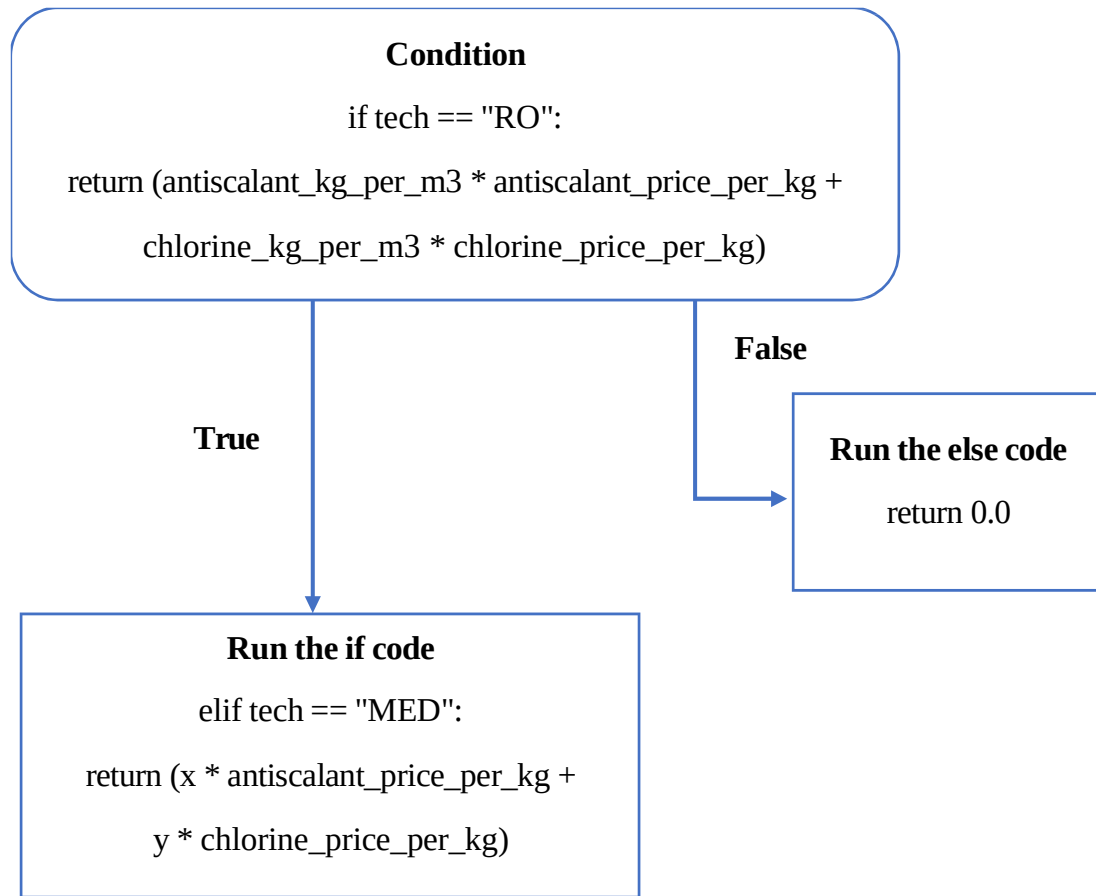


Fig III.2: Conditional Statement Structure in code.

Moving on to the membrane replacement section and distillers model the cost of replacing the criticized components:

-RO: membranes (one membrane per 300 m³/d, 125 \$/unit, lifespan of 5 years).

-MED/MSF/VC: distillers (with unit capacities varying from 1800 to 2200 dollars, with a 25-year lifespan). Each technology is assigned a fixed additional cost of m³ to represent other operating costs such as administration and divers.

Fig II.3 shows the evolution of total CAPEX for desalination plants as a function of conventional membrane and thermal processes (RO, MED, MSF and VCD). We obtained these trends by applying the double logarithm model (Wittholz, 2008) to a representative sample of desalination plants that have already been built and are operational. The values are given with confidence intervals according to Student's theory, which applies to statistical estimation with small sample sizes. A confidence interval is described by the following equation (Cf, Annex III.1):

$$\text{Confidence interval formula: } IC = \bar{x} \pm t \times (\sigma/\sqrt{n}) \quad (\text{III.1})$$

$\bar{x}$ = sample mean; t = Student's critical value; σ = sample standard deviation; n = sample size.

RO has the lowest CAPEX, at 1593 USD/m³/day, which reflects a more straightforward, modular and well-manufactured industrial installation. On the other hand, the MSF requires the highest investment at 2391 USD/m³/day, which is justified by sophisticated infrastructure, high thermal consumption and heat recovery systems.

The MED and VCD have intermediate prices of 2063 and 1899 USD/m³/day, respectively. With 1757.5 USD/m³/day, RO/MED* exhibits a good compromise from the hybrid side.

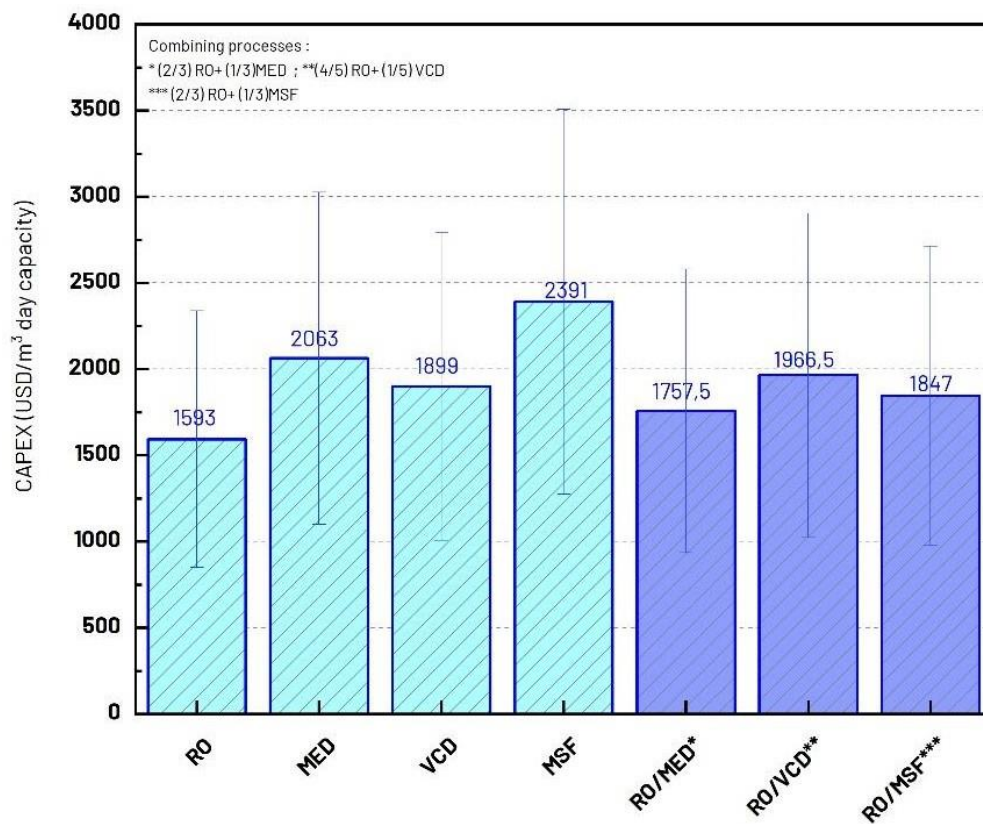


Fig III.3: CAPEX analysis of desalination technologies.

The subsequent results illustrate what was found empirical correlation based on the examples of precedent 11 plants, the graph follows indicates that the RO technology has the lowest exploitation cost at 0.826 USD/m³, making it the most cost-effective alternative for large

installations in terms of energy and resources. The hybrid alternatives display intermediate economic performance. For instance, by combining 2/3 RO + 1/3 MED, it is possible to significantly lower OPEX to 1.217 USD/m³, which is a significant decrease when compared to MED alone. At 0.8715 USD/m³, the RO/VCD system is even more efficient than RO alone. On the other hand, 2/3 RO + 1/3 MSF shows a higher OPEX (1.498 USD/m³), yet it is still less than MSF pure. This demonstrates how the partial integration of RO technology enables the utilization of its effectiveness while maintaining the robustness of thermal processes.

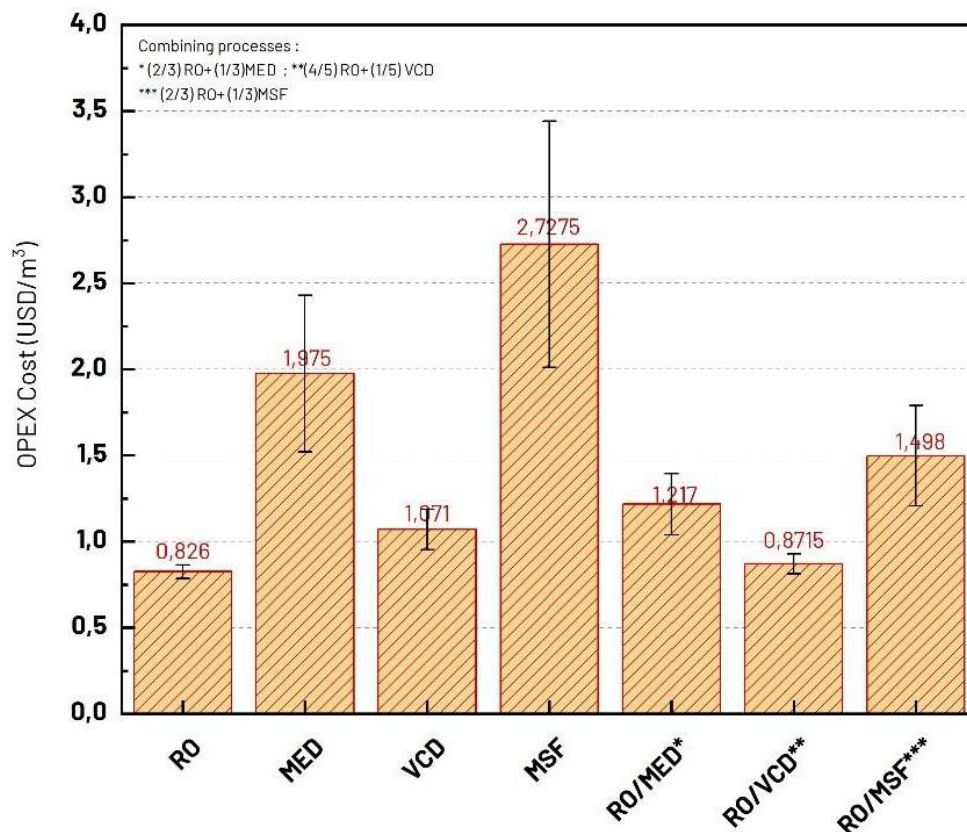


Fig III.4: OPEX analysis of desalination technologies.

As investment and exploitation costs, RO is still the most competitive technology on a techno-economic level. However, in some specific contexts such as extremely salinized water, thermal reliability requirements or cogeneration, the hybrid RO/MED and RO/VCD alternatives represent great compromises, however VCD is only suitable for small installations. They moderate global CAPEX while providing significant OPEX reductions compared to thermal technologies alone. These findings support the current trend toward hybrid desalination processes, which aim to integrate the advantages of each technology from an economic and energy sustainability standpoint.

III.2.2. Hybrid plants results

Hybrid desalination plant's performance and cost-effectiveness are largely dependent on: the entire energy profile and cost balance are determined by the RO to MED capacity ratio (Khawaji et al., 2008). Energy consumption of 3,5 kWh/m³ is the lowest of the hybrid systems examined with competitive annual operating cost of 33.8 M.USD, with a cost per square meter of 0.59 and environmental impact is decreased CO₂ emissions are kept to 2.8 kg/m³ because of improved thermal energy recovery use of substantial solar resources to meet energy needs in an ecological setting.

Tab III.5: Analyze of different desalination processes (*The Cost of Desalination* [no date]).

Processes	Benefits	Limits
RO	Low CAPEX, OPEX and energy efficiency	Sensitive to water quality
MED	Low power consumption, reduce maintenance	High CAPEX, external heat requirement
MSF	Reliability for large capacities	High energy consumption
VCD	Efficiency for small installations	High maintenance costs
RO/MED	Energy and costs optimization	Integration complexity
RO/VCD	Reduce of chemicals costs	Complex maintenance

Energy costs with thermal operations particularly vulnerable to heat prices. Salinity and quality of feedwater have a direct impact on membrane lifetime and pretreatment requirements. Environmental and regulatory considerations, which might result in extra costs or limitations on operations.

According to the study by Zhou et al. (2021), RO/MED or RO/MSF hybrid systems optimize the energy consumption of desalination by combining the advantages of membrane (RO) and thermal (MED/MSF) processes, according to the following mechanisms:

1. Waste heat recovery: the procedure involves preheating the feed water for reverse osmosis (RO). Hot brine or low-pressure steam from the MED/MSF (generally at 60-80°C) is used to preheat the seawater before it enters the RO.

2. Reuse of concentrated brine: Reverse Osmosis (RO) brine (warmer water reduces viscosity than raw seawater) is injected into the MED/MSF, reducing the thermal energy required for evaporation and reducing the pressure required (10-20% energy saving in RO).

3. Optimizing flows and reducing losses

- Effluent coupling:

RO permeate can be mixed with MED/MSF distilled water to achieve the desired quality, avoiding energy-intensive post-treatment. The brine from the MED/MSF (less concentrated than that from the RO) can be recycled into the RO feed, improving overall efficiency.

- Minimization of brine discharge:

Hybrids reduce the volume of brine discharged, thus limiting the energy spent treating or disposing of it. This is the case at the Al Jubail hybrid plant (Saudi Arabia), this flexibility enables overall energy savings of 25–30% compared with separate systems.

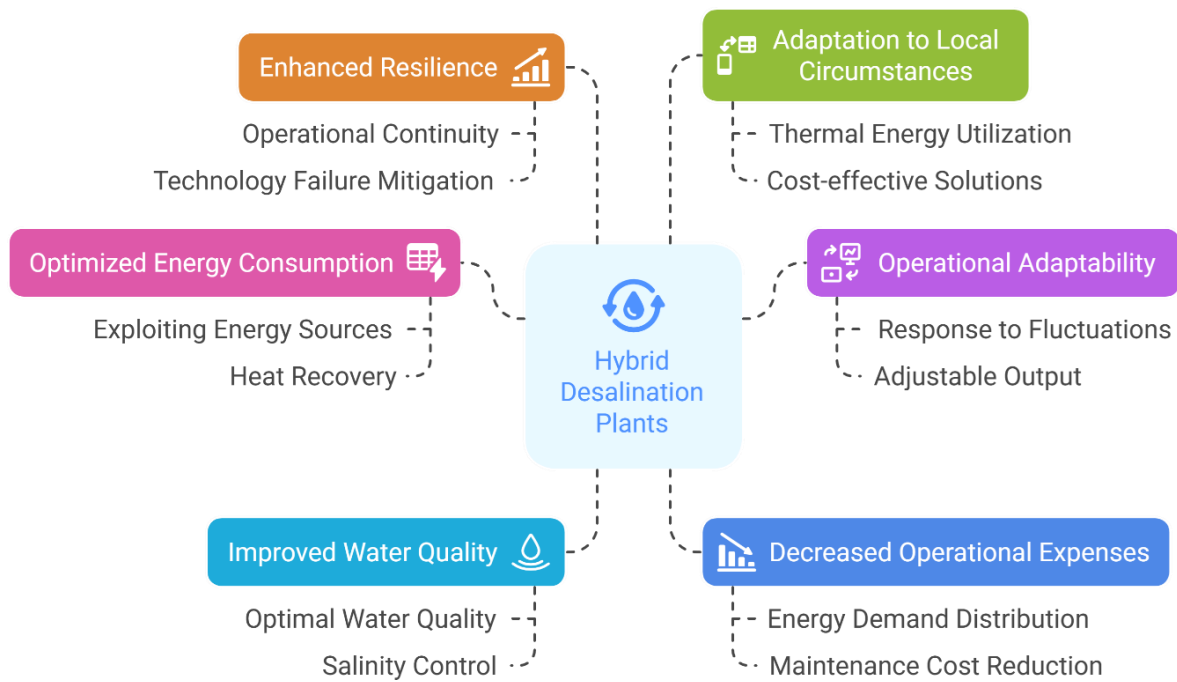


Fig III.5: Benefits of Hybrid Desalination Plants.

The cost of a hybrid RO/MED desalination plant depends on several factors of technology, location and energy source. Initial Investment Cost is higher due to complexity thermal integration, exchangers, etc. Desalinating seawater is more expensive as intensive pretreatment is one of factors influencing with energy: If the MED uses waste heat (power plant), the cost decreases and the local infrastructure as transport, labor and taxes. Then, operational cost [0.50 to 1.20\$/m²] compared to [0.30-0.80\$/m²] for RO alone. MED slightly increases costs (thermal maintenance), but can be offset by cheaper energy (e.g, waste heat). However, use of renewable energy like solar thermal for the Mediterranean Sea is one of the most important elements that reduce costs and public subsidies in water-stressed countries with economies of scale for plants that have daily production of 200 000 m³/d or more that.

➤ Concrete cost examples

Ras Al-Khair plant in Saudi Arabia with capacity of 1 000 000 m³/d (hybrid RO/MED) with initial cost approximated with 1.5 billion\$ in 2014 and 1500 \$/m²/d since energy recovery systems have greatly helped RO increasing its effectiveness and reducing expenses. The amount of effects and recovery ratio have an impact on MED performance. Particularly when waste heat is available for thermal input, hybrid systems exhibit potential like shown table below comparison between literature and the results of the calculated code for capacity 300 000 m³/d.

Tab III.6: Comparative overview of desalination technologies: CAPEX, OPEX and energy requirements.

Tech	Total CAPEX (M. \$)	Unit OPEX (\$/m ³)	Electrical energy (kWh/m ³)	Thermal energy (kWh/m ³)	Observations	Reference
* Results of the calculated code for capacity 300 000 m³/d.						
RO	800-2500	0.5-1.5	3-6	0	Improved with energy recovery devices	Ghaffour et al., 2013 and Elimelech & Philip, 2011
	2120*	0.77*				
MED	1500-3500	1-1.8	1.5- 3	40-90	Depends on number of effects and recovery ratio	Team 2019 and (Plimmer 2024)
	3000*	1.5*				
VCD	1500 – 2500	0.5 – 2.5	7 - 15	0	Suitable for small capacities	Team 2019; (<i>GW</i> [no date]) and (<i>Home</i> [no date])
	2720*	0.94*				
MSF	2000-4000	1.5-3	3-5	60-120		Team 2019; (<i>GW</i> [no date]) and (<i>Home</i> [no date])
	3610*	2.06*				
RO/MED	1800-3500	1-2.2	3-4	30-60	Reduced through waste heat utilization	Shahred et al., 2017
	2330*	1.02*				
RO/VCD	1500-3000	1-2.5	5-13	0	Suitable for small capacities	
	2200*	0.81*				

RO/MSF	2000-4000	1.2-2.5	3-5	50-100		
	2470*	1.2*				

III.3. RESULT AND DISCUSSION

The following graphs show several hybrid configurations of desalination that combine various renewable energy sources (photovoltaic, solar thermal and wind) with different technologies. CAPEX which represents variability remains significant for all configurations in the first graph, indicating an uncertainty related to industrial scale or variations in component prices, membranes for RO and membranes with distillers equipment for others, PV modules. The operational costs in USD per square meter produced for the same setups are shown in the second graph:

With an OPEX about 0.4835 USD/m³, the RO/VCD + photovoltaic configuration is the most economically viable to use, highlighting the combination's appeal in terms of energy sobriety. On the other hand, the RO/MSF with solar thermal system achieves a pic (~0,9745 USD/m³), highlighting the high energy consumption and high maintenance requirements of MSF units, which are exacerbated by intermittent renewable energy sources. The hybrid RO/MED systems oscillate between 0.72 and 0.82 USD/m³, providing a consistent, average performance.

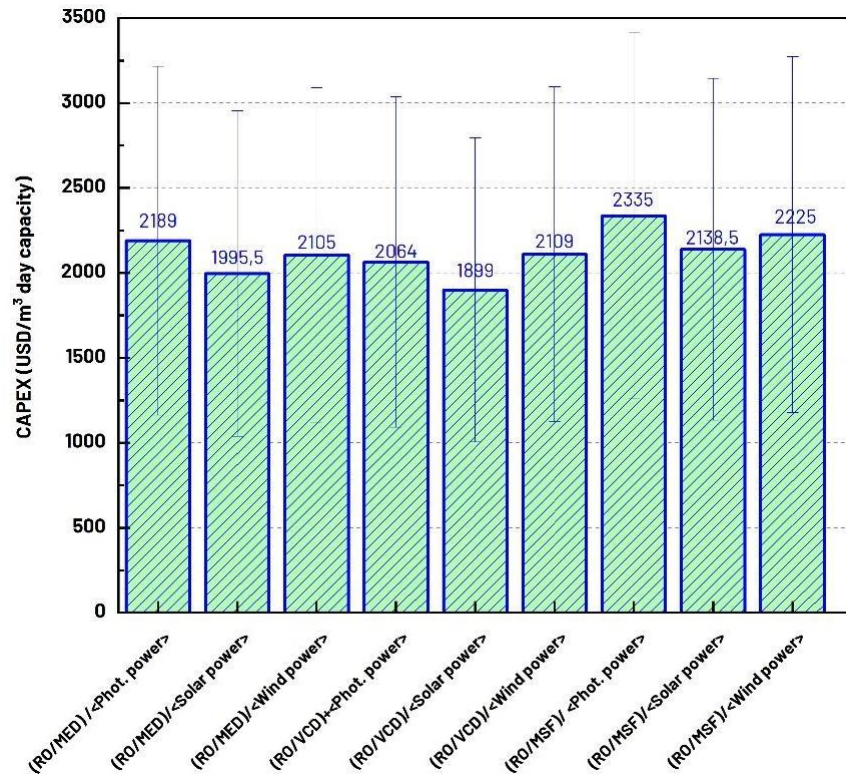


Fig III.6: Comparison of the capital expenditures for hybrid desalination systems using various renewable energy sources.

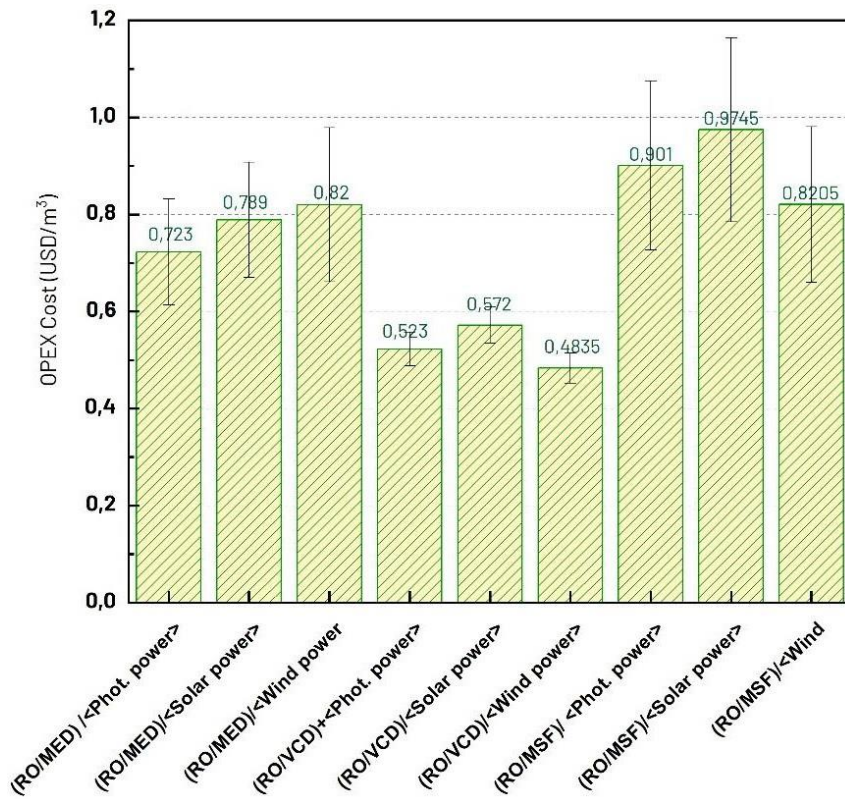


Fig III.7: Comparison of the operational expenditures for hybrid desalination systems using various renewable energy sources.

Comparative research shows that hybrid systems that incorporate RO/VCD technology and are connected to a photovoltaic or thermal solar power source are the most cost-effective both at the CAPEX and OPEX levels but is not adapted with large plants. Even while RO/MSF systems provide strong capabilities, they are hindered by higher investment and exploitation costs. The findings support the significance of selecting technological solutions based on both their technical performance and suitability for the local location of renewable energy sources. This is in line with a contextual approach to hybrid processes that aims to optimize the overall cost (CAPEX + OPEX) based on the energy resources and unique economic conditions of each location. Then content to represent these processes for the production of 300 000 m³/d compared with desalination plants worldwide.

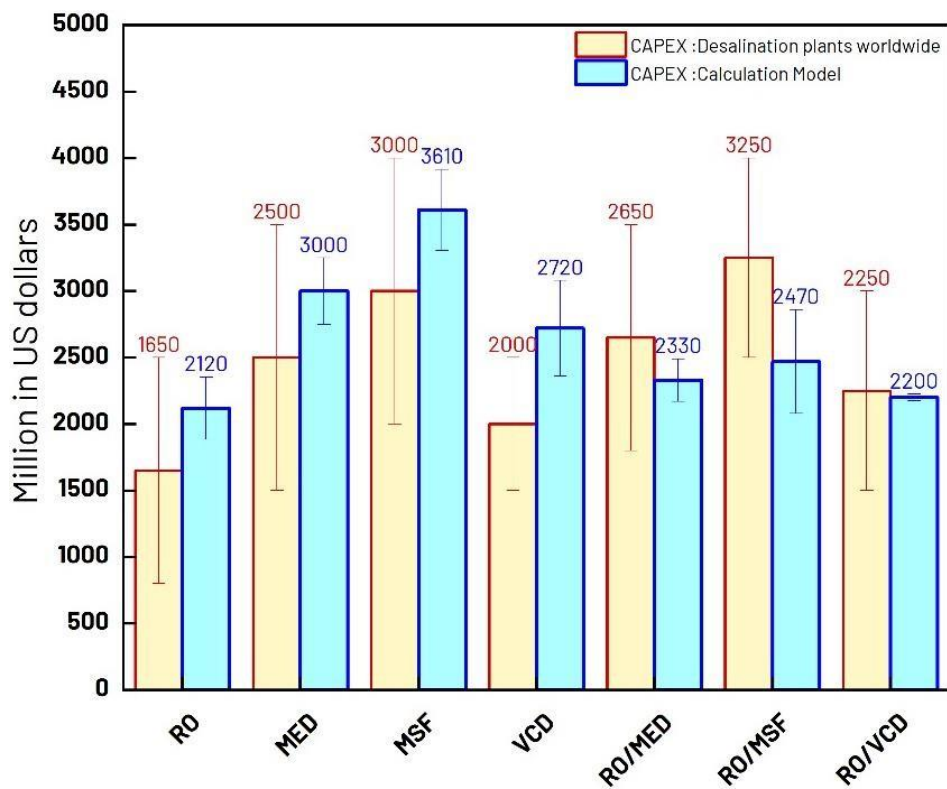


Fig III.8: Capital expenditures for the production of 300 000 m³/d compared with desalination plants worldwide.

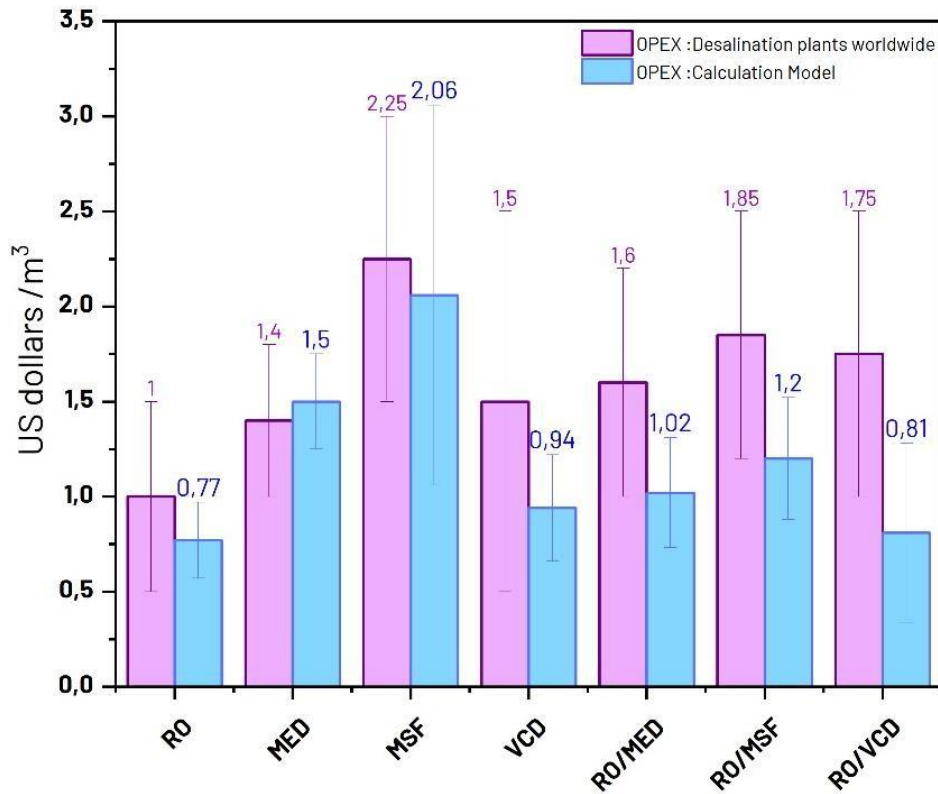


Fig III.9: Operational expenditures for the production of 300 000 m³/d compared with desalination plants worldwide.

Hybrid desalination plants that combine SWRO and MED technologies offer several advantages over the use of a single technology:

➤ **Optimized energy consumption**

MED uses thermal energy, often from waste heat (e.g. from a power station), while SWRO uses mainly electrical energy to pressurize the water. A hybrid station can exploit the two energy sources in a complementary way, thereby reducing overall energy costs.

By integrating the two technologies, heat recovery can be optimized. Excess heat generated by one facility can be used in the other, improving overall energy efficiency.

➤ **Operational adaptability**

Hybrid systems provide enhanced response to fluctuations in local variables, including water temperature and saltwater quality. For instance, during intervals of compromised seawater quality, SWRO may be suspended while MED assumes operation, or conversely. The adaptability of employing any or both technologies allows for output to be adjusted based

on water demand, or the system to be optimized corresponding to the prevailing cost of energy (thermal or electrical) at any given moment.

➤ **Improved water quality**

The integration of the two technologies yields optimal water quality. SWRO typically generates water with little salt, but MED might yield water with a marginally elevated salinity. Combining the two types of water can get a certain salinity level in accordance with requirements.

➤ **Decreased operational expenses**

Employing both processes concurrently minimizes operational expenses by distributing the energy demand among available resources, including power and waste heat. MED technologies are durable and need less maintenance owing to the lack of high-pressure membranes, as seen in SWRO, hence lowering maintenance expenses in hybrid facilities.

➤ **Enhanced resilience**

Exhibits greater resilience, as the failure of one technology allows the other to maintain operation. This guarantees the uninterrupted producing drinkable water.

➤ **Adaptation to local circumstances**

Hybrid systems are more suitable for areas with ample thermal energy, such as nations with extensive industrial or energy infrastructures, where electrical energy may be costlier. This optimizes the utilization of accessible local resources.

A hybrid SWRO and MED desalination facility integrates the benefits of both technologies with improved energy efficiency, operational flexibility, and water quality, while reducing operating costs and assuring increased system resilience.

III.3.1. The CAPEX/OPEX ratio

Which balances initial investment and operating costs, is a vital indicator that Determine the balance between the original investment and operating costs. Direct technological and conceptual decisions Impact the financing strategy.

- A high ratio (>5): initial investment is significant while operating costs are moderate.
- A low ratio (<3) means that the initial investment is more modest but the operating costs are higher.

This ratio typically falls between 3 and 7 for Algeria's contemporary desalination plants, depending on the particular technology and setup as shown figure follow.

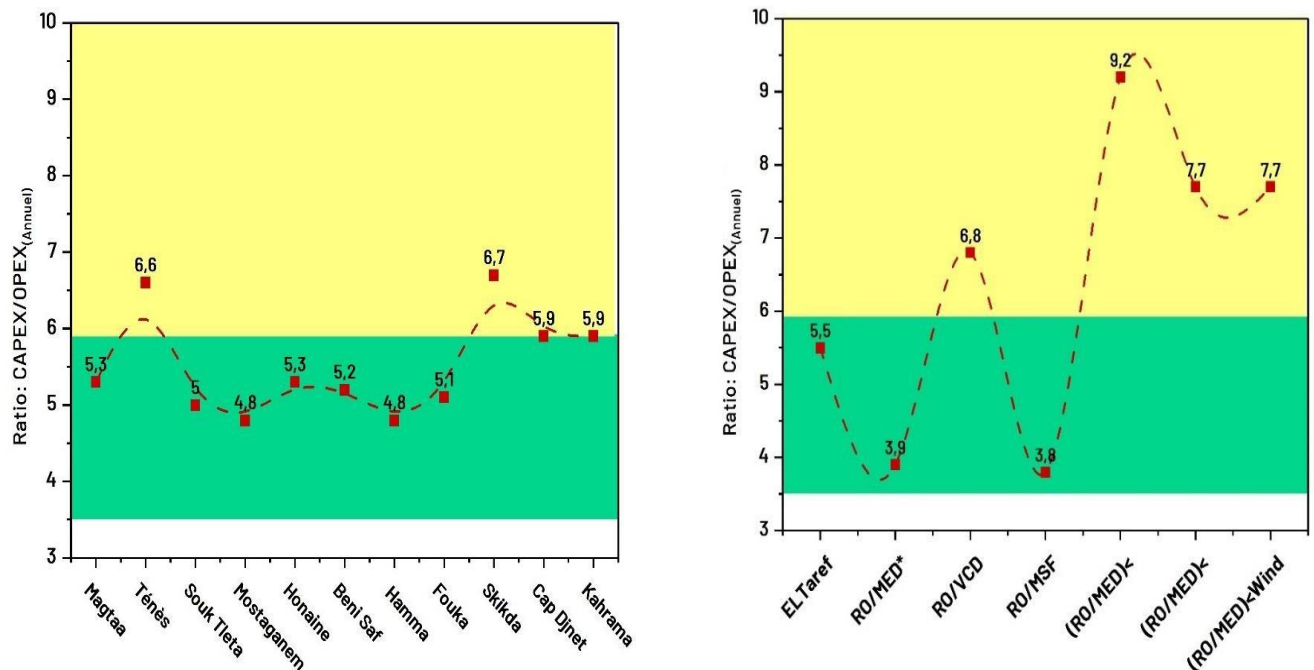


Fig III.10: The annual CAPEX/OPEX ratio for Algerian desalination plants based on technologies.

In order to do a quantitative analysis, the majority of installations are located in the ideal vertebral zone (ratios of 3.5 to 6), indicating a good understanding of the economic balance between exploitation and investment. The stations of Tenes and Skikda with 6.7 years, somewhat above the ideal threshold, indicating a more significant initial investment that may be justified by more lasting or effective technological choices.

The second graph shown that the "EL Taref" "RO/MED*" and "RO/MSF" systems offer a good economic compromise. Although they are more expensive to install up to 9.2, hybrid alternatives with photovoltaic, solar and wind lower OPEX, which may be advantageous in the long run.

Conclusion

This chapter's calculation model is a powerful tool for optimizing the operational parameters of hybrid desalination stations that integrate RO and MED technologies. The model combines sophisticated algorithms with a parametric approach for investment and operating costs, enabling the simulation of various scenarios based on available energy options, specifically renewable energy sources. The results provide a comprehensive overview of the factors influencing installation performance and rentability while taking into account several conceivable configurations.

This calculation methodology is crucial for making strategic decisions within the framework of desalination hybrid projects, enabling the achievement of cost- and energy-efficient optimisation solutions. However, a specific case study is required to validate these findings and their applicability in a real-world setting.

Therefore, the next chapter will examine the Koudiet Draouche station in El Taref, which is a concrete example of the principles discussed. This station serves as a relevant example for assessing the effects of various energy configurations and alternatives in a large-scale project.

CHAPITRE IV

CASE STUDIES, KOUDIET DRAOUCHE DESALINATION PLANT PROJECT (EL TAREF)

Introduction

The seawater desalination plant Koudiet Draouch with a capacity of 300 000 m³/day of drinking water production located in EL TAREF municipality of Berrihane includes the following facilities:

- **Water Intake System:** Intake towers, sulfuric acid dosing, sodium hypochlorite dosing, seawater intake chamber.
- **Seawater Supply Station and Chlorination System.**
- **Pre-Treatment System:** Clarifiers, intermediate pumping station, dual-media pressurized sand filters, cartridge filters, chemical reagent dosing stations
- **Reverse osmosis system:** High pressure group, energy recovery system based on pressure exchange, booster pumps, RO chassis composed of pressure tubes containing RO membranes, chemical cleaning and flushing system membranes, chemical reagent dosing stations.
- **Post-treatment system:** Permeate will be conducted to the remineralization stage which is constituted by: Calcite beds, calcium bicarbonate remineralization (CaCO₃), two storage and dosing systems CO₂, PH adjustment, chlorination system and all of this works through multidisciplinary systems:
 - Delivery system: Drinking water tanks, potable water pumps, commercial flow meter.
 - Anti- network system fire and diesel storage.
 - Wastewater treatment system.
 - Instrument air production.

The design of the plant is defined to guarantee the reliability of operation and its maximum availability, the optimization of specific consumption and energy efficiency and the reduction of environmental and visual impact.

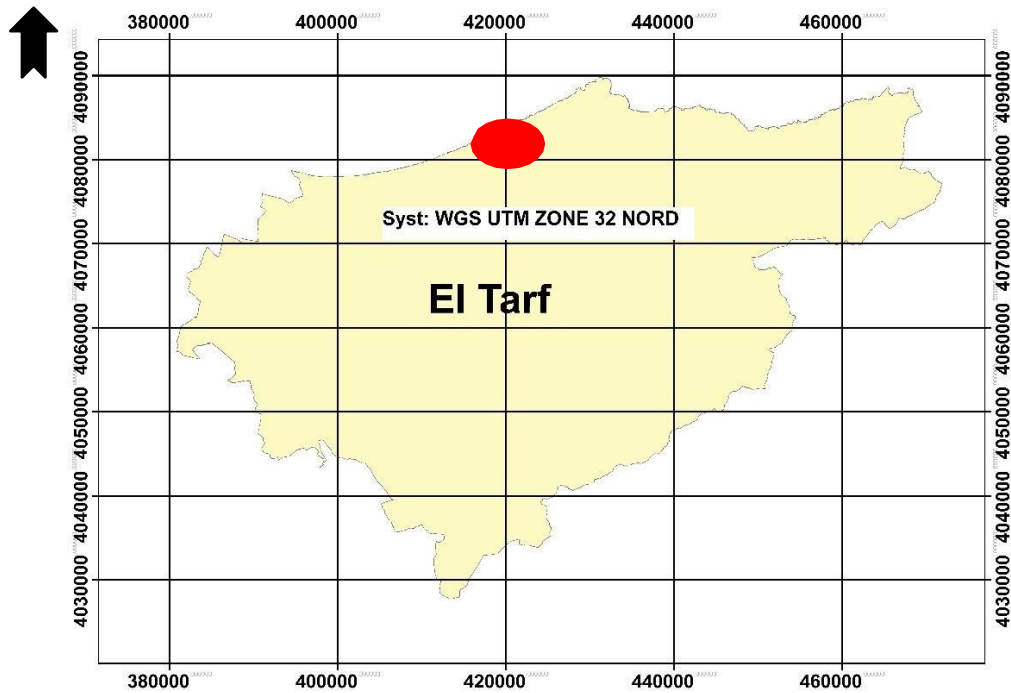


Fig IV.1: Location of the desalination plant, Scale: 1/500 000.

IV.1. Key features of the EL Taref plant

IV.1.1 Installed capacity

This plant is a significant advancement in supplying drinkable water to areas facing water scarcity. However, to ensure sustainable management of water resources, Annaba must deal with significant water shortages, with demand expected to reach 148 million m³/year by 2070. The three dams in the El Taref wilaya Cheffia 155Mm³, Mexa 24Mm³ for 13m and Bougous 60Mm³ also dam of Hammam Debagh 182.67Mm³ in Guelma are primarily responsible for the current provisioning (the capacities of the dams are given after last battemetric rising of 2019), although they are insufficient to meet the growing needs (1381 [no date]). With a growing population Skikda is seeing an increase in water demand, particularly from the agricultural and industrial sectors. It was estimated that agriculture used 112.77 million m³ of water, while industry used about 33.83 million m³ of freshwater. (Samia et al., 2013).

Tab IV.1: Distribution of permeate flow (Miah EL TAREF, 2024).

Water flow produced	m ³ /d	300 000
Water flow produced to “Lac des Oiseaux”		218 352
Water flow produced to “Chaïba”		81 648

An overproduction of 2% is considered for safety reasons. Each production unit that constitutes the plant will guarantee a production capacity equal to the total capacity produced divided by the total number of production units that constitute the plant that will be able to produce 110%.

- The production of 330 000 m³/day is called the plant design capacity.
- The plant's nominal capacity is 300 000 m/day.

IV.1.2 Characteristics of the seawater to be treated

For the baseline analysis, data from the studies "Report of marine water and sediment quality of the general studies of a seawater desalination plant project" (Roberts et al., 2010) are taken into account.

Tab IV.2: Characteristics of the seawater (Miah EL TAREF, 2024) .

Parameter	Units	Min	Average	Max
Ph	-	7.9	8.2	8.4
Temperature	°C	12	20	28
Turbidity	NTU	1	2	5
TSS	mg/l	1	4	15 (Peak value)
Oil and grease		-	-	0.1
TDS		36 000	38 300	40 000
TOC		1.05	1.9	3
Bore		4.8	5.48	6.67
Chloride		20 200	20 360	21 500
Sulphate		2800	2830	2950
Calcium		410	430	450
Magnesium		1130	1360	1500
Sodium		11 170	11 260	11 700
Potassium		390	400	420
Barium		0.005	0.006	0.007
Strontium		1.24	1.33	1.4
Bicarbonates		104	130	140
Carbonates		10	13	15
Silica		0.06	0.08	0.11
Nitrates		0.001	0.002	0.004
Fluor		0.3	1.00	1.3

The system is designed to treat seawater with a total dissolved solids (TDS) concentration of approximately 40 000 mg/l. It should be noted that this value is higher than the actual TDS concentration, which varies between 36 000 and 38 300 mg/l, contributing to long-term design reliability and stability.

- **Sea water reference conditions**

When dimensioning, the Contractor will take into account the minimum and maximum conditions defined in the table below:

Tab IV.3: Sea water reference conditions (Miah EL TAREF, 2024).

Parameters	Min	Max	Reference conditions
Temperature (°C)	12	28	20
Salinity (mg/l)	36 000	40 000	38 300
Suspended matter (MES) (mg/l)	1	200 (Peak)	15
Boro (mg/l)	4.8	6.67	5.48
Hydrocarbons (mg/l)	-	0.1	-

The reference conditions will be validated with the results obtained from new analyses during the development of the project before or after realisation.

- **Assurance of saleable water quality from the plant**

The quality of the water produced must comply with the standards required by the Algerian regulations in force concerning the quality of drinking water (executive decree n°14-96 of 04 March 2014 amending and supplementing decree n°11-125 of 22 March 2011) and the World Health Organization.

Tab IV.4: Main parameters of water quality produced (Miah EL TAREF, 2024).

Parameters	Value
Total hardness	50 to 65 ppm CaCO ₃
Alkalinity	65 ppm of CaCO ₃ (minimum value)
pH	8 to 8.5
Langelier index	0 to 0.4
Bore	Annual average value less than or equal to 1.3 mg/l
TDS	<500 ppm

IV.2. Sea water catchment area

IV.2.1. Seawater intake chamber

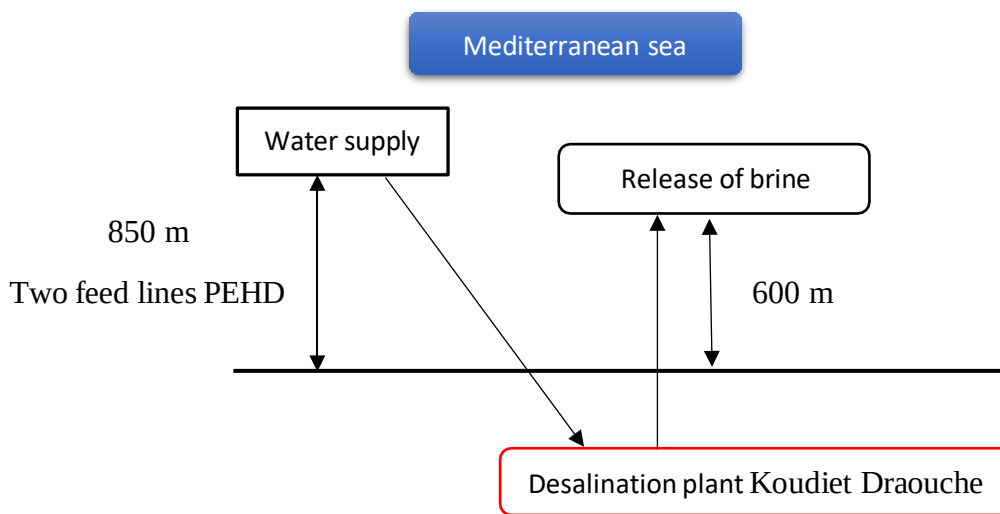


Fig IV.2: Distances of seawater intake chamber.

There are two primary methods:

- Direct intake of surface water through supply pipes in the open ocean: Use pipelines or syphons for surface water intakes through an exposed pipe.
- The indirect inflow occurs either through collecting drains or coastal wells. Coastal well intakes: a collection of wells that are connected to the treatment facility via a collector, intake through drain collection.

The type of seabed and its population must be studied in accordance with the source, such as surface or deep-sea water, in order to select the appropriate intake with a visual inspection of 300 meters. The average speed inside the pipe must be between 1 and 2 metres per second in order to prevent deposits and the growth of algae, and the appropriate materials be chosen: Able to withstand chemical assault, adaptable with an available diameter, and suitable for the seabed types.

Generally, the pumps that can be used in corrosion-resistant desalination plants made of stainless steel or nickel alloy manufactured in series are centrifugal pumps with vertical or horizontal axes, such as multicellular centrifugal high-pressure pumps, with pistons for small flow rates less than 5 cubic meters per hour or with screws to eliminate large waste. The main criteria for choosing the type of pump:

- Ensure the total manometric pressure and feed flow rate are greater than the osmotic flow rate.
- High rotation speed with better efficiency.
- Ensure the required net spray height.

There is a large volume of published studies describing that the sea water intake chamber is designed to receive sea water through intake pipes placed at sea. The chamber consists of a reception chamber, then raw sea water is channeled through compartments by regulating with shut-off valves. Then passes through the screen and is directed to the pump shaft outlet located in isolated pumping chambers. The dimensioning of the chamber is based on Hydraulic Institute Standards in order to cancel any turbulence that might occur. The screen and shut-off valves are located on an intermediate slab to reduce excessive height of equipment, including pump shaft.

The reference level at the location of the seawater intake chamber to begin construction of the mounded wall is +16 m, which corresponds to the top of the concrete of the seawater intake chamber. The top of the base slab is at -6.80 m at the pump bay, with a variable 400 mm slope reaching +6.40 m at the inlet chamber of the water intake pipe. The upper level of the slab in the discharge chamber is -3.50 m. Screening channels; Screen (coarse filtration) and Rotary sieves (fine filtration).

Three filter channels (2 in operation + 1 in Reserve) have been adopted.

Sieve washing pumps will be included to rinse and clean the teams, the water is pumped by six (6) pumps (5+1) for the plant's design capacity (330 000 m³/d). The water will be pumped through two pipes (2x100%) constructed in glass fiber-reinforced polyester (FRP) at pretreatment (Clarifiers) with yield > 80%.

Tab IV.5: Clarification and coagulation chamber feature (Miah EL TAREF, 2024).

	TSS 15 mg/l	TSS 65 mg/l	TSS 100 mg/l	TSS 200 mg/l
Nominal flow of seawater to be clarified: m ³ /h	29 262			
Flow of seawater to be clarified for plant design capacity: m ³ /h	32 200			
Total sludge in the coagulation chamber inlet (nominal flow): kg/d	10 534	45 648	70 228	140 456
Total sludge at the coagulation chamber inlet (flow rate for plant design capacity): kg/d	11 455	49 639	76 367	154 560

There have been several studies in the (Calculs des Process TARF-00-PRO-CAL-001) reporting Due to the quantity and nature of suspended matter expected, a high-flow lamellar decanter design is realized. Different MES/TSS scenarios have been described to illustrate the wide range of operation of the system. The 200 ppm MES scenario represents an exceptional operating situation for the desalination plant. It is considered that in heavy rainfall, the aggregates of the coast can be entrained into the sea, creating peaks of MES/TSS which can reach the water tower for six days. The MES/TSS is 100% inorganic since it is sand. For values below MES/TSS 15 ppm, it will not be necessary to operate the lamella. The flow will be diverted to the reservoir and intermediate pumping. A bypass channel will be installed to route seawater to the buffer tank upstream of the pressure filters without passing through the clarifiers. The clarifiers will start operating as soon as sea water exceeds 15 ppm of MES. The control system will manipulate it automatically.

IV.2.2. Pretreatment system

Al-Abri et al., 2019 highlights the need to protect the process and to guarantee the longevity and proper operation of the station's facilities. It is necessary to reduce and eliminate the percentage of impurities that are obtained through water intake, and this is the goal of pretreatment using techniques that are rarely used alone or in combination: fine or gross filtration, the addition of chemical products like floccants and coagulants, the decantation of suspended or ultra-violet particles, and ozonation which is more expensive.

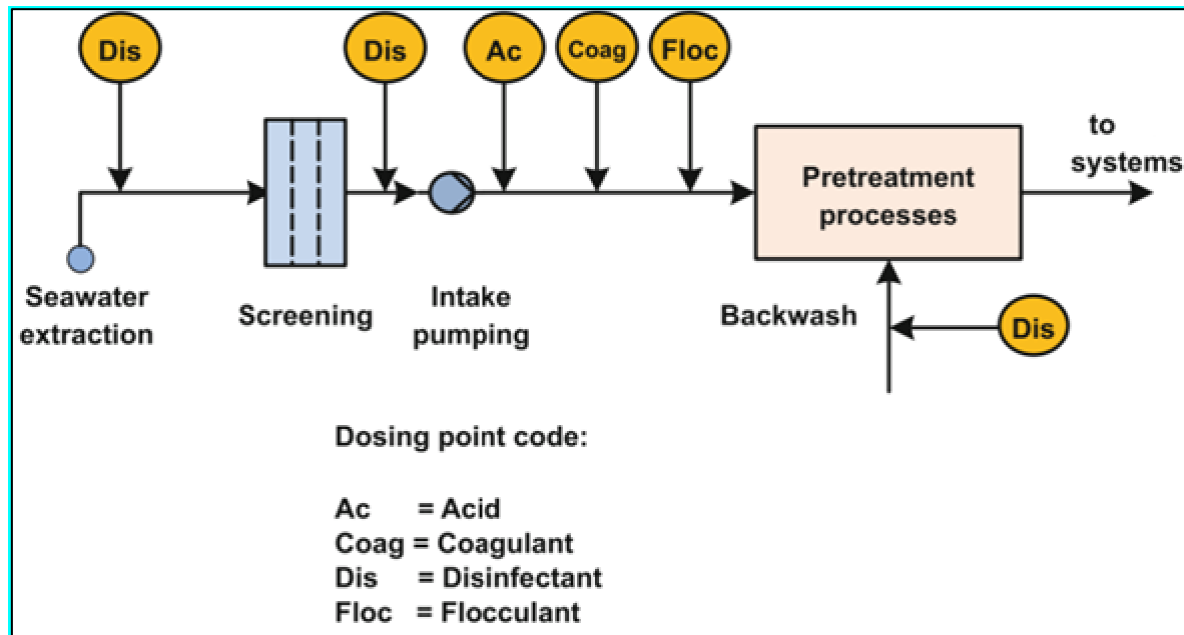


Fig IV.3: Intake and pretreatment chemical dosing points (Ludwig, 2022)

The SDI, modified fouling index, bacterial growth potential, organic fractions and microbial adenosine triphosphate were monitored during the pretreatment processes of two full-scale SWRO facilities. Weekly chlorination of the pretreatment, which is advised to neutralize chlorine prior to media filtration rather than after, as is the case in many full-scale SWRO systems, results in decreased biological activity. When comparing the total removal using the pretreatment to that of without pretreatment, improved the removal of organic fouling potential, improving the removal of biopolymers by 40% and 16%, respectively. It would be beneficial throughout the pretreatment processes to enhance biological degradation and lower the likelihood of biofouling in SWRO feed water (Abushaban et al., 2021).

The first stage of pretreatment consists of an in-line coagulation system, flocculation chambers and a lamellar decanter.

Chemical dosages in ppm FeCl_3 of Ferric chloride are 10 equivalents to Dose of iron 2.419kg/d follow the recommendations of the book (Sincero, 2002) powder flocculant with continuous type dosage for injection point upstream of cartridge filters, concentration 99% with dilution of 0,50%, the projected area per slab will be $13 \text{ m}^2/\text{m}^3$.

In addition, two portable pumps of 50 m^3 at 15-20 m will be available for the drainage of sludge collection chambers from decanters instead of a gravity drainage line. The MES/TSS is considered to be 100% inorganic since it is sand and therefore the material will be easily decantable. Lamella decanters with a retention time between 20 and 30 min may be able to decant particles up to 20-30 microns (Sedimentation rate references "American Water Works Association"). For this specific case, with a design having a retention time of 25 minutes and an easily decantable material, an efficiency of 90% is estimated for MSE 200 ppm.

The intermediate pumping station has (5+1) for plant design capacity. The estimated retention time of 5min is sufficient to stop the intermediate pumping station in case of pump failure in the gross intake pumping station for adopted volume of 2200 m^3 .

The intermediate pumping of super duplex steel, resistant to seawater, chemicals and aggressive marine environment will be dimensioned to pass water through sand filters, cartridge filters, and reach the inlet of the high-pressure system with the necessary conditions for its proper functioning.

The pressurized sand filter system will have 2 lines installed, with 16 units per line. As an energy efficiency measure, the backwash of sand filters is carried out with brine. At the end of each backwash and the return to service of the filter, the first filtered water is sent to the drain to avoid salinity peaks at the osmosis entrance due to the brine that still remains inside the filter. Therefore, when a filter is put into service, the flow rate to be treated in sand filters will be necessary for the production of drinking water ($27\,000 \text{ m}^3/\text{h}$) and the flow rate of a filter sent to discharge ($950 \text{ m}^3/\text{h}$).

32 units installed:

- Line 1: 16 units "14 units in operation. One filter in washing and another filter in maintenance"
- Line 2: 16 units "14 units in operation. One filter in washing and another filter in maintenance"

It is recommended that a backwash sequence be established as follows:

1. Reduce the water level to a few centimeters above the surface of the media.
2. Inject air for 3 minutes at a speed of 50 m/h
3. Keep the air flowing and inject water at a low flow rate of about 12 m/h on average, this does not produce bed expansion (The non-expansion velocity values are 15-17 m/h).
4. Continue this phase until the water level reaches the drain channel, so as not to lose the filter/antracite media.
5. Stop the air injection and after one or two minutes of waiting, increase the water flow about 35 m/h on average. The time required for this step will last until the turbidity of the effluent reaches the appropriate value considering 10 minutes.

Before moving to the reverse osmosis system, a cartridge filter stage is installed to protect the RO membranes. The water will be sent through two pipes (2x50%) constructed in FRP from the sand filters to the cartridge filters which are offered in two lines with a total of 14 filters.

IV.2.3. Reverse osmosis phase

The water will be sent through two pipes (2x50%) constructed of FRP from the cartridge filters to the RO system. The new flow became 12.27 l/mh, this proposal includes 3560 pressure vessels and 24920 membranes (Cf. Annex IV.1). These pipes will be connected and under nominal conditions will function as a single pipe to allow for optimal center of pressure behavior in the RO system where membrane contain polyamide, polysulfone, polyester with two feed spacers.

Tab IV.6: Reverse Osmosis Phase (Miah EL TAREF, 2024).

Equipments	Number
High pressure group	5+1 units
Reverse Osmosis Chassis	10 units
Booster Pumps downstream of the energy recovery system	10 units
Number of energy recovery systems (PX systems)	10 units
Number of PX chambers per system	26 units

Refer to the attached RO projections and conclusion cases

❖ Chemical Cleaning System:

Three cleaning pumps (two in service and one in reserve) will be installed. A 5 m³ tank for dissolving and mixing cleaning chemicals incorporates an electronic stirrer.

- Two transfer pumps, one in operation and the other reserve to transfer the concentrated cleaning solution to the storage tank of the cleaning solution.

- Two filter vertical cartridge cleaning solution manufactured FRP.

A 250 m³ rinse tank, the injection of rinsing water into the process lines occurs through suction from the high-pressure pumps after the corresponding valve on the main line has been closed and the valve controlling the rinsing of the line undergoing this process has been opened.

Tab IV.7: The main data of the chemical cleaning system design (Miah EL TAREF, 2024).

Parameters	Units	Value
Pressure tube wash flow	m ³ /h	6-9
Volume for membrane	liters	50
Number of pressure tubes to be cleaned in	unit	356
Average wash flow	m ³ /h	8.24
Volume for pressure tube	liters	350
Number of refills	units	1 + 1S units
Volume of water to be heated (per chemical cleaning tank)	m ³	243
Minimum water temperature	°C	12
Maximum water temperature	°C	28
The energy that is transmitted	kWh	2844.22
Adopted unit power	kW	75

IV.2.4. Proposition of hybrid installation

RO/MED offers a good balance between initial investment and operating costs and the most environmentally friendly setup. Algeria benefits from a high sunshine, which is perfect for integrating photovoltaic systems with industrial infrastructure: It is possible to mobilize local expertise in the petroleum and gas industry for upkeep and exploitation. There are certain drawbacks: high suspension solids require advanced precautions to prevent membrane encroachment, reducing subsidies might result in higher energy costs, and ongoing process optimization is required. In Algeria, the hybrid arrangement is the best option for 300 000 m³/d. She aligns with national energy transition goals while combining economic viability, environmental durability, and energy efficiency.

Tab IV.8: Different value of Hybrid Configurations and comparison by Total CAPEX RO.

Configuration	Total CAPEX (M.\$)	Annual OPEX (M.\$)	Unit TWC (\$/m³)	Difference (%)	Ratio CAPEX/OPEX_{annual}
RO/MED	523	346.8	1.124	18.03	3.9
RO/MSF	547	387.3	1.242	19.2	3.8
RO/VCD	560	285	0.967	25	6.8

Hybrid systems, which combine two or more desalination technologies, to take advantage of their comparative advantages. These systems may include thermal distillation and membrane desalination, sometimes producing energy electric at the same time as pure water. According to some studies, hybrid systems are considered as economically advantageous. They can, in the reduction of energy consumption, the of scale and fouling, as well as water cost salt. This improves recovery rates (less water supply needed) and overall quality of water. Innovations should improve resilience of the coastal environment by limiting impacts the environment and thus better suited to the ecosystems concerned. Currently, RO is considered the most economically viable. It has also improved its energy efficiency. Although further improvements are expected through energy recovery it is unlikely to be substantial progress. In addition to the energy consumption, it is also important to consider the potential impacts of technologies and sea water capture infrastructure processes of brine removal and the impact on marine flora and fauna. The use of chemicals in the pretreatment desalination process and cleaning must also be taken into account.

Hybrid systems can function in pre-treatment mode, where MED distillate feeds the RO; in cascade mode, where RO brine feeds the MED; or in parallel mode, where each system runs independently.

In the Middle East, the idea of hybrid plants has just lately gained traction. It involves putting one or more distillation desalination units and one or more reverse osmosis desalination units on the same location, along the sea's edge the figure below in parallel mode.

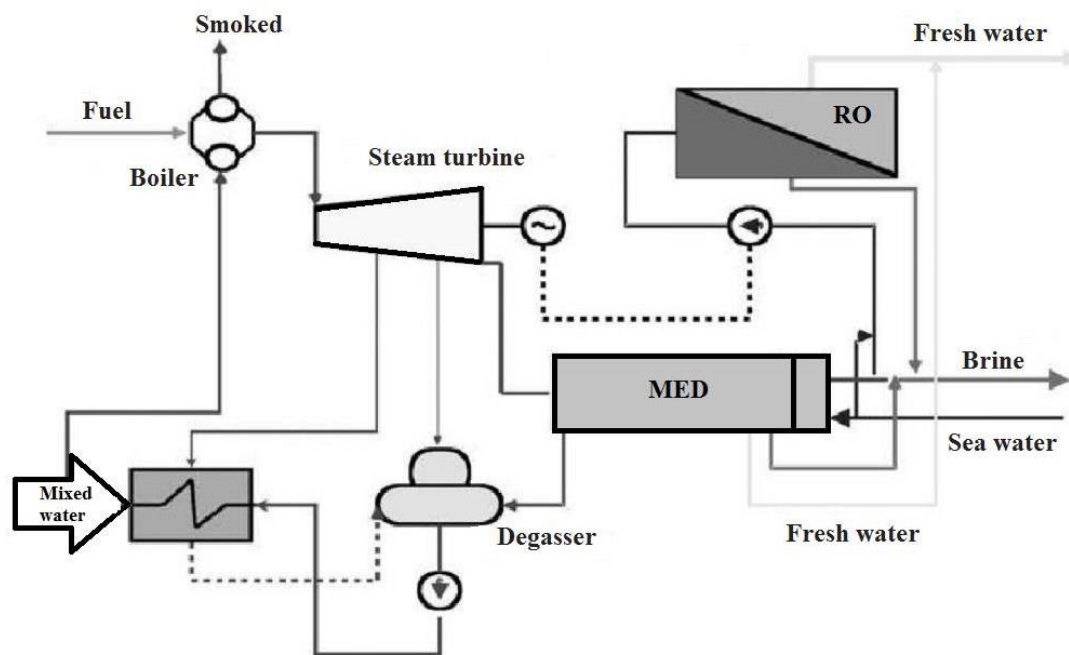


Fig IV.4: Details of hybrid plant (Maurel., 2006).

Such a system has several benefits:

By using seawater that has been heated to 40°C by the distillation unit, the RO unit's output may be increased by 3% per °C, greatly lowering the amount of saltwater used in both processes. Water that meets drinking water requirements may be obtained by mixing the water from the reverse osmosis unit (salinity 400 ppm) with that from the distillation unit (salinity around 25 ppm); The distilled water's low salinity can sometimes inhibit the reverse osmosis unit's ability to pass through a second stage and decrease the membrane's surface area by a factor of two. If usage of water is anticipated, the distillation device's efficiency can be changed to enhance the water/electricity balance.

Tab IV.10: Results of hybrid installation (RO/MED) (Miah El Taref, 2024).

Seawater salinity	40 000 ppm
Temperature	12-28 °C
Energy	42.32 MW
Fresh water production	
RO	220 000 m ³ /d
MED	110 000 m ³ /d
Total	330 000 m ³ /d

IV.2.5. Post-treatment and drinking water system

Usually, system design, regulatory requirements, and finished water quality standards dictate the selection and order of posttreatment processes that's typically required based on a number of elements that fall into a number of categories and are all connected to the quality of the water: Stability of chemicals, microbiological consistency, customer acceptability and palatability.

To increase their acceptability in particular to lessen their aggressive attack on materials desalinated water are sometimes mixed with little amounts of more mineral-rich fluids. When using seawater for this purpose, the main ions added are sodium and chloride. Blending water should be completely drinkable. For a lot of water suppliers concern has recently been raised over the effects of major ion composition or ratio extremes on human health (Duranceau., 2009)

➤ **CO₂ storage and metering**

To achieve the required drinking water quality carbon dioxide is injected into the permeate line before passing through the calcite beds. A system for storing and dosing CO₂ has been considered to guarantee one month autonomy; three tanks of minimum capacity 81 tons will be installed. Carbon dioxide will be injected into a stream of permeate water under pressure is then mixed into the total flow to be treated in calcite beds.

Tab IV.11: CO₂ metering pumps*.

Total required flow	m ³ /h	250
Number of pumps in operation	unit	1
Number of pumps in reserve	unit	1
HMT	bar	6

➤ **Calcite beds**

Remineralization considering the permeate quality of reverse osmosis projections approved by the customer (design with 356 pressure tubes installed per chassis). For better operation of the calcite beds, two blowers (one in operation and one in reserve) will be installed. Estimated airflow 75 m³/h/m².

- Storage quantity required: 1 681 813 kg.

Tab IV.12: Water quality of permeate*.

Parameters	Units	Min	Max
temperature	°C	12	28
Total mixed permeate flow	m ³ /h	12 500	12 500
TDS	mg/l	233	405
Ca ²⁺		24,18	24,09
Mg ²⁺		1,59	3,62
TH	ppm CaCO ₃	67,00	75,13
Calcium hardness		60,45	60,23
Na ⁺	mg/l	48,34	110,00
K ⁺		2,4	6,559
HCO ³⁻		73,19	72,13
Alkalinity	ppm CaCO ₃	59,99	59,12
SO ₄ ²⁻	mg/l	3,47	7,90
Cl ⁻		79,21	180,30
NO ₃ ⁻		0,00	0,00
B		0,54	1,29

CO ₂ libre		4,05	3,95
Ph	-	7,60	7,61
Conductivity	μS/cm	330,82	574,98

There are two tanks of water produced and pump station of water produced take into account the modes of normal operation and securing pumps in “Chaïba” from flow to pump (10 000m³/h) and “Lac des Oiseaux” (12 500m³/h).

Two chemical transfer pumps with two dosing pumps in operation, two chemical storage tanks for 15 days storage.

Tab IV.13: Design of major chemical assays (Miah El Taref, 2024).

Chemical product	Objectif	Area
Sodium Hypochlorite	Disinfection	Pretreatment (Capture Towers and Capture Basin)
Sulphuric acid	pH adjustment	
Ferric chloride	Coagulation	Pretreatment
Polyelectrolyte	Flocculation	
Sodium metabisulfite	Free chlorine removal	RO membrane system
Antiscalant	Scale inhibitor	
Sodium hydroxide	pH adjustment	
Citric acid	Chemical cleaning	
Sodium EDTA		
Sodium hydroxide		
Calcite	Remineralization	Post- treatment
CO ₂ dosage	Remineralization	
Sodium hydroxide	pH adjustment	
Sodium hypochlorite	Disinfection	
Polyelectrolyte	Dehydration (calculation will be submitted later)	Sludge treatment
Sulphuric acid	Chemical solution neutralization	Neutralization system
Sodium hydroxide	Chemical solution neutralization	

Tab IV.14: Storage system*.

Maximum consumption in pretreatment per day	l/day	2.571
Free time with storage product	day	7
Number of storage tanks	units	2
Volume of each storage tank required	m ³	8
Volume of each storage tank adopted		8
Diameter of each storage tank	m	2
Height of each storage tank		2.5

IV.2.6. Sludge treatment system

The dimensioning of the sludge line must be carried out taking into account two fundamental data, the intake of expected solids in suspension which is a data that the AEC has clearly defined at 200 ppm and the discharge limit to be established in the environmental impact study which remains to be determined.

The treatment of the sludge line includes a phase of sludge thickening, a dosage of polyelectrolyte and a centrifugation step to end in a silo from which a truck will collect the sludge at a concentration of 20%. The water recovered during the sludge dewatering process will be sent to the discharge chamber where it will be mixed with the brine for subsequent discharge at sea in accordance with regulations.

- ❖ The calculations of sludge discharge and dehydration line for 15 ppm, 65 ppm, 100 ppm and 200 ppm suspended solids scenarios.

IV.3. Calculation of investment costs

A number of important elements and considerations need to be taken into account for desalination facilities to calculate CAPEX

Tab IV.15: The basic elements for calculating CAPEX.

Equipment	Quantity	Capacity
Bar Screens	2+1S Units	2,6m. 3,7m. spacing 30mm

Rotary Screens	2+1S Units	(3mm) washing pump included
Flocculation Chamber	28 Chamber	$T_{\text{retention}}=14,2$ min ; V per chamber= 7616m^3
Lamella Settler	14 Units	$T_{\text{retention}}=20$ min ; V per chamber= 864m^3
Sand Filters (Anthracite+ sand gravel)	32 Installed Units in two lines. Line 1: 16 Units (14 in operation, 1 in backwashing, 1 under maintenance)	SDI water filtered at 100% of the time is ≤ 5 and at 95% of the time will be ≤ 4
Air Blower	1 Unit for Sand Filter (Line 1) + 1 Unit (Line 2) + 1S Unit	$Q = 3700 \text{ m}^3/\text{h}$, HMT = 0.6 Bar $T=15\text{min}$ Air rate = $50 \text{ Nm}^3/\text{h}$
Cartridge Filters (vertical)	14 Units Line 1: 6+1S Units Line 2: 6+1S Units	474 Cartridges per Unit polypropylene L=70inch
Air Blowers for Calcite Bed	1+1S Units	$Q = 2304 \text{ Nm}^3/\text{h}$, HMT = 0.7 Bar
Tanks		
Filtered Water Basin		$V = 2200 \text{ m}^3$
Backwash Water Discharge Tank		$V = 450 \text{ m}^3$
Filtered Backwash Water Tank		-
Wastewater Collection Basin		-
Brine Discharge Sump		-
CIP Tank	1+1S Units	$V = 250 \text{ m}^3$ (FRP)

Neutralization Basin		V = 15 m ³ (Concrete)
Chemical Product Dissolution and Mixing Tank	One + (1+1S) transfer pumps + 2 FRP cartridge filters	V = 5 m ³ (FRP)
Rinse Tank	1 Unit	V = 250 m ³ (FRP)
CO Storage	1 Unit	V = 245 Tons
Drinking Water Reservoirs	1 Unit	V = 15 000 m ³ (Concrete)
Thickener	2 Units	ø = 16 m V=1729 m ³ /chamber
Polyelectrolyte System	2 Units	Capacity = 25 kg/h
Mechanical Sludge Dewatering	2 Units	
Silo	2 Units	V = 100 m ³
Reverse Osmosis		
RO System (First Pass)	356 Pressure Tubes / Skid	125m ³ /skid
Pressure Exchanger	10 Modules, 26 Chambers per Module	Px
Cartridge Filter	1+1S Units	550 Cartridges per Unit
membranes Model 7XTM820MM440	24920 = 3560 recipients* 7	36000-40000 ppm; 12-28°C; age 5yrs; R=45%

Cleaning and Rinsing System	2+1S Units	Q = 1467 m ³ /h, HMT = 28-50 m.w.c
Calcite Beds	2 Lines, 8 Units per Line	
Rinsing Pumps for Rotary Screen and Bar Screen	1+1S Units	Q = 28 m ³ /h, HMT = 30 m.w.c.
Seawater Pump (in load, super duplex steel, horizontal, automatic, pressure regulator, R=80%)	5+1S Units	Plant Design Flow = 6440 m ³ /h, HMT = 26- 30 m.w.c.
Sludge Pumps	14 Lines	Plant Design Flow = 42 m ³ /h, HMT = 1 bar
Intermediate Pumps	5+1S Units	6310 m ³ /h, HMT = 48-59 m.w.c.
Sludge Pumps	3+1S Units	Q = 50 m ³ /h, HMT = 6 m.w.c.
Washing Pumps	1+1S Units (Line 1) 1+1S Units (Line 2)	Q = 2600 m ³ /h, HMT = 12-15 m.w.c.
High-Pressure Pumps	6 (5W+1S) Units	2784 m ³ /h, HMT = 541-771 m.w.c.
Booster Pumps	10 Units	1664 m ³ /h, HMT = 21-39 m.w.c.
Neutralization Pumps	1+1S Units	Q = 75 m ³ /h, HMT = 1.5 bar

Chemical Cleaning Solution Preparation Pumps	1+1S Units	Q = 40 m ³ /h, HMT = 1.5 bar
CO₂ Dosing Pump	1+1S Units	Q = 250 m ³ /h, HMT = 6 bar
Service Water Pump	1+1S Units	Q = 30 m ³ /h, HMT = 6 bar
Drinking Water Pumps(Horizontal centrifugal pump	1+2S (Line 1) 1+2S (Line 2)	3.4m ³ /h 9.09m ³ /h
Potable Water Network Pumps	1+1S Units	Nominal Q = 15 m ³ /h, HMT = 6 bar
Centrifugal Feed Pumps for Sludge Treatment	2+1S Units	Q = 32 m ³ /h, HMT = 20 m.w.c.
Polyelectrolyte Pumps	2 Units	Q = 3200 l/h, HMT = 2 bar
Sludge Pumps	1+1S Units	Q = 8 m ³ /h, HMT = 20 m.w.c.
Dosing Pump	2+1S Units	-
Piping (8 principal) FRP		
Pipe 46 km		DN1500mm, Steel PN16
Pipe 25 Km		DN1800mm, Steel PN25

IV.4. Exploitation costs

The main components of a desalination plant's operation are power consumption costs, workforce size, maintenance requirements, and chemical usage. This is crucial for the effective administration, financial oversight, and sustainability of the desalination initiative. To forecast

total operating expenses and Reverse Osmosis forecasts, additional investigations may explore more intricate financial models based on the criteria listed in the table below, including labor rates, energy expenses, and chemical costs.

Tab IV.16: The basic elements for calculating OPEX*.

	The consummation	unit
Energy		
Apparent power	49.79	MVA
Energy	42.32	MW
Specific consummation	3.26	KWh/m ³
Staff		
Engineer	10	12 monthes
Operator	5	
Laborantins	6	
Security guard	6	
Workers	12	
Chemicals		
Flocculants		Kg
Average quantity of product (flow rate for plant design capacity)	16,3	kg/h
Maximum product quantity (flow rate for plant design capacity)	48.8	
Average quantity of product (nominal flow)	14,8	
Maximum quantity of product (nominal flow)	44,3	

Sequestrent	-	-
Density of commercial product	1.2	kg/l
Sodium metabisulfite	-	-
sodium hydroxide Density of commercial product	1.27	kg/l
Maintenance: The annual maintenance cost of the entire station amounts to 5% of the investment price		
Administrative costs and membrane change		

Conclusion

In light of this study, it appears that the optimal hybrid method for a desalination plant with an installed capacity of 300 000 m³/day would incorporate a combination of RO membrane processes and distillation technologies such as MED, which remains a variant offering greater resilience and sustainability of the public drinking water service in the event of a process shutdown for one of the reasons mentioned in Chapter 1 above.

However, the hybrid RO option combined with the VCD process remains unsuitable for the time being, as compression distillation is unsuitable for large plants with a production capacity of more than 80 000 m³/day, compared to the MSF process, which remains more reliable but also more expensive and energy-intensive at over 27 kWh/m³.

Furthermore, it is crucial to recognize that enhancing the efficiency of the MED process, by integrating the energy demands of the thermal power plant with the desalination plant, can be achieved by utilizing the residual heat from the thermal power plant to generate the steam necessary for the MED process, as well as recovering energy from the reverse osmosis pumps when these processes are amalgamated in a hybrid system.

This plan would ensure consistent output while maximizing investment and operational costs. Moreover, incorporating environmental conservation strategies at a desalination facility is crucial for maintaining the United States' Sustainable Development Goal 14, which seeks to protect and sustainably utilize oceans, seas, and marine resources, while also ensuring the project's enduring viability. This strategy facilitates a balance among technical progress, potable water production, and marine environment conservation, serving as a vision for the future chapter.

CHAPITRE V

ENVIRONMENTAL PRESERVATION STRATEGIES FOR THE PLANT SITE IN LINE WITH SDG14

Introduction

There are two main types of impact on marine life: Impingement or crushing: when adult or large aquatic organisms become trapped against the screens or filters due to the water flow. For instance, the water flow may strike or immobilize a large fish against the screen. The second type is entrainment (trapping): when small organisms such as plankton, larvae or even fish are sucked into the water and pass inside the facilities, which can harm their life cycle (Voutchkov., 2011).

With an emphasis on technological innovation, cost reduction and performance optimization, the future of using renewable energy sources in water desalination is bright. Enhancing the efficiency and durability of desalination systems powered by renewable energy sources may be made possible by advancements in fields like energy storage, desalination membranes and artificial intelligence. The solar desalination center for Barka's seawater in Oman, the project to desalinate Al Khafji's seawater in Saoudite, Arabie the Djiboutian Wind-Powered Water Desalination Project. The Kwinana project in Perth, Australia, which uses wind energy, depends on an efficient integration of hydroelectric energy.

Burning fossil fuels releases a lot of toxic chemicals and greenhouse gases into the atmosphere. A seawater desalination process using fossil fuels to produce 10 million m³/day of water is estimated to release 200 million tons of CO₂, 200 000 tons of SO₂, 60000 tons of NO_x, and 16 000 tons of volatile organic compounds (VOCs) annually. Therefore, given the 40 million m³/day desalting plant capacity that is already in existence worldwide, total emissions would be four times these values; however, this might be avoided if desalination were powered by renewable energy sources. It is anticipated that fresh water can be generated using the desalination technology now in use.

Additionally, Xue et al., 2013 investigated the use of graphene single-leaf. Their calculations showed that these materials might achieve a complete rejection of the ions present in seawater while providing very high-water permeability, thereby outperforming conventional inverse osmosis membranes. Chiavazzo et al., 2017 developed a solar distillatory that is passive, adjustable, and reasonably priced.

Their device has achieved a distillation threshold of around 3 l/m²/h under solar energy below the sun, providing a promising alternative for isolated communities or emergency situations. For instance, a study by Do et al. (2023) demonstrated the effectiveness of farad-ionized water (FDI) in desalinating seawater. The authors showed that using special high-charge surface electrodes along with small channels can greatly reduce the salt in water while also making the process use energy more efficiently.

V.1 Type and origin of rejects

V.1.1 Atmospheric rejects

Water desalination techniques need a lot of energy, yet this consumption may be decreasing as a result of technological advancements. Nevertheless, the energy used frequently comes from fossil fuels, which results in the emission of air pollutants such carbon dioxide, sulfur and azote oxides, as well as solid particles. This might result in the daily emission of millions of tons of CO₂ for a production of several million-meter cubes each day. In the context of current attempts to combat climate change, this contribution to the cooling effect is significant.

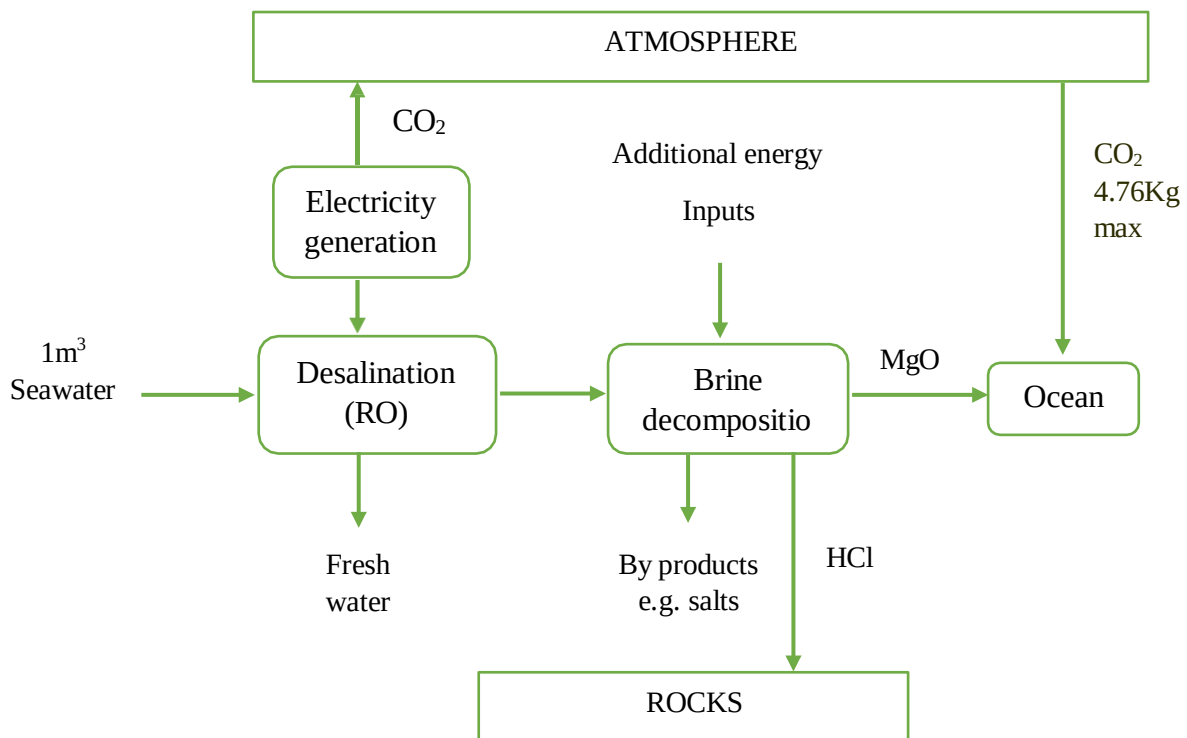


Fig V.1: Concept of proposed process using desalination reject brine to absorb carbon dioxide from the atmosphere (Davies, 2015).

Desalination facilities have indirect effects on the atmosphere even when they don't directly release large volumes of pollutants into the sky:

- **Energy Use:** Desalination requires a lot of energy. It adds to greenhouse gas emissions if it is fueled by fossil fuels (Wave of innovation aims to make desalination sustainable)
- **Potential for CO₂ Sequestration:** Novel strategies are being investigated by using magnesium in reject brine. CO₂ from the atmosphere may be absorbed by utilizing solar thermal energy to convert magnesium chloride in the brine to magnesium oxide and then to magnesium carbonate. The CO₂ emissions linked to the desalination process might be compensated for by this technique.

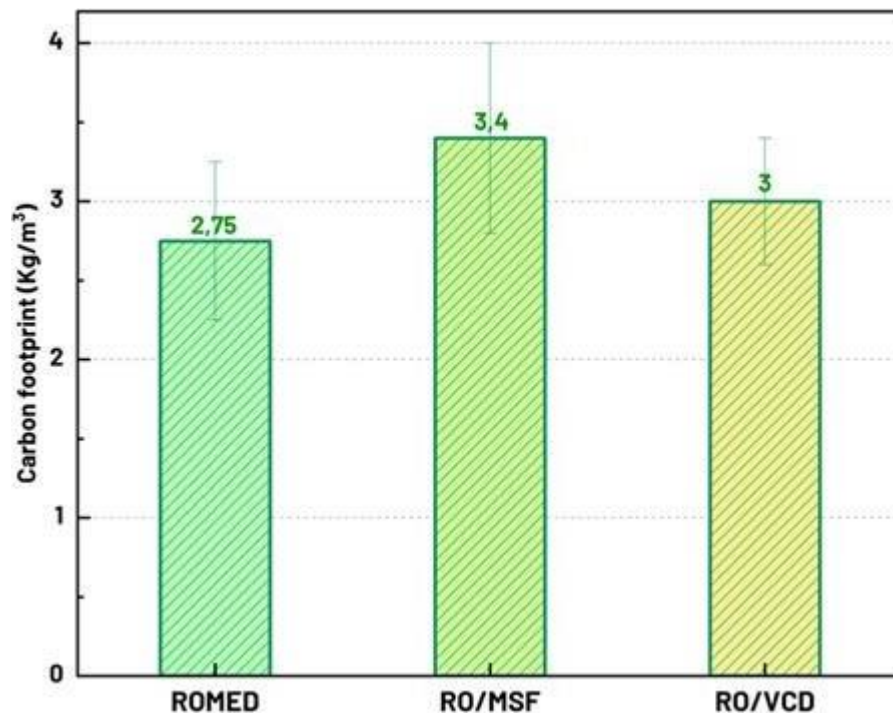


Fig V.2: The carbon footprint (Kg/m³) for a hybrid desalination plant with a capacity of 300 000 m³/day.

RO/MED is the most climate-friendly hybrid for a 300 000 m³/day plant. It produces the least amount of CO₂ per m³, which results in the lowest overall daily emissions, which are about 825 000 kg CO₂/d. Then, with almost 1 million kg of CO₂ per day, RO/MSF is the most carbon-intensive of the three. The third type of hybrid desalination process has intermediate emissions, but they are still much greater than the first one.

V.12 Chemicals reject

All desalination plants look to chemical products for the pretreatment of drinking water and the post-treatment of produced water. The majority of these products are primarily used as flocculants, coagulants, anti-scale, and anti-corrosion agents, which increases the concentrated brine's composition. Furthermore, the composition of this concentrated sulfur is also impacted by the presence of certain metals that result from the corrosion of the installations (Al-Handhaly et al., 2003).

Concentrated brine rejections. The death of sensitive organisms near the emitter may result from high salt concentrations in the discharged waters as well as salinity fluctuations. Additionally, wastewater from desalination plants, which have a higher density than seawater, may end up in the ocean, which might have detrimental effects on benthic communities.

Tab V.1: The use of chemicals in desalination procedures and their effects on the environment (Tech 2024).

Type of Chemical	Examples	Function	Environmental potential Impact
Biocides / Disinfectants	Chlorine, ozone, chlorine dioxide	Kill microorganisms	Toxic to marine fauna
Antifoulants	Polyacrylates, phosphonates	Prevent biological fouling	Bioaccumulation, disruption of natural cycles
Anti-scalants	Citric acid, polyphosphates	Prevent salt deposits	Poorly biodegradable, sediment pollution
Acid / Bases	HCl, H ₂ SO ₄ , NaOH	PH adjustment	Local acidification / alkalinization
Coagulants / Flocculants	Ferric chloride, aluminum sulfate	Remove colloidal matter	Metallic residues
Cleaning agents	EDTA, acids, alkaline solutions	Chemical cleaning of membranes	Difficult to degrade, persistent in the environment
Heavy metals	Copper, iron, nickel	Originating from corroded piping	Chronic toxicity

A study on the desalination factory in Bou Ismaïl-Algeria, found the following concentrations in the rejected sample:

Tab V.2: Brine composition from desalination plant (Belhout et al., 2022).

Substance	Concentration in brine (mg/l)
PH	6.45
Sodium (Na ⁺)	17 600
Chloride (Cl ⁻)	29 700
Sulfates (SO ₄ ²⁻)	1010
Calcium (Ca ²⁺)	560
Magnesium (Mg ²⁺)	1090
Total dissolved solids (TDS)	68 000

V2 Dilution and dispersion techniques of discharges

To mitigate the environmental impacts of brine discharges from desalination plants, several strategies have been proposed and implemented globally. One common approach involves the use of dilution systems, such as multi-port diffusers, which allow the concentrated brine to mix more effectively with seawater, thereby reducing its salinity and temperature before discharge. This method helps minimize the localized impacts on marine ecosystems by improving dispersion and lowering toxicity levels (Kaya et al., 2009).

In addition, the selection of environmentally friendly pre-treatment chemicals is essential. Using eco-friendly anti-scales and safe biocides can greatly lower the amount of harmful chemicals in the brine, helping to keep marine life safe from dangerous substances that can build up in their bodies (Jayawardhana et al., 2019).

Another promising avenue is brine valorization, which involves recovering valuable minerals such as magnesium, lithium, or even rare earth elements from the brine, or repurposing it for use in aquaculture or salt production. These applications not only help reduce waste but can also enhance the sustainability and economic viability of desalination operations.

Tab V.3: Comparative summary of brine discharge management techniques.

Techniques	Principles	Avantages	Limitations	References
Multiport Diffusers	Several small high-velocity jets discharge brine to promote rapid mixing with seawater.	Rapid localized dilution; optimized design.	High construction cost; requires hydraulic modeling.	Lattemann et al., 2008 ; Roberts et al., 2010
Single Submerged Outfall	Brine discharged from a single underwater outlet without multiple ports.	Simpler installation.	Lower dilution capacity; stronger local impact.	Roberts et al., 2010
Blending with Power Plant Cooling Water	Brine is mixed with warm cooling water before being discharged.	Reduces salinity and temperature impacts.	Depends on proximity to a power plant.	Voutchkov (2011)
Coastal Mixing Basins	Use of shallow areas or constructed basins for passive natural dilution before open sea dispersion.	Passive approach; limited mechanical systems.	Requires large coastal areas; potential local ecological impacts.	Lattemann et al., 2008
Natural Currents Utilization (Timed Discharges)	Scheduling discharges during peak tides or strong currents.	Improves natural dispersion; minimal infrastructure cost.	Dependent on natural cycles; complex control needed.	Roberts et al., 2010
Deep-Water Diffuser Discharge	Discharge at great depths where salinity and temperature effects are naturally minimized.	Less surface impact; better natural dispersion.	High cost of installation and deep-water engineering.	Voutchkov (2013)

The most frequently suggested method is to utilize multiport diffusers in conjunction with a hydrodynamic modeling to optimize their positioning and design. The connection to renewable energy sources (to lower the thermal charge of the discharge) is also being researched more and more.

Monitoring and reducing marine pollution from desalination facilities requires a mix of procedural and technical techniques. First, in order to track salinity, pH levels, and heavy metal concentrations in brine discharge zones, it is imperative to implement continuous water quality monitoring systems, such as automated sensors and real-time data platforms. This makes it possible to identify detrimental alterations early and regulate outflows adaptively.

Tab V.4: Relevant airborne emissions produced by desalination systems based on fossil fuels (Cipollina et al., 2009).

Emission per m³ desalted water	MSF	MED	RO
kg CO₂	23.41	18.05	1.78
g dust	2.04	1.02	2.07
g NO_x	28.29	21.41	3.87
g NMVOC	7.90	5.85	1.10
g SO_x	27.92	26.29	10.68

Greenhouse gas and pollutant emissions per m³ of water generated, RO is unquestionably the most ecologically benign method. Due to their high thermal energy consumption, which is frequently provided by fossil fuels, thermal technologies (MSF and MED) are far more emission-intensive, particularly in CO₂, NO_x, and SO_x. In contrast, MED is somewhat better than MSF in all categories but still lags well behind RO.

V3. The effect of suspended solids on seawater collection in RO desalination and mitigation solutions

Fouling processes cause suspended particles to significantly lower RO membrane performance, leading to a 50% drop in permeate flux and a 15%–30% rise in energy use. The most successful mitigation techniques are combination of dissolved air flotation (DAF) + UF/MF systems (85-90% efficacy) for existing plants with difficult intake circumstances and subsurface intakes (95% effectiveness) for new facilities. Around the world, RO desalination has emerged as a vital method for the generation of freshwater. However, the effectiveness and durability of RO systems are seriously hampered by suspended particles in saltwater. This study looks into how suspended particulates affect RO desalination procedures and offers evidence-based suggestions for input methods to lessen these problems. (*Unique Wastewater Treatment Solutions Manufacture - JX Purification* [no date]) provide major obstacles to RO desalination systems in saltwater, largely by causing different membrane fouling processes. These consist of colloidal fouling from small particles, organic fouling from naturally occurring organic matter, biofouling from microbial growth and biofilm development, and inorganic scaling such calcium carbonate precipitation. Operational performance is significantly impacted by certain fouling types.

Permeate flow can drop by as much as 50% when fouling worsens, significantly lowering water output (Gude et al, 2017). Furthermore, greater operating pressures are required due to increased resistance across the membranes, which results in a 15–30% increase in energy consumption (Voutchkov et al., 2018). Additionally, membrane lifetime is jeopardized, operational lifespans may be reduced by up to 40% leading to a higher frequency of replacements. Lastly, membrane fouling reduces the effectiveness of pollutant removal, which degrades water quality (JMDesign [no date]).

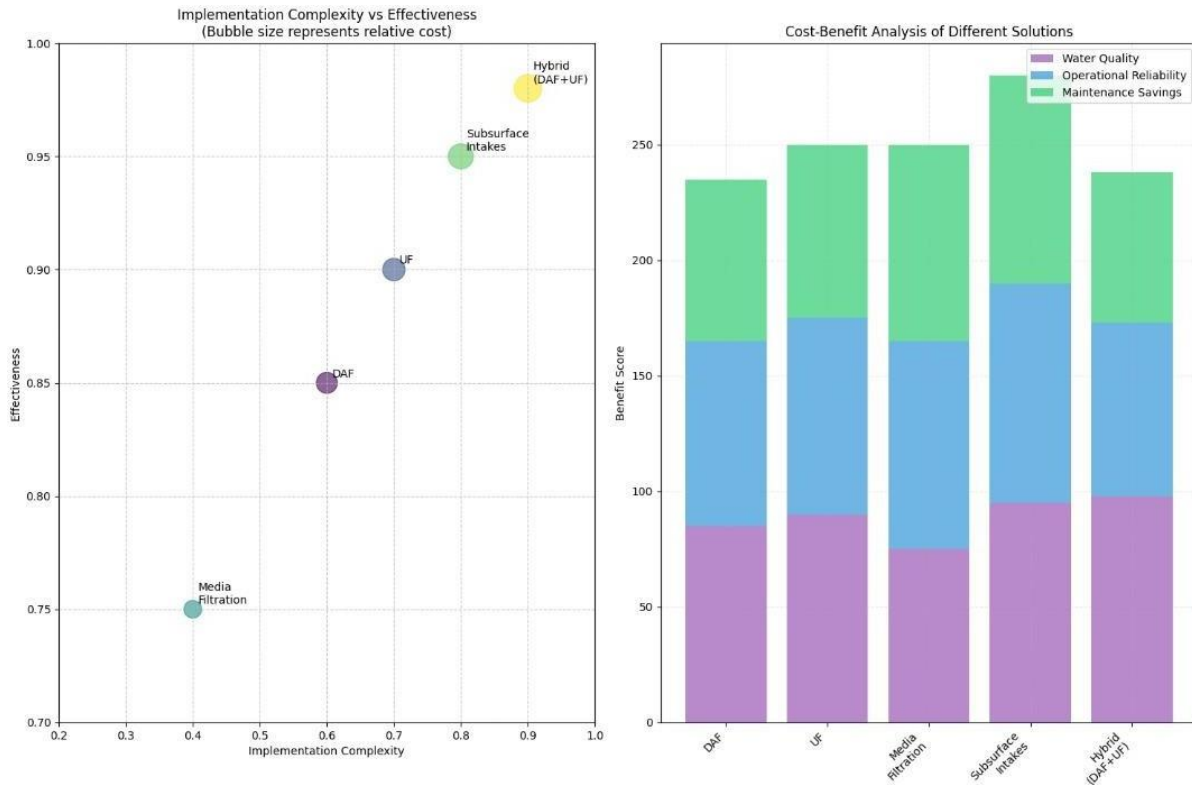


Fig V.3: Mitigation Solutions, cost benefits and complexity (Jafari et al., 2021).

This graph evaluates three performance criteria for each technology: water quality (in violet), which indicates the degree of purity achieved; operational reliability (blue), which shows the performance over time and maintenance savings (green), which indicates the long-term reduction of maintenance costs. One important thing to keep in mind is that the subsurface intakes offer the best overall balance of these three factors, whereas the Système Hybrid DAF+UF stands out for having great water quality even if it generates fewer maintenance savings.

The next visualization clearly demonstrates the trade-off between performance and investment by comparing the three main water treatment technologies (System Hybrid DAF+UF, subsurface intakes, and Media filtration) based on their effectiveness, implementation complexity, operational costs and profits.

According to recent studies, hybrid DAF+UF systems may reduce suspended materials by up to 99%; however, they come with 30–40% higher exploitation costs than conventional systems (Jamaly et al., 2014). According to Missimer et al., 2013, aquaculture can reduce the need for chemical products for treatment by 68% while also reducing the RO membranes' deterioration by more than 75%. Additionally, filtration on media provides the best cost-effectiveness ratio for removing particles larger than 10 μm , with operating costs that are lower than 40–60% compared to membrane technologies.



Fig V.4: An example of an ultrafiltration system that is a part of the DAF+UF hybrid system
(*Photovoltaics Report - Fraunhofer ISE* [no date]).

The figure below is a technical illustration that shows how the concentration of suspended solids affects the pace at which RO membranes foul and the associated pre-treatment requirements. Unfortunately, there is no source or information to determine where it came from (Filmtec™ reverse osmosis membranes. Technical Manual).

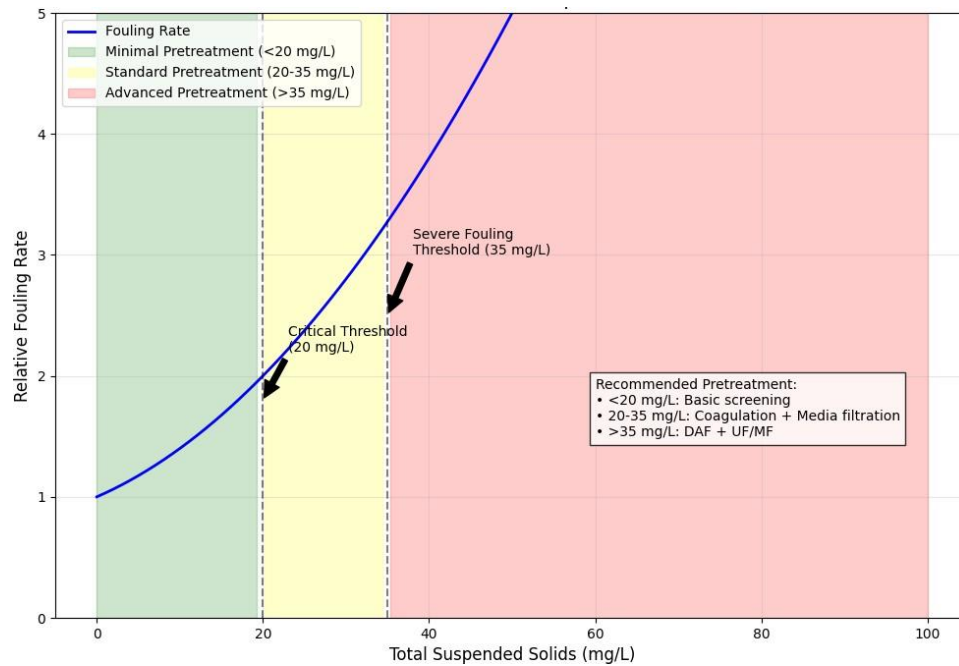


Fig V.5: Impact of suspended solids on RO membrane fouling rate and pretreatment requirements (Antony et al., 2011).

As demonstrated in the analysis above, total suspended solids (TSS) concentration directly correlates with membrane fouling rates, with critical thresholds determining pretreatment needs:

- **< 20 mg/l:** Minimal pretreatment required (Basic screening)
- **20-35 mg/l:** Standard pretreatment necessary (Coagulation + Media filtration)
- **> 35 mg/l:** Advanced pretreatment essential (DAF + UF/MF)

Even relatively low concentrations of suspended solids (20-35 mg/l) can double the fouling rate, highlighting the importance of effective pretreatment systems.

Several intake solutions have been developed to mitigate the effects of suspended solids:

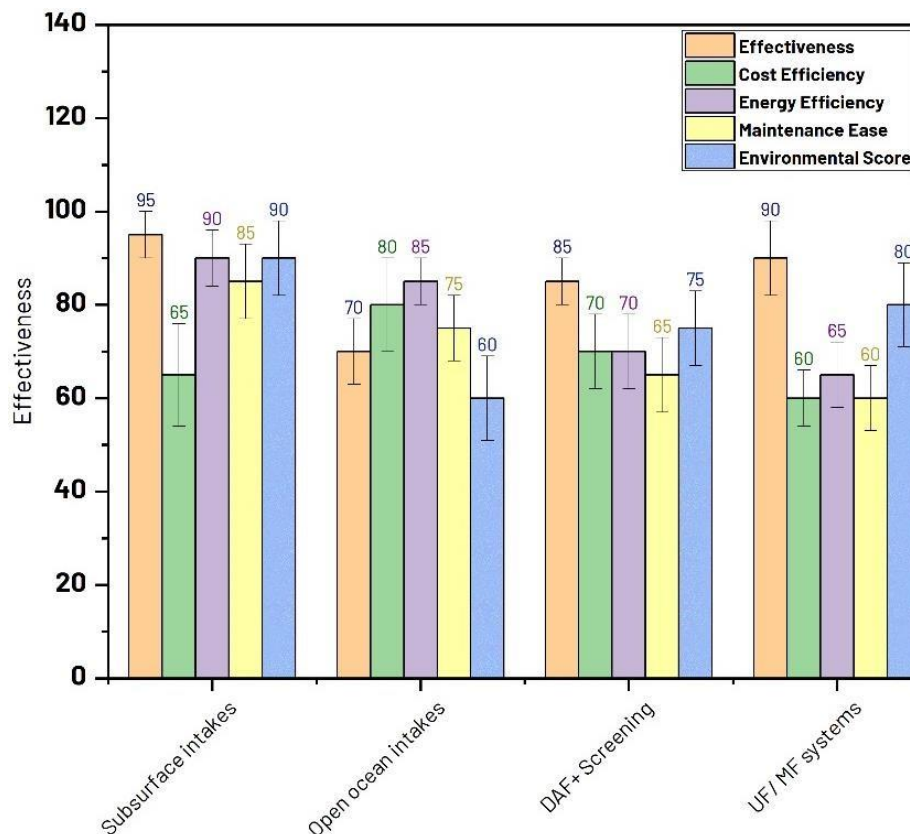


Fig V.6: Comparative analysis of seawater intake solutions for RO desalination plants (Tayeh et al., 2025)

Missimer et al., 2013 affirmed to by naturally filtering saltwater via sand and sediments, subsurface intakes such beach wells and infiltration tunnels have remarkable efficacy (95/100), greatly lowering suspended particles, organics, and biological pollutants. Nevertheless, they have site-specific limitations, reduced flow capacity, and increased capital expenditures. Large plants can benefit from open ocean intakes with advanced screening (effectiveness 70/100), which employ fine screens (80–120 microns). However, water quality might change during storms or algal blooms, necessitating further preparation and creating greater environmental concerns. Especially during algal blooms, DAF devices (effectiveness 85/100) effectively remove suspended particles using air bubbles; nevertheless, they need a substantial amount of energy and chemicals, as well as professional operation (*Ultrafiltration* [no date]).

V4 Recycling of brine

The goal of the zero liquid discharge (ZLD) water treatment procedure is to remove all liquid waste from a desalination plant. In the context of desalination, ZLD refers to a process in which all wastewater produced by a station is treated, recycled, or eliminated in a way that prevents any liquid from being released into the environment. The optimal system is created to maximize resource recovery.

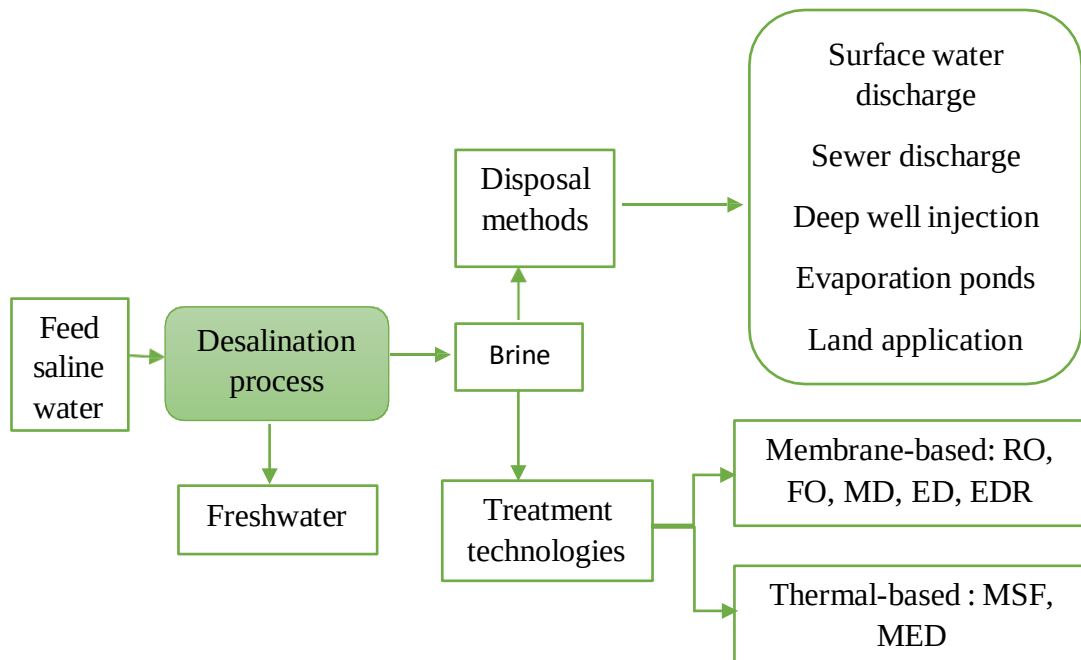


Fig V.7: The goal of the ZLD water treatment procedure (Panagopoulos et al., 2019)

As shown table below MSF plants thermal and salty discharges encourage algae development without altering community variety, maybe as a result of native species adapting to the severe circumstances in the Arabian Gulf. In the Eastern Mediterranean Sea (RO with power plant cooling water), salinity, temperature, and the presence of Fe-based coagulants have a number of effects, including decreased cell counts and chlorophyll levels as well as decreased phytoplankton growth efficiency when exposed to iron (Fe). The Eastern Mediterranean Sea's effects include temperature, salinity, phosphonate (P) anti-scales, and Fe coagulants, which reduce biodiversity and cause environmental imbalance.

Tab V.5: An overview of how desalination brine and chemicals released into the environment affect microbial populations (Belkin et al., 2015)

Area	Desalination technology	Stressor	Parameters	Observed effect (and stressor, when attributed)
Arabian Gulf	MSF	Salinity (S), Temperature (T)	Chlorophyll, Picoplankton, Zooplankton	Increase: PP, no change phytoplankton species composition
Eastern Mediterranean Sea Inconclusive changes: PP and BP Decrease: chlorophyll	RO with power plant cooling waters	Salinity (S), Temperature (T), Fe coagulant	Chlorophyll, Picoplankton number, PP, BP	Cell numbers (T and S) and phytoplankton growth efficiency (Fe)
Red Sea	RO	Salinity (S),	Picoplankton number	Reduced numbers (Dilution of effluent)
Eastern Mediterranean Sea	RO with power plant cooling waters	Salinity (S), Temperature (T), Fe coagulant, Phosphonate (P) Antiscalant	Chlorophyll, Picoplankton and bacteria numbers, PP, BP.	Increase: Gammaproteobacteria, BP (Fe+P) and cell specific BP (Fe+P) Decrease: Alphaproteobacteria and cyanobacteria, chlorophyll (Fe) and PP, diversity of bacteria.

V5. Adaptation with renewable energies

By balancing environmental preservation with economic efficiency, the use of renewable energy sources in the water desalination sector marks a dramatic shift toward sustainability. Using renewable energy sources like hydropower, wind, and solar energy for water desalination has several benefits.

Renewable energy-based technologies can be used to improve living conditions. Renewable energy typically provides a number of advantages over fossil fuels since it may reduce air pollution and carbon emissions. In the future, researchers want to see these technologies advance from pilot projects to commercial applications and contribute significantly to the world's electrical supply. The conceptual designs of popular renewable energy systems are covered in the sections that follow.

The Algerian government is aggressively looking for international suppliers with cutting-edge equipment and knowledge in important areas of renewable energy. Utility-scale solar PV engineering, high-efficiency PV modules, energy storage devices (rotors, batteries, and rotating equipment), and solar tracking systems are among the top priorities. Additionally, there is a need for off-grid solar systems, solar-powered water treatment units, agricultural solar kits, universal certification competence, and wind turbines and associated parts. From (The Algeria Country Commercial Guide lists) these requirements and emphasizes chances for foreign cooperation and investment.

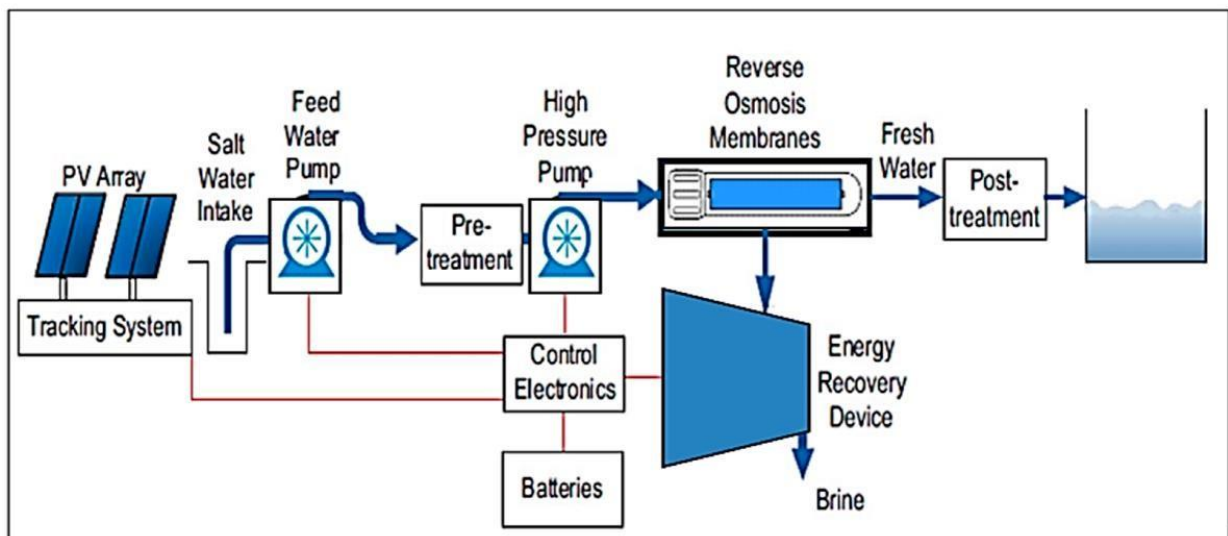


Fig V.8: A PV/RO desalination system illustration using an ERD (Al-Obaidi et al., 2024).

Desalination facilities can employ a number of tactics to increase energy efficiency and lower carbon footprints. By combining solar, wind, or tidal power, hybrid renewable energy systems can drastically cut greenhouse gas emissions and reliance on fossil fuels. Additionally, by collecting energy from the brine flow, energy recovery systems such as pressure exchangers can increase overall system efficiency and reduce emissions and operating costs. Kaya et al., 2009. Furthermore, the establishment of green infrastructure, including planting vegetation buffers around the building, may improve local biodiversity and absorb CO₂, making the operation more ecologically friendly (Jayawardhana et al., 2019).

For desalination operations to be sustainable, community involvement and adherence to regulations are equally important. To ensure that local concerns and environmental protection objectives are taken into account, the decision-making process should include stakeholder interaction with local communities, fishers, and environmental groups. Furthermore, adjusting operating strategies and reducing any environmental hazards are facilitated by routinely doing Environmental Impact Assessments (EIA) and revising them as necessary. Additionally, compliance with national environmental regulations and international agreements such as the Barcelona Convention and MARPOL guarantees that desalination facilities meet environmental requirements and support larger global conservation initiatives (Huang et al., 2021).

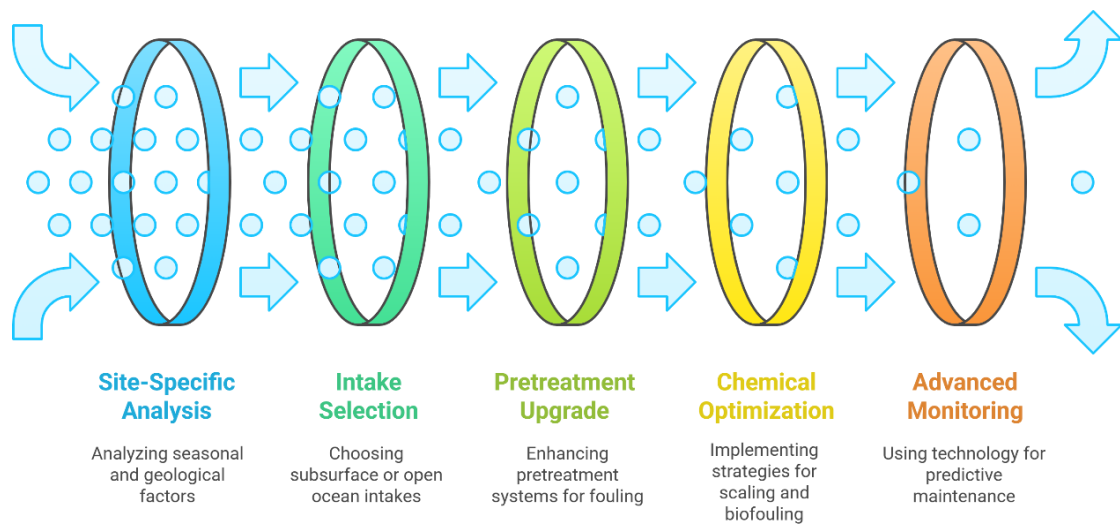


Fig V.9: Schematic illustration of the desalination plant process optimization.

Implementation and Recommendations

Based on the comprehensive analysis, the following recommendations are provided for different scenarios:

For new desalination plants

A. Conduct site-specific assessments:

- a. Analyze seasonal variations in suspended solids concentration
- b. Evaluate geological conditions for subsurface intake feasibility
- c. Consider environmental impact and regulatory requirements

B. Prioritize subsurface intakes where feasible:

- a. Implement beach wells or infiltration galleries when site conditions permit
- b. Design for appropriate hydraulic loading based on soil characteristics

C. For open ocean intakes:

- a. Select optimal locations with deeper, clearer waters
- b. Implement fine screening (80-120 microns) as first-stage protection
- c. Design flexible pretreatment systems to adapt to variable water quality

For existing plants facing fouling issues

D. Upgrade pretreatment systems:

- a. Implement DAF for facilities experiencing algal blooms or high organic loading
- b. Add UF/MF systems before RO membranes for enhanced protection

E. Optimize chemical pretreatment:

- c. Implement site-specific coagulation strategies
- d. Apply antiscals to prevent inorganic scaling
- e. Consider periodic shock chlorination with dichlorination for biofouling control

F. Implement advanced monitoring systems:

- f. Continuous monitoring of TSS, turbidity, and SDI (Silt Density Index)
- g. Develop automated response protocols for water quality fluctuations
- h. Utilize machine learning for predictive maintenance.

Conclusion

An increasingly significant component of the water processing sector is brine management. Brine discharge into open water bodies is not always feasible or environmentally sustainable, necessitating alternative disposal techniques. Meanwhile, the need for brine concentration has grown as a result of legislation and environmental concerns.

Suspended solids significantly impact the efficiency and longevity of RO desalination systems through membrane fouling, increased energy consumption, and reduced water quality. The optimal solution for mitigating these effects depends on site-specific conditions, plant capacities, and budget constraints. By implementing such solutions, desalination plants can enhance their resilience to variable water quality, reduce maintenance expenses, and ensure consistent production of high-quality drinking water.

Rejections of contaminants with high concentrations (around 70 g/l) and inadequate dilution may harm aquatic ecosystems while also lowering water quality. Installing diffuser systems allows for controlling the dilution of the water with seawater and limiting the extent of the affected area, which is the current approach being used to mitigate this environmental impact. Furthermore, it is crucial to conduct a review and monitoring of the removal of pests and chemical products, along with an assessment of the effects on wildlife and plants, both terrestrial and marine.

Overall Conclusion

This study effectively met a number of important goals pertaining to optimising water desalination technology. It also sheds important light on the problem of water stress in eastern Algeria, emphasising the pressing need for long-term solutions for managing water resources. Indeed, waves and currents stir up the seabed, increasing turbidity and the concentration of suspended matter. This results in a halt in production, potentially harming the quality of the public drinking water service and posing a mobilisation challenge in the eastern part of the country.

As part of this study, we evaluated and modelled the optimisation of a large-scale desalination unit using a hybrid configuration that combines membranes and thermal processes. We applied this solution to the actual Koudiet Draouche factory in El Taref. The results show that the combination of RO and MED technologies enables the conciliation of operational reliability, economic optimisation and energy efficiency. The Reverse Osmosis (RO) process, which is known for its low specific electrical energy consumption and lower investment costs, can be advantageously coupled with the MED process, whose performance is less sensitive to the quality of the alimentation water and which can take advantage of low-temperature heat sources, such as renewable energy sources or industrial waste.

The technical and economic analysis carried out using different hybrid desalination scenarios has highlighted the benefits of coupling the two processes in a proportionate manner, enabling a significant reduction in operating costs (OPEX) while ensuring the sustainability and flexibility of drinking water production, an improvement in water quality and greater resilience to external disturbances (variability in salinity, power cuts, etc.).

In addition, research into the integration of renewable energies (photovoltaic, solar, thermal and wind) has made it possible to assess the viability of reducing the carbon footprint of a hybrid desalination system, particularly in the context of the national energy transition policy.

The feasibility of a hybrid model partially powered by renewable energy sources is confirmed by an assessment of land availability based on specific energy requirements (kWh/m^2). With this target in mind, it is important to highlight Algeria's efforts to introduce

renewable energies, which aim to produce 30% of its electricity needs from renewable sources by 2030, with an installed capacity of around 15 000 MW.

According to the National Renewable Energy and Energy Efficiency Plan (PNREEE), launched in 2015 and revised in 2019, renewable energy production is diversified into several types of installation: 13 575 MW of photovoltaic solar, 2000 MW of wind, 400 MW of biomass and 15 MW of geothermal (*Statistiques de Capacité Renouvelable* 2022).

The feasibility study for a desalination plant using the hybrid RO/MED process at the Koudiet Draouche site found that, when looking at the funding, the costs for building (CAPEX) and running (OPEX) the plant make sense considering the challenges and specifics of (*TORAY MEMBRANE* | *TORAY* [no date]).

The recommended hybrid solution (RO/MED) offers advantages in terms of water safety and greater flexibility in plant operation while minimising OPEX expenditure per cubic meter. This variant unquestionably offers better quality drinking water and less environmental impact, with a clear reduction in the volume of brine discharged into the sea and fewer chemical reagents.

We strongly suggest that this proposed desalination solution should be given serious consideration by the Algerian Energy Company (AEC) when studying future desalination plant projects with a view to optimising water resources and guaranteeing water security through the resilience of the water production system. This is especially important for regions where there are no other options for supplying drinking water from renewable resources, whether they are surface or underground.

BIBLIOGRAPHIC REFERENCES

1381, [no date]. International Trade Administration. . Online. Available from: <https://www.trade.gov/> [Accessed 28 April 2025].

ABUSHABAN, Almotasembellah, SALINAS-RODRIGUEZ, Sergio G., PASTORELLI, Delia, SCHIPPERS, Jan C., MONDAL, Subhanjan, GOUELI, Said and KENNEDY, Maria D., 2021. Assessing Pretreatment Effectiveness for Particulate, Organic and Biological Fouling in a Full-Scale SWRO Desalination Plant. *Membranes*. Online. 27 February 2021. Vol. 11, no. 3, p. 167. DOI 10.3390/membranes11030167.

accueil, [no date]. *Plan-bleu : Environnement et développement en Méditerranée*. Online. Available from: <https://planbleu.org/> [Accessed 21 March 2025].

ADDA, Asma, BEZARI, Salah, ABBAS, Mohamed, et al. Techno-economic feasibility of reverse osmosis desalination scale coupled with solar energy: Case of Algeria. *The Journal of Engineering and Exact Sciences*, 2024, vol. 10, no 3, p. 18299-18299.

ALABI, Adetunji. Insights into an emerging and bioenergy-producing desalination technology: Microbial desalination cells (MDCs). *Journal of Cleaner Production*, 2025, p. 145324.

AL-ABRI, Mohammed, AL-GHAFRI, Buthayna, BORA, Tanujjal, et al. Chlorination disadvantages and alternative routes for biofouling control in reverse osmosis desalination. *NPJ Clean Water*, 2019, vol. 2, no 1, p. 2.

AL-HANDHALY, Juma K., MOHAMED, A. M. O., et MARAQA, Munjed. Impact of chemical composition of reject brine from inland desalination plants on soil and groundwater, UAE. *Desalination*, 2003, vol. 156, no 1-3, p. 89.

AL-HOTMANI, Omer Mohamed Abubaker, AL-OBAIDI, Mudhar Abdul Alwahab, JOHN, Yakubu Mandafiya, et al. An innovative design of an integrated MED-TVC and reverse osmosis system for seawater desalination: process explanation and performance evaluation. *Processes*, 2020, vol. 8, no 5, p. 607.

AL-KARAGHOULI, Ali et KAZMERSKI, Lawrence L. Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. *Renewable and Sustainable Energy Reviews*, 2013, vol. 24, p. 343-356.

AL-OBAIDI, Mudhar A., ALSADAIE, Salih, ALSARAYREH, Alanood, et al. Integration of renewable energy systems in desalination. *Processes*, 2024, vol. 12, no 4, p. 770.

ANTONY, Alice, LOW, Jor How, GRAY, Stephen, et al. Scale formation and control in high pressure membrane water treatment systems: A review. *Journal of membrane science*, 2011, vol. 383, no 1-2, p. 1-16.

Astee - L'association française des professionnels de l'eau et des déchets, [no date]. Astee. Online. Available from: <https://www.astee.org/> [Accessed 03 April 2025].

BELHOUT, Dalila, TIGRINE, Zahia, MOSNEGUTU, Emilian Florin, et al. Management

of reverse osmosis concentrate by solar distillation. *Water Supply*, 2022, vol. 22, no 8, p. 6490-6503.

BELKIN, Natalia, RAHAV, Eyal, ELIFANTZ, Hila, et al. Enhanced salinities, as a proxy of seawater desalination discharges, impact coastal microbial communities of the eastern Mediterranean Sea. *Environmental microbiology*, 2015, vol. 17, no 10, p. 4105-4120.

BENAHMED, Abdelhafid, BESSEDIK, Madani, ABDELBAKI, Cherifa, et al. Investigating the long-term economic sustainability and water production costs of desalination plants: A case study from Chatt Hilal in Algeria. *Egyptian Journal of Aquatic Research*, 2025, vol. 51, no 1, p. 31-38.

BOUROUNI, K., M'BAREK, T. Ben, et AL TAE, A. Design and optimization of desalination reverse osmosis plants driven by renewable energies using genetic algorithms. *Renewable energy*, 2011, vol. 36, no 3, p. 936-950.

BUNDSCHUH, Jochen, KACZMARCZYK, Michał, GHAFFOR, Noreddine, et al. State-of-the-art of renewable energy sources used in water desalination: Present and future prospects. *Desalination*, 2021, vol. 508, p. 115035.

CHIAVAZZO, Eliodoro, MORCIANO, Matteo, VIGLINO, Francesca, et al. Passive solar high-yield seawater desalination by modular and low-cost distillation. *Nature sustainability*, 2018, vol. 1, no 12, p. 763-772.

CIPOLLINA, Andrea, MICALE, Giorgio, et RIZZUTI, Lucio. Seawater desalination. *Green Energy and Technology*, 2009.

DAVANI, Abbasali, KASHFI, Mehdi, et MOZAFARY, Vahid. Experimental analysis of a multistage water desalination system utilizing an evacuated parabolic solar trough with a solar tracker. *arXiv preprint arXiv:1712.06576*, 2017.

DAVIES, P. A. Solar thermal decomposition of desalination reject brine for carbon dioxide removal and neutralisation of ocean acidity. *Environmental Science: Water Research & Technology*, 2015, vol. 1, no 2, p. 131-137.

DesalData, [no date]. . Online. Available from: <https://www.desaldata.com/> [Accessed 17 April 2025].

DO, Vu Q., REALE, Erik R., LOUD, Irwin C., et al. Embedded, micro-interdigitated flow fields in high areal-loading intercalation electrodes towards seawater desalination and beyond. *Energy & Environmental Science*, 2023, vol. 16, no 7, p. 3025-3039.

Documents & Reports - All Documents | The World Bank, [no date]. *World Bank*. Online. Available from: <https://documents.worldbank.org/en/publication/documents-reports> [Accessed 14 April 2025].

DURANCEAU, Steven J. Desalination post-treatment considerations. *Florida Water Resources Journal*, 2009, p. 4-18.

EL-DESSOUKY, Hisham T. et ETTOUNEY, Hisham Mohamed. *Fundamentals of salt water desalination*. Elsevier, 2002.

ELTAWIL, Mohamed A., ZHENGMIN, Zhao, et YUAN, Liqiang. A review of renewable energy technologies integrated with desalination systems. *Renewable and sustainable energy*

reviews, 2009, vol. 13, no 9, p. 2245-2262.

EYL-MAZZEGA, Marc-Antoine et CASSIGNOL, Élise. Géopolitique du dessalement d'eau de mer. *Études de l'IFRI*, 2022.

FERIA-DÍAZ, Jhon Jairo, CORREA-MAHECHA, Felipe, LÓPEZ-MÉNDEZ, María Cristina, et al. Recent desalination technologies by hybridization and integration with reverse osmosis: A review. *Water*, 2021, vol. 13, no 10, p. 1369.

GHAFFOUR, Noredine, MISSIMER, Thomas M., et AMY, Gary L. Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability. *Desalination*, 2013, vol. 309, p. 197-207.

GUDE, Veera Gnaneswar. Desalination and sustainability—an appraisal and current perspective. *Water research*, 2016, vol. 89, p. 87-106.

GW, [no date]. . Online. Available from: <https://www.globalwaterintel.com/topics/desalination> [Accessed 16 April 2025].

GW, [no date]. . Online. Available from: <https://www.globalwaterintel.com/> [Accessed 07 April 2025].

HAMICHE, AitMimoune, STAMBOULI, A. Boudghene, FLAZI, S., et al. Desalination in Algeria: Current state and recommendations for future projects. *Thermo-Mechanics Applications and Engineering Technology*, 2018, p. 37-58.http://dx.doi.org/10.1007/978-3-319-70957-4_2

Home, [no date]. *American Water Works Association*. Online. Available from: <https://www.awwa.org/> [Accessed 21 March 2025].

Home, [no date]. KSA. Online. Available from: <https://ksa.com/> [Accessed 14 April 2025].
<https://doi.org/10.1016/j.watres.2010.04.036>

HUANG, Haibo, YANG, Chuanhe, HE, Chunhua, et al. Combining biofilm and membrane flocculation to enhance simultaneous nutrients removal and membrane fouling reduction. *Science of The Total Environment*, 2021, vol. 796, p. 148922.

HUEHMER, Robert P. Detailed estimation of desalination system cost using computerized cost projection tools. In : *12th annual conference, Desalination Visions for the Future*. 2011. p. 14-15.

JAFARI, M., VANOPPEN, Marjolein, VAN AGTMAAL, J. M. C., et al. Cost of fouling in full-scale reverse osmosis and nanofiltration installations in the Netherlands. *Desalination*, 2021, vol. 500, p. 114865.

JAMALY, S., DARWISH, N. N., AHMED, I., et al. A short review on reverse osmosis pretreatment technologies. *Desalination*, 2014, vol. 354, p. 30-38.

JAYAWARDHANA, Yohan, GUNATILAKE, Sameera R., MAHATANTILA, Kushani, et al. Sorptive removal of toluene and m-xylene by municipal solid waste biochar: Simultaneous municipal solid waste management and remediation of volatile organic compounds. *Journal of environmental management*, 2019, vol. 238, p. 323-330.

JMDESIGN, [no date]. Flotación por aire disuelto DAF y sistemas MBR. *Sigmadaf*. Online. Available from: <https://sigmadafclarifiers.com/> [Accessed 10 April 2025].

KAYA, Ahmet, AYDIN, Orhan, et DEMIRTAŞ, Cevdet. Experimental and theoretical analysis of drying carrots. *Desalination*, 2009, vol. 237, no 1-3, p. 285-295.

KHAWAJI, Akili D., KUTUBKHANAH, Ibrahim K., et WIE, Jong-Mihn. Advances in seawater desalination technologies. *Desalination*, 2008, vol. 221, no 1-3, p. 47-69.

LATTEMANN, Sabine et HÖPNER, Thomas. Environmental impact and impact assessment of seawater desalination. *Desalination*, 2008, vol. 220, no 1-3, p. 1-15.

LOTFY, Hesham R., STAŠ, Jan, et ROUBÍK, Hynek. Renewable energy powered membrane desalination—review of recent development. *Environmental Science and Pollution Research*, 2022, vol. 29, no 31, p. 46552-46568.

LUDWIG, Heinz. *Reverse Osmosis Seawater Desalination Volume 2: Planning, Process Design and Engineering—A Manual for Study and Practice*. Springer Nature, 2022.

LYONNET DU MOUTIER, Michel. Financement sur projet et Partenariat public-privé: la relation entre concédant et concessionnaire dans les BOT d'infrastructure. *Politiques et management public*, 2003, vol. 21, no 1, p. 1-25.

MAUREL, Alain. *Dessalement de l'eau de mer et des eaux saumâtres: Et autres procédés non conventionnels d'approvisionnement en eau douce*. Tec & doc, 2006.

MCKINNEY, Wes, et al. Data structures for statistical computing in Python. *scipy*, 2010, vol. 445, no 1, p. 51-56.

MIKLYAEV, Mikhail, JENKINS, Glenn P., et ADESINA, Precious P. *Ex-Post Evaluation of The Algerian SWRO Desalination PPP Program*. Queen's Economics Department, 2022.

MISSIMER, Thomas M., GHAFfour, Noredine, DEHWAH, Abdullah HA, et al. Subsurface intakes for seawater reverse osmosis facilities: Capacity limitation, water quality improvement, and economics. *Desalination*, 2013, vol. 322, p. 37-51.

MUHCEN, Majda and PROJECTS, Zawya, [no date]. Algeria to invest \$3bln in second phase of water desalination expansion. . Online. Available from: <https://www.zawya.com/en/projects/utilities/algeria-to-invest-3bln-in-second-phase-of-water-desalination-expansion-yulif0pn> [Accessed 02 April 2025].

NAJAFI, Fazil T., ALSAFFAR, Mona, SCHWERER, Serafina C., et al. Environmental impact cost analysis of multi-stage flash, multi-effect distillation, mechanical vapor compression, and reverse osmosis medium-size desalination facilities. In : *2016 ASEE annual conference & exposition*. 2016.

ODUNLAMI, Olayemi, VERSHIMA, Denen A., TAGBO, Chukwudi V., et al. Microbial desalination cell technique-A review. *South African Journal of Chemical Engineering*, 2023, vol. 46, no 1, p. 312-329.

PANAGOPOULOS, Argyris, HARALAMBOUS, Katherine-Joanne, et LOIZIDOU, Maria. Desalination brine disposal methods and treatment technologies-A review. *Science of the Total Environment*, 2019, vol. 693, p. 133545.

- PAPAPETROU, Michael, CIPOLLINA, Andrea, LA COMMARE, Umberto, et al.** Assessment of methodologies and data used to calculate desalination costs. *Desalination*, 2017, vol. 419, p. 8-19.
- Photovoltaics Report - Fraunhofer ISE, [no date].** *Fraunhofer Institute for Solar Energy Systems ISE.* Online. Available from: <https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html> [Accessed 21 May 2025].
- PLIMMER, Gill, 2024.** Wave of innovation aims to make desalination sustainable. *Financial Times*. Online. 22 March 2024. Available from: <https://www.ft.com/content/961507b3-b533-4a22-9b95-d32f97c05bce> [Accessed 10 April 2025].
- Public-Private Partnership Resource Center | Public Private Partnership, [no date].** . Online. Available from: <https://ppp.worldbank.org/public-private-partnership/> [Accessed 07 July 2025].
- QIU, Hu, XUE, Minmin, SHEN, Chun, et al.** Graphynes for water desalination and gas separation. *Advanced Materials*, 2019, vol. 31, no 42, p. 1803772.
- RIERA, Jefferson A., LIMA, Ricardo M., HOTEIT, Ibrahim, et al.** Simulated co-optimization of renewable energy and desalination systems in Neom, Saudi Arabia. *Nature communications*, 2022, vol. 13, no 1, p. 3514.
- ROBERTS, David A., JOHNSTON, Emma L., et KNOTT, Nathan A.** Impacts of desalination plant discharges on the marine environment: A critical review of published studies. *Water research*, 2010, vol. 44, no 18, p. 5117- 5128.
- ROBERTS, Philip JW, SALAS, Henry J., REIFF, Fred M., et al.** *Marine wastewater outfalls and treatment systems*. IWA publishing, 2010.
- SAMIA, Titi Benrabah, HOURIA, Kherici Bousnoubra, NACER, Kherici, et al.** Assessment and management of water resources in Northeastern Algeria: case of watersheds Kebir West Safsaf and Guebli rivers, Skikda. *Applied Water Science*, 2013, vol. 3, no 2, p. 351-357.
- SASSI, Kamal M. et MUJTABA, Iqbal M.** Simulation and optimization of full scale reverse osmosis desalination plant. In : *Computer Aided Chemical Engineering*. Elsevier, 2010. p. 895-900.
- SEABOLD, Skipper, PERKTOLD, Josef, et al.** Statsmodels: econometric and statistical modeling with python. *SciPy*, 2010, vol. 7, no 1, p. 92-96.
- SHAHZAD, Muhammad Wakil, BURHAN, Muhammad, ANG, Li, et al.** Energy-water-environment nexus underpinning future desalination sustainability. *Desalination*, 2017, vol. 413, p. 52-64.
- SIDDIQUI, M. U., GENEROUS, Muhammad M., QASEM, Naef AA, et al.** Explicit prediction models for brackish water electrodialysis desalination plants: Energy consumption and membrane area. *Energy Conversion and Management*, 2022, vol. 261, p. 115656.
- SINCERO, Arcadio P. et SINCERO, Gregoria A.** *Physical-chemical treatment of water and wastewater*. CRC press, 2002.
- SOLUTIONS, DOW Water.** Filmtec™ reverse osmosis membranes. *Technical Manual, Form*, 2010, vol. 399, no 609-00071, p. 1-180.

Statistiques de Capacité Renouvelable 2022, 2022. . Online. Available from: <https://www.irena.org/publications/2022/Apr/Renewable-Capacity-Statistics-2022-FR> [Accessed 18 March 2025].

SUEZ: an expert in water and waste management - SUEZ, 2025. . Online. Available from: <https://www.suez.com/en> [Accessed 28 April 2025]

TAYEH, Yousef A., ALAZAIZA, Motasem YD, ALZGHOUL, Tharaa M., et al. A comprehensive review of RO membrane fouling: mechanisms, categories, cleaning methods and pretreatment technologies. *Journal of Hazardous Materials Advances*, 2025, p. 100684.

TEAM, SWM Editorial, 2019. IDE Technologies. Smart Water Magazine. Online. 13 February 2019. Available from: <https://smartwatermagazine.com/ide-technologies> [Accessed 28 April 2025].

TECH, Genesis Water, 2024. Osmose inverse de l'eau de mer : la solution ultime. *Genesis Water Technologies*. Online. 8 June 2024. Available from: <https://fr.genesiswatertech.com/article-de-ce-blog/osmose-inverse-d%27eau-de-mer/> [Accessed 20 April 2025].

The Cost of Desalination, [no date]. . Online. Available from: <https://prod-cm.advisian.com:443/en/global-perspectives/the-cost-of-desalination> [Accessed 26 April 2025].

TORAY MEMBRANE | TORAY, [no date]. . Online. Available from: <https://www.water.toray/> [Accessed 10 March 2025].

Ultrafiltration, [no date]. . Online. Available from: https://xflow.pentair.com/en/our_technology/ultrafiltration.html [Accessed 02 May 2025].

Unique Wastewater Treatment Solutions Manufacture - JX Purification, [no date]. . Online. Available from: <https://www.jx-purification.com/> [Accessed 01 May 2025].

URREA, Sigrid Arenas, REYES, Felipe Díaz, SUÁREZ, Baltasar Peñate, et al. Technical review, evaluation and efficiency of energy recovery devices installed in the Canary Islands desalination plants. *Desalination*, 2019, vol. 450, p. 54-63.

VIRTANEN, Pauli, GOMMERS, Ralf, OLIPHANT, Travis E., et al. SciPy 1.0: fundamental algorithms for scientific computing in Python. *Nature methods*, 2020, vol. 17, no 3, p. 261-272.

VOUTCHKOV, N. (2011). Desalination Plant Intakes–Impingement and Entrainment–Impacts and Solutions.

VOUTCHKOV, N. (2013). Desalination engineering: planning and design.

VOUTCHKOV, N. (2018). *Desalination project cost estimating and management*. CRC press. Water, D. American Water Works Association.

Water Treatment and Management | ACCIONA | Business as unusual, [no date]. . Online. Available from: <https://www.acciona.com/solutions/water> [Accessed 28 April 2025].

WETTERAU, Greg. *Desalination of seawater: M61*. American Water Works Association, 2011.

What is build-operate-transfer (BOT)? | Learn how build-operate-transfer models work | Build-operate-transfer examples and benefits, 2025. Lumenalta. Online. Available from:

<https://lumenalta.com/insights/what-is-build-operate-transfer-bot> [Accessed 27 July 2025].

WILF, Mark et AWERBUCH, Leon. *The guidebook to membrane desalination technology: reverse osmosis, nanofiltration and hybrid systems: process, design, applications and economics*. Balaban Desalination Publications, 2007.

WITTHOLZ, Michelle K., O'NEILL, Brian K., COLBY, Chris B., et al. Estimating the cost of desalination plants using a cost database. *Desalination*, 2008, vol. 229, no 1-3, p. 10-20. <https://doi.org/10.1016/j.desal.2007.07.023>

ZHOU, Y. et al. (2021) : "Hybrid desalination systems for reduced energy consumption", *Desalination*, 500, 114852

ANNEX I.1

Conference programme on water desalination in October 1998

BLIDA, le 25 & 26 Octobre 1998

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JOURNÉE DU DIMANCHE, 25 / 10 / 1998

<i>HORAIRE</i>	<i>PROGRAMME</i>
8h.30 - 9h. 15	<i>Accueil et Enregistrement des Participants</i>
9h.15 - 10h.45	<i>Allocutions de Messieurs les Ministres</i>
10h.45-11h.00	<i>Discours de Monsieur Le Directeur de l'Ecole Nationale Supérieure de l'hydraulique</i>
11h.10 - 12h.00	<i>Visite des Stands d'Exposition</i>
12h.00 - 13h00	<i>Déjeuner à l'honneur des participants</i>
13h.10- 13h.40	<i>Mr B. BENGUEDDACH (M.E.A.T) Potentialités des Ressources en Eaux et leurs Affectations</i>
13h.45-14h.15	<i>Mr A. MELBOUCY (HYDRO-MARINE ingénierie) Augmentation et Economie de la ressource en Eau Douce par le biais de Moyens Non Conventionnels ; Impact et perspectives</i>
13h.15-14h.45	***DEBATS***
14h.45-15h.00	=====PAUSE CAFE=====
15h.05- 15h35	<i>Mr M.A. MASRI (I.A.P) L'Osmose Inverse dans le Dessalement d'Eau de Mer</i>
15h.40-16h.10	***DEBATS***

ANNEX II.1

A breakdown of the selling price of water from a desalination plant

Invoice Number
Dollar vs. Dinar Exchange Rate T_t
Dollar vs. Dinar Exchange Rate T_0
1/Availability Bonus (PRDO) (fixed costs):
Expatriate Personnel Costs
Costs of Subcontracted Services and O&M Headquarters
Spare Parts Costs
Membrane Costs (80% fixed cost)
Cleaning Chemical Costs
Operating Period Insurance Costs in Foreign Currency
Other Operating Costs in Foreign Currency
Investor Remuneration
Algerian Personnel Costs
Expatriate Personnel Costs (VF, CS, IRG)
Subcontracted Services Costs
Operating Period Insurance Costs in Dinars
Debt Service Cost
IBS on Foreign Subcontracts
IBS Due by the Project Company
TAP and Other Duties and Taxes
Customs Duties
Fixed Electricity Costs
Other Operating Costs in dinars
TOTAL AVAILABILITY BONUS:
WATER COSTS:
Cost of chemicals and filters
Cost of membranes (20% Variable cost)
Cost of chemicals and filters
Customs duties
Other Operating Costs in dinars
TOTAL WATER COSTS:
ELECTRICITY COSTS:
Cost of electricity
TOTAL ELECTRICITY COSTS:
OPEX VARAIABLES TOTAL

ANNEX III.1

Table of Student's critical values (t)

- t-values according to degrees of freedom (ddl = n-1) and confidence levels

ddl (n-1)	90% ($\alpha=0.10$)	95% ($\alpha=0.05$)	99% ($\alpha=0.01$)	99.9% ($\alpha=0.001$)
1	6.314	12.706	63.657	636.619
2	2.920	4.303	9.925	31.598
3	2.353	3.182	5.841	12.941
4	2.132	2.776	4.604	8.610
5	2.015	2.571	4.032	6.859
6	1.943	2.447	3.707	5.959
7	1.895	2.365	3.499	5.405
8	1.860	2.306	3.355	5.041
9	1.833	2.262	3.250	4.781
10	1.812	2.228	3.169	4.587
11	1.796	2.201	3.106	4.437
12	1.782	2.179	3.055	4.318
13	1.771	2.160	3.012	4.221
14	1.761	2.145	2.977	4.140
15	1.753	2.131	2.947	4.073
16	1.746	2.120	2.921	4.015
17	1.740	2.110	2.898	3.965
18	1.734	2.101	2.878	3.922
19	1.729	2.093	2.861	3.883
20	1.725	2.086	2.845	3.850
21	1.721	2.080	2.831	3.819
22	1.717	2.074	2.819	3.792
23	1.714	2.069	2.807	3.767
24	1.711	2.064	2.797	3.745
25	1.708	2.060	2.787	3.725
26	1.706	2.056	2.779	3.707
27	1.703	2.052	2.771	3.690
28	1.701	2.048	2.763	3.674
29	1.699	2.045	2.756	3.659
30	1.697	2.042	2.750	3.646
40	1.684	2.021	2.704	3.551
50	1.676	2.009	2.678	3.496
60	1.671	2.000	2.660	3.460
80	1.664	1.990	2.639	3.416
100	1.660	1.984	2.626	3.390
120	1.658	1.980	2.617	3.373
∞	1.645	1.960	2.576	3.291

- α = significance level ($\alpha = 1 - \text{confidence level}$)

ANNEX IV.1

Projections obtained from Toray membranes

RO system design data	Units	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO
TDS	Ppm	38 300				40 000			
Water temperature	°C	20		12				28	
Age of membranes	Yrs	0.5	3.5	0.5	3.5	0.5	3.5	0.5	3.5
recovery conversion	%	45							
total flow to be pumped	m³/d	666.667							
total flow to be pumped	m³/h	27.778							
High pressure pumping									
Flow rate to be pumped by high pressure systems	m³/h	12.653							
Number of high pressure pumps installed	Units	6							
Number of high-pressure pumps operating	Units	5							

RO system design data	Units	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO
TDS	Ppm	38 300				40 000			
Water temperature	°C	20		12				28	
Age of membranes	Yrs	0.5	3.5	0.5	3.5	0.5	3.5	0.5	3.5
Number of reserve high pressure pumps		1							
Nominal flow to be pumped for each high-pressure pump	m ³ /h	2530							
Maximum supply pressure to the membranes	Bars	58.6	60.6	63.5	66.7	66.3	69.8	58.2	59.6
High pressure pump discharge pressure	Bars	59.9	62.0	64.9	68.1	67.7	71.2	59.6	60.9
High pressure pump suction pressure (minimum)	Bars	2.2							
Differential pressure of the high-pressure pump	Bars	57.8	59.8	62.7	65.9	65.5	69.0	57.4	58.8
High pressure pump differential pressure	mce	573	593	620	652	647	682	570	584

RO system design data	Units	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO
TDS	Ppm	38 300				40 000			
Water temperature	°C	20		12				28	
Age of membranes	Yrs	0.5	3.5	0.5	3.5	0.5	3.5	0.5	3.5
Booster pumps									
Flow to be pumped by the booster pumps	m ³ /h	15 125							
Number of pumps installed	Units	10							
Number of pumps in operation	units	10							
Output per pump	m ³ /h	1512,5							
Maximum discharge pressure of the high-pressure pump	Bars	59.9	62.0	64.9	68.1	67.7	71.2	59.6	60.9
Differential pressure of the Booster pump	Bars	4	4.4	4	4.4	4	4.4	4	4.4
Booster pump differential pressure	mce	39.8	43.8	39.7	43.7	39.7	43.6	39.9	43.8

RO system design data	Units	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO
TDS	Ppm	38 300				40 000			
Water temperature	°C	20		12				28	
Age of membranes	Yrs	0.5	3.5	0.5	3.5	0.5	3.5	0.5	3.5
Energy recovery system									
Type of energy recovery system		ERI							
Chambers model		PX-Q300							
Total flow of brine to chambers	m ³ /h	15277.8							
Total inlet flow of seawater into chambers	m ³ /h	15 125							
Inlet flow of seawater into chambers (1 reverse osmosis chassis)	m ³ /h	1513							
Minimum inlet pressure of sea water in chambers	Bars	2.16							
Lubrication as % of brine flow rate		1.0%							

RO system design data	Units	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO
TDS	Ppm	38 300				40 000			
Water temperature	°C	20		12				28	
Age of membranes	Yrs	0.5	3.5	0.5	3.5	0.5	3.5	0.5	3.5
Number of installed reverse osmosis lines (chassis)	units	10							
Number of operating reverse osmosis lines	units	10							
Number of chambers per line	units	26							
Number of chambers installed	units	260							
Number of chambers in operation	units	260							
Nominal rate of the brine per chamber	m ³ /h	58.8							
Maximum rate of brine per chamber	m ³ /h	67							
Mixture	%	2.4							

RO system design data	Units	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO
TDS	Ppm	38 300				40 000			
Water temperature	°C	20		12				28	
Age of membranes	Yrs	0.5	3.5	0.5	3.5	0.5	3.5	0.5	3.5
RO system									
Nominal production conception	m ³ /d	300 000							
Membrane model Name		TM820M440							
Number of RO lines installed (chassis)	units	10							
Number of reverse osmosis lines in operation	units	10							
Production design of each line	m ³ /d	30 000							

RO system design data	Units	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO	10 racks of RO
TDS	Ppm	38 300				40 000			
Water temperature	°C	20		12				28	
Age of membranes	Yrs	0.5	3.5	0.5	3.5	0.5	3.5	0.5	3.5
Membranes per pressure tube		7							
Number of stages		1							
Number of pressure tubes per frame		356							
Total number of force tubes installed		3560							
Total number of force tubes in operation		3560							
Numbre of membranes per image		2492							
Total number membranes		24 920							